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Irrigation and the Environment

A review of environmental issues
Part II: Environmental considerations in planning and operation

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IRRIGATION AND THE ENVIRONMENT

A review of environmental issues

Part I Influence of Irrigation on the Environment and Vice-Versa

Part II Environmental Considerations in Planning and Operation

Part II Environmental Management for Irrigation

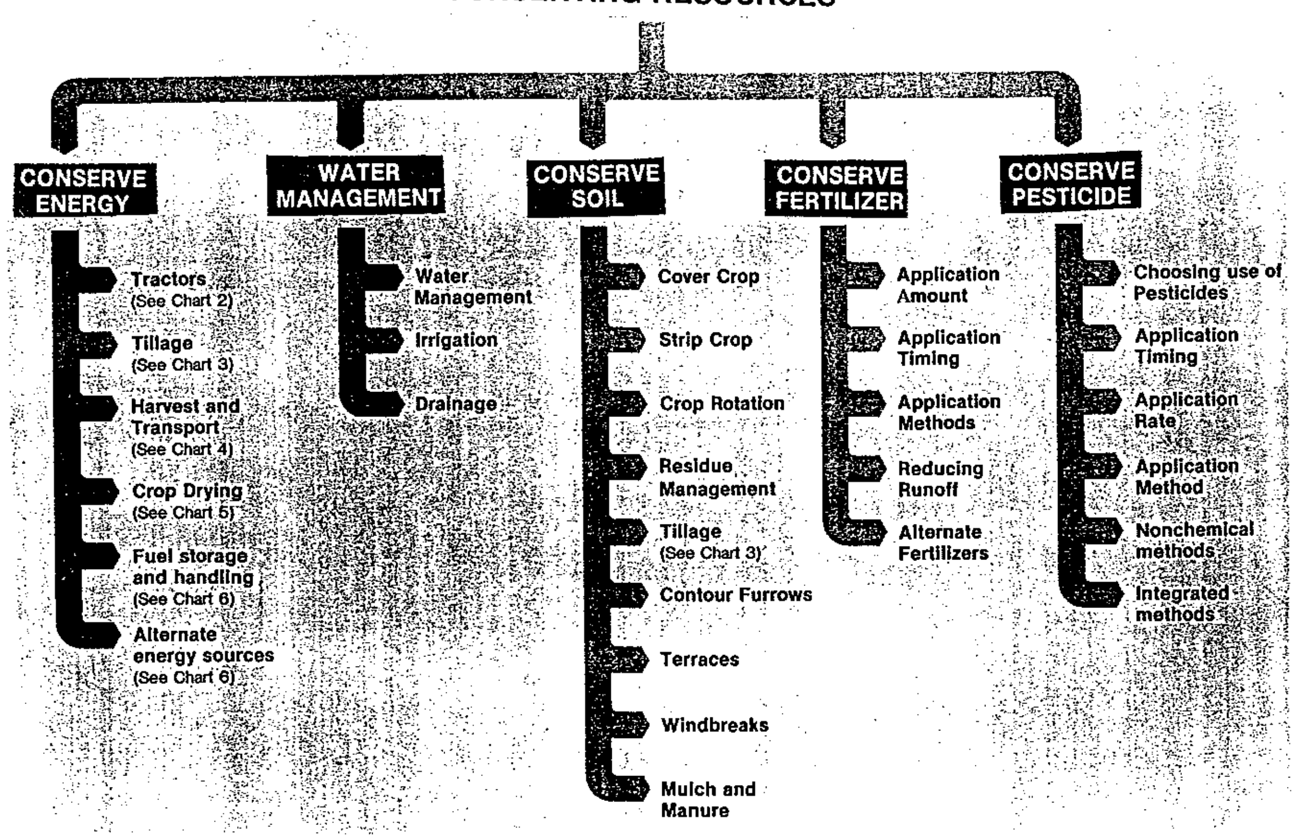
Tables

Fig. 01

CONSERVATION FARMING

Conservation farming is a system of management which combines two major objectives:

- *To maintain production of profitable, high yielding crops (Fig. 1)*
- *To conserve energy, water, soil, and other resources*



Source: Hughes 1980

Preface

This part of the review has been developed to serve as a working document to those engaged in environmental appraisals and management of irrigation projects. In this respect it is **complementary** to the 'GTZ-Working Aids for Operational Irrigation Systems Management' (Walker/Cleveringa eds., GTZ 1989). The planners and managers are typically confronted with a wide range of tasks and they need to digest a huge range of various information, from hydrological or pedological to health problems. This section should be helpful in identifying potentials and constraints to irrigation development in the context of promoting sustainability and the efficient use of natural resources: water, soils, biological resources, public health, and socio-cultural values which are related to the use of these resources.

This section should not be taken to be a universal recipies-book but rather as a multidisciplinary compendium. It is intended to **stimulate** and **facilitate** a situation-specific working process which provides information for environmentally sound recommendations and decision-making.

Environmentally sound planning of irrigation projects is nothing new and there are many recommendations for conservation farming available (see Fig. 01). The agricultural and engineering design methods and planning tools which are outlined in this section 3 have long been used by those designers and managers of irrigation projects who aimed at the development of **sustainable irrigation**. The wise use of land and water resources as well as the participation of the 'target group' has been in the past and will be in future the best way to achieve environmentally sound and sustainable irrigated agriculture.

There are, of course, some **new trends** in design, operation and maintenance of irrigation projects. These are the result of experience gained from the poor performance (low efficiency) of many projects, widespread degradation of natural resources, detrimental impacts imposed on other users of natural resources, the spread of water-related diseases, and from under-utilisation (or under-mobilisation) of human resources in irrigation development. The following sections focuses on those new trends.

The sections are **organised** so that they can be read individually, ie each chapter can be consulted to obtain information, independently from other chapters. Cross references are given at the beginning of each chapter. For detailed information the reader is referred to the figures and tables attached to the main text, although the references should be consulted for more detailed information.

By its nature, such a working document is a compromise between conciseness, comprehensiveness and ease of handling. Much information is highly generalised, providing guidance to decision-making or to conceptional recommendations. On the other side, attention is given to planning tools which can be used in environmental appraisals or by the specialist on the spot. It is acknowledged that this multidisciplinary compendium offers a lot of scope for amendments and suggestions to improve its usefulness are welcomed.

Environmental management is understood as a process which is aimed at the efficient and sustainable use of natural resources water, soils, air, bioresources, public health, socio-economic values associated with those goods (see Part I section 1). This includes the development of conflict minimising-strategies in situations where the scarcity of natural goods leads to competition amongst various users (see section 1.1).

The management functions are: planning, organising, leading, and evaluating, each of which demands a continuous decision-making process. Management functions are performed on all levels, ie the project planner, at institutional levels (donor agency, implementing institution, other involved institutions, controlling institutions), project level and the farmers. In this comependium, attention is mainly given to the planning level, to environmetnal appraisals performed by responsible institutions and the project level.

1 Irrigation in the Context of Land and Water Resources Planning and Agricultural Development

1.1 Environmental Management - A Systems Approach

Key Words

human life quality; human environment; natural goods & services; system analyses; conflict resolution; natural hazards; environmentally sound planning; quality of non-human life; regional conceptional models; inventory of goods & services; conflict identification; real & apparant conflicts; preservation & management; ecologically sensitive areas; importance-value-management feasibility; social dimension

Cross References: sections

Part II sections 1.2, 1.3, 3.1, 3.2; Part I sections 1.2, 4

Main References: OAS 1987; ADB 1989

1.1.1 Introduction

The ultimate goal of environmental management must be to preserve a favourable level of resource qualities which can sustain the long-term productivity of irrigation schemes and thereby contribute to the economic and social development of farmers.

This chapter is written with the objective of collating, reviewing and analysing the existing research and field information concerning the interaction between

(i) the human-made irrigation ecosystem which is seen as an agricultural production system which mobilises physical and human resources (land, soil, water, energy, labour, management skills, techniques etc.) for the production of food and other products

(ii) neighbouring natural or human-made ecosystems which may be affected by that agricultural and water resources development.

An understanding of the role of ecological factors and the potentials or constraints in the use of natural goods and services is a prerequisite for the development of managerial guidelines towards ecologically sound development of the irrigatated agriculture ecosystem.

A major concern and drawback in the evaluation of environmental impacts of irrigation projects associated with water resources development and agricultural development is the fact that both cooperation and transfer of knowledge between the disciplines involved is often limited or rare, eg between irrigation engineers and health specialists. In the past this has contributed to some analytical confusion with regard to cause-effect relationships amongst scientists, planners, decision-makers and public observers, and even more importantly, it has hampered the introduction of environmentally sound planning principles into practice.

1.1.2 Competition for Natural Goods and Services

Development in its economic, social and cultural dimensions can be regarded as the process of improving human life. This process involves manipulation of the complex, interrelated natural and man-made components and processes of human environments. Concepts

Fig. 1-1

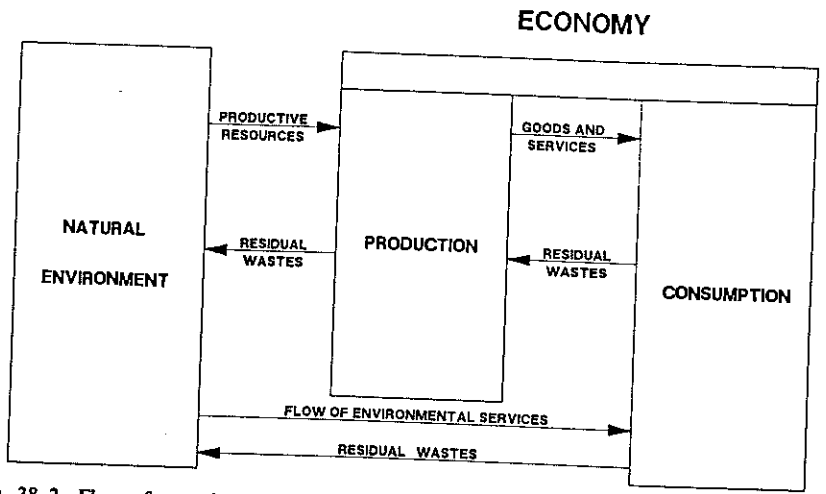


Fig. 38-2. Flow of materials between the natural environment and the economy (Gutema & Whittlesey, 1983).

Source: Stewart ed. 1990

in 'environmentally sound development' may be defined by the terms 'human quality of life', 'human environments', 'system goods, services and hazards', and 'environmental management' (OAS 1987).

Human quality of life refers to the physical health or welfare of an individual, a village community or a society. Health and welfare, in turn, depend on the degree to which a person's or a society's environment satisfies needs. Needs may vary substantially by culture, age, education, season, climate, etc. Some must be satisfied before others are felt. In practice, it is difficult to distinguish between 'needs' and 'wants', lack of information or understanding. If the allotment of resources required to satisfy any of their perceived needs is threatened, or is not sufficient, that individual or group will struggle to save or restore it.

Human environment is the aggregate of all external conditions and influences affecting life and the behaviour and development of individuals or societies. Each human environment overlaps, influences, and is affected by other environments. They resemble ecosystems, ie units of space where biotic and physical components and processes interact to develop patterns of energy, and material flow and cycles. In human environments these components and processes are not restricted to 'natural ecosystems' but include cultural, social, political, and economic components. A reductionist approach to environmental complexity, though useful during analysis, cannot resolve development conflicts. Although some components and processes are more determinant than others, there is no easy way to decide for any group of people which are the important ones.

Consequently, the global environment consists of numerous environments, which have various components and levels and which occupy different spaces, eg the biosphere, a watershed, an irrigated area or a village community. Therefore, in a systems approach the phrase 'protection of the environment' should be avoided, unless the type and function of the environment are defined. The question 'whose environment?' is always important. Because sectoral human activities, such as irrigation, use, improve, conserve or damage the external components (environment), decisions based on these activities are the cause of 'environmental problems'. Consequently, problems are created by efforts to improve the quality of life in one environment at the expense of reduced quality of life in another. Hence, 'the environment' should therefore not be treated separately from 'development'.

Natural goods and services (resources) comprise the materials and the space in which human societies develop and evolve (see Fig. 1-1). The concept of 'goods, services and hazards' links the concepts of environmental quality and life quality, since a 'quality environment' is one that both provides the necessary materials to satisfy the needs and wants of an individual or a society and which mitigates the severity of an encounter with a hazardous event. Natural components of ecosystems are classified as goods and services if they are of interest to anyone; natural goods are those natural resources which are useful for development. Thus, within the natural resource 'land', those parts which are irrigable are a 'natural good' to farmers. Natural services are derived from natural characteristics of ecosystems' structure and function and include the flow of energy and materials, eg yields from irrigated fields, water flow and floods, and the existence of rangeland. Natural goods and services have values in the following categories:

(i) economic, cultural and social values which are important for actual development. Some of them may be quantifiable in monetary market systems but others are not (welfare economy). Together they contribute to the richness, identity and diversity of a society and to its historical perspective.

(ii) scientific or optional value which is important for future development. These are of importance to the global environment and to those who search for new technologies or new uses of natural goods for development purposes. For example, protection of endangered species, representative ecosystems or wildland reserves and germplasm conservation fall in this category.

(iii) controlling values for ecosystem functioning and maintenance, ie they are important to ensure the sustainable flow of goods and services. Human activities may include soil erosion control, flood control, salinity control, conservation and protection measures

To summarize, the process of development is made up of those activities which lead to the **use, improvement**, or **conservation** of natural goods and services in order to maintain or improve the human quality of life. A negative environmental impact, in turn, is the **destruction, impoverishment, mis-use** or non-use of natural goods and services, often with an associated degradation in the quality of life of another group of people.

Source: modfied after OAS 1987

1.1.3 Objectives of Environmental Management

The objective of environmental management is to **improve** the quality of life of peoples. It involves the **mobilisation** of resources and the **utilization** of both natural and economic goods and services. Based on principles of ecology, it uses system analysis and conflict resolution to distribute the costs and benefits of development activities amongst the populations affected. Hence, conflict identification is an important task in 'environmental management planning', and conflict avoidance or resolution is a fundamental part of 'environmentally sound planning'.

The interrelated nature of ecosystems' structure and function implies that any activity or process of development (both human-made and natural) in one ecosystem will always affect the quality of life elesewhere, irrespective of spatial or time dimensions. The impact may be direct or indirect, it may be hazardous to one ecosystem whilst simultaneously being favourable to another: for example, although floods are detrimental to development, buildings and infrastructure in the upper watershed they are responsible for transporting of fertile sediments to agricultural plains (cycling of nutrients).

Environmental impacts may become environmental problems when conflicts between two or more activities within one sector or between two or more sectors. In thise cases

(i) the quality of life within a given sector may not be improved, as anticipated; the time dimension by a given activity is important. For example, irrigation may not improve life substantially in the long-term if salinity and drainage control are poor. Here, the conflict is within the same sector or the same group of people are involved.

(ii) an activity in one sector may cause damages (costs) to another sector. For example, if drainage flows from irrigated fields contain toxins which destroy downstream fisheries, or if withdrawal of water upstream reduces water availability for downstream users, conflicts between two (or more) sectors are created.

It should be noted that the consideration of the quality of non-human life is often dealt with superficially. This is due to the following factors:

(i) irrigated agriculture is seen as a human activity to improve the quality of life

(ii) time, funding, and expertise available at the planning level especially for a single sectoral activity such as irrigation often do not allow for in-depth studies which analyse all interrelated cause and effects of all living things in all ecosystems that may be directly or indirectly affected at all times.

(iii) neither science nor planning for human development will be advanced much by expenditures of large amounts of funds for research or by extended periods of planning.

This does not imply that the quality of non-human life is not considered and conflicts between natural ecosystems (their protection, conservation and development) and human development are not addressed. However, the major concern are those sectoral activities which often do create problems and to those on whome these problems impact.

Conflicts may also arise from natural hazards, such as floods, poor water quality, earthquakes or hurricane. Any economic 'disaster', however, is by definition human-made because the selection of a project site should take into account natural risks, and strategies for environmental management should be developed to avoid or minimize impacts that may jeopardize the objectives that the development activities were desinged to meet.

The techniques of conflict resolution are well known and indeed, conflict fills the matrix in which we live. This is a world of uncertainties, shortages of goods and information, a wide range of values, interests and attitudes, and overlapping and interdependent environments constantly generate conflict on many different levels and scales.

Source: modified after OAS 1987

1.1.4 Definitions of 'environmentally sound planning'

The common definitions of 'environmentally sound planning' are regarded as being **untenable**: 'it does not disturb nature', 'not surpassing the carrying capacity' and 'avoiding loss of long-term natural productivity'. There is no development project that can meet all these restrictions, even so called 'environmental conservation projects' which, indeed, may have negative impacts on other resources or users. The following problems arise:

(i) the definitions do not meet the objectives of development, since development objectives that do not treat life quality make no sense because no one will benefit, whether activities are environmentally sound or not.

(ii) the level of aggregation cannot be clearly defined: which natural system is refered to? Any human activity will disturb, or even destroy, natural systems at a certain level; even the collection of food implies a negative impact on the plant from which fruits are collected. Therefore, avoiding disturbance per se could even not be used to describe an activity which is 'environmentally sound'.

(iii) the definitions are subject to subjective: is the long-term natural productivity an essential criteria when a choice is made between irrigation of a fibre crop and protein delivering-crops?

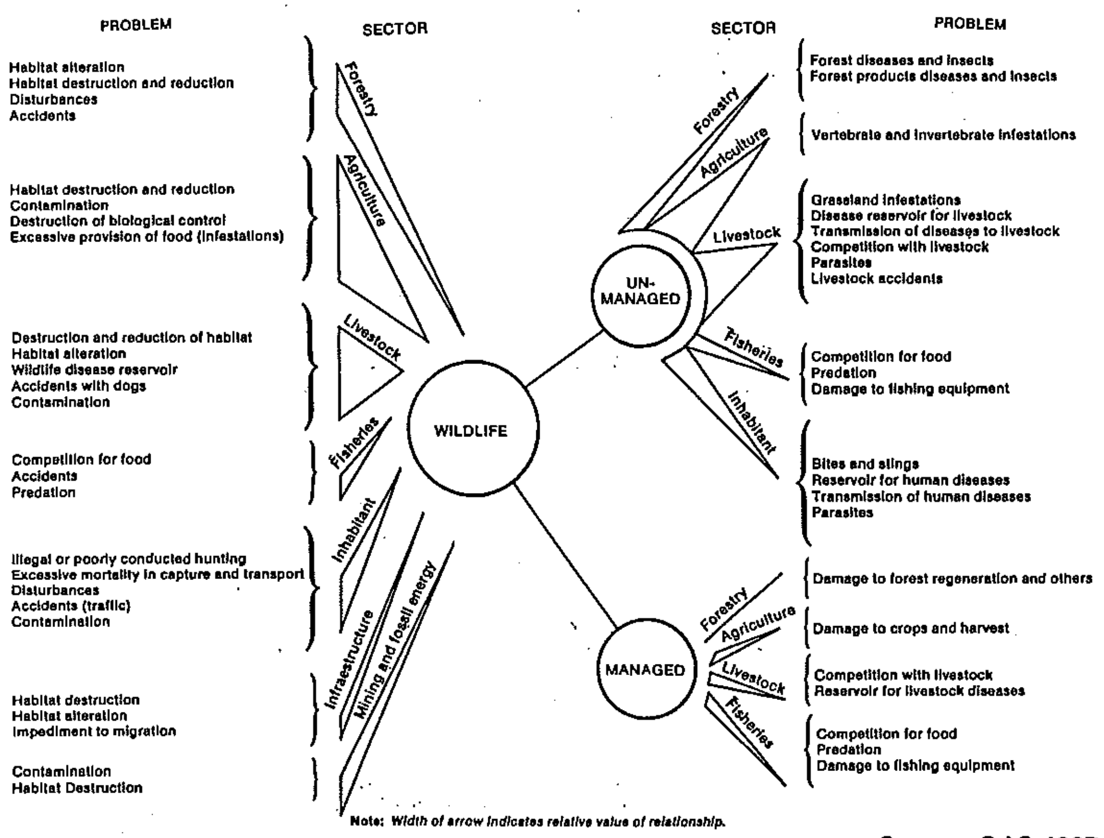
(iv) generalized criteria are not adequate: is carrying capacity of a given ecosystem relevant when it can be significantly increased through the application of even the simplest technical measures? For example the 'productivity' of an irrigated area may be increased by drainage, or rangeland can be improved by management measures; it follows that productivity is a variable measure of natural goods and services.

(v) the definitions do not provide clarity nor specificity: though degradation may be identified by indicators and defined by standards it means different things to different people. For example, is an irrigation project 'environmentally sound' if balance is maintained but a species is lost or added because of irrigation? Is a trade-off justified, between the extinction of an arid soil fauna and flora (usually with a limited total population and limited variety of species) and the development of soil microfauna and flora of an irrigated soil with a higher number of species and a significantly higher total population?

To avoid such problems 'environmentally sound development' should be defined as a process having the objective of sustained improvement, for as many people as possible, the quality of human life. It is a process of active manipulation of ecosystem structure and function in order to utilise or maximise the goods and services offered by the local ecosystem. It minimises the conflict inherent in the utilisation of these goods and services, it

Fig. 1-2

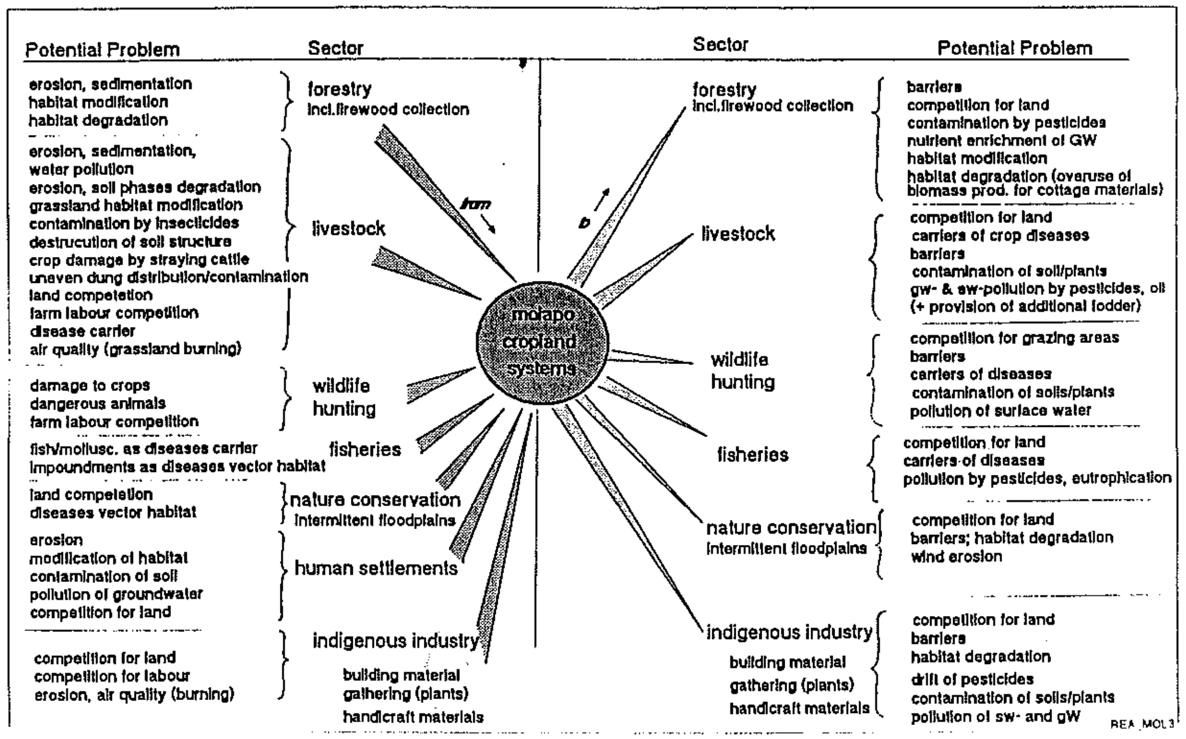
PRINCIPAL CONFLICTS BETWEEN WILDLIFE AND ACTIVITIES TO USE OTHER RESOURCES



Source: OAS 1987

Fig. 1-3

Principal Potential Conflicts between Activities of Molapo Farming and Activities of other Sectors



maximises the compatibility of the activities required and distributes the costs and benefits as widely as possible among the people affected (see also section 1.4.)

Conservation is defined as the management of human use of the biosphere so that it may yield the greatest sustainable benefit to present generations while maintaining its potential to meet the needs and aspirations of future generations (World Conservation Strategy, IUCN 1986).

Source: modified after OAS 1987

1.1.5 Identification and Solution of Sectoral Problems and Conflicts

Principal problems between wildlife and other users of natural resources in the humid tropics are outlined in Fig. 1-2 and Table 1-1. Another example is given for potential conflicts between agricultural floodplain cultivation and other uses in Molapo agriculture (Botswana) in Fig. 1-3.

Resolution of conflicts between inter- and intrasectoral activities may follow the following planning sequences:

(1) Development of a **regional conceptual model** which describes the structure and function of the ecosystems in detail. The region (or any specific area) constists of producers and the consumers which are interrelated. The available information is obtained from various disciplines. The degree of detail must be adjusted to the situation for which an activity (eg irrigation project) is planned. It may be more important in conceptual modelling only to include relevant interrelations between important consumers and producers of goods and services than to provide precise quantifications and complice the model by incorporating unimportant or non-affected parts of the system. Following an OAS-approach (1987), the procedure may comprise a generalised 'National Systems Model' and a 'Regional Systems Model'. In addition, a 'Local Systems Model' may be developed for the project level (Fig. 1-2). This regional modelling procedure is based on Odum/Odum (1976) who uses diagrams to focus on key elements and interactions.

(2) **Inventory of goods and services**: in addition to land use planning inventory methods (see sections 4.4 and 4.5) an inventory of goods humans may take and use from ecosystems. Table 1-2 shows important goods and services that can be provided by natural ecosystems in the humid tropics. Each planning exercise must develop a site specific list based on interviews which represent the perceptions of the groups involved. Table 1-3 shows the goods and services available for protected areas in the americal humid tropics; Table 1-4 provides an example from Botswana.

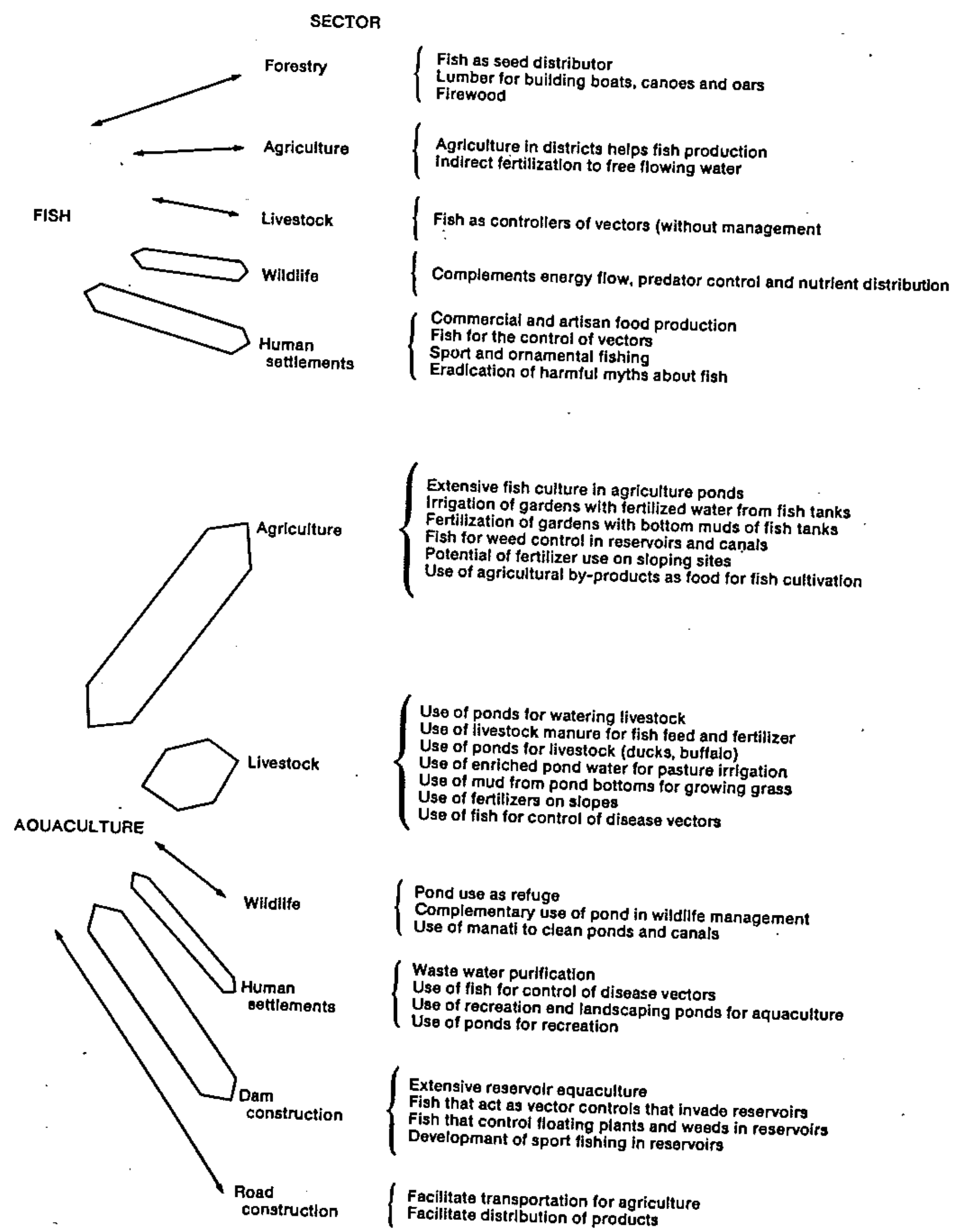
(3) **Inventory of natural hazards**: the same natural ecosystems that supply minerals, water and soils for food production, are also characterised by hazards, such as floods, heavy rainfall, saline soils, erosion, wild animals that destroy human life and crops (Table 1-5). Since they restrict the development of human activities, they must be identified, described and if possible quantified and the severity of the threat must be predicted. Table 1-6 shows the natural risks in molapo farming (Botswana)

(4) **Conflict identification**: conflict may arise either from open competition for goods and services (eg scarce water) or as a result of human activities changing the quality or quantitiy of goods and services available to other consumers (eg change in water quality or increased soil erosion). Several procedures should be followed after potential conflicts have been identified:
- planning should be coordination in oder to reduce potential conflicts,
- during planning the conceptual model may be revised as new interactions become evident, or as others are dropped because the affected group feel that they are unimportant.

Fig. 1-4

Figure 16-6

PRINCIPAL RELATIONSHIPS OF SUPPORT AND BENEFIT BETWEEN THE ACTIVITIES OF OTHER SECTORS AND THE ACTIVITIES OF AQUACULTURE AND FISHING



Note: Width of arrow indicates relative value of relationship.

Source: OAS 1987

- conflicts can be listed, showing goods and services in the subsystem under evaluation and the individual sectors which utilise them. Since each component of the system is linked to others, the use or conservation of any component will influence the availability and quantitiy/quality of other goods and services. Other sectors which are interested in the same goods and services from the same or linked subsystems should be identified.

A general example is shown in Table 1-7: Ecosystem I has land on which rainfed agriculture, irrigation, liverstock, settlements, wildlife habitat, recreation (park), industry, sewage water treatment plants, or sewage land treatment areas (wastewater infiltration) could be established. It would be impossible to undertake all these activities on the same piece of land at the same time. Consequently, a irrigation project would be in competition with the other users, providing these were interested in development activities.

Likewise, ecosystem II has groundwater which can be used for irrigation in areas A and B, domestic supply (town), or aquaculture. In this case, all users depend on the quantity of groundwater actually available and the demand of each sector and subsector. Since subsystem II also has land for industry, the groundwater may be contaminated by industrial wastes. The degree of contamination may restrict the use for domestic supply and aquaculture, but not for irrigation. Then, conflict exists between industry and domestic water supply and aquaculture. Continued use of groundwater for domestic supply will require either that the industry be sited outside ecosystem II, or treatment of wastewater must meet standards for potable waters. Conflicts are identified and visualised, recognising that a decision in favour of one activity will negatively affect the others,

(5) An **activity matrix** may allow conflicts to be visualized. It requires a fairly complete understanding of the different sectoral activities as well as in-depth discussions between representatives of the interests involved. Table 1-8 provides an example with the following activities proposed: rice culture, irrigation of grain crops, vegetables and orchards, livestock production, silviculture and a wildlife protection area. The conflicts can be described and the impacts may be quantified.

(6) **Real and apparent conflicts** should be distinguished. Some conflicts occur because objectives and methods are not clear to all parties involved. Thus information should be shared and issues should be clarified. In another case, consumers may encounter a common problem as they attempt to reach different compatible objectives. There may be a conflict of interests where objectives and the means to meet them are opposed. Here, the solution may be achieved by technique of third party arbitration. However, it should be noted that not all relationships need be conflictiving. Fig. 1-4 identifies relationships between aquatic life/aquaculture and other development activities, which are supportive rather than conflicting.

Source: modified after OAS 1987

1.1.6 Alternative Goals for Ecosystems' Management

In designing ecosystem management (mitigating) plans, one must decide which attributes of the ecosystem should be managed for restoration or preservation. Three alternative goals may exist:

i) **preservation of ecosystem processes**: a land use plan may be designed to optimise restoration or preservation of one or more ecosystem functions, such as soil binding, hydrological balance, nutrient assimilation and releases, population regulation, radiation or gas exchange. This aim may be accomplished by doing nothing or specific management practices may be required (eg weeding, irrigation or fertilization). Awareness of the scale is important for management plans which aim to particular ecosystem feature.

ii) **preservation of integrity of biological communities**: wilderness preservation aims to restore and preserve ecosystems in some self-regulating condition that is assumed to approximate their state before major disturbances by human society and technology (industialisation). In natural systems there is a tendency towards restoring balance after any disturbance (resilience). Species interact and maintain their structure and function in a self-regulating homeostatic fashion (biological integrity). Commonly, the focus of preservation is not on an ecosystem process but on its structure, with the assumption that if the structure is preserved, function will be also. However, no one pattern will be equally effective in preserving species. Thus in seeking to preserve the structural integrity of a wilderness, choices must be made about what and how much of each type to preserve. However, a balance of habitat types in a landscape mosaic is not completely arbitrary. A river is affected in its trophic status and associated fauna and flora by the amount and quality of water, sediment, and nutrients it receives from catchment areas.

iii) **management of ecosystems for human purposes**: natural ecosystems (land/soil, water, biotic resources) may be modified to maximise the provision of particular services to people, eg yield in irrigated farming, mining for energy production, and recreational enjoyment. Ecosystems composed of many non co-evolved species will take on a structure and function which is virtually impossible to predict with precision. Planned communities (altered ecosystems: eg cropland) can clearly yield desired goods or services whose benefit exceeds their management costs. The assumption underlying the biological integrity goal, however, is that given natural selection, the natural ecosystem is the system most likely to achieve and maintain an internal balance, without further human intervention. If the properties of such a system are considered to be desirable, the system that sustains them must be maintained. This goal involves choices about what to preserve, just as does implementing the goal of managing an altered ecosystem, eg an irrigated field.

Source: modified after Westman 1985

1.1.7 Identification of Ecologically Sensitive Areas

Ecologically sensitive areas (ESAs) are defined by their importance for biological, cultural, social, economic, political, and ethical reasons and may include wetlands, river valleys, coral reefs, dunes, mangroves, mountains, tropical forests, etc. Habitats are considered ESAs if they:

(1) provide protection to steep slopes (eg soil conservation areas),

(2) support important natural vegetation on soils of inherently low productivity. these soils will produce little of value to human communities if transformed (eg many tropical forest soils),

(3) regulate and purify water flow, such as valleys, valley forests, floodplains, wetlands,

(4) provide conditions essential for the perpetuation of species of medicinal and genetic conservation value,

(5) maintain conditions vital for the perpetuation of species which enhance the attractiveness of a landscape or the viability of protected areas,

(6) provide critical habitat that threatened species use for breeding, feeding, or migrating.

Other sensitive areas may include habitats or areas which:

(7) provide a livelihood for specific vulnerable or minority population groups, ie areas of specific social and cultural interest,

(8) areas of unique historical, archeological, or other cultural heritage, or important to cultural or religious beliefs.

Source: ADB 1989

Typically, irrigation may adversely affect areas under criteria iii) to vi) if development and land conversion takes place within floodplains, wetlands or valleys which provide functions Typically, floodplains, deltas and estuaries are sensitive ecosystems because they depend on energy and materials from outside (ie water, solids, solutes, organisms from upstream reaches).

The data needed to identify ESAs and develop management plans include national compilations of the flora and fauna, at least higher plants and vertebraes, and assessments of stocks of materials and natural food resources (trees, plants, fish). The identification of ESAs should incorporate various economic, social and biological parameters which are given as follows:

(i) evaluation of physical pattern of habitats; soils, mineral resources, water, climate, current land use, populations, fauna and flora,

(ii) establishing criteria for selecting ESAs in the national context of each country,

(iii) identification of vulnerable areas of high biological diversity, and areas of high economic value in the natural state,

(iv) preparation of a strategy for conserving ESAs, including establishing objectives, economic relationships, legislative regulations, institutional responsiblity.

for details see: ADB 1989

Each country will need to design its own approaches to ESAs according to its particular social, biological, economic and political context and particular opportunities and constraints. The basic principle should be that the distribution of costs and benefits of both conservation and exploitation should be equitable and should lead to long-term sustainable use of natural resources. Criteria which may serve to identify ESA's are:

1) Criteria which determine the importance to human society:

- economic benefit: long-term benefits such as tourism, watershed protection,
- diversity: sites which have a great variety of species and ecosystems, great variety of landscape features, soils, water regimes, microhabitats; sites which are sufficiently large to contain viable populations of important species
- international value: the site is essential to the survival of one or more threatened species which occur in no other country or contain landscapes or features of outstanding universal value
- national value: the site is essential to the survival of one or more species which are threatened, or contain the nation's only example of a certain ecosystem or the ecological functioning of the area is vital to the healthy maintenance of a natural system beyond its boundary, such as important catchment areas for lowland irrigation, protection of coastal areas
- cultural diversity: the site supports populations of indigenous people who have developed mechanisms for sustainable living in balance with the natural resources
- urgency: action is required quickly at the site in order to avert an immediate threat

2) Criteria to determine additional elements which enhance the value

- demonstration: the site demonstrates the benefits, values, or methods of protection
- representativeness: the site is representative with regard to habitat type, ecological process, biological community, physical features, etc

- tourism: the site lends itself to forms of tourism wich are compatible with the aims of conservation; this is often related to social acceptance and economic benefit
- landscape: the site has features of outstanding natural beauty but the area's amenity value may be easily destroyed by uncontrolled access
- research and monitoring: the site can be used to measure ecological changes occurring elsewhere; the site may support scientific insights and arguments
- awareness: education and training within the site can contribute to knowledge and appreciation of regional values

3) Criteria to assist in evaluationg feasibility:

- social acceptance: the site is already protected by local people or official protection is welcomed by local people to protect against outside exploitation
- opportunism: existing conditions or actions at the site lend themselves to further action, such as the extension of an existing area
- conveniency: the site is accessible to researchers or conservation practitioners
- availability: the site can be acquired easily.

Source: ADB 1989

1.1.8 The Social Context of Conservation

The conservation of nature must be seen a social, economic and political context. Decisions affecting the natural environment are influenced by pressures and incentives that go far beyond technical and biological considerations and include aspects of social equity (including participation), political desirability and technical feasibility. Therefore, conservation action is an interdisciplinary task which involves land use planners, engineers, biologist/ecologists, economists, rural sociologists, agronomists, and politicians which may take decisions in cooperation with local resource users. In addition, the role of the community based NGOs is becoming more important. The identification of the legitimate self-interests of rural people is required and any managment plan must ensure that the interests of conservation and of community self-interest coincide. The conflict minimizing-strategy may be used as a design tool (section 3.1).

The social dimension must be addressed when establishing plans for conservation of ESAs. It is a common feature that the people living around such protected areas often have a hostile attidute. Often, local populations pay most of the costs - in terms of reduced access to resources they may consider as theirs, social disruption, etc. - but gain few or none of the benefits of such conservation areas which instead go to the nation at large or even to the international community (tourism or research). These imbalances must be redressed and costs must be shared more widely.

Further reading: ADB 1989

Case Study

In the Okavango delta of Botswana, most parts may not be used as seasonal pasture or farmland. Strict regulations are imposed on hunting, a traditional source of income and food, and farming is strictly prohibited. Actually there are abundant alternative lands for cropping, pasture and fishing and hunting resources available outside the conservation area. Nevertheless, the economic development of some tribes and communities bordering these restricted areas is hampered by these regulations, and there are complaints about their costs in terms of no development options. In practise, tribes are paying for national conservation goals and for international tourism without an adequate share of the benefits. Hence, such regulations should only be established in cooperation with all affected groups, eg by conflict minimising strategies (see section 1.1).

1.2 Irrigation as a Part of Water Resource Planning

Key words:

interrelated resource systems; irrigation impacts; constraints for conservation in DC; holistic farm stategies; upper watershed problems; linkages uppstream-downstream users; development problems and options for uplands; policies-programs; planning requirements: technical & social-institutional dimensions; criteria for plans; framework for watershed management: process-system-activities; irrigation and regional water master plan

Cross References: sections

Part II sections 1.1, 1.3, 2.2, 3.1

Main References:

Doolette/Magrath 1990; Easter et al. ed. 1986; FAO (CG 14) 1986; Gil (FAO SB 44) 1985

1.2.1 Introduction

The need for watershed management arises from the relations between water, soil and land use systems. Improved water management and especially watershed management are the highest-priority aims in environmental policies and it is a common perception that more integrated approaches are required:

> There should be "closer integration of water-related concerns in the sectoral policies (agriculture, energy, industry) affecting water resources, with emphasis on the principles of multiple use and prevention" is needed" (OECD 1991, p.69).

Irrigation has distinct impacts on water resources in downstream drainage basins, and, vice-versa upstream watershed management has effects on irrigation (see section 2.3). Irrigation as a major user of water (and land) resources is one component in watershed management, and, hence, it may contribute to degradation downstream of the command area and it may be adversely affected by upstream degradation. Consequently, any irrigation development strategy should be treated on a watershed basis regardless of the scale of irrigation development. The magnitude of impacts from an individual irrigation project (or single farm) and the degree of dependency on scarce water resources may determine and modify the depth of integration into comprehensive watershed mangement plan.

A watershed is an area which drains into a river basin; a major river basin may be divided into an upper and lower watershed.

The watershed comprises a sequence of interrelated drainage systems. The linkage, however, is one way. This complicates the situation for integrated watershed management planning and implementation in two ways:

(i) typically, different government agencies have responsibility for different parts of the watershed and for the management of different resources
(ii) private parties in the upstream section of a watershed are not motivated to take into account the costs they impose on the downstream sections. In practice, the lack of coordination, regulations and poor management may also result in impacts from non-private users.

In addition to these watershed management problems, new land use practices and land occupancy in upper watersheds for rainfed farming, grazing or oter land uses are increasingly creating pressure on soils, land, and water resources, associated with increased erosion and water pollution. Irrigation may contribute to watershed problems, but generally, the direct (land use) impact on upper watersheds is rarely significant because upper watersheds are currently less frequently used for irrigation than lower watersheds. However, flood plains in upper watersheds have high potentials for irrigation, and any impact on downstream users should be strictly controlled and regulated.

Irrigated agriculture in upper watersheds is typically characterized by smallholder schemes or smallholder private farms with low (actual) potential for chemical pollution of water. Soil erosion on these small farms varies, although the common practice of basin irrigation typically tends to reduce risks of sediment pollution. Water abstraction quantitites are rather low, and a large proportion of surface or subsurface drainage water returns to the main stream Hence, interference in the hydrological cycle is rather low.

Flood plains in the lower watersheds are the traditional irrigated areas. Problems created by irrigated agriculture in large river or deltaic plains usually result in intra-sectoral conflicts, ie other downstream agricultural users are potentially negatively affected, including rural settlements which withdraw water from the river and river fishery. Occassionally, inland lake or delta-fishery or towns are affected.

1.2.2 From Soil Conservation to Watershed Management

Early concepts and techniques of soil and water conservation for cropping, rangeland and forestry systems were developed in the USA and Europe. They are well adapted to large farming units, with structural and engineering measures for market oriented farms with high technology inputs.

The transfer of some isolated technical solutions to smallholder farming sysems in developing countries has generally not been successful. Important constraints are: diverse cropping systems, extremes of topography and climate, financial resources, limited adequate technology, lack of acceptance by traditional farmers, highly diversified farming systems without attention to a single activity. The ability and willingness to adopt and maintain soil conservation measures may also be hampered by social, tenurial and economic factors typical of the farming system.

Therefore, in the past most watershed conservation programmes were heavily subsidised during implementation, and individual recurrent costs (maintenance, loss of productive land) made the measures uneconomic to many farmers. In addition, incentives to adopt soil and water conservation methods in traditional agricultural systems are often marginal due to the temporal asymmetry of most impacts: on-farm sediment losses will cause detrimental downstream effects only after some time has elapsed, eg some 40 years are required for sediments to be flushed from the drainage systems of large basins. Thus, in terms of the present value of works, any reductions in sediment made possible by the adoption of conservation measures will be of marginal economic significance to a single user. Farmers, especially in highly-diversified subsistence systems, need direct short-term benefits from any innovation in their farming practices.

New concepts of watershed management are characterised by a holistic view of conservation-oriented farming in the uplands; farming systems and individual production treatments combine to conserve soil and water and to improve total production and net benefit. Several strategies are under discussion:

- problem-solving approach: site specific evaluation of the key constraints and the techniques to resolve the problem,
- selected problem-solving approach: here the starting point for propagation of conservation measures (or other improved technologies) are those farming activities which meet conservation needs and enhance production and income without unduly increasing economic risks; this approach needs basic knowledge of the farming system,

- non-site specific approach: eitehr the propagation of packages of conservation and yield-increasing interventions, or the propagation of single measures, eg improved grass covers, seeds, contour cultivation or plantations which have immediate yield-increasing effects,
- comprehensive integrated agricultural watershed management, especially to enhance upland development, eg by intensifying agriculture through irrigation, rangeland management, propagation of contour farming in rainfed agriculture,
- comprehensive integrated rural development approach for watershed management; here, also non-agricultural activities are included.

1.2.3 Why Watershed Management?

In the absence of unified management, or some comparable arrangement, upstream users will adopt practices without regard for impacts on downstream users. Major upper watershed problems, usually resulting from population pressure and poverty, are:

- Loss of agricultural productivity due to soil erosion. Most hilly and mountain areas in Asia are seriously affected while many hilly regions in Africa and Latin America are moderately affected. The type and degree of erosion varies greatly, depending on soil properties, climate and soil and water management. It is estimated that in Asia the total watershed population is about 130 M living on slopes greater than 30 % within upper watersheds,
- Deforestation, including overcutting and grazing on remaining forest stands. Deforestation has a distinct influence on water regime by increasing total flow volumes, peak flow and continuous flow for any rainfall event
- Downstream sedimentation causes siltation problems in reservoirs and canals, and may block structures,
- Flooding, although occurring under natural flow regimes, is increasingly disastrous to agricultural lands, settlements and natural ecosystems. Flooding is mainly caused by reduced interception and increased run-off from soils in upper catchments, reduced storage capacity of river sections (eg by bunding-off the plains), river constrictions, and increased run-off from central and lower catchments, caused by continued sealing and compaction of soil by villages, roads etc. Temporary flooding may be beneficial for agricultural productivity in general as it contributes to nutrient supply and replenished soil moisture,
- Dry season stream flows are reduced as a consequence of flash floods during the rainy season (or snow-melt); storage capacity is reduced on a micro-level (soils) and macro-level (sections of river basins). Reduced dry season flows have consequences for irrigation and other users (domestic, industrial, power generation).

Source: after Magrath/Doolette in: Doolette/Magrath ed. 1990

There are various intersectoral and intrasectoral linkages between

- irrigated and non-irrigated agriculture,
- crop production (including fodder and fruit trees), livestock farming (range management) and forestry (silviculture),
- agricultural and domestic water users,
- agriculture, domestic users and industrial production.

1.2.4 Upper Watershed versus Lowland Watershed Users

The potential linkages between upstream and downstream users are:

i) Physical linkages due to impacts on water quality (total salt load, chemical constituents, presence of toxins, sediment load) and stream flow (total water volume, distribution of flow, timing of flows). Extreme peak flows have effects on all downstream water users. Irrigation exacerbates the detrimental effects of major catastrophic floods by occupying major flood plains which may otherwise serve as temporary reservoirs. There are also interactions between erosion and streamflow; reduced runoff in upper watersheds results in reduced erosion. Sedimentation of channel beds may contribute to flood hazards by reducing the channel discharge capacity. Physical linkage provide the basis for watershed management interventions.

ii) Economic linkages may exist or have a potential for development. Upland areas may provide primary raw materials or special horticultural crops or animal products. Income from these may contribute to strengthening linkages between uplands and lowlands, which provides opportunities for expanding sustainable agricultural systems in uplands. Additional sources of upland income are lowland employment opportunities (seasonal or permanent) in agriculture.

iii) Political linkages are often weak because the attention of policymakers is drawn to urban areas and agricultural activities in the lowlands. Nevertheless, due to the asymmetry and rigidity of impacts from upstream to downstream users there is growing interest in public sector ivolvement.

iv) Agricultural policy linkages, especially price and incentive policies between uplands and lowlands may have an important role. This, in turn, can create incentives for upland farmers to shift to cropping patterns that integrate conservation. Favourable environments are created by access to markets, intensification of agriculture, utilizing irrigation, and local industrialisation, influenced by high income-elasticities of demand for vegetables, fruits and livestock products.

Source: Magrath/Doolette in: Doolette/Magrath ed.1990

1.2.5 Watershed Development for Upland Areas

The essential elements of a strategy for upland development are those that apply for lowland development and include the need for a positive incentive framework and the availability of appropriate technological innovations. However, there are several limiting factors which characterise upland development:

- areas have a greater diversity of ecology and land suitability,
- areas are less amenable to large scale development, eg irrigation,
- areas are naturally prone to high erosion risks,
- many areas have a lower production potential for a majority of crops.

Watershed problems are multi-faceted and solutions may be amenable through:

- physical actions requiring investment, eg development projects which improve technical efficiency of watersheds or introduce technological change,
- policy reform (see section 2.2),
- research into physical resources, eg establishing land use plans,
- identification and development of human potentials and resources
- adaption and accomodation of existing land uses and development plans.

Watershed management projects are often multipurpose and multisectoral, and as discussed in section 3.1.3, a policy aim should be to leave none of the current users worse off. Agriculture-related interventions for improved management may be:

- diversifed production activities in various sectors: forestry, rangeland, cropland (rainfed, water harvesting and irrigation),
- intensified production activities in all sectors, or
- intensified agricultural production and conservation in a special sector: eg soil stabilisation and revegetation in the forestry sector.

Technologies and techniques for improving agriculture are often related to soil and moisture conservation. A key technique for rainfed farming is contour cultivation (or ridging across-the-slope) which may also integrate improved agronomic techniques, propagation of improved varieties (high-quality seeds), improved pest management and tillage practices. The techniques can be grouped as

(i) structural measures, eg bench terraces (reverse-sloped, outer-sloped), conservation terraces for soil conservation and water harvesting and level bench terraces for irrigation, eg paddys,

(ii) vegetative or cultural measures, including crop rotation, contour cultivation, tillage, cover crops, strip cropping, vegetative strips (eg leucaena, vetiver grass),

The latter usually have some advantages over structural systems:

- they can be promoted at low cost, eg establishing vetiver grass hedgerows,
- they are better adapted for farmers as they do not require detailed design and implementation skills,
- they are farmer controlled, ie farmers can take initiatives in adaption.

Source: Magrath/Doolette 1991

1.2.6 Watershed Management Policies and Programmes

There is an increasing need to integrate irrigation projects into entire watershed resources management planning. Some successful large-scale watershed management projects have comenced over the last decade by several donor agencies. Most of these projects integrate forestry and agriculture, including irrigation and some of them were planned as integrated rural development projects.

Implementation is often disbursed across several agencies: agricultural, land use and forestry agencies, watershed development authorities and soil conservation services. Besides water laws and regulations institutional innovation is also required to overcome traditional barriers to interagency cooperation and to manage activities (see section 3.1) from the watershed management perspective. The inclusion of nontraditional land use systems, the intensification of existing land use systems (eg by irrigation) and the greater integration of upstream and downstream development activities should form the basis of watershed management policy.

The common approach is to focus on the implementation of physical infrastructure on private or public land, often with a predominant single technical solution, and on encouraging local farmers in the adoption of soil and water conservation methods.

1.2.7 Planning Watershed Management

Effective watershed management requires both the provision of solutions to technical problems in the fields of physical planning, agricultural planning, engineering, operation and maintenance, and social and institutional planning and decision making.

Planning units can be hydrological, administrative or social units (eg a set of villages). Often social and physical units roughly coincide, especially in mountain areas. They are the preferable units for planning the use of land and water resources within a watershed.

Single solutions have rarely been successful in the past, and comprehensive approaches should be sought. Single technical solutions should be avoided as should solutions which do not combine agricultural development and soil and water conservation. An approach which provides a package of technical solutions both at the regional and local levels is preferable, so that users can select according to personal conditions and preferences.

Planning levels may be at the regional or the local level. Site-specific guidelines should be established for selecting appropriate on-site soil and water conservation measures and strategies for improved productivity. These guidelines must be adapted to the immediate needs, socio-economic capabilitites and perceptions of the local people, either individual farmers, whole village communities or groups of villages. Over-simplifications, inadequate design criteria and poor implementation standards, must be avoided, since traditional upland ecosystems and agroecosystems are highly diversified. Standardised approaches to agricultural development often do not fit these conditions and are, consequently, not adopted by farmers. Thus, regional plans should provide the conceptual, technical and legal framework for planning, but should leave enough flexibility to allow implementation at the local level. Given the importance of physical, economic and social/political linkages between various users in watersheds (see above) regional planners should also have responsibility for solving problems between various users of physical resources, using the 'minimum conflict' approach for environmental management (see section 1).

Regional plans for small and medium watersheds (<200,000 ha) or subwatersheds (<15,000 ha) should be drawn up on the basis of comprehensive land use development options, including all users within the watersheds and all agricultural sectors such as rainfed, irrigation, rangeland, and forestry. Regional plans should be based on farming systems analysis, land use capability, and water resources analyses (demand versus availability). Techniques include:

- **Hydrological inventories**: eg IHP-approaches (Card ed. UNESCO 1984; UNECO / UNEP 1987, Haimes ed. UNESCO 1987)
- **Rapid Rural Appraisals** (RRA) which assess biophysical and socioeconomic conditions, identify development issues and constraints and opportunities confronting the local people or village communities, and determine appropriate implementation strategies for community based projects (see RRA-Notes, IIED)
- **Regional planning procedures**, land use evaluations and soil suitabaility classification (see sections 4.4, 4.5)
- Developing **standards** and **indicators** for sustainable growth and environmental degradation.

Large watersheds (>200,000 ha) are often self-contained and there is less need to integrate them into development plans. However, any upstream development must be continuously monitored and assessed for possible impacts on downstream users. These may arise especially with the development of large water reservoirs (dams) or the occurence of serious (chemical) point-pollution of upstream waters. If there are any physical linkages between upper and lower watershed users, the same principles of planning should apply as for small and medium scale watersheds.

Criteria for Effective Watershed Management Plans

An interactive planning process should identify sustainable development options which are in the interest of all people involved. These may involve users of agricultural systems, industrial sites or settlements/towns. In addition, the management of natural resources must be considered (see section 3.1). Since land in upland watersheds is often under private or communal ownership with limited access of central government authorities, watershed management must meet the immediate needs of the individual farmers (or community) to be sucessfully implemented. Important criteria for effective planning are:

- improved **efficiency** of land use in a particular agro-ecological area: activities and technical measures should minimise or avoid degradation of physical resources (water quality and quantity and soil productivity),
- **acceptance** by local people: activities and measures must be in line with socio-cultural attitudes and beliefs and must avoid increased risk; they should increase or stabilize profits,
- **equity**: activities and measures should be available to all farmers or members of a village,
- **participation**: planning and implementation must be undertaken in mutual collaboration with the users; formal participation may be prefered, eg through committees, but this may not result in equitable access to innovations, especially with respect to gender.

Conceptual Framework for Watershed Management

The following framework includes three dimensions:

(i) Watershed management is a **process** involving separate but closely linked stages of planning and implementation: plan formulation, design, installation, operation, and maintenance. Planning and implementation should proceed in tandem, with information gained during implementation fed back promptly into design,

(ii) Watershed management is a **planned system** of activities and tools applied to an area through a set of institutional and organisational arrangements: This is illustrated in Table 1-9 in which water management is shown as a planned, aggregated system. In a broader context, watershed management can be seen as a system that uses management inputs along with natural inputs to produce goods/services with consequent on-site and off-site effects on natural systems (see also secion 1.1 and Fig. 1-5),

(iii) Watershed management is a set of **linked activities** for which specific management tasks are required. For analytical purposes several specific steps may be identified (Table 1-10).

Taken together, a three-dimensional analytical framework is formed. This can be depicted as a cube with 45 individual cells, each of which provide a basis for analysis: Fig. 1-6.

The unit of analysis is the task which may be those required to plan for major land-use assignments or those required to provide implementation tools to encourage adoption of re source utilisation activities.

In theory, investigation of all cells would be required for a comprehensive watershed management analysis. In practice, the content of most cells will be of little importance: only three cells are important for planning, while five cells have importance for implemenatation. The analytical task can be simplified by the construction of two-dimensional tables (eg Table 1-11) and through the cells considered to be of special interest. Selective analysis of other cells would allow other tasks required at the planning stage, in formulating action requirements, implementation tools, and institutional arrangements to be identified. In Table 1-12 a range of implementation tools are identified, and the tools used during installation are shown in the outlined box.

Fig. 1-5

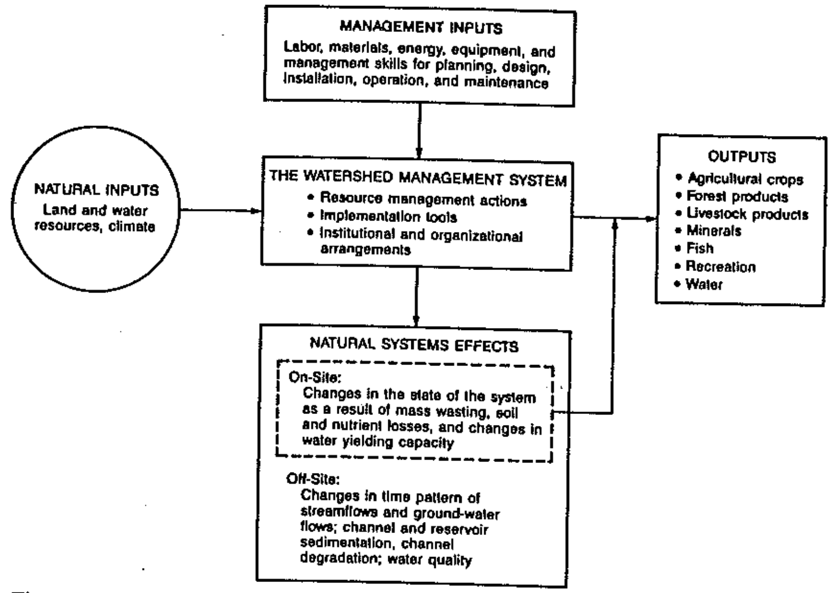


Figure 2.3
Generalized watershed management system in physical output terms.
Note: This schematic can be used to depict a system in the planning, design, installation, or operation stage.

Source: Easter ed. 1986

Fig. 1-6

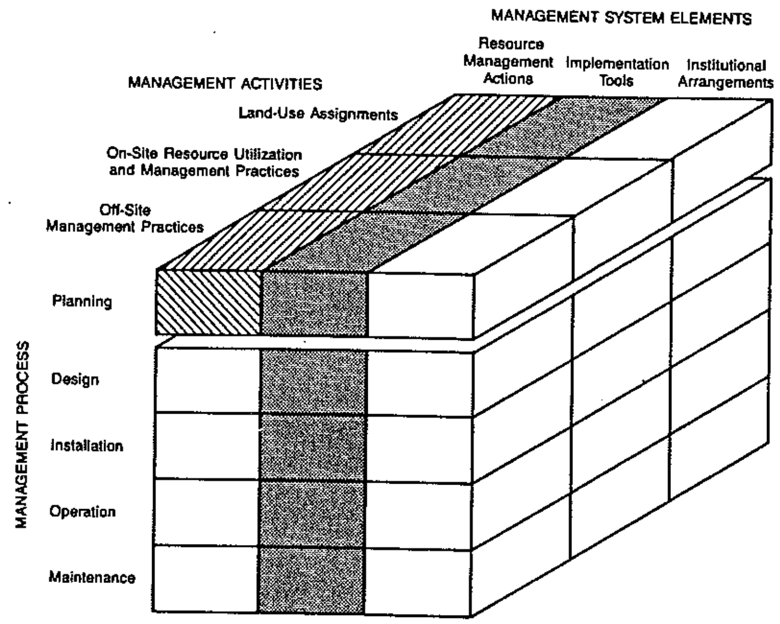


Figure 2.4
A three-dimensional analytical framework for watershed management.

Source: Easter ed. 1986

This analytical framework comprises a planning tool which assists in isolating specific parts of watershed management for more detailed study and provides a basis for monitoring watershed management experience. Management failures, resulting in watershed degradation, can usually be traced to inadequacies in planning.

Source: M.M.Hufschmidt in: Easter et al. ed. 1986

Further readings in: Easter et al. ed. 1986

1.2.8 Irrigation and Regional Water Scarcity

Under conditions of water scarcity, irrigation must compete with other water users. In considering the competition for irrigation water, it should be noted that the quantities used represent a compromise between social and political considerations and a maximum volume corresponding to the requirement of the whole area that can potentially be irrigated (with land availability and human labour acting as constraints). Other considerations concern the water volumes needed per unit under irrigation with reference to the marginal increases of costs and benefits. Traditional water users rights must also be observed and considered.

The regional needs should be defined by government authorities in water master plans. These should indicate the indispensable requirements such as drinking water demand which must be fully met before other users (industrial, domestic and agriculture) may be satisfied. A regional water master plan may be based on

- the analysis of **available water resources**: surface water, groundwater and recycled waters. Water sources must be assessed in terms of reliability and volumes, over various time intervals (usually monthly or annually)
- an analysis of the **water demand** of various users, assuming different development scenarios
- subsequently, models are used to reach decisions on the **quantities of water to allocate various users**. The models are characterised by comprehensiveness and impartiality. Also nature conservation goals must be considered as an objective function. In the first instance no specific demand is given priority over another, except previously defined indispensable demands. Once conditions and parameters are fixed, the models act automatically to determine the maximum usefulness for the region (watershed) as a whole with maximum usefulness generally being taken as the maximum economic return from alternative uses of water. Socio-economic goals, set by policy-makers, may be met through imposing constraints or setting priorities that cannot be justified in economic terms.

  Models may be by 'optimisation-' or 'simulation' types. The optimisation model uses linear programming to identify a solution for the 'optimal scheme', while the simulation model checks the effectiveness of the scheme by simulating its behaviour on the basis of anticipated relationships over long hydrological periods. Objective assumptions may be taht irrigation has a high social value and infrastructure costs should be low. Definitions of time horizons are important because of the variability of flow and the low flexibility of the users' demand. In practice, the use and efficiency of those models restricted because the data base for both hydrological data and cost/benefit analysis may be only tentatively available. Furthermore, social welfare economics is still a difficult subject due to problems of quantification and political decisions often outweight objective functions.

  Source: Beomonte in: ICID (STS-A5) 1991

  Main References: GITEC 1992; Doolette/Magrath (WB) 1991; Easter et al. ed. (1986); FAO (CG14) 1986; Gil (FAO SB 14) 1985; FAO (CG1) 1977; Card ed. (UNESCO) 1984; Haimes ed. (UNESCO) 1987; UNESCO/UNEP 1987

  Further reading and irrigation case study: Integrated Watershed Management Plan in Java: McCauley in: Easter et al. 1986; Watershed Planning in Northern Thailand: Hoare in: Easter et al. 1986

Fig. 1-7 a

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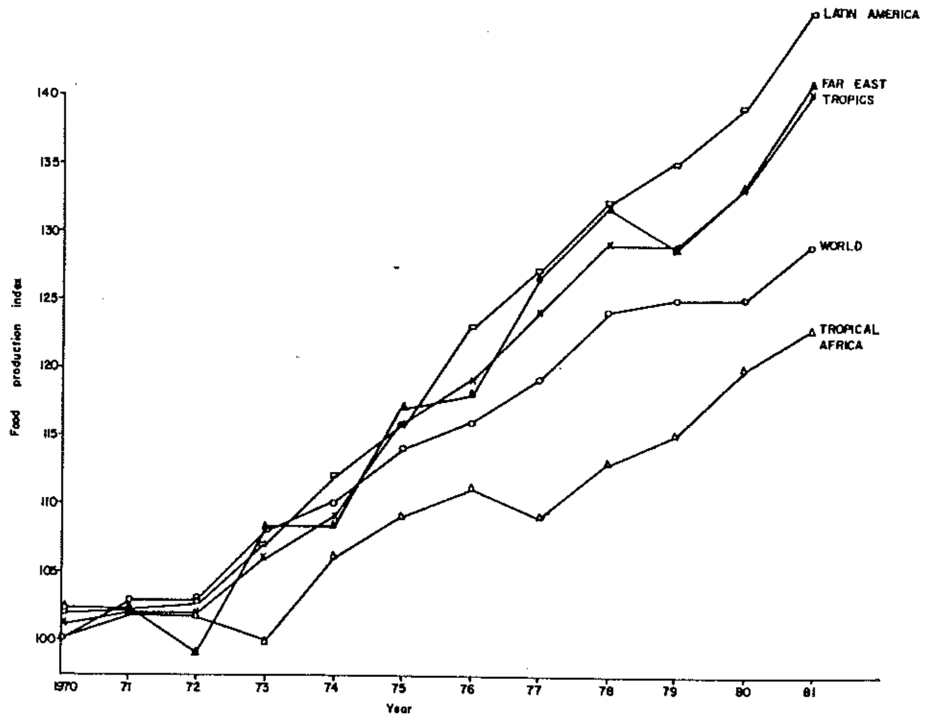


Figure 1.7 Food production index of tropical regions (FAO, 1981). *Reproduced by permission of the Food and Agriculture Organization of the United Nations*

Source: Lal ed. 1987

14

Fig. 1-7 b

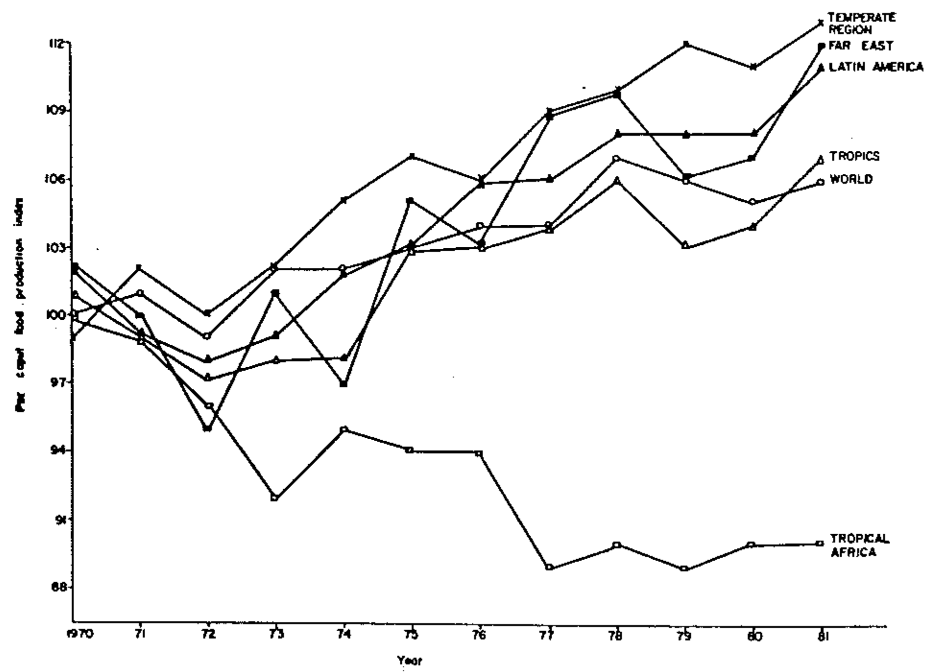


Figure 1.8 Per caput food production index (FAO, 1981). *Reproduced by permission of the Food and Agriculture Organization of the United Nations*

Source: Lal ed. 1987

1.3 Irrigation as a Part of Agricultural Systems Development

Key words:

horizontal expansion and technology improvements; food production technologies; emerging technologies for increased productivity; environmental implications; irrigation efficiencies; trends in irrigated crop production; environmental quality enhancement through production improvements; eight technology clusters versus environmental decision factors; decision matrix for crop production clusters

Cross References: section

Part II sections 1.1, 1.2, 3.1

Main Refferences: Canter 1986

1.3.1 Introduction

The trend in agricultural production during the second half of the 20th century is characterised by an unprecedented **growth in agricultural productivity.** In the industrialised countires total productivity factor rose by between 1 and 2% annually. Labour productivity grew at rates above 5% annually. In some decades crop production has grown by 30% (Canter 1986). In comparison, livestock production increased marginally. In developing countries the trends are more diversified due to developments in different agricultural systems; for example in some areas the technologies of the green revolution dominate whereas in other areas shifting cultivation is still predominant.

Actually, in most developing countries the increase in production is mainly due to expansion of croplands. In the decade ending 1980 the permanent cropland area increased by 6 % and 14% in Asia and Africa, respectively (Lal 1987, from FAO figures). These efforts resulted in an increase in per capita food production in all zones except Africa (Fig. 1-7a-b). Major long-term increases in food production will also be required in future to cover the world's food demand which will constantly grow due to increasing population and income growth. Future enhancement of food production quantity and quality should not be focused only on increasing horizontal extension of croplands but also technological improvements. The latter depend on increasing biological productivity and in particular on the potential for genetic improvements:

> greater photosynthetic efficiency, improved biological nitrogen fixation and otehr symbiotic processes, genetic improvements, more efficient nutrient and water uptake and use, minimizing losses from nitrification and denitrification of nitrogen sources, more resistance to competing biological systems (weeds, diseases, parasites, nematodes), alleviation of climatic and environmental stresses (drought, unfavourable temperatures, mineral stresses), and hormonal systems and their regulation (Canter 1986).

1.3.2 Agricultural Systems

Choices have to be made between several types of food production technologies. These may be grouped as follows:

(i) **resource consuming (exploiting) system**: a highly mechanised and land-, water- and energy-intensive system (eg USA and Europe). There is a high food output per unit of labour and land with very high input demands and several serious environmental impacts resulting from the indiscriminative use of agro-chemicals, heavy machinery and unbalanced crop rotations: water pollution, soil contamination, and energy waste, high land use and cultivation factor,

(ii) **high technology resource-mobilizing system**, here, a bilogically and scientifically based and sparing land-, water-, and energy resources system (eg Japan and Korea) is characterised by: high food output per unit of land; lower direct and indirect demands in energy, increased use of on-site energy resources; lower levels of pollution and contamination than in (i); very high efficiency of land and water resource use, lower labour productivity due to lower degree of mechanisation than in (i); very high land use and cultivation factor,

(iii) **land resource-consuming system**: traditional non-mechanised, extensive subsistance system with intensive land demand, inefficient use of water and land resources, but rather independant from purchased inputs; very limited use of energy resources (direct and indirect) resulting in low output per unit of land and labour, but with very limited impacts on water and soil resources, although excessive areal occupancy, if shifting cultivation and bush fallow techniques are used; erosion and soil degradation may be accelerated; low land use and cultivation factor,

(iv) **intermediate technology resource-mobilizing system**: ecofarming systems with efficient land and water uses and limited energy demand: lower labour productivity than in (i) and (ii), limited pollution of water and soil, limited mechanisation but efficient cropping patterns (eg multiple cropping and seeds) as well as improved soil and water management techniques (eg improved tillage); use of on-site energy resources and low level of inputs from outside (eg energy, materials, machinery, fertilizers, pesticides); medium land use and cultivation factor.

modified after: Lal 1989; Lal 1987; Wittwer in: Canter 1986; Ruthenberg 1980; Nye/Greenland 1960; land use factor and cultivation factor may be quantified according to: Allan 1965 and Ruthenberg 1980

1.3.3 Emerging Agricultural Technologies

There are recent trends in industrialised countries, as competition for resources increases, to transform the dominating agricultural system towards systems with raised levels of crop outputs per unit of resource input and to reduce the constraints imposed by the relatively inelastic supplies of land, water, energy and agro-chemicals.

Consequently, there will be a move towards more efficient use of soils, agro-chemicals and water, including irrigation, to achieve the goals of high and stable production. The following emerging agricultural technologies will have the potential for increasing agricultural productivity:

(1) **genetic** and plant breeding engineering: genetic manipulation to improve crop varieties (drought-tolerance and salinity tolerance, improved hybrids),
(2) **water** and **irrigation** management: systems which use less water and energy and reduce soil compaction, salinity control and drainage return flow control,
(3) **crop pest control** strategies: resistant varieties, biological controls,
(4) multiple and intensive **cropping**,
(5) reduced or minimum **tillage**,

Source: USDA, modified after Canter 1986; only those technologies which may be relevant for situations in developing countries are quoted.

1.3.4 Environmental Implications of Agricultural Trends

In non-irrigated agriculture the four most important technologies regarding resources and environment are: runoff and erosion control, improved crop varieties, conservation tillage, and using scouting and integrated pest controls.

A complete list of the most important 10 technologies and trends in their development are shown in Table 1-13. Detailed descriptions are given in Canter 1986: Chapter 3.

Tentative estimates of the overall performance of some improved technologies on the efficiency of irrigation are as follows (USA-experience):

Estimates of performance of improved technologies in irrigated farming

measure	increase in efficiency %		improvement in quality %	
	fossil fuel	water use	soil	water
improved drainage and optimizing soil-water conditions	6	15	4	?
improved soil management	12	13	18	16
improved erosion control	13	12	20	28
reduced tillage	6	9	12	7
improving N-fixation and photosynt.	19	9	6	5
less harmfull and more efficient agro-chemicals	3	-	-	10

Source: after Boucher/Drobnick 1983 in: Canter 1986 (page 30 cont.; shortened) weighted mean estimates by the most confident and expert groups

It may be concluded from the significantly lower overall efficiencies of most agricultural systems in developing countries that the impacts of improvements can be even higher than could those given for conditions in the USA, especially regarding soil and water management measures.

The **envrionmental implications** of recent trends in irrigated crop production are shown in Table 1-14. The potential interactions between specific practices and contamination of water, air and soil pollutants are shown in matrix from Table 1-15.

Most trends which are applicable for upland crops are also relevant for irrigated crops: eg crop management, soil-water management, nutrient management, pest control, and resource use. Differences are related to soil and water management either to mitigate the effects of drought or to control salinity, erosion and drainage losses. The most important trends for irrigated crops are:

(1) improving water application: practices to optimise water application by the development of scheduling systems which are flexible with regard to specific crop demands. Also the control of tailwater in surface systems. Beneficial effects are expected with respect to reduced soil and water pollution

(2) runoff and erosion control: measures such as land grading, contour farming, terracing and cover crops which stabilise soil and reduce runoff; this trend is less important for well designed sprinkler systems (except mobile rain-guns) and drip irrigation systems

(3) method of nutrient application: increasing efficiency of fertiliser applications and thereby reducing losses to water and air; multiple applications and improved placements are effective practices

(4) developing integrated pest control measures: integration of biological, chemical and mechanical methods to improve pest control and reduce soil contamination and water pollution by pesticides,

(5) use of soil-plant analyses: demand-oriented fertilisation, but such an approach needs a data base. Reduced fertilizer applications and thus reduced losses

(6) direct monitoring of irrigation needs: efficient water use requires basic data on soil moisture and irrigation applications

(7) using the most efficient irrigation system: sprinklers and sprays give the most uniform applications; trickle systems are most effective under saline soil conditions and water shortages etc.

(8) seed and plant improvements: give higher yields

(9) developing nitrogen-fixation sources: increasing N-fixation by microorganism, improving symbiotic relationships between plants and microorganism in the rhizosphere,

(10) developing improved fertilisers: nitrate inhibitors increase efficiency and reduce water pollution; controlled release reduces losses.

Source: Unger 1977, cit. in: Canter 1986

Table 1-16 identifies the most important technical measures involved in these trends, eg contour farming, terraces, cover crops and land grading are the most important practices to runoff and erosion control.

1.3.5 Summary of Technology Trends

Some years ago the popular perception was that growth in agricultural productivity and output would automatically result in environmental degradation. This would imply static technology and unchanging management practices. However, through qualitative improvements of inputs, advances in management practices and appropriate treatments to deal with pollutant residues, environmental quality (in terms of soil, water and air quality) may be maintained or even enhanced. Improvements in air and water quality legislation against industrial pollution has (over the past decade) demonstrated that environmental trends can be reversed even with increased production (OECD 1991).

The five most important trends are summarised in Table 1-17 for both non-irrigated and irrigated crop production. As indicated, the irrigation trends are based on water management related practices, whereas increased efficiency in non-irrigated crop production is related to a mixture of management practices and qualitative improvements in inputs. Table 1-17 may be extended for irrigation trends by adding the use of renewable energy resources or increasing the efficiency of power systems in water supply and drainage (see Chapter 4.15).

1.3.6 Comparison of Emerging Crop Production Technologies

Following the approach of Canter, there are eight important emerging technology clusters. Their important production and environmental impacts are as follows:

(1) nitrogen fixation, fertiliser requirements will be reduced but slightly increased erosion rates may occur,

(2) genetic engineering: these may increase water use efficiencies and reduce fertiliser requirements resulting in an increase in crop production,

(3) enhancement of photosynthetic activity: this may help to reduce fertiliser requirements resulting in an increase in crop production,

(4) water management: this should decrease the water demand, reduce runoff and reduce deep percolation losses which may lead to soil contamination and salinisation if minimum leaching is not practiced; otherwise crop production should increase,

(5) plant growth regulators: reduce fertiliser requirements but pesticide requirements may increase; increased crop production,

(6) erosion control and soil managament: (6.1) conservation tillage and (6.2) runoff control; both reduce water demand and increase yields; but fertiliser and pesticide requirements may increase (weed control etc.); reduced runoff leaves pesticide residues on-site,

(7) multiple cropping: this reduces erosion and runoff but fertiliser and pesticide use may increase; water demand may increase with double cropping; production increases,

(8) pest control strategies: reduction in chemical pesticide applications; increased production.

Source: Canter 1986 after Unger 1977

In a trade-off analysis these eight clusters are compared, based on the degree to which they increase agricultural productivity and reduce environmental impacts. The latter are subdivided into water, soil, air, noise and solid waste impacts which may be detrimental or beneficial. Canter uses the weighting-ranking approach. Based on known or anticipated information, the technology clusters are listed in terms of beneficial or detrimental environmental impacts in the following two matrices.

A final decision matrix for the trade-off analysis shows that if equal weight is given to all three major decision factors, environmental impacts, natural resource and land use efficiency. The following priority order of the three major technological clusters is determined: Genetic Engineering - Water Mangement - Plant Growth Regulations. The following list shows the **ranked technology clusters** differentiated for three **environmental decision factors:**

Marix 1

Final Decision Matrix for Crop Production Technology Clusters

decision factor Environmental Impact	decision factor Resource Use Efficiency	decision factor Land Use Efficiency
1. Genetic Engineering	1. Soil Erosion/Management	1. Genetic Engineering
2. Water Management	2. Water Management	2. Water Management
3 Growth Regulators	3 Genetic Engineering	3 Growth Regulators
	3 Nitrogen Fixation	3 Enhancement of Photosynthsis

Source: after Canter 1986: chapter 7, Table 77 (if no order number is shown the clusters are ranked equally)

Matrix 2

Evaluation of Technology Clusters with regard to their Environmental Impacts

Environmental Decision Factor	Emerging Crop Production Technology Clusters (1)	(2)	(3)	(4)	(5)	(6.1)	(6.2)	(7)	(8)
Surface water (7.5)									
sediment	-	+	+	++	+	+	+	+	0
nitrogen	+	+	+	++	0	+	+	+	0
phosphorus	+	0	+	+	+	+	+	+	0
pesticides	0	0	0	+	0/-	-	+	+/ 0	++
inorganic salts	0	0	0	++	0	0	0	0/-	0
biodegradable	-	-	-	0	-	-	+	0/-	0
Groundwater (7.5)									
nitrates	-	+	-	++	0	-	-/ 0	-	0
pesticides	0	0	0	+	0	-	-	-	++
inorganic salts	0	0	0	++	0	0	-	0	0
Air (3.5)									
gases	+	0/+	0	0/+	0/+	+	0/-	0/-	0/+
particulates	-	+	+	+	+	+	+/-	0	0
Land/Soils (5.5)									
water erosion	-	+	+	++	0	++	++	++	0
wind erosion	-	+/0	+/0	++	+	++	+	++	0
salinity	0	0	0	-	0	0	0	0/-	0
heavy metals	0	0	0	0/-	0	0	0	0	0
pesticide residues	0	0	0	-	0/-	-	-	-	++
biodegradable org.	0	-	-	0/-	-	-	-	0	0
Noise (1)	+	+	+	+	+	-	-	-	+
Solid Waste (2)	-	-	-	-	-	-	-	-	0/+

The relative importance is shown in brackets: noise = 1 (less); soil erosion = 5.5 (more important)

+ or ++ relative environmental benefits relative to the item via the introduction of the process

0 denotes no appreciable change from current conditions

- or -- relative environmental costs via an increase of the process

0/- or 0/- range of possible impacts: neutral to negative or neutral to positive

Source: slightly modified after Canter 1986: chapter 7, Table page 76

1.4 Sustainable Agricultural Development

Cross references: sections

Part I section 1.1 (especially 1.1.4)

Key words:

sustainability, land saving activity; categories of sustainability; sustainable systems; critical issues; population growth; constraints in Africa; carrying capacity; scarce water resources; appropriate approaches for Africa

Main reference: Edwards et al. ed. 1990

1.4.1 Aspects of Sustainabiity

A universal definition of sustainable agricultural (irrigation) development could be:

> *An agriculture that can evolve indefinitely toward greater human utility, greater efficiency of resource use, and a balance with the environment that is favourable both to humans and to most other species*
>
> Harwood in: Edwards et al. ed. 1990

Well planned and managed Irrigated agriculture can be regarded in several ways as a system which satisfies the definition of sustainable agriculture as a whole or in parts:

* It uses the natural resources in the **most efficient** ways (for human use) as it eliminates or reduces the adverse drought effects in many farming systems. Inadequate soil moisture is the major factor limiting crop growth; since the biomass production of a plant is directly related to the evapotranspiration index.
* Irrigation is a **'land saving'** land use system, because it occupies less area per unit of production than other traditional systems under given natural conditions. Irrigated multiple cropping systems can be regarded as the most productive human land use system. The land use factor for shifting cultivation systems is in the range of 5 to >10, whereas irrigated multiple cropping systems may have a coefficient of less than 1 (Table 1-18), ie irrigation may use the land by the factor 5 to 10 times more efficient than shifting cultivation.

However, irrigation may also be regarded as a system which exploits natural resources such as water and soils to the disadvantage of other human or non-human users. Furthermore, inadequate irrigation farming practices may lead to (i) a rapid deterioration of natural soil fertility (such as alkalinisation, salinization, waterlogging, soil contamination) and (ii) the pollution of water resources, with detrimental effects to other human or non-human users. Furthermore, the construction of large reservoirs for irrigation water supply may cause environmental damage. Hence, irrigated farming may be designated as 'sustainable' to 'sustainable only under specific circumstances' (see Table 1-18) according to the scale and type, various socio-economic and environmental factors are involved such as soils, water, land, climate, public health.

Agendas for sustainable agricultural development may be grouped into the five <u>categories</u>:

1 Increase the **utility** of agriculture: maintain adequate production; provide adequate livelihood, considering equity, stability, safety, lifestyle for all participants,

2 Increase **productivity**: develop more productive systems

3 **Maintain** an environment favourable to humans and most other species: protection of water from pollution and soils from contamination; recognition of animal rights (reduce stress in confinement, provide for a degree of natural activity)
4 Assure the ability to evolve **indefinitely**: minimize soil loss, prevent overdraft of fossil groundwater, reduce (fossil) energy use, maintain existing genetic diversity
5 Develop patterns of geographical **distribution** and scale consistent with those agendas: create adequate physical and institutional infrastructure; develop market channels that respond to market and social needs.

Source: Harwood in: Edwards et al. ed. 1990

Hence, sustainable agriculture requires the successful management of resources for agriculture to satisfy changing human needs while maintaining or enhancing the natrual resource base and avoiding environmental degradation (TAC 1988; quoted in Harwood). Sustainable farming systems

* maintain or improve the natural resource base
* protect the environment
* ensure profitability
* conserve energy
* increase productivity
* improve food quality
* create viable socio-economic infrastructure for farms and the rural community.

Source: Parr et al. in: Edwards et al. ed. 1990

Irrigated farming may contribute towards achieving these objectives under specified circumstances which need to be defined in regional socio-economic and environmental context. The principle critical issues causing unsustainable development under irrigation include:

* poor water management which causes system inefficiencies
* inadequate site selection with regard to soil and water qualities
* poor maintenance of hydraulic infrastructur
* lack of public health safeguards and mitigating measures for public health controls
* poor agronomic practices with regard to soil fertility maintenance, water pollution and soil contamination hazards.

Further reading: Edwards et al. ed. 1990

1.4.2 Environmental Considerations for Food Security in Africa

Food security means ensuring that all members of a country have access to enough food throughout the year to lead an active, healthy life (World Bank 1986, quoted in Brown/Thomas 1990). The conditions in Africa are briefly outlined in the following.

The ability of people in Africa to feed themselves has declined markedly in recent years. The decline in grain yields over a 30-year period indicates a decline in primary productivity, especially in Sub-Saharan Africa (Table 1-19). These lower yields are probably caused by civil war, socio-economic instability and environmental factors such as 'desertification', prolonged and unpredictable natural droughts, inappropriate land use, or a combination of these factors.

With a steadily increasing population, the need for sustainable development has become especially acute. The **population growth** rate of some 2-3% per year results in an annual addition of 16 million people to Africa's present population of some 640 M people (1990).

The world population growth by geographic regions and the projected population size at stabilization for selected countries are shown in Tables 1-20 and 1-21. The population of Ethiopia is projected to invrease fivefold before stabilisation in an area where war, poor land-use and ill-conceived agricultural policies have already led to widespread starvation.

The sheer numbers alone will exert enormous pressures on the **carrying capacity** of the land use systems. Under present land use practices, some areas in sub-Saharan Africa have almost reached or have exceeded their carrying capacity for food and fuelwood production (Table 1-22). With such a large population and environmental degradation undermining economic progress all across Africa, the only successful economic development strategy will be one that promotes and sustains the natural ecological systems. The two major challenges facing African agriculture are: how to manage land so that conntinuous production is realized from areas characterized by erratic environmental constraints?, and (2) how to effect a balance between input-intensive and the purely organic style of agriculture so that the practice remains productive and environmentally friendly (Brown/Thomas 1990). Since Africa is a continent of extreme diversity, sustainable development will require different methods and solutions according to the local environment.

In most tropical African regions, unlike Latin America and most Asian areas, water is a **major limiting factor** in agricultural production (FAO 1986):

* over 54 % of the land area is deficient in rainfall,
* some 46 % of the area has less than 74 days growing period,
* in more than 50 % of the land area in tropical Africa, rainfall reliability, expressed as the deviation from the average, ranges from 20 to 40% .

Periodic drought is common and the natural rainfall pattern (onset, duration, intensity) is often unfavourable for high yields under rainfed farming. In combination with high evaporation rates, most areas in Africa suffer from drought and, thus, irrigation may be the major measure to mitigate drought effects in many areas. However, there are several constraints to increasing agricultural production through irrigation development in Africa:

* **sufficient water** is not available in those places or regions where it is needed
* **water management** practices and technological knowledge are generally poor
* this is aggreviated by the fact that **soil** and **land drainange** conditions pose specific management problems which would require sophisticated systems of soil and water management practices
* **socio-economic** constraints are widespread, including (a) unfavourable land tenure systems, (b) shortage of labour at peak periods of demand during planting, weeding, and harvesting, (c) poor credit facilities, (d) poor marketing facilities and pricing structure, (e) high cost and unavailability of inputs, (f) high rates of illiteracy among farmers, which hampers adoption of new technologies, (g) poor performance of extension services, (h) inappropriate agricultural development policy (Okigbo 1990)
* **logistical conditions** are unfavourable for intensified production systems.

Nevertheless, it is obvious that traditional farming systems, whilst ecologically sound and adapted to prevailing conditions and the needs of the farmer when population density was low, are becoming increasingly outmoded and **unable to meet the demands** of rapid population growth, high rates of urbanisation, increased mobility, and rising incomes (Okigbo 1990). Generally speaking, the traditional farming systems in Africa are characterised by a mosaic of crops, tradition, and technologies that does not reveal a center, a nuclear area or a single point of orign (Harlan, quoted in Okogbo 1990):

- the objective of farming is mainly for subsistance, increasingly commercial farming is introduced in whole or part for cash earnings
- farm size is small, ie <80% of farms are <5 ha in size

- slash-and-burn clearance systems are widespread
- labour is mainly manual with simple tools; use of livestock for draft is limited
- marked division of labour between men and women with respect to operations performed and commodities produced
- soil fertility is dependent on nutrient cycling and biological processes; use of fertillizers and other inputs is limited
- cropping systems are rather complex in terms of enterprise mix and range of commodities produced on each farm
- limited irrigation is used in traditional tropical Africa. In arid areas, however, traditional irrigation systems were developed
- arable farming is to various degrees associated with hunting, fishing, gathering and livestock production; thus the intensification of one activitiy collides with others
- yields are low due to the widespread use of unimproved crop varieties and low agricultural inputs; production per unit of energy, however, is higher than in modern agricultural systems

Source: Okogbe 1990

Appropriate approaches for much of Africa may be small-scale and **labour-intensive** methods of irrigation, including water harvesting methods (Brown/Thomas 1990).

Source: Brown/Thomas in: Edwards et al. ed. (SWCSA) 1990

Further reading: Okigbo in: Edwards et al. ed. (SWCSA) 1990

2 Considerations for Water Resources Conservation

2.1 Water Availability and Quality Assessment for Irrigation

Key Words:

groundwater exploitation; bias in parameter choice; standard laboratory analysis; preservation methods for analysis; water quality parameters; FAO-standards; salinity problems; infiltration problems; specific ionic problems; clogging hazard; calcium precipitation; iron precipitation; corrosion & encrustation standards; brackish water; reuse of drainage water; irrigation methods; foliar damage, blending water; cyclic applications; intermittent leaching; experimental LR; practical leaching approaches; drip irrigation; preconditions for saline water use; wastewater; effluent characteristics; quality indicators; standards for use; quality guidelines

Cross-References

sections 1.2, 3.1, 3.3, 4.1 and 5.1, 5.2; Part I section 2

Main References: Ayers/Westcot (FAO) 1985; Shainberg/Oster 1978; Shainberg/ Shalhevet 1984; Rhoades/ Loveday in: Stewart et al. ed. (ASA) 1990; Yaron 1981, Feigin et al. 1990; Pescod/ Arar ed. 1988; Shuval et al. (WB) 1986

2.1.1 Surface and Groundwater Resources Estimates

Water resources assessments for irrigation are subject to hydrological and hydrogeological investigations. An overview of estimates on surface and groundwater resources is given in Helliwell and Wilkinson/Clark (in: Rydzewski 1987) with further references. Details of hydrometry, catchment yield assements, reservoir yield assessments, groundwater resources investigations can be derived from these sources.

The exploitation of groundwater resources should meet the following criteria:

1) ready accessibility at adequate costs (depending on the economic conditions and the anticipated farm economics),
2) satisfactory rate of recharge to the aquifer, either from surface water sources or rainfall; the mining of groundwater deserved special attention,
3) sufficient storage within the aquifer to enable reliable yields to be maintained also during drought periods,
4) water quality should be acceptable for the desired use.

Sources and further reading: Wilkinson/Clark in: Rydzewski 1987; Helliwell in; Rydzewski 1987

DVWK/GTZ 1990 Guidelines 301/1990. Manual for waterlevel gauging and discharge measurements

2.1.2 Water Quality for Agriculture

This section considers the quality of water from river or groundwater sources which is not designated as 'saline water' or 'wastewater'. The latter, derived either from sewage, naturally saline sources or agricultural drainage effluents, are treated separately under sections 2.1.3, 2.1.4 and 2.5, because for these waters different standards and remedial measures have been established.

Criteria regarding water quality requirments for irrigation are already well established and internationally accepted standards exist (eg Ayers/Westcot, FAO 1985). In addition, various national standards may deviate slightly from each other, due to agro-climatic circumstances, different irrigation methods and practices, crops grown or soil and groundwater conditions.

Approach and discussion

A serious bias in classifying waters for irrigation is that only a few parameters are usually chosen as indicators in order to classify the quality for a given use. These usually comprise total **salinity** (ECw) and **sodium** as the ion of specific interest, because it may cause sodification.

This approach, however, is limited because it does not take into account the actual manifold physical, chemical and biological characteristics of waters and the dynamics of changes which occur in soil-water solutions. Most importantly, this approach does not allow properly for various **management** decisions on the part of the irrigator. Sustainable irrigation with high production levels can be carried out using relatively 'poor-quality' irrigation water, whereas poor crop and water management might result in salinity, sodicity or other toxicity problems even when using relatively 'good-quality' water.

As a result, the question regarding water quality should no longer be 'how good is the water' but rather **'what can be done with this water if used for irrigation'**. This implies a change in emphasis away from the assignment of a specific quality index to a given irrigation water, and towards consideration of water quality in the context of **management practices** (McNeal in: Yaron 1981).

The viewpoint that water quality is **not an inherent property** of the water itself, but rather a **property** related to the management of soil and water for crop production applies not only to advanced irrigation farming in California, Europe or Israel but to all kinds of irrigation practices throughout the world. On the other hand, it is obvious that this approach has sometimes failed to achieve its objectives in some new projects and in the rehabilitation of older irrigation systems. The individual inflexibilities at various levels of planners, extension service and research officers and farmers regarding adjusted production goals, crop management practices, soil management practices, and water management practices may all contribute to such arising difficulties.

Hence, in practice, there is still some need for 'generalised guidelines and classifications' of water quality for irrigation. However, it should be bourne in mind that the classifications are in a strict sense 'Guidelines' which leave considerable room for circumstantial interpretation and adjustments. They have widespread application for **preliminary** assessments of possible hazards and necessary remedial measures required for sustainable irrigation management and to avoid environmental deterioration.

Irrigation water analysis

Irrigation water should be assessed regarding four water quality related problems which occur under irrigation:

- **salinity** which should be seen in the context of potential build up of soil salinity
- water **infiltration** rate and permeability properties of soils
- specific **ion toxicity**
- miscellaneous, eg excessive nutrients (eg N), abnormal pH or excessive corrosion and deposits.

The assessment must be made in relation to crop tolerance to salinity; how much leaching will be achieved; and what level of soil water salinity will be obtained. The following chemical characteristics are usually determined:

- total **salt** concentration as electrical conductivity (EC as dS/m) or sometimes given as total dissolved solids (TDS as ppm or mg/l)
- concentration of **soduim** in relation to calcium and magnesium. An indicator of the soil sodicity risk is the sodium absorption ratio, which is defined as $Na/\sqrt{(Ca + Mg)/2}$. A high SAR in itself can cause permeability hazards

- conentration of **boron B**, a plant nutrient which is toxic at slightly increased levels
- **pH** which is an indicator for abnormal waters which require further analyses.

Further analyses may be required, including:

- **trace** elements, some are nutrients, but should be evaluated for toxic effects
- **chloride** analyses (chloride sensitivity of some crops)
- **Nitrogen**-N; **Ammonium**-N (10 mg N/l = 45 mg NO_3/l = 13 mg NH_4/l)
- **anionic composition**, especially those causing alkalinity (bicarbonate, carbonate) or relevant for soil amendment applications (eg gypsum requirements).

Details of the most common analyses are shown in Table 2-1. Water quality **parameters** for comprehensive analyses are presented in Table 2-2 and suggested water preservation **techniques** are given in Table 2-3 (see also soil analyses in section 3.2.2)

Quality Standards

Guidelines for assessing water quality under average **irrigation** conditions are shown in Tables 2-4/1 to 6 (USDA, FAO and other standards). They are based on certain assumptions (eg on the leaching fraction) and with changing circumstances the degrees and classes should be modified (Text to Table 2-4/1). For example, guidelines for semi-arid conditions in Australia are shown in Table 2-5a-b (Shaw/Thorburn 1985) and guidelines for different soil conditions are shown in Tables 2-4/5 and 6.

Guidelines for **livestock** uses are shown in Table 2-6a-b (FAO-standards, mainly adapted from experience in the USA)

Salinity problems (see also section 3.3 and Part I section 3.1) are related to

- potential build up of soil salinity resulting from salts added with each irrigation
- blending of saline water (see sections 2.1.3 and 2.4)
- land reclamation and development methods for salinity control
- irrigation methods (see also sections 2.3 and 2.5)
- management of the salt balance by means of leaching and providing adequate drainage (see also section 2.4)
- cultural practices; land preparation, timing of irrigation, seedbed preparations, placement of seeds, use of fertilisers (see also sections 2.3.3, 2.5 and 5.2).

Infiltration rates can be reduced by the use of irrigation water which results in soil salinity and sodicity. Fig. 2-1 shows potential problems as related to sodium concentration and total salinity in the irrigation water.

Recent methods to assess the extent of sodicity hazard (SAR-value) are given in Table 2-7a-b. Soil and water amendments such as gypsum and acid-forming amendments are effective means to manage infiltration problems (see section 3.3.4).

The contribution of common **fertilisers** to acidity or alkalinity is shown in Table 2-8.

Specific toxicity problems occur if plants themselves are susceptible to excessive uptakes. The degree of damage (yield reduction) depends upon time, concentration, crop sensitivity and crop water use. Toxic ions include chloride, sodium and boron for which various crop tolerances are given in Tables 2-9a-b (chloride), 2-10a-b (sodium) and 2-11a-b (boron), respectively.

In some areas, high levels of trace elements (namely heavy metals) may occur in irrigation waters, which may be derive from natural sources (dissolution from minerals) or from industrial or domestic effluents (see section 2.5). The mere occurrence of heavy metals at

Fig. 2-1 a

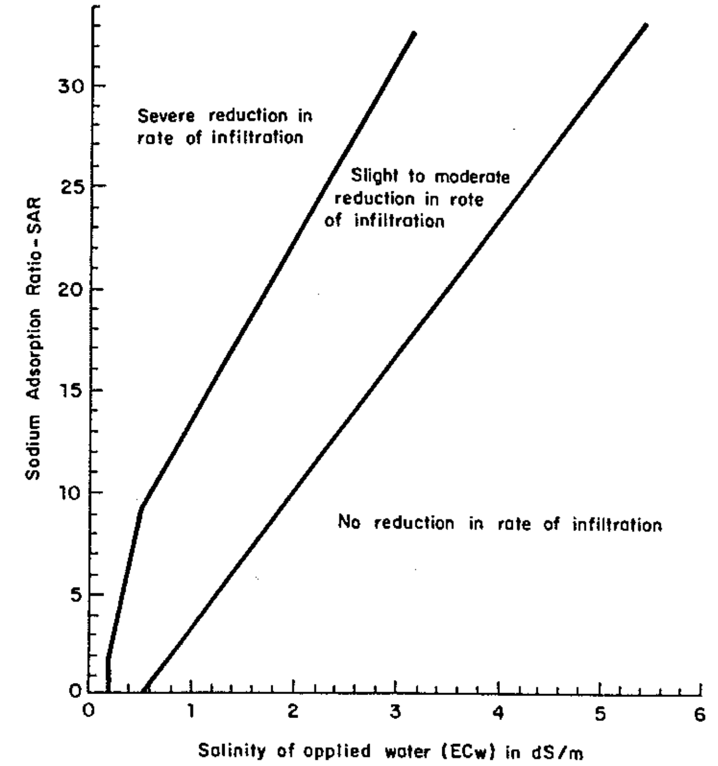
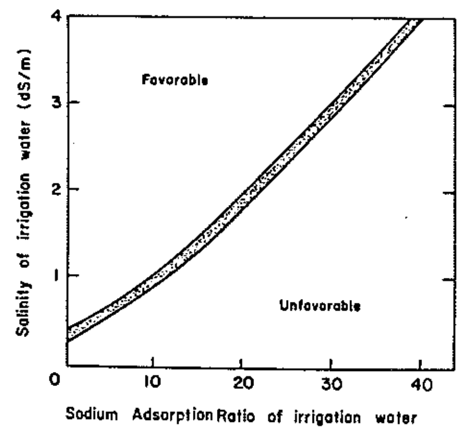


Fig. 21 Relative rate of water infiltration as affected by salinity and sodium adsorption ratio (Adapted from Rhoades 1977; and Oster and Schroer 1979)

Source: Ayers/Westcot 1985

Fig. 2-1 b

Fig. 3.4 Salinity and sodium adsorption ratio boundary indicating SAR and EC combination promoting favorable and unfavorable permeability conditions (After Oster et al. 1984)



Source: Feigin et al. 1991

Fig. 2-1 c

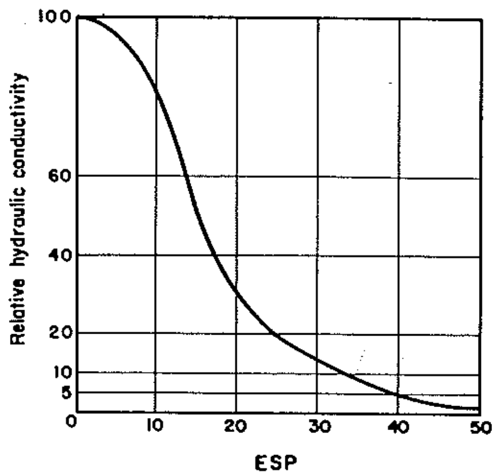


Figure 20 Schematic diagram showing the relative hydraulic conductivity of a soil as affected by increasing ESP

Source: FAO (SB 39) 1988

high concentrations does not necessarily render the water unsuitable for irrigation. As water precolates through the soil, metals may be precipitated, adsorbed, or fixed on soil particles, and thus become inactive (see Part I section 3.6). Maximum permissible levels of various elements in irrigation water are shown in Tables 2-12a-b. These limits have been established to prevent continuously irrigated soils from being contaminated by waters that contain constituents exceeding such levels (see also section 2.4).

Pollution problems may occur if excessive nitrogen is present (high contents >50 mg/l NO_3-N) in groundwaters or wastewaters. This may be toxic to sensitive plants at high concentrations (>50 mg/l), but may also create problems associated with excessive algae and aquatic plant growth in canals or natural waters, resulting in plugged valves, pipelines, sprinklers, or drip outlets.

Scale deposits from water containing high concentrations of calcium, bicarbonate and sulphate may create problems under sprinkler irrigation due to the formation of white deposits on leaves or fruits which restrict their marketability. They may also (as with high suspended sediment loads) enhance the clogging problems of sprinkler and drip irrigation systems.

Abnormal pH-values (<5.5 or >8.5) may cause indirect problems due to reduced availability of nutrients (eg trace elements) or corrosion of irrigation equipment. High magnesium contents may result in imbalanced calcium uptake by crops from the soil solution.

Clogging Hazards

Clogging induced by poor water quality is a major hazard when drip and (generally less often) sprinkler irrigation systems are used. The principal physical, chemical and biological contributions to clogging are summarised in Table 2-13. The factors are usually interrelated and a combination is often reported to worsen the problem: eg bacterial slime growth causes further clogging by suspended particles due to reduced flow rates.

The main parameters which should be analysed especially for drip irrigation are summarised in Tables 2-14 and 2-15. A relative scale for situations when problems are likely to occur is presented in Table 2-16. However, the standards should be treated only as indicators which require further tests to determine the suitability of possible solutions (eg in economic terms). The term 'no restriction' does not imply that remedial measures and monitoring are not required.

The tendency of water to cause calcium precipitation in the soil can be predicted using the saturation index SI, Langelier-index, as a function of the degree of $CaCO_3$ saturation of the soil solution: pHa - pHc, derived respectively from actual and theoretical pH values. Table 2-17 can be used for calculating the theoretical pH value. Positive SI values indicate a tendency for Ca-precipitation, which will increase the SAR of the soil solution

The SI can also be calculated from SI = 8.4 - pH_c (where 8.4 is the pH of a non-sodic saline soil in equilibrium with CaCO3) to give an estimate of the magnitude of precipitation, since there is a linear relationship between the amount of CaCO3 precipitated and the value of the SI at pHc < 8.4, as shown in Fig. 2-2. It is also evident that as the leaching fraction (LF) increases, precipitation of CaCO3 decreases.

Further details in Shainberg/Oster 1978; Ayers/Westcot (FAO) 1985

Iron precipitation often occurs as compounds of iron in bacterial slime. Problems are reported to occur at concentrations of >2 mg/l Fe. About 5 mg/l Fe should be considered as the maximum concentration for drip irrigation.

Chlorination, filtration oxidation ponds to encourage Fe precipitation, in combination with filters, can be used as remedial measures (see section 2.5). Chemical treatment is generally applicable to control bacterial growth, especially for sulphur bacteria. However, its

Fig. 2-2

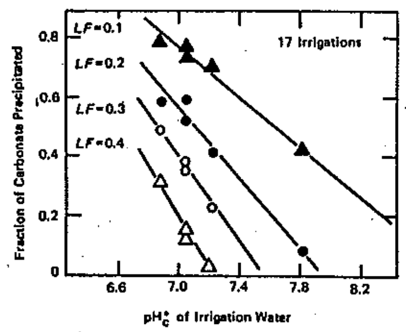


Figure II.7 Precipitation of $CaCO_3$ as related to pH$_c^*$ of irrigation water and leaching fraction.

Source: Shainberg/Oster 1978

use under average conditions in developing countries is often too expensive and requires careful management.

Drip irrigation using qater which poses bacterial-induced problems should not be regarded as preferential to other irrigation systems unless good management is ensured.

Corrosion and Encrustation Problems

Most groundwaters are mildly corrosive to iron and some will even affect more resistant metals. Corrosion problems are usually associated with low salinity and encrustation problems with high salinity. Both processes are complex and interactive and, therefore, the figures presented in Table 2-18 should only be used as an indicator to potential problems.

Reference: Ayers/Westcot (FAO) 1985; Shainberg/Oster 1978, McNeal in: Yaron 1981

2.1.3 Use of Saline Waters for Irrigation

Highly saline (brackish) waters used for irrigation may derive from drainage effluents as return flows to the groundwater or surface waters. Occasionally, saline water may be from saline groundwater aquifers (or marine intrusions) or highly saline surface waters from rivers or lakes. Brackish waters include those with a salt concentration which is high enough to cause serious damage to a specific crop when normal irrigation practices are used or salinity control measures are inadequate (see also section 3.3).

The reuse of highly saline **drainage** water is one option to reduce ground- or surface water pollution induced by irrigation. The reuse must be regarded as a remedial measure which has typically beneficial effects on downstream water users but may have detrimental on-farm effects by increasing the risks of soil and groundwater salinity build-up within the command area. Consequently, any short-term reuse of saline water must also be based on a long-term land use concept which ensures the sustainable use of a given area. This may include its future use for grazing or for other uses under high salinity conditions (eg halophytic shrub plantations: Malcolm/Swaan 1989; Malcolm 1986).

> The use of brackish water is widespread especially in India and Pakistan, but also in Iraq, Egypt and the USA, where large scale field trials are underway (Rhoades et al. 1988; Westcot 1988; Armstrong et al. in: Wooldridge 1991). Field experiments in India, USA, Israel, Iraq and elsewhere have shown that irrigation with brackish water can be used on a sustainable basis if certain criteria are observed. Analysing data from a worldwide survey it was concluded that waters of up to 10 dS/m can be used successfully in commercial farming. Other sources state a limit of about 7.5 dS/m (review cited in Rhoades et al. 1989). However, most experience has been that under conventional management saline water irrigation results in increases in pH and Na saturation in soils, reduced water infiltration rates and decreased yields (Bajwa et al 1986).

On-farm management options for irrigation with saline water include the following on-farm practices:

- irrigation methods,
- management of multi-source irrigation water of different qualities,
- irrigation scheduling (depth of water and irrigation intervals),
- leaching scheduling (depth of water and timing),
- agronomic practices,
- adequate drainage (see also section 2.4).

Sources: Ghassami et al. 1993, Kandiah ed. (FAO) 1990; Rhoades in: Stewart et al. ed. (ASA) 1990; Rhoades 1989

Irrigation Method

The choice of the irrigation method for saline water reuse should consider:

* Distribution of salt and water in soils under different irrigation methods; furrow, sprinkler and especially drip irrigation are suitable for saline waters.
* Crop sensitivity to foliar wetting and yield reduction under sprinkler irrigation. Most vegetables and forage crops are rather insensitive, while fruit trees are sensitive. Despite some evidence of foliar damage for example, of tomatoes and potatoes (Table 2-19), there is little effect on yields. High frequency and intermittent wetting causes most damage, especially at high temperatures. Night-time sprinkling can reduce salt deposition on leaves.
* Ease with which high solute and matrix potential can be maintained. In sprinkler and especially in drip systems, the pattern of salt distribution is favourable and constantly high matrix potentials can be maintained. This is attributed to the distinct three-dimensional pattern of lateral and vertical distribution of water and salts; high soil water content with greater leaching around the emitter and markedly lower water content and accumulation of salts at the outer radius of the wetted zone. Roots accumulate in the moist, less saline zone. After the cropping season accumulated salts must be leached out of the root zone.

Water sources of different qualities may be available at the same location, termed multi-source irrigation. Commonly surface drainage water is reused by blending it with river water, canal water or groundwater. **Blending** of water is usually done to use an additional source of water for irrigation if there is shortage of supply or to improve the chemical properties of a water and thus reduce toxicity problems (Ayers/Westcot, FAO 1985). Blending is especially effective in reducing the risk of sodicity. Although blending enhances the quality of a low quality (saline) water, it implies the **irreversible degradation** of a high quality water. Therefore, blending water may be inappropriate under certain situations, eg under conditions of water scarcity and where there is competition for high quality waters, namely a potable water supply (see also Rhoades 1989, 1992).

Many groundwaters are rich in sodium, and blending with surface waters rich in calcium may be effective (Table 2-20a). In practice, however, blending of high sodium water is not very common, because good quality water is used whenever it is available, and during times of shortage the poor water is used. However, this may aggravate soil structure problems since the use of non-saline water (or rainfall) following application of high sodium water may cause deflocculation of soil particles. In such cases the blending of water is preferable. When water is blended it must be ensured that the additional amount of leaching water required does not exceed the net gain in amount of blended water available. An example of the method used to calculate the additional leaching requirements of blended water for maize is shown in Table 2-20b.

Alternative cyclic applications of 'low' and 'high' salinity waters on the same field may be advisable if there is **no sodicity** hazard. One option is to use less saline water during the early season and high salinity water during less sensitive crop stages. This method can efficiently be used for crops which have very sensitive early growth stages (eg tomatoes). Another option is the use of good quality water for less sensitive crops while reserving the poor quality water for tolerant crops on different fields. Flexible management and irrigation supply systems are required for these options, especially where water of varying qualities is used at different times of the growing season. Under good management **network dilution** may be favourable to blend tailor-made water for each crop at various stages and for all soil conditions.

A successful example of a combination of switching water qualitites and network dilution is given by Rhoades (in Shainberg/Shalhevet 1984):

- crop: cotton; drainage water: 9 dS/m; aquaduct fresh water 0.7 dS/m

- 50/50 blend = 36% yield reduction; 100% drainage water = 50% yield reduction
- 100% aquaduct water during seedling stage and lateron 50/50 blend = 20% yield reduction.

Rhoades et al (1989) proposes a dual rotation system (crop and water) of management where saline water is substituted for low salinity water without significant yield losses, loss in cropping flexibility, or change in current farming operations at certain times during the crop rotation. Salt sensitive crops in the rotation (lettuce, alfalfa, etc.) are irrigated with low salinity water while saline water is applied to tolerant crops (cotton, wheat, etc.). For the tolerant crops, the change to saline water occurs after seedling establishment. Preplanting and initial irrigation use low salinity water (Rhoades et al. 1989. p.35).

Another option for good yield performances is intermittent leaching, with low saline water applied once or twice during the season depending on salinity levels while saline water is used throughout the rest of the season (Shainberg/Shalhevet 1985).

Field experiments (cited in: Shainberg/Shalhevet 1984) have shown that the relationship between yield and evapotranspiration (ie the water production function) for a given crop is independent of the quality of the water applieed and, therefore, information on consumptive use for irrigation with non-saline water can be also applied for saline water. Decreasing the irrigation interval resulted in the same relative increase in yield for waters of various salinity. The bulk of evidence does not support the proposition that the effect of salinity can be moderated by increasing irrigation frequency. High frequency sprinkler irrigation with saline waters tends to have detrimental effects on foliage.

Experimental Leaching Requirement

The experimental leaching requirement is the ratio between the salt concentration (EC) of the irigation water and of the drainage water or leachate (ELR = Ci/Cd). The leaching requirement incrases with increasing salinity of the irrigation water. Leaching is required in order to maintain acceptable salinity levels in the soil solution (Fig. 2-3). In practice, application of the equation given above is hampered by uncertainty as to the appropriate rates of salt tolerance of crops. Empirical analyses have shown that

* the traditional '50% reduction' approach (Cd taken as that concentration when the yield is 50% of the maximum non-saline yield level) overestimated the leaching requirement and
* the 'zero yield' approach (Cd as EC of soil-water solution at which no yield is obtained) understimated the experimentally measured ELR (Fig. 2-4).

The computation of ELR from mean root zone salinity and crop tolerance thresholds (based on steady state mass balance and continuity equations) provided better approximations between the calculated ELR and measured ELR values obtained from field tests.

Main References: Rhoades in: Stewart et al. 1990; Shalhevet in: Shainberg/Shalhevet 1984

Further reading: Rhoades 1992; Rhoades et al.1989; Rhoades 1989; Bajwa et al.1986; Mantell et al.1985; Lyle et al.1986; Bresler in: Yaron 1981; van Hoorn/vanAart in: ILRI 1980

Leaching Requirement under Field Conditions

Present irrigation practices in many areas inadvertently provide excessive leaching because of low irrigation efficiencies. The cost of surplus leaching is high in terms of:

- on-farm loss of inputs and natural resources (water resources, energy, plant nutrients, labour),
- deterioration of environmental quality (excessive nutrient and salt pollution of ground- and surface water),
- increased needs for drainage facilities.

Fig. 2-3

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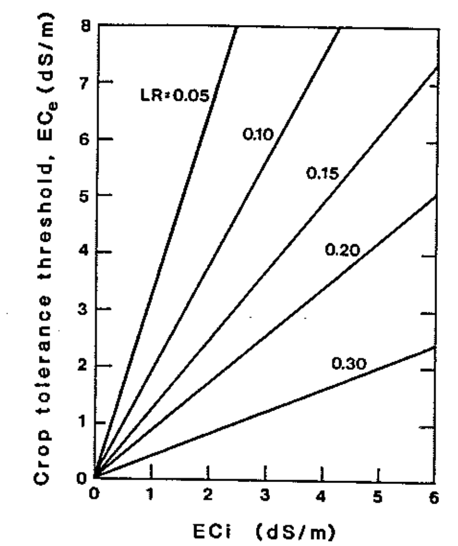

Fig. 10. Graphic solution for the leaching requirement (LR) as a function of irrigation water salinity (EC_i) and the salt tolerance threshold value (EC_e) for the crop (Hoffman and Van Genuchten 1983)

Fig. 2-4

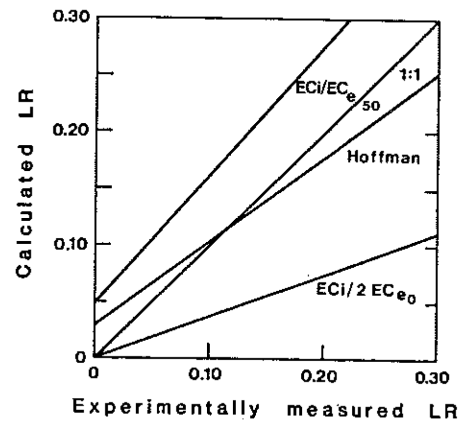

Fig. 11. Comparison of experimentally measured and calculated leaching requirements (LR), using three methods for calculating LR (Hoffman and Van Genuchten 1983)

Source: Shainberg/Shalhevet 1984

Consequently, quantification of leaching requirements is important, although obtaining these under practical field conditions is still a complex problem (see section 3-3).

The leaching requirement (LR) is related to the consumptive use (CR) crop water requirement: LR = 1 - CR/Di , where Di is the total seasonal depth of irrigation required.

LR is very sensitive to errors in estimating CR or inefficiencies of application (varying values of Di). In addition to inaccuracies in estimating the potential rate of evapotranspiration by various methods (eg Penman, class A-pan), which may be in the range of at least 15%, and which thus give simlar errors in the CR value, spatial variabilities in soil properties as well as non-uniformity of water applications may necessitate increasing Di by 10 to 20% to achieve the desired leaching over the entire field. Consequently, no direct quantitative evidence may be obtained of yield response to leaching requirement under field conditions (Shainberg/Shalhevet 1984).

Therefore, most studies on crop specific salt tolerances and leaching requirement were performed under steady state conditions in greenhouses. Despite generally good relationships between yield and leaching requirement (and the leaching fraction LF) there are some shortcomings:

- normal irrigation practices seldom result in steady state conditions, except for high frequency irrigation and over-irrigation with low salinity water where steady state conditions may exist in the upper soil layers,
- the strategy for leaching of a short season crop is different from that under steady state conditions and with perennial crops; for a short cropping season it may be a better strategy to replenish soil water depletion up to the time when salt accumulation becomes excessive and then apply the required leaching, rather than apply leaching with every irrigation (ie intermittent leaching approach versus continuous leaching approach),
- rainfall may prevent steady state conditions from being reached; if rainfall occurs during the cropping season in substantial amounts, calculation of the seasonal LR based on steady state conditions is meaningless,
- interpretation of most field tests is hampered by the confounding effect of leaching fraction (LF) on soil salinity and soil water contents, the increased LF may result in increased yields either because of reduced salinity or because of increased water supply.

To summarise, the recommended method of applying saline water is drip irrigation, wherever this method is technically and economically feasible and good crop management is provided. There is evidence that for practical reasons the best method would be intermittent leaching, ie excess water is applied when the concentration of salts in the soil-water solution exceeds the threshold value of a specific crop. However, this requires continuous monitoring of soil-water salinity and a flexible approach to water application.

The principal preconditions for the successful use of saline water for irrigation can be summarised as

- the presence of soils of **permeable** soils and absence of waterlogging
- cultivation of **salt tolerant** crops
- good **water management** providing sufficient and properly distributed water
- adequate land drainage and field drainage facilities (natural or artificial)
- skilled and well-equipped farmers
- trained and experienced extension staff.

Modified after: van Hoorn/vanAart in: ILRI 1980

Fig. 2-5

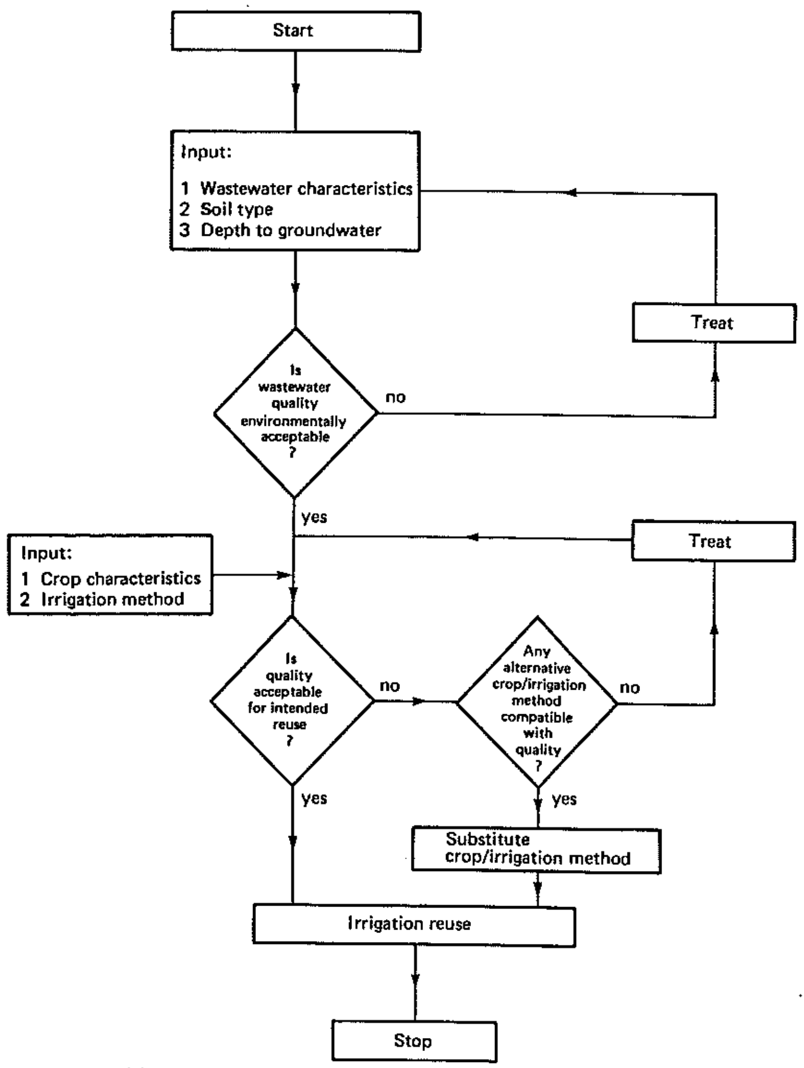

Figure 3.5 Decision model for wastewater treatment for reuse

Source: Pescod/Arar 1988

Environmental Concerns

Environmental concerns are mainly related to the obvious hazard of soil salinity build up and the evental degradation of soils such that they cannot be used under irrigation nor in extreme cases for any other productive use. Another concern is related to the disposal of drainage waters which tend to be even more saline when released from the irrigated area, either to groundwater or into streams, and may also cause toxins or other pollutants. Environmentally sound management of drainage effluent should be based on:

- efficient use of water at the farm level
- minimising drainage volume by capture and successive reuse.

Ultimate disposal options are:

- discharge into evaporation ponds or saline lakes/ocean
- treatment to remove specific toxins where appropriate,
- discharge into rivers under appropriate flow regimes (eg high flood regime),
- possibly, injection into deep aquifers.

Source: Kandiah (FAO) 1990

References: Rhoades 1992; Kandiah ed. (FAO) 1990; Rhoades in: Stewart et al. 1990; Rhoades et al.1989; Rhoades 1989; Bajwa et al.1986; Mantell et al.1985; Lyle et al.1986; Shalhevet in: Shainberg/ Shalhevet 1984; Bresler in: Yaron 1981; van Hoorn/vanAart in: ILRI 1980

2.1.4 Sewage Effluent Quality for Irrigation

In assessing effluent quality criteria the wastewater quality, land and soil suitability, cropping systems, and irrigation characteristics must be considered altogether. A decision model for setting effluent characteristics is given in Fig. 2-5 (see also section 2.5). It should be noted that it is not possible to cover all local situations when preparing water quality criteria and standards, and the approach should be to present guidelines that stress the management needed to successfully use water of a certain quality (Pescod/Arar 1988).

Sewage effluent used for irrigation usually originates from domestic sources and may contain varying amounts of industrial wastewater. If it is released from combined sewerage systems it may also contain stormwater. The quantity of wastwater produced is about 80% of the total domestic water consumption and varies between 100 and 300 l/d and capita (in Near East towns where sewerage systems exist, Feigin et al. 1990). Agricultural wastewaters usually occur as runoff into rivers (or groundwater) where they can contribute to eutrophication, contamination (from pesticides) and salinity increases. Industrial wastewaters or domestic water which contains (or will contain; future developments should also be considered) considerable amounts of industrial sewage should not be considered as suitable for reuse under irrigation due to likely contamination with synthetic organic compounds and heavy metal loads (Shuval et al. 1986, Biswas/Arar 1988).

Sewage Characteristics

Sewage effluent comprises 99.5 to 99.9% water and 0.1 to 0.5% organic and inorganic solids in suspended (settable) and soluble forms. Raw sewage may contain pathogenic microorganisms as well as parasitic worms or eggs. The characteristics of the raw wastewater depends mainly on

* composition of fresh supply water (original water characteristics)
* use of water
* possible addition of softeners
* method of water collection.

Due to evaporation from sewage retention basins, and the fact that the water has been used in one way or another, there is always an increase in salts in sewage water compared with the fresh water from which it originates (Table 2-21). The salt concentration of sewage is usually higher in arid regions and in areas with lower water consumption rates per capita. Wastewaters are a complex mixture of organic and inorganic compounds defying complete chemical and biological analyses. The principle parameters (used as indicators) that characterise wastewater and that affect treatment and reuse systems are:

- **temperature** which affects settling rates and filtration efficiency by changes in viscosity; removal of pathogens, biological growth of microorganisms
- **turbidity**, caused by colloidal particles
- **colour** as an indicator of state of degradation and concentration of microorganisms
- **odour** (environmental nuisance; caused by anaerobic processes)
- **solids** (dissolved [TDS] or suspended [SS or TSS] which are inorganic or organic in nature; total salt content; ionic composition of dissolved salts; grain size of suspended load; all are important parameters for irrigation. Usually also pH, ECw, SAR, ammonia-N, organic-N, total-N, and PO_4-P are analysed
- **oxygen demand** (dissolved oxygen [DO], **biochemical oxygen demand** [BOD], **chemical oxygen demand** [COD], **total organic carbon** [TOC] are indicators of the degree of pollution, the available options for treatment of wastewaters and for the design and operation of treatment plants; these are important for sewage disposal into rivers or lakes, but less important for irrigation
- **biological indicators** are viable nematodes eggs and faecal/total coliform bacteria.

The actual sewage effluent characteristics depend on the treatment processes which are applied to remove solids and to decrease the content of inorganic and organic pollutants. There are numerous systems in operation. Types of wastewater treatment recommended for wastewater reuse under irrigation in developing countries are outlined in section 2.5.

Typical quality parameters for raw sewage and effluents used for irrigation are presented in Tables 2-22a-c. Typical raw domestic sewage contains 107-109 coliforms per 100ml (see Table 2-25).

Wastewater Quality Standards

The most important indicators of sewage effluent characteristics relevant for reuse under irrigation are

- **coliform** counts (what should be as low as possible to reduce health risks; faecal coliform bateria are reliable indicators of other bacterial pathogens),
- **nematode** counts what should be as low as possible to reduce health risks,
- total dissolved salts, TDS (what should be as low as possible to reduce salinity risks),
- total suspended solids, TSS (what should be as low as possible to avoid sedimentation and clogging, although organic matter in the effluent may add humus to the soil),
- sodium adsorption ratio, SAR (what should be as low as possible to avoid risk of sodicity and alkalinity in soils; often alkaline softeners are applied in domestic waters),
- **nutrient** analyses, especially N, P, K (nutrients should be high but not excessive so as to add fertilisers in non-toxic concentrations),
- **boron**; concentrations should be less than 1 mg/l, perferably 0.5 mg/l, to avoid build up of toxic levels,

- other **chemical pollutants**, mainly toxic compounds from industrial sources; these should be kept below the critical threshold values.

Quality guidelines regarding health hazards were established by the WHO (1973) and later revised as the Engelberg guidelines (IRCWD 1985). Pioneering regulations were based on the standards developed in California in 1918 (revised 1968, Table 2-23).

Wastewater quality standards have been established in various countries, mainly based on international guidelines. Current guidelines and standards are presented in Tables 2-24 a (WHO), 2-24 b (IRCWD) and 2-24 c-d (various countries).

Most guidelines and standards are expressed in terms of **maximum permissible contents** and define **minimum treatment requirements** (primary-secondary-tertiary) according to the class of crop to be irrigated (eg raw or cooked or fruits being consumed).

Biological standards (with coliforms as the indicator) which were developed in the late 1960s were rather strict (parts of the EC-guidelines 1976 for sewage reuse were even more rigorous than for bathing water quality), as they were based on an evaluation of the potential risks associated with pathogen survival in wastewater, soil and crops. Evaluation of epidemiological evidence indicated that these standards may be unjustifiably restrictive (Part I section 8.1). Moreover, designs of waste stabilisation ponds, the preferable method for many developing countries, had been refined and, therefore, the internationally accepted guidelines were revised in 1985 by a meeting of experts (IRCWD 1985, Table 2-24 b), which also considered the risk assessment for persons exposed to wastewater (section 2.5 and Part I section 8.1).

Research confirmed that at a concentration of <1000 faecal coliforms per 100 ml, which implies usually a >99.99 % (or 4-6 log10 units) removal of faecal coliforms, bacteriological pathogens will be either absent or present in negligible numbers (Table 2-25). Effluents of this quality can be readily produced by a cascade of 4-6 stabilisation ponds in series with an overall retention time of 20 days at 20oC. Effluents of higher quality (eg <100 faecal coliforms per 100 ml) may be used for irrigated public parks and hotel lawns (see section 2.5).

Main References: Feigin et al. 1990; Shuval (WB) 1990; Shuval et al. 1986; Mara/Cairngross (WHO) 1989

Further reading: Ayers/Westcot (FAO) 1985; Kandiah in: Pescod/Arar 1988; Biswas/Arar eds. 1988

2.2 Reducing Impacts on Water Resources

Key Words:

scarce water; inefficiency in irrigation; strategies; surface water; groundwater; system analysis; pollution control; monitoring; utilising froundwater; fossil water; self-correcting mechanisms; regulations; interventions; policy options;

Cross-references:

sections 1.2, 2.3, 2.4

Main References:

WRI 1991; GITEC 1992; OECD 1989a; UNESCO/UNEP 1988; Rydzewski 1987

2.2.1 Alternative Supply Options

The water crisis will worsen as a result of rising demands by the increasing world population and of continued pollution of waters which limits their use for domestic and agricultural uses. The total global water consumption over the 20-century (1900-2000) increased about ten-fold. The total agricultural water requirement increased 6.5 times. In 1900, agriculture accounted for nearly 90% of total water requirements, but by the year 2000, the corresponding figure will be around 62%. Industrial water use, almost 6% in 1900, will increase to some 24% by the year 2000 (see Part I section 2.1).

There is no doubt that, on a global scale, the demand for water in sufficient quantity and quality will further increase while the availability remains limited with the exception of a few tropical regions, eg Angola, Mozambique, Ethiopia, South America, etc. (FAO 1987). Hence, **traditional approaches of water consumption** cannot be met in the future. This includes the **wasteful use of water in agriculture**, namely inefficiency in irrigation. *Water conservation, the efficient use of water and water quality management will inevitably become major issues in future.* Experiences from arid regions of the USA may be used to learn the lessons for strategies to meet the water crisis also in developing countries, although the technical implications and potential for implementation may differ there, requiring different technical, organisational and managmerial concepts.

References: Biswas 1991a, b; GITEC 1992

The formulation of **alternative** water supplies for irrigation will become increasingly important for both established and new projects. Pressure will be caused either by increasingly limited surface or groundwater of sufficient quality or by economic considerations, and in future irrigation will have to enhance its water use efficiency, regardless of whether government schemes or individual farmers are involved. In many regions, including developing countries, comprehensive watershed management plans, which allocate water resources to various users are already planned or being implemented.

However, the solutions to efficient water use will be as varied as the watershed basins themselves and the people who use and manage them. Hence, it is impossible to define a single optimum use which is valid for all situations, and for each watershed a unique environmental management strategy should be identified.

There are several alternative options and combinations of possible strategies:

- improving the efficiency of existing systems
- developing further surface water resources at greater efficiency
- developing further groundwater resources at greater efficiency
- developing drainage water reuse on-farm
- developing options for using saline water for irrigation

- developing more economically viable methods for desalinization of sea water.

All of these options involve **physical**, economic and **institutional** development as well as a stronger commitment by the **farmers** themselves for better environmental and resource management.

Surface waters typically have the advantage of **low salinity**. Typical disadvantages are their long and costly transportation and difficulties in matching demand and availability. Reservoirs are costly, have a relatively restricted lifetime (before becoming silted up) and need regular maintenance.

Surface water resources still have some potential to be further exploited for irrigation, especially on a micro-watershed basis. Techniques of 'water harvesting' are increasingly becoming more important to store and supply water to individual farms. Small reservoir (tank) systems are important for example, in India, Thailand, and Southern Africa. Optimisation of tank layouts is related to design parameters: tank shape or dimensions, computation of optimal volume, and placement of tanks in the microcatchment (Helweg 1985). Furthermore, in general, design and implementation of small dams do not receive the necessary attention in selection of sound foundation and sealing methods as it is the case for large dams, resulting in frequent small dam failures.

Groundwater has the advantage that

- it is usually automatically filtered by the soil, resulting in a lower level of pollution than surface waters, especially from pathogens,
- transport costs are often low if the well is located within the command area,
- it has a vast storage potential, making groundwater a more reliable source (in terms of seasonal fluctuations and quantity) than surface waters.

Typically, groundwater resources allow a higher **flexibility** of application, both in terms of scale and use. Disadvantages of groundwaters may include occasionally poor qualitities (eg high salinity, in coastal aquifers with seawater intrusions), high pumping costs and difficulties in locating reliable aquifers during hydrogeological surveys at reasonable costs. Once an aquifer is contaminated or exhausted, restoration is difficult or time-consuming and usually not feasible in developing countries.

In non-formal irrigation farming systems, unrestricted groundwater use may pose problems due to **overdraft** (mining) which cannot be readily evaluated and in addition, regulations are often difficult to enforce.

In some situations, groundwater may be either too cold or too hot for its immediate application. Additional reservoirs or tanks are then required to achieve appropriate temperatures.

Groundwater supply alternatives should be optimised for both the well-field design and the individual well design. A well field incorporates a trade-off between the increased delivery cost from wells spaced further apart and the increased pumping costs from well interference. In many hydrological situations, a trade-off may exist between the drilling of one large well and that of several smaller wells (Helweg 1985).

Recycling water promotes efficiency in water use but limited quality may restrict its use which requires good soil, water and crop management practices (Rhoades 1989) for its sustainable use.

References: Wilkinson/Clark in: Rydzewski 1987; Helliweg in: Rydzewski 1987

Fig. 2-6

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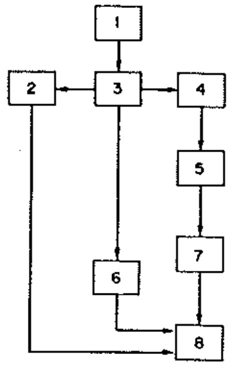

Fig. 2.12. Simplified block-diagram of the return water-quality model. (1) Irrigation régime; (2) drainage flow; (3) flow in the non-saturated medium; (4) chemical interaction; (5) chemistry of the non-saturated medium; (6) flow in the saturated medium; (7) chemistry of the saturated medium; (8) drainage-flow forecast.

Source: ICID 1980

Fig. 2-7 a

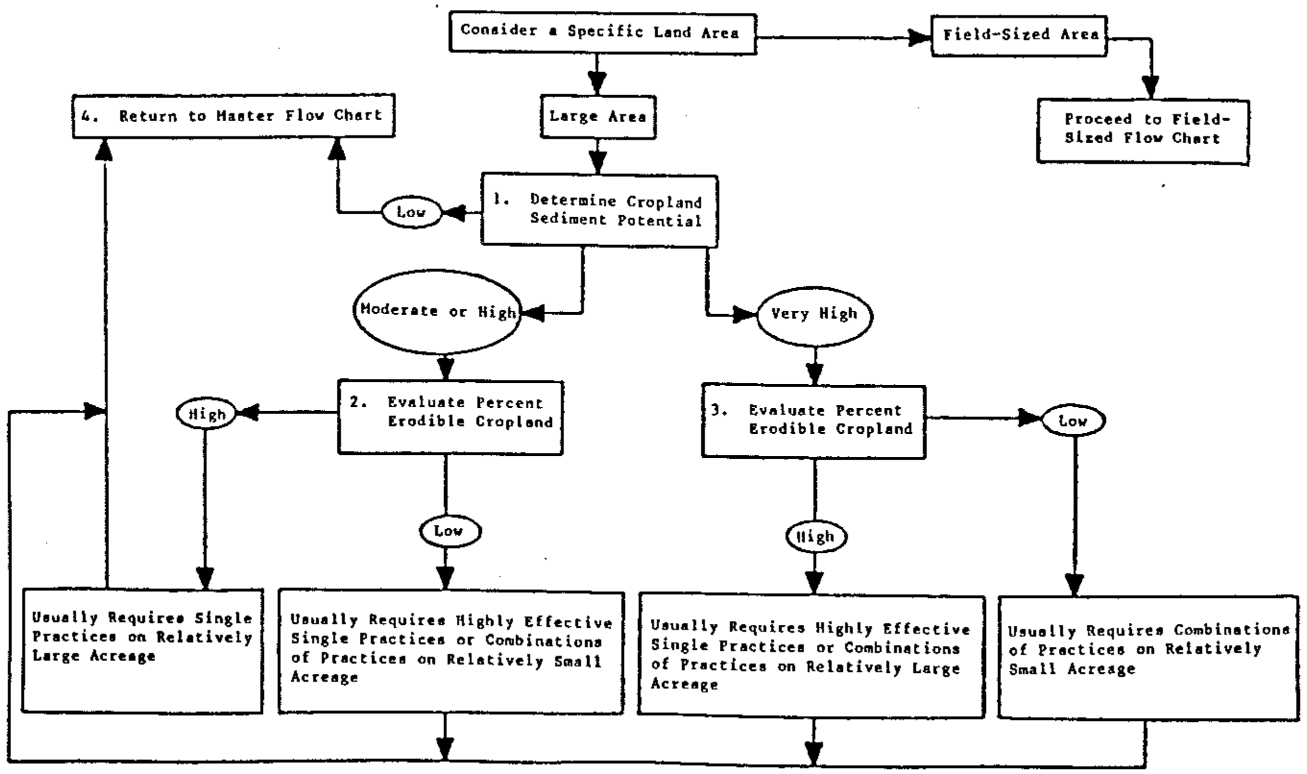

Figure 22: Flow Chart for Assessing Soil Erosion Problems and Controls Over Broad Areas (Frere, et al., 1977)

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Source: Canter 1986

2.2.2 Systems Analysis

Quantitative predictions of qualities of return water from irrigation projects can be conducted by systems analysis (ICID 1980). An example of such a return flow model is given in Fig. 2-6 with a schematic presentation of the components:

irrigation inflow - flow in unsaturated soil - drainage outflow - chemical interaction - chemistry of unsaturated soil - flow in saturated soil - chemistry in saturated soil.

The evaluation of water supply alternatives is within the scope of activities for conventional hydrological planning. Such alternatives are dealt with in detail elsewhere (eg Rydzewski et al. 1987; Helweg 1985).

A multistep planning model for conjunctive use of surface and groundwater resoruces for irrigation is in Onta et al. (1991). A model for release policy for a multi-purpose reservoir is in Harboe et al. 1988. Further models which can be used for enviromentally sound water resources development are in Biswas et al. 1990.

2.2.3 Control of Water Pollution

Models developed to assist in the control of soil erosion are often related to 'best management practices' (BMP). These are the key to environmental management, applicable to irrigated and non-irrigated agriculture in most aspects. They are developed from experiences and investigations in the industriallised countries. However, results and main conclusions can partly be transfered with some modifications to situations in developing countries. Flow charts for assessing erosion problems and controls at two different spatial levels (field level, catchment area) are presented in Fig. 2-7 a-b.

Further reading on soil/water conservation: Carson 1989

Monitoring of salts, sediments, and fertiliser and pesticide residues in surface and groundwaters should become a part of the environmental monitoring of each irrigation scheme. Monitoring may be based on an assessment of the risks imposed by irrigation.

Monitoring has three main objectives (Madhun/Freed in: Cheng et al. ed. 1990):

- surveillance monitoring: periodic observations made to support an enforcement programme and to ensure compliance, eg compliance with water protection laws or with best management practices, defined in the environmental management strategy of a particular irrigation scheme,
- subjective monitoring: spot-checking for open-ended exploration of an actual or potential problem,
- objective monitoring: provision of data for use in developing or confirming the results of quantitative models.

An essential component of monitoring is an inventory of the sources of impairments to downstream quality and of the exposures to impaired waters by consumers. In irrigation schemes, surveillance and subjective monitoring may be conducted, whereas objective monitoring may only be feasible when it is conducted in cooperation with scientific institutions. Comprehensive environmental monitoring which includes monitoring of biota (aquatic organism, plants, accumulator species) only usually feasable for point pollution sources and where high concentrations of chemicals are released, eg from industrial plants. For nonpoint sources, such as irrigated agriculture, periodic sampling of water would be sufficient in most situations. A monitoring programme for a large scale irrigation scheme may include the following analysis:

Fig. 2-7 b

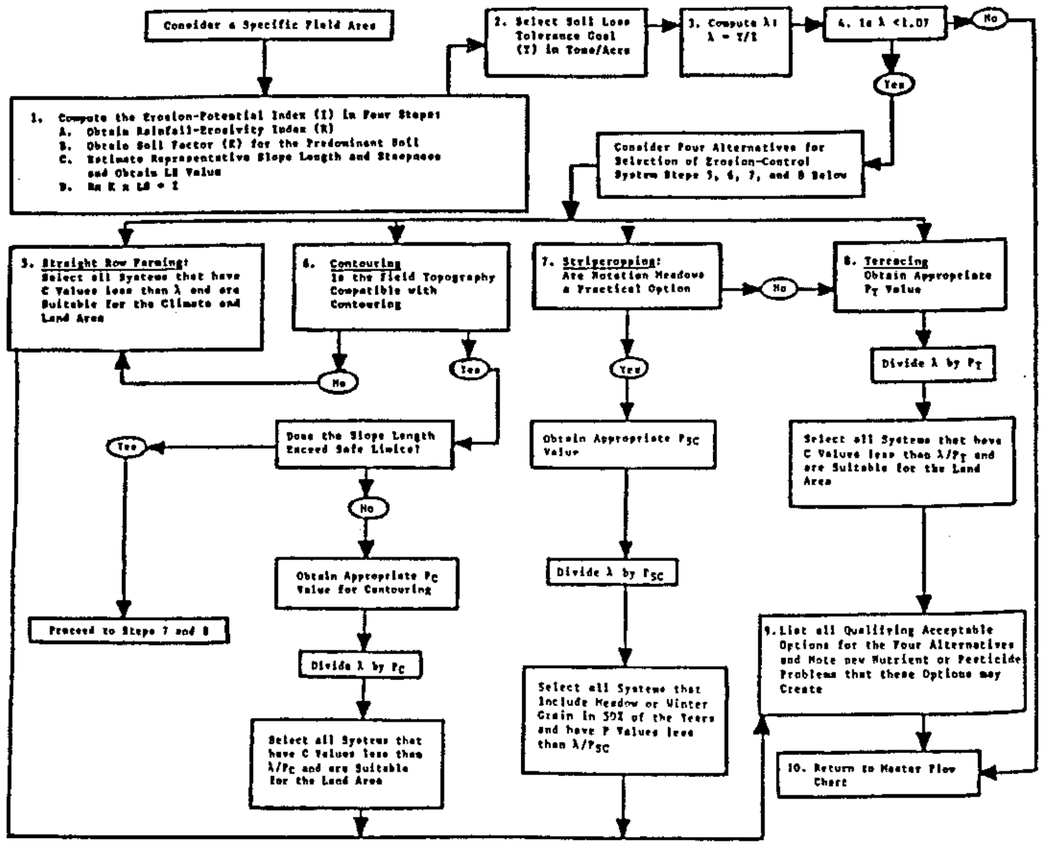
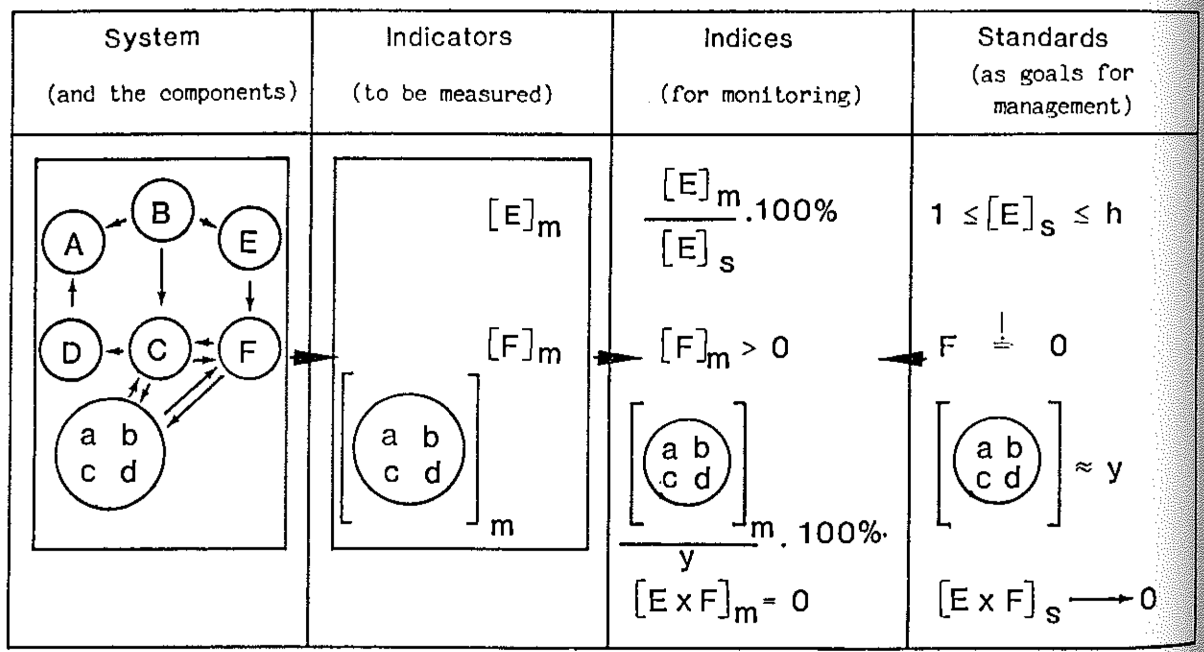


Figure 23: Flow Chart for Assessing Erosion Problems and Selecting Physically Feasible Control Practices for Field-Size Areas (Frere, et al., 1977)

Source: Canter 1986

Fig. 2-8



System: Systems result from the integration of pure (A...F) as well as combined (a, b, c); (A, B, C, D) environmental elements. Elements as well as their interactions are "components" of the system.

Indicators: Some of the components can be observed or their concentrations and/or reactions quantitatively measured; they are "indicators".

Standards: In man managed systems important components, especially those which have a key role in the system or have specific uses, are given numerical values (upper and lower limits) to guarantee quality, stability and security of the total system with respect to specific characteristics of use. They are "standards".

Indices: In defining the relationship between observed concentrations and desired or set limits, the integration of certain observed indicators is used to compare the status of the existing system (or certain components) with the desired system (or certain components). ~ expressions obtained are called "indices".

Figure 2.2 System, indicators, and indices (Hartmann)

Source: UNESCO/UNEP 1987

Total salts: EC in groundwater (command area, neighbouring areas) and surface water outlets

Fertilizers: N in surface water outlets, groundwater in the command area.

Sediments: TSS at drainage canal outlets.

Pesticides: organophosphates, carbamates, synthetic pyrethroids in groundwater (command area) surface water: drainage outlets,

Hydro-environmental indices for environmental management were established by a UNEP/UNESCO-working group (UNESCO/UNEP 1988; UNESCO/UNEP/EMINWA 1987; Card ed. (UNESCO) 1984). Detailed lists of potential indicators of water quality are shown in Table 2-26. Typical indicators are: conductivity, pH, BOD, oxygen saturation, cell counts (indicators for health safeguards see sections 2.5 and 4.3) and chemicals present in local situations. The concept of indicators and indices is explained in Fig. 2-8.

Further reading: Madhun/Fried in: Cheng et al. ed. (ASA) 1990

2.2.4 Sustainable Development of Groundwater Resources

Groundwater is often regarded as a **'free, but scarce'** water resource. Different concepts and techniques for the development of shallow groundwater resources for domestic use, livestock or irrigation were repeatedly practiced in the past without adequate investigations of aquifer characteristics, evaluation of the economic viability or of operational and management difficulties (Khan 1988). In future, more rigid concepts and regulations should define its use for irrigation in relation to the rising pressure of demand and its availability at reasonable costs to the benefit of all potential users.

There are a range of possible strategies for utilising groundwater which allow for appropriate use, and conservation and groundwater policy implementation according to local circumstances and financial resources:

- regarding **supply**: ample - limited - temporary (seasonal) supply, depending on properties of the aquifer and pumping or lifting facilities
- regarding **depth** of aquifer: shallow - deep - very deep
- regarding **replenishment**: fully - partly - no (mining of fossil water); climatic and aquifer characteristics are needed for assessments.

Typical situations are:

- deep aquifers which are typically exploited by large and medium scale government schemes or by private farmers or communities under government assistance,
- deep and fossil aquifers with ample supply (lifespan >50 years) are typically exploited in major production and settlement schemes, for example in Libya, Algeria, Saudi Arabia,
- shallow aquifers are typically exploited by private farmers or village communities with or without government subsidies and assistance,
- shallow and limited supply aquifers are typically exploited in village communities with government assistance or subsidies, for example in Pakistan, India and Bangladesh.

Groundwater should always be treated as a precious resource and any withdrawal in excess of safe yield of the aquifer should be avoided unless the long-term consequences of groundwater exploitation are known with regard to sustainable development of all parts of the society involved. Potential future conflicts amongst various users (including natural ecosystems) must be identified and strategies to minimise conflicts should be adopted.

Problems in groundwater management typically occur in situations where groundwater is scarce but readiliy available and conflicts exist between **equity**, **efficiency** and **feasibility**:

For example, concern will be greater where recharge is limited but means to abstract water are readily available to a large number of farmers than where high costs of exploitation limit actual abstraction. In this latter case, the long-term consequences of limited groundwater mining may outweigh the adverse distributional impact of having groundwater available only to those able to mobilise the high investment costs needed. By contrast, where groundwater is in plentiful supply and where its abstraction would improve land drainage conditions, policy can be oriented towards maximising access to groundwater and spreading the benefits amongst all farmers (Reference: eg Toulimin/Tiffen 1987)

The use of fossil water from aquifers, ie groundwater mining in excess of long-term aquifer replenishment, may only be justified if the optimum use of water is secured in production or settlement schemes for either the national welfare or to the benefit of local populations. Its use in irrigation requires a rigid socio-economic justification, and alternative water development options should be sought. If irrigation is regarded as an essential option for development, eg in oasis (desert) development, then all precautions must be observed to promote water saving technologies and advanced water management practices (discussion in Allan 1991).

Typically, the development of shallow groundwater resources is undertaken in isolation, ie each farmer operates his own water supply facilities. Traditional water rights often allow free access to groundwater, and the choice of private ownership has operational advantages (eg higher flexibility) and promotes the social prestige of an individual farmer. Regulations for restricted groundwater use are, therefore, often unpopular and difficult to enforce (eg Shah 1990). Furthermore, it is difficult to monitor the water extraction on privately owned and managed farms. Therefore, basic data on water abstraction are either absent or based on rough estimates only. In addition, precise assessments of groundwater resources require sophisticated and timely field investigations and (computerised) data analysis. This contributes to the fact that in most developing countries inventories on groundwater resources and predictions of groundwater are often not available on a regional or subregional scale.

Source: Toulimin/Tiffen 1987

In minor or medium scale irrigation systems some **self-correcting mechanisms** may be developed on a village level. These might involve internal mechanisms for equitable regulation of water use (Shah 1990). Such simple individual and group strategies have been formulated for villages in India in Table 2-27. A shared and improved understanding among well owners of hydrological conditions (eg aquifer conditions, interactions between a single well and aquifer, and interaction among different wells) is essential for full achievement. Effective enforcements of checks on the withdrawal and wasteful use of groundwater may be introduced on a village level in a self-regulatory mechanism.

Another strategy is the **transformance** of government or publicly owned (shallow) wells to private farmer control. Experience in India and Pakistan has shown that well systems under the individual control of the farmer have higher yields because the supply systems are better adapted to on-demand supply where water is applied at the right time and quantities (Table 2-28). Farmers will be more likely to adopt improved water management (saving) strategies and will accept realistic water prices under conditions of improved production. Furthermore, individual control over water supply will promote self-reliance and responsibility amongst farmers.

Regulation measures for sustainable groundwater management may include restriction (rationing) and improved management practices on an individual level and the committment

of national and/or regional water authorities to an overall management strategy based on regional water development plans

- control of the number of new wells per unit area,
- control of borehole/well extension or deepening,
- control of well siting,
- lowering the discharge rate of existing pumps,
- restricted pumping periods, various options are possible: eg temporary or areal restriction,
- indirectly through the limited installation of power lines or limited fuel supply,
- promotion of water conservation measures on the field level,
- promotion of crops and cropping patterns which reduce water demands,
- recharge of groundwater with surface water (either drainage or rainfall runoff),
- policy options regarding credit facilitites for well development and operation,
- water pricing policy to encourage water savings,
- fuel/diesel pricing policy to encourage water savings,
- conjunctive use of surface and groundwater resources towards more flexible systems,
- conjunctive use of groundwater and surface water supply systems to encourage the control of waterlogging and salinity by improved drainage.

Legal interventions may also be promising in restricting groundwater abstraction to safe levels. For example, wells or water abstractions may be licensed (eg in Burma and Malawi) or the number of wells per unit irrigated area may be restricted. In other countries such laws are difficult to formulate or to enforce at the local level, eg in the Middle East (Shah 1990). The main **formal policy intervention** points are:

- **credit policy** for installation of wells,
- **type** of ownership of wells: individually, formal or informal groups, cooperatives, government or parastatal institutions,
- **pricing policy** of water and energy,
- well **siting controls**.

Additional interventions are related to technical and agronomic assistance to farmers, eg through the extension service.

Typical water policy options for situations in the Middle East are shown in Table 2-29. In formulating strategies to **maximise efficiency of groundwater use** under irrigation there are four categories to distinguish:

- **environmental efficiency**: maximising yield output when scarce water resources are used in comparison with other possible actual and potential (future) water uses,
- **economic efficiency**: maximising returns to financial inputs (at the farmer and government level),
- **water efficiency**: preventing waste, maximising returns of a unit of water,
- **energy efficiency**: maximising returns per unit of energy and fuel.

These forms of efficiency may coincide, but usually do not do so. The project appraisal should include all of them if environmental and water efficiency are to be improved. Water and energy pricing policy should be more closely related to actual consumption and the application of water saving practices. In situations with plenty of groundwater, pricing policy can be more oriented towards ensuring the equity of accessibility (Svendsen 1986) unless the resource conservation is endangered.

Some important policy issues are addressed in the following:

- **depth of groundwater**: this determines expense of tapping, type of pump and discharge rates; optimum use of deep wells requires typically large command areas and intensified cropping; further investments for canals require cooperation amongst farmers or government inteventions, and management becomes a more complex affair; individual supply and small mechanised units serving one farmer or a small (cohesive) group are easier and more flexible to manage,
- in cases where a choice between several groundwater **options** (eg shallow versus deep aquifer tapping) is possible, social, economic, agronomic and technical pros and cons must be balanced. The conflict minimising strategy may be used to find environmentally, technically and socially appropriate and sustainable solutions; farmers usually prefer shallow wells with individual or small cohesive group control than government run deep wells which often require technical and financial or energy inputs which are often outside the control of farmers (Toulimin/Tiffen 1987). However, aquifer control may be easier to enforce with government run deep wells and they may be more economically if efficiently operated,
- a major issue of government interference in groundwater uses is based on the principles of equity. There are several means to make groundwater accessible to poor farmers: (i) credit programmes to groups or individual farmers; (ii) technical assistance during drilling and operation; (iii) providing public-run wells which either provide water to supply canals on identical terms to canal water or sell water direct from the well; (iv) government installation of wells and subsequent selling to farmers or groups; (v) manipulation of power tariffs or fuel prices,
- policies to subsidise agriculture have also led to over-extraction of groundwater resources, eg in the USA. In many countries electric power or fuel to the farm sector is heavily subsidised, eg in India, which provoke over-extraction of aquifers and has a number of adverse impacts on other potential users of power (Toulimin/Tiffen 1987). In most countries a complex web of policy exists: on the one hand, siting restrictions to control over-use of groundwater exist while, on the other, farm price support and cheap power encourage high and inefficient levels of groundwater use. A more rational system of policies towards irrigated farming should be developed.

Further environmental policy issues are addressed in: OECD 1991c, 1991d, 1989a, 1989b, 1989c

2.2.5 Prognostic Tools and Environmental Standards

Regulations for the permission to abstract groundwater for irrigation should be based on an assessment of the potential risk of

- reduced stream flow to a degree that disturbs the ecological balance and which conflicts with other downstream users. Acceptable levels can be designed using data on the annual or seasonal runoff, based on the average ratio between the mean and the minimum acceptable water depth. For example, some 15% reduction of design median-minimum runoff is set as an acceptable reduction in stream flow in order to protect salmon (Madsen in: van Hoorn ed. 1988). Such standards are probably difficult to define in semiarid areas with high seasonal and inter-annual variations of rainfall and river discharges
- lowering water tables to a degree that disturbs the ecological balance and creates problems for neighbouring areas, eg subsidence. Acceptable standards must be individually designed considering the productivity of neighbouring agricultural areas, domestic water supply impacts and impacts on natural ecosystems.

Assessments may employ analytical and numerical models to predict the influence of well abstraction on stream flow. Such models for humid areas have been evaluated by Mad-

sen (in: van Hoorn ed. 1988). The application of most models requires considerable research inputs and they are sensitive to several site specific aquifer variables. Due to the lack of precise field data in most situations with new irrigation developments these models may be unsuited for rapid assessments during environmental appraisals, especially for medium and minor irrigation projects.

Further reading: CNCID 1991; INCID 1991; Shah 1990; Bhuiyan in: ICID 1989; Khan 1989; Westcot in: Hoorn 1988; Madsen: in van Hoorn ed. 1988; Toulmin/Tiffen 1988; Helweg 1986

2.3 Techniques for Improved On-Farm Water Management

Key words:

water consumption; water saving methods; tools; irrigation methods; efficiencies; environmental concerns; scheduling; management of irrigation; water conservation methods; avoiding over-irrigation; subsurface return flow; best-management-practices; monitoring; performance assessments; techno-economical indices;

Cross-references:

section 2.5, 3.1, 3.2, 3.3, 3.4, 5.1

Main Reference:

ICID 1991; WB 1988; Hillel 1987; Kruse et al and Heermann et al, both in Stewart ed. 1990

2.3.1 Need to Increase Overall Irrigation Efficiency

Irrigation management must be viewed in relation to other agronomic techniques which aim at achieving sustainable development. Only a limited response can be expected from irrigation if crops are not well adapted and if likely problems occurring under irrigation are not taken into account. Also impacts on water and soil resources may be considerable if soil and crop management techniques are not oriented towards **soil and water resources conservation.**

Water consumption per unit area will vary due to differences in climatic conditions, soil properties, irrigation method, irrigation management and crop specific water requirements. Nevertheless, the differences in technologies employed and inherent climatic and soil conditions can only partly explain the large differences in **water consumption** in various regions: Europe: 4-6,000 m^3/ha, USA and Mexico about 8,000 m^3/ha, Asia 8-12,000 m^3/ha and former USSR 12,500 m^3/ha (Guskov 1991 in: ICID 1991).

It seems obvious that in most developing countries and the former USSR there is the potential to reduce water consumption. On the other hand, a major bias in efforts to improve irrigation efficiency is quite often caused by a lack of economic incentives for better water management because of cheap and plentiful water. This applies to many government schemes with centrally organised water supply facilities and inadequate water costing.

2.3.2 Irrigation Method and Water Management

Whether the goals are to reduce existing diversions into irrigated croplands because of limited water availability, to reduce existing diversions to provide supplies for new demands (agricultural or non-agricultural), to minimise water quality degradations downstream resulting from irrigation, to maximise agricultural production on existing irrigated areas,

Fig. 2-9

Fig. 57 Model of the Most Efficient Water Management for Agriculture

Source: Surarerks 1986

or to save energy by saving water, the solutions are identical: *improved water management practices which include both technical and managerial/organizational improvements* (Fig. 2-9).

Water savings may be achieved by selection of more efficient irrigation methods:
- improved irrigation efficiency: conveyance and application efficiency,
- effective use of seasonal rainfall and optimising cropping pattern,
- cultivation of crops with smaller water requirements,
- flood detention methods (surface methods).

Conveyance efficiency may be improved by:
- reducing seepage losses and leakages from canals,
- avoiding overtopping,
- illicit tapping and damages,
- reducing evaporation,
- providing coordinated input supply systems.

Application efficiency may be improved by:
- using regulation and measuring devices,
- providing individual turnouts to each farm from the tertiary canal,
- efficient use of effective rainfall,
- adopting appropriate irrigation methods and field or furrow lay-outs,
- precise calculation and verification of irrigation requirements based on climatic and soil data and application efficiencies,
- adopting water saving agronomic measures: tillage, mulching etc.,
- land levelling,
- establishing a cropping calendar.

Water management tools include:
- coordination system for input supply and water delivery arrangements between various users,
- data base and information system on flow quantities and qualitites in canals and drains;, soil moisture and salinity data, crop data,
- establishing a decision support system,
- establishing joint management committees at various levels (site specific).

Source: Kamladasa in: ICID (STS-C25) 1991

Methods which promote the coordination of irrigation terms and rates with crop requirements and actual availability of soil water are most promising for large scale applications schemes. In general, irrigation schedules must be handled more flexible, determined by site-specific approaches regarding technology employed, managerial skills and water requirements. This, however requires a continuous monitoring of the field conditions, eg actual water contents and assessments of water deficits. The use of information-advise systems (IAS) which provide guidelines for irrigation operations may be applicable in irrigation schemes with modern facilities, skilled farmers and trained extension service. These information systems, in combination with automation of surface irrigation yielded to water savings, power savings, yield increases (15%) and economic efficiency.

References: Kamladasa in: ICID 1991; WB 1988; Plusquellec/Wickham (WB) 1985

2.3.3 Comparison of Irrigation Methods

Irrigation methods (or systems) are conventionally divided into four main categories:

- surface methods: irrigation is applied at one edge of a field and flows across the soil surface by gravity, infiltrating into the soil while the stream advances across or is ponded on the field; various methods are: flooding, contour ditches, border dike, graded furrow corrugation, level basin, basin-furrow,
- sprinkler/spray: water is supplied via pressurised networks and emitted from sprinkler or spray heads mounted on either fixed or moving supports,
- micro (drip/trickle): low pressure systems where water is conveyed through plastic conduits and emitted through drippers, tricklers, bubblers, etc. with the water infiltrating at the point where it is applied,
- subirrigation is provided to crops via underground popes.

Source: Kruse er al. in: Stewart ed. (ASA) 1990

These irrigation methods can be evaluated for site specific irrigation developments according to their

- suitability with regard to land constraints, soil suitability, water availability and water quality, and crop requirements (see sections 3.1 and 3.2),
- agronomic and water management methods or technologies available in respect of (ii) and (iii),
- options for automation or improved mechanisation,
- options and methods to achieve high (field) water application efficiency,
- options to achieve higher energy consumption efficiency (or use of renewable energy resources) (see section 5.4),
- potential impacts on off-site and on-site physical resources (water, soil, land, biosystems),
- potential impacts on human health risks (see section 4),
- managerial skills of farmers,
- labour requirements and other socio-economic constraints or benefits,
- financial resources for development and operation (farm economy issues),

Increased efficiencies may be obtained from improved uniformity of water application, reduced leaching and runoff losses, improved scheduling, and reduced application times. The efficiency values given in section 2.2.3 (Part I) represent seasonal values that are considered to be obtainable with good design when fully irrigating the field. The range of values given for each system represents a combination of management levels from average to excellent and various design and site considerations.

Key **features** and **cost estimates** for the development of different irrigation systems are shown in Table 2-30 with regard to equipment costs, maintenance costs and average efficiencies of various improved and mechanised irrigation systems. Each system may have advantages or disadvantages with regard to any of these issues. The most important issues with regard to environmental concerns are

- selection of **suitable land** with regard to various irrigation methods: mainly referring to topography, soils and drainage characteristics,
- use of methods which minimize extractions of limited **water resources**
- use of methods which optimize integrated **watershed management**, ie in combination with soil and water resources,
- use of methods which allow for **flexible water management** and the application of **soil and water conservation practices**,

- use of methods which allow **salinity** management,
- use of methods which allow irrigation of other **problem soils**,
- use of methods which allow reduced applications of pest control **chemicals**
- use of methods which reduce impacts on soil **erosion** and **surface water pollution**, ie the control and management of surface return flows,
- use of methods which reduce or eliminate **groundwater pollution**, ie the control and management of subsurface return flows,
- use of methods which reduce (non-renewable) **energy** consumption,
- use of methods which reduce **health risks** to farmers, crop consumers or neighbouring villages (related to airborne, water-based or vector-borne diseases).

The various application techniques should not only be considered in terms of their technical suitability, cost, efficiency, but also regarding environmental concern and agronomic-managerial terms such as divisibility, sustainability, risks, management complexitiy, organisational requirements, and yield/profit potential.

A simple categorization of these factors is presented in Table 2-31 for various types of irrigation methods (systems). The following explanations are given:

- **Divisibility**, suitability and adaptability for small land holdings. Various application technique techniques may be economically fitted to any plot size (totally divisible) or may be divided only with difficulty or at high expense (partially divisible) or may only suitable for large fields (not divisible).
- **Organizational requirements** are a function of the divisibility of field application systems and whether the pressurised water delivery system could be operated by a group or agency. Systems with total divisibility can be operated independently by each private farmer. Application systems supplied by a shared pump or distribution network should be considered as being only partially divisible. With partial divisibility group/cooperative effort is usually required. Direct operational assistance from an agency/institution is usually needed to manage and operate an application system with no divisiblity. The same applies where very large pumping plant and pressurised distribution is used.
- **Risk** is a category that addresses the potential crop loss due to equipment breakdown.
- **Management, operation, and maintenance** are closely linked; they should be considered together in terms of management requirements, considering the skills needed for operation, levels of support services required for servicing and spare parts and what agronomic technologies are needed in order to make irrigation cost effective and sustainable. Skill levels are ranked as simple, medium, master, and complex; the latter indicates sophisticated technical skills and reading ability. Effort levels of 1 through 10 indicate the relative management time and labour required to manage, operate, and maintain various types of irrigation systems. A fair quantitative indication of the average number of days required per ha and per month are given.
- **Maintain by....** is a category which considers the complexity of the technology in terms of its overall physical sustainability, ie it indicates who has the capacity to maintain the system. 'Farmer' implies ordinary farmers who raise traditional crops. 'Grower' is an advanced farmer, with high value crops; 'Shop' indicates local merchants having some facilities and capacity to repair equipment; 'Agency' indicates that very specialised equipment, facilitites, and skills are needed. Engine driven pumps typically require 'shops' or 'agency' to be maintained.
- **Ruggedness** indicates the durability of the water conveyance and application equipment.

Source: Keller in: ICID 1990; Kruse et al. and Tanji/Hanson both in: Stewart ed. 1990

Further reading: Brouwer 1989

2.3.4 Irrigation Scheduling Techniques and Management

Irrigation management options apply to variations in timing and quantity of water applied. Farmers' management objectives include

* irrigation for optimum yields
* irrigation for maximum benefits with water saving components to maximise average net return per unit of water used (compromising between efficient water use, maximum yields and net return)
* irrigation for maximum economic benefit which also includes a balance between farm input costs and income
* irrigation for maximum long-term benefits which includes maintaining soil fertility and reducing health risks.

Scheduling options may also include strategies to minimize labour inputs. It is obvious that only the last management option contributes directly to environmentally sound and sustainable irrigation development. Other objectives are unlikely to contribute to sustainability if the policy framework do not provide direct or indirect incentives for the preservation of the environment, eg water pricing and reducing subsidies for fertilisers and pesticides.

Various **approaches** are now available for optimum irrigation scheduling under various conditions. The most appropriate technique is a function of the irrigation water supply (timely availability, quantity and quality of water), technical ability of the irrigator, irrigation system, crop value, crop response to irrigation, cost of implementation, personal preference, and off-site and on-site environmental considerations. Historically, many irrigation schedules are based on the water availability and the irrigated area, and this is probably still the case for most situations in developing countries. On-site **environmental concerns** such as the prevention of soil degradation have been considered to some extent in the past, however off-site impacts are a much more recent consideration in design and operation.

Various **instruments** are also available which can be used to measure soil water, plant water and evaporation for establishing irrigation schedules (Table 2-32). These can be used to develop, calibrate and validate irrigation water management models, as well as to support scheduling decisions (Table 2-33). The most important methods are:

- **forecasting** schedules, eg using evapotranspiration measurements.
- instruments to **monitor** the soil water **status**
- instruments to **monitor** crop water **stress**

Improvements in the management of irrigation methods (supply, conveyance and distribution) aim at providing water for irrigation at the times and in the volumes required to satisfy the needs of crops. In addition, other objectives may be to reduce conveyance and distribution losses, achieve other water savings, and combine upstream decisions with downstream demands. Developments regarding supply systems may include (see Table 2-34):

- the use of **alternative water sources**, such as water reuse systems, increased use of groundwater
- improve **hydrological forecasts** (from national or international agricultural and hydrological services; drought forecast)
- application of optimisation and **decision analysis techniques** to improve water delivery schedules.
- techniques for **water augmentation**, eg reduced evaporation, use of mulches
- techniques for increasing **flexibility** of conveyance and distribution systems, for example the use of intermediate reservoirs and variable versus constant discharges

and durations. Generally, delivery schedules must be better adapted to farm irrigation schedules and nighttime delivery should be avoided wherever possible, also for for health safeguards,

- improvements in **operation and maintenance** systems: this probably represents the highest potential for immediate improvements in most developing contries (see WB 1988; FAO 1986; Campbell FAO 1986). The development of monitoring and evaluation systems is required.

Source: Pereira 1989

Water budget simulation approaches exist for irrigation scheduling strategies in modern irrigated farming (eg Losada et al. 1990; Heermann et al. in: Stewart ed. 1990). Generally, the economic criteria for optimising the use of limited water are different than for scheduling with an 'unlimited' source, but appropriate strategies will depend on each situation. Criteria under 'limited supply' may be: maximising average net return (or crop yield) per unit of water used; then, the optimal cropping pattern and associated irrigation depth depends upon the profitability of yield responses to water. In planning for the optimal irrigated area (maximising total farm yield) different criteria are used than when planning for maximum yields on a small area. In low-capacity systems (eg groundwater supply), irrigation may be restricted in time and quantitiy, for example to certain periods of high water stress or sensitive growth stages. The cropping pattern under irrigation with limited supply may be designed to reduce seasonal requirements by using efficiently natural rainfall, especially in subhumid regions.

Source: Heermann et al. in: Stewart ed. 1990

Irrigation scheduling models for operation on computers include: Jensen for the USDA (cit. in: Heermann et al. in: Stewart et al. ed. 1990); also: FAO- CROPWAT model (FAO 1988).

Methods of estimating seasonal crop water **requirements**, ie matching the water supply and irrigation requirements, which consider daily rainfall, the soil reservoir and water shortages are described in FAO (SB) 1985 (chapter A.6); a simplier procedure is described in Doorenbos/Pruitt (FAO) 1979.

Field guidelines and training **manuals** on irrigation water management were developed recently by FAO (Brouwer 1985, 1986, 1988, 1989).

Sources: Heermann et al. in: Stewart et al. ed. 1990; Pereira 1989; Hillel (WB) 1987; Campbell (FAO) 1986; FAO 1986; Doorenbos/Kassam (FAO) 1979; Doorenbos/Pruitt (FAO) 1977

Further reading: Barghouti/Le Moigne ed. (WB) 1990;

2.3.5 Irrigation Water Conservation Methods

The various means to achieve water savings at the farm level with surface, sprinkler, drip/trickle and reuse systems are summarised in Table 2-35. Adequate tools for increasing water and energy efficiencies, improving the uniformity of application, and applying programmes for water saving and reducing off-site impacts can be utilised with all irrigation methods. Generally, rational irrigation management techniques are easier to achieve with drip and to a lesser degree with sprinkler systems under managerial and technical conditions in industrialised countries.

Field programmes in the USA have revealed that improved water management practices for furrow systems can decrease water and energy consumption by as much as 25% (Bronger 1991). Since water use efficiency is usually considerably lower in developing countries, the potential for saving water or energy may be accordingly higher (see also section 5.4).

The following methods are applicable to surface irrigation methods to avoid over-**irrigation** and increase uniformity and thereby reduce tailwater and drainage losses:

- reduction in stream size (especially in furrow systems),
- widely-spaced furrows (reduction in wetted area can range from 20-50%) (Stone et al. 1982),
- reducing furrow grade or slope
- tailwater re-use systems, utilising tailwater recovery ponds, vegetation buffers, sediment retention ponds etc.,
- surge irrigation: intermittent application of surges (pulses) of water to sets of furrows; surge management considers the advance phase and the cut-back phase; it is relatively easy to implement and operate, can be easily integrated into existing gated pipe systems, and can easily be adjusted to specific soil conditions. Management guidelines for surge irrigation are outlined by Humphery (1989); research showed that water use is reduced by 30 to 50% compared with conventional continuous flow (Goldhammer et al. 1987; cit. in: Tanji/Hanson 1990),
- cutback irrigation, which means decreasing the unit or furrow inflow rate after the water advance is complete, also reduces return flow but it is labour intensive and difficult to implement,
- cablegation: automation of gated pipe irrigation and automatic application of continuous stream size.

Sources: Tanji/Hanson in: Stewart et al. ed. 1990; Humphery 1989; USDA-SCS 1983

It is obvious that most of these techniques require a higher level of management than conventional methods such as continuous delivery. On the other hand, in addition to water savings these methods also allow more flexibility in reducing deep percolation (drainage effluent), surface runoff (erosion) and provide management tools for vector control by eliminating pools, puddles, and seepage areas.

Surface irrigation, especially furrows, is difficult to combine with minimum or reduced tillage systems because ensuring the advance of water requires considerable labour and continuous attention. The average time requirement may increase by some 30% for irrigated minimum till systems compared with areas under conventional tillage (Bronger in: ICID 1991).

Sources: Bronger in: ICID (STS-C8) 1991; Tanji/Hanson in: Stewart ed. 1990; Humpherys 1989; Pereira 1989

In sprinkler systems the strategies for water conservation must be aimed at minimising losses during application, especially direct losses.

Application losses in **sprinkler systems** such as centre-pivots and mobile drip systems consists of the following components

direct losses:

- 10% due to evaporation during application at low winds
- 30% due to evaporation/uniformity losses during applications at high wind speeds (>3-4m/s)
- 7% from interception and direct evaporation
- 1% from soil evaporation before infiltration
- 1% run-off
- 1% other

indirect losses:

- 4% from the pump drive
- 10% from irregular machine movement and irregular water distribution

Fig. 2-10

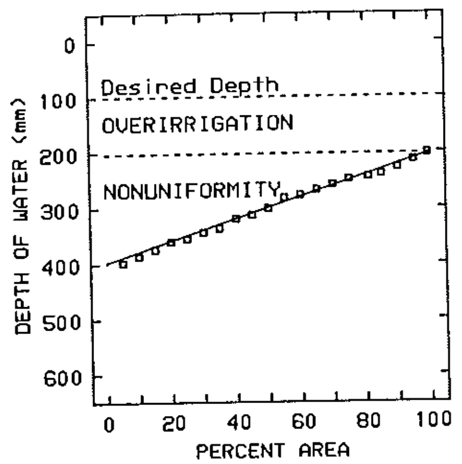


Fig. 35-7. Distribution of applied water showing amount of subsurface drainage because of overirrigation and amount due to irrigation system nonuniformity.

Source: Stewart ed. 1990

Fig. 2-11

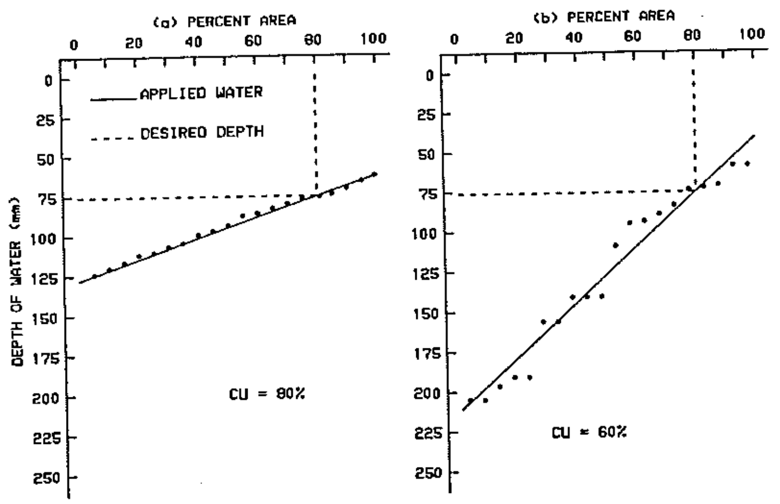


Fig. 35-8. Distributions of applied water for CU's of (a) 80 and (b) 60%. Area between dashed and solid line is the subsurface drainage.

Source: Stewart ed. 1990

crop water use inefficiency losses

may vary from zero to a probable maximum of about 80%, due to applications in excess of the needs of the plant. These losses are usually due to poor scheduling plans, or a lack of adequate extension advise to private farmers.

Source: Sourell 1991

2.3.6 Subsurface Flow Control

Excessive subsurface return flows are associated with the following hazards:

- pollution of groundwater by salts and agro-chemicals,
- rise in groundwater table which causes waterlogging in the rootzone and capillary rise of saline groundwater during the dry or non-irrigation season.

There are two strategies to control the subsurface flow:

- reducing the amount of return flow through reduced water applications,
- reducing return flows in high water table areas by utilisind subsurface drainage water to meet crop needs.

Sources of subsurface drainage are over-irrigation and **non-uniform application** practices which result in water being applied in excess of the water retention capacity of the soil profile. This is illustrated in Fig. 2-10 where the desired depth is determined by soil water retention and infiltration characteristics. Proper irrigation management can reduce overirrigation, while adequate irrigation system selection, design, operation and land levelling can control the uniformity. Attainable efficiencies are given in Part I section 2.2.3. The higher the uniformity, the higher the potential for subsurface drainage reduction as illustrated in Fig. 2-11 a-b.

Typically, irrigation systems are designed to apply the desired amount of water to 80% of the field, or some 90% for high value crops. If the uniformity is not improved and if no over-irrigation occurs, subsurface drainage can only be reduced by deficit irrigation on a considerable part of the field. If overirrigation occurs, then the cumulative distribution in Fig. 2-11 b applies.

The minimum and advisable drainage flow under field conditions would be about 10% of applied water with an overall leaching fraction of 15% (also sections 2.4 and 3.3). Because of the non-uniformity of applied water it may vary from zero to some 34% over the field (Willardson et al. 1977, cit. in: Tanji/Hansson 1990).

Some 'best management practices' for controlling subsurface return flows are:

- improving water delivery efficiencies through canal and ditch lining,
- improving management of the water delivery system through irrigation scheduling on demand and to meet demands,
- improving the uniformity of surface irrigation system by using larger stream flows such that the advance time equals 25% of the minimum intake opportunity time,
- using tailwater return systems and cutback irrigation,
- improving land grading,
- changing to sprinkler and drip irrigation (if applicable),

Source: Walker et al. 1978, cit.in: Tanji/Hanson 1990

Where high water tables exist, subsurface return flows can be reduced through water table management using a subsurface drainage system. This involves seasonal control of the depth of the water table in order to maximize the crops' use. This approach may be applicable where the groundwater is only slightly saline and where leaching from rainfall is sufficient. Under good management saline groundwaters can also be used (Californian experience; cit.in: Tanji/Hanson 1990).

Sources: H.Sourell in: ICID (STS-B23) 1991; Guskov in: ICID (STS-C11) 1991; Bronger in: ICID (STS-C8) 1991; Humpherys 1989; Tanji/Hansson in: Stewart et al. 1990

2.3.7 Water and Soil Temperature versus Crop Growth

Crop growth is influenced by soil temperatures especially during **germination** and **early growth**. Vegetables and many rice varieties are sensitive to extreme temperatures which must be considered in the supply of irrigation water. On the other hand, irrigation may also be used to modify extremes of soil and air temperatures, namely to reduce extremely high temperatures in arid areas or for frost protection. These effects may be obtained directly by applying cooler water, or indirectly due to the cooling effect achieved when water evaporates from moist surfaces.

Cold discharges may be derived from large or medium sized reservoirs when water is removed from the cooler lower layers. Warm water may be obtained from deep aquifer supplies. Some methods for modifying water temperatures at the farm level include: warming in basins, or in broad canals, and reducing water losses and thus energy losses by evaporation supression, and compaction of the deeper soil layers to reduce percolation of warm water, and several inlets to a field, flooding quickly, and holding the water with a minimum flow. Skimming warmer water from reservoirs or providing afterbays may be a further option when reservoirs are used for supply.

Further reading: Raney/Mihara in: Hagan et al. ed. (ASA) 1976

2.3.8 Monitoring and Performance Appraisals

Irrigation professionals have been found to rate performance assessment as the highest priority management issue (Pearce 1987). An important determinant of irrigation system performance is water control which, in turn, is directly related to resource conservation, productivity and return on investment. Performance measurements, of course, also include institutional, participatory and social impact analysis.

System performance assessment requires a broad conceptual framework. The ultimate goal (on the farm level) is that farmers are encouraged to improve irrigation performance towards achieving improved agricultural productivity, resource conservation, water control, and income generation. The following outline of a reference methodology requires inputs from various disciplines and includes eight steps:

(1) agreement on **goals** for irrigated agriculture (on farm level): eg stabilising and increasing agricultural production to a specified level on a specific site; or alternatively: specified cropping pattern on a specified area,

(2) definition of **system boundaries**: eg irrigated command area of a farm/scheme,

(3) establishing irrigation management **objectives**: eg water control, efficiency of water use

(4) identification of **general performance indicators**: eg equity, reliability, supply and application efficiency, real income

(5) identification and measurement of **performance variables** which are site-specific; for example, equity evaluation should consider the delivery to various typical farmers and evaluate whether distribution is 'fair', depending on traditional rights, appropriate cropping pattern, soil characteristics, location, etc,

(6) identification of **low performance indicators**: general or irrigation related constraints such as inadequate farmer participation in system management; limited technical capability of farmer or of supporting services; poor communication between farmers and institutions; inadequate coordination among various institutions serving irrigated agriculture; poor status of hydraulic infrastructure; poor irrigation system design, inadequate maintenance, inadequate operation of irrigation control structure, inadequate extension services, etc.,

(7) identification of major factors contributing to low performance,

(8) definition of strategies to improve irrigation system performance.

Source: Oad/McCornick 1989

Source management objectives and suggested performance indicators are shown in Table 2-36. Further techno-economical indices include:

Group 1: Indices of **irrigation water utilisation** include:

efficiency of utilising irrigation water resource S (%) as S = (Wp/Wd) × 100

where Wp and Wd are the design and actual annual water discharge

gross annual irrigation quota M, as M = W/A (m^3/year/ha)

where W = annual water supply at the field

irrigation application efficiency E (%), as E = (Wf/Wh) * 100

where Wh is discharge delivered at headworks and Wf is volume used in fields.

Group 2: Indices of **agricultural engineering** aspects include:

efficiency of actual irrigated area F (%) as F = (A/Ad) × 100

where Ad is the designed area and A the currently irrigated area (ha)

ratio of area provided with field irrigation to drainage system D (%) = (Af.a/Af.d) × 100

where Af.d and Af.a are the design and currently areas provided with systems

percentage of facilities in good condition G (%) as G = (Nq/N) × 100

where N is total number of facilities for irrigation/drainage; Ng in good conditions.

Group 3: Indices of **economic benefit** include:

yield per unit area y, as y = Y/A (t/ha/year),

where y = gross yield from irrigated fields and A = gross area irrigated

yield per unit quantity of irrigation water yw (kg/m^3) as yw = Y/W

income from irrigation water charges per unit area i ($/ha/year), as i = Iw/Ad

where Iw is current total annual income from irrigation water charges

irrigation benefit per unit area b ($/ha/year), as b = (y-yo).c + (y1 - y1o).c1 - h

where y and yo are annual yields with and without irrigation, resp.; y1 and y1o are

annual quantities of by-products per unit area with and without irrigation (t/ha/year);

c and c1 are the values of agricultural products and by-products ($/t) and h is annual expenditure per unit area for irigation ($/ha/year)

irrigation benefit per unit quantity of irrigation water bw ($/m3) as bw = b/M

percentage of financial self-sufficiency J (%), as J = (I/H) × 100

where H is total annual expenditures of supporting institutions and farmers ($/year) and I is total annual income from water charges and other revenue sources.

Source: Zhi 1989

Table 2-37 shows the evaluation of a large scale rice irrigation project (174,000 ha) in China before and after rehabilitation. The main factors contributing to low performance were: management organisation's restricted access to financial resources; lack of policies and regulations; no right for management to allocate water; irrational rate of water charges; poor headworks; imperfect field irrigation and drainage systems; poor maintenacne of canals; poor conditions of some ponds; irrational irrigation scheduling or actual deliveries to farmers (Zhi 1989).

A critical issue is the appropriate definition of the desired level of performance. There are situations when low efficiencies are acceptable in economic terms because there are (currently) no environmentally significant hazards or negative effects of agricultural production. For example, conveyance canal lining or closed systems have many advantages over open earth canals because they minimise supply and distribution losses with beneficial impacts on conservation of water resources and reduced health hazards. However, costs are much higher and economic incentives for closed and automatic control systems are lacking at least in most developing countries. Assuming that return flows from seepage losses along open canals are available for downstream users, the salinity of return flows is low, land drainage is sufficient and water savings are not required, then there is no justification for the costs involved in increasing conveyance efficiency. Hence, efficiency must always be assessed in the given socio-economic and physical context (land, water, soils, drainage, salinity, etc).

Source: Langley 1984

2.4 Land Drainage for Irrigation

Key Words:

control of salinity and wetness; pollution problems; design variables and criteria; o-site and off-site effects; environmentally sound drainage; drainage effluent disposal; multiple objectives; leaching; minimum drainage: flexible systems; multiple objective water control; best-management-practices; regional planning; wetland buffer zones;

Cross-references:

section 1.2, 3.3, 5.1

Main References:

Lesaffre ed. 1990; vanHoorn ed. 1988; FAO (IDP 38) 1980; various ICID-articles

2.4.1 Introduction

In 1990, about 233 M ha were being irrigated throughout the world and about 4-5 M ha are being added each year. About 1-1.5 M ha are anually damaged to some degree through secondary salinisation (see Part I section 3.1). It seems that about half of the 233 M ha needs either rehabilitation or drainage for sustainable productivity of irrigated agriculture.

Figures from: ICID 1991; FAO 1991; OECD 1991

Further reading: Lesaffre in: Lessafre ed. 1990; LeMoigne et al. 1987; Kovda 1983

Drainage for irrigation is required to control soil salinity and wetness within the rootzone and the capillary fringe zone by lowering the watertable. Artificial drainage facilitates percolating water to discharge from the irrigated area and lowers the watertable in locations where this process is not adequately provided by natural land drainage. Thus, drainage helps to maintain or to improve the potential production level of agricultural (and irrigated) lands, increases crop yield, improves crop quality and allows for greater flexibility in cropping pattern and crop selection and farm mechanisation (Fig. 2-12).

Fig. 2-12

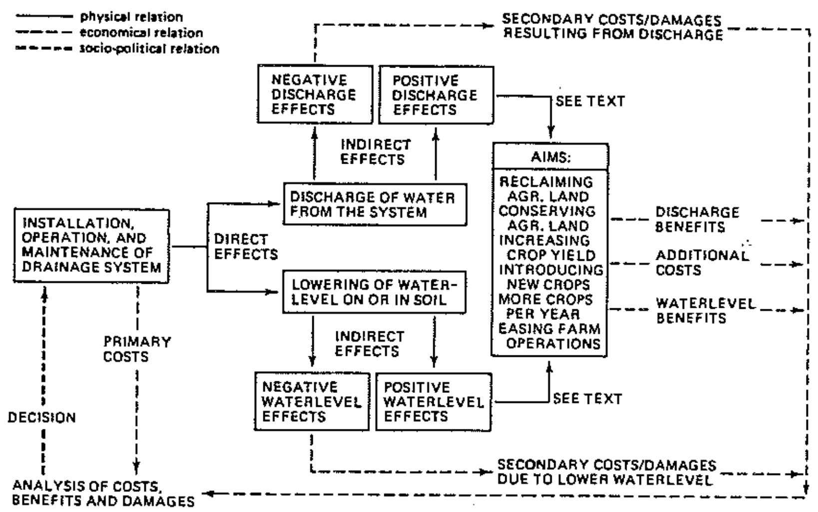


Fig. 1. Generalized diagramn of effects of subsurface drainage on agriculture, and their economic evaluation.

Source: van Hoorn ed. 1988

On the other hand, drainage may present **pollution problems** due to the presence of nutrients, sediments and toxic constituents in the effluent; pollution problems are easier to control if the drainage outflow can intercepted and collected. In addition, the lowering of the watertable may pose problems in water supply to natural vegetation in affected areas (Part I section 2). Therefore, a new dimension in drainage design should be introduced besides economic feasibility, agronomic needs and engineering: avoiding or reducing detrimental environmental off-site impacts.

Sources: Dierickx in: Lesaffre ed. 1990; Armstrong/Rands/Castle in: van Hoorn ed. 1988; Dierickx in: van Hoorn ed. 1988; Feddes in: van Hoorn ed. 1988; Oosterbann in: van Hoorn ed. 1988; El-Mowelhi et al. 1988; Wesseling in: vanSchilfgaarde ed. 1974;

Further reading: Lesaffre ed. 1990; van Hoorn ed. 1988; Smedema/Rycroft 1983; vanSchilfegaarde ed. 1974

This section addresses some issues and concepts relevant for environmentally sound drainage systems for irrigation. A distinction is drawn between surface and subsurface drainage systems. Surface systems rapidly convey surplus water off the field while subsurface systems tend to reduce peak flows from fields and are also more effective in buffering the pollution of drainage effluents. In many irrigation projects combined systems exist and, therefore, the advantages of both systems may be used to reduce the detrimental effects of effluents. Some issues which are critical in humid zones with high fertiliser/pesticide applications may in many places not (yet) be relevant in developing countries:

- **surface runoff** usually causes P and organic N pollution, whereas subsurface drainage cause high NO_3-N concentrations: it is unclear which situation poses greater hazards. Maintaining high water levels increases the potential for denitrification but may also increase outflow during wet periods; controlled drainage (with higher watertables) may influence nutrient concentrations in outflows by increasing surface runoff resulting in greater transport of P and sediments than would occur under uncontrolled drainage.
- **subsurface drain**age tends to lower peak runoff by providing more storage for infiltrating rainfall (or excessive irrigation water); good subsurface drainage, however, increases nitrate outflow concentrations by about threefold (experiments by Skaggs 1987, cit. in: Hoffman in: Lesaffre ed. 1990). Improved surface drainage or controlling the discharge from subsurface drains to increase runoff would significantly reduce the discharge of nitrate from subsurface drains.

Further reading: Evans/Gilliam/Skaggs in: ICID 1990; Hoffman in: Lesaffre ed. 1990; Deal et al. 1986

2.4.2 Drainage Requirement Criteria

In conventional drainage systems, the optimum design must satisfy crop drainage requirements, and the dominant crop in the command area of a collector drain has a major effect on the system.

In drainage design four kinds of variables are important (see Fig. 2-13):

- **engineering** variables: they represent different possibilities for the technical components of the system, eg drain depth, spacing, dimensions, materials, length, diameter of openings
- **environmental** variables: represent the natural conditions under which the drainage system has its function, eg irrigation, rainfall, soil properties, groundwater depth and fluctuation, capillary fringe zone; they may vary considerably in time and space; a fixed value chosen for the design is called a parameter
- **object** variables: represent different degrees to which the aim of draiange is realised; crop production can be used but also workability or other production factors

Fig. 2-13

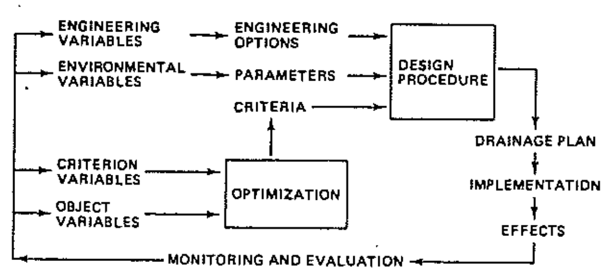


Fig. 2. The role of criteria in the optimization, design, and evaluation of drainage systems. There is a feed-back in the proces.

Source: van Hoorn ed. 1988

- **criterion** variables: related to object and engineering variables, eg in the production function and drain-spacing equations; a typical criterion variable is the desired watertable level.

Source: Oosterban in: van Hoorn ed. 1988

Criteria and variables can be evaluated for steady state flow, falling watertable, fluctuating water table, salinity control, root zone aeration status, as well as other root zone parameters and trafficability. There are numerous **equations** to establish drain spacings, and each method has its advantage in specific site conditions, for example:

- the steady state method is suitable for field conditions when irrigation water is frequently applied in small quantities,
- the falling watertable criterion is usually applicable for gravity irrigated fields
- salinity control is important in permanently irrigated fields where salinity build-up within the root zone must be prevented (Bower in: van Schilfgaarde ed. 1974),
- in humid areas adequate aeration for optimum crop growth must be assured; then, the critical root zone aeration level is the most desirable drainage criterion.

Sources: El-Mowelhi in: Lesaffre ed. 1990; Further reading: Smydeme/Rycroft 1983; FAO 1980; van-Schilfgaarde ed. 1974; ILRI 1972-74; Hiler 1969, 1977

Usually, drainage system design criteria are

- desirable watertable level and subsurface drainage depth (Table 2-38); in areas with salinity problems drain depth should be generally deeper than 1.5 m (see also Figs. 2-15 a-c). In humid areas where potential salinity is not a problem the minimum drainage design depth is at about 0.7 m to protect the conduit from damage, and to provide maximal root zone extension. Most designers use field drain depths of 0.9 to 1.2 m in humid zones and 2.0 to 2.3 m in arid zones with salinity risks (Ochs in: Lesaffre ed. 1990)
- drainage design rate (steady state)
- drain spacing
- drain slope
- catchment area.

Sources: El-Mowelhi in: Lesaffre ed. 1990; Ochs in: Lesaffre ed. 1990; Oosterbaan in: van Hoorn ed. 1988; FAO (IDP 38) 1980

2.4.3 Environmentally Sound Drainage

Drainage is practiced on irrigated and non-irrigated fields where it exerts distinct impacts on the environment. Changes occur as

- **on-site effects** on soils, groundwater regime and quality,
- **off-site effects** on ground and surface waters by drainage effluents which induce quality and river flow changes.

Under irrigation, impacts on soils are to some extent unavoidable and by the introduction of additional water for crop growth there is already a significant change imposed on soil physical and chemical properties. Hence, drainage is designed to remove excess irrigation water from the rootzone to prevent prolonged waterlogging, and any changes in soil properties due to adequate drainage are favourable for crop production. Adequate drainage is, therefore, absolutely essential to the sustainability of irrigated lands and the drainage function must be sustained to protect and ensure the long term productivity of irrigated lands:

- drainage should be considered as a component of the total water and land management system and the drainage system should be designed in concert with irrigation and farming practices (eg farm water management, delivery systems),
- on a larger (watershed) scale, the long term drainage needs should be considered within an integrated land use system that includes the land, water and natural ecosystem resources and basinwide considerations for sustainable use.

Source: Skaggs in: Lesaffre ed. 1990

There are essentially three alternatives for preventing or minimising negative impacts from drainage effluent pollution: (i) divert drainage disposal to isolated areas or separate from aquifers which are important for domestic supply, (ii) treatment prior to reuse or discharge, and (iii) provide dilution (FAO (IDP 31) 1979).

Most important regarding off-site impacts are quantities and areas of drainage **effluent disposal**. In conventional drainage systems disposal is typically selected in terms of economic and technical feasibility. Envrionmental considerations in order to minimise impacts should be introduced, too. Disposal may involve the use of natural river systems, evaporation ponds, direct discharge to the sea or lakes, re-use for irrigation, or the creation of infiltration buffer zones (wetland buffer zones).

Drainage systems typically have multiple objectives and constraints in all climatic regions. These include workability, protection from excessive water, salinity and alkalinity control, and environmental considerations. The objectives should be addressed in a manner that will conserve and sustain land and water resources. Systems required to satisfy drainage objectives during certain growing periods may remove too much water and increase irrigation requirements and increase off-site groundwater pollution during other periods.

- in irrigated areas in arid to semiarid regions there is usually a need to control salinity by adequate leaching and disposal by drainage systems. Excessive drainage, however, may contribute to serious pollution of ground- and surface waters by effluents. Therefore, the aim must be to control salinity while creating a minimum quantity of drainage effluent. This may be achieved by modifying the operation of the drainage system and by agronomic practices,
- in irrigated areas where salinity hazards do not exist, eg in subhumid regions and some arid-semiarid regions with excellent water quality, '**minimum drainage**' should be performed. This may be achieved either by modifying the drainage design depth and/or by operational measures and agronomic practices. For example, excessively deep and intensive drainage systems may remove the potential for meeting multiple objectives.

Concepts for environmentally sound drainage systems (for either irrigated or non-irrigated farming) are typically aimed at controlling the **operation** of the drainage system. Field drainage is operated during times when this is required for plant growth (and salinity control) and to a minimum depth which allows satisfactory growth during the cropping season. Outside these periods the drainage system should

- be able to provide 'subirrigation' that satisfies partially or fully the crop water demands (eg cover crops, green manure)
- be closed to allow for restoration of the original water table situation, ie before drainage.

Source: Kochev in: ICID 1990

Hence, a flexible drainage system is required which regulates seasonal variations of the water table during vegetative and non-vegetative periods and also offers possibilities for reusing the drainage water either within the command area or off-site. In Bulgaria, such flexible systems resulted in water savings in the range of 30 to 50% of the total water demand for irrigation (Kochev in: ICID 1990).

Fig. 2-14

For the design of groundwater drainage systems, the desired watertable regime must be suitably formulated on the basis of the relationship as depicted in figure 1.

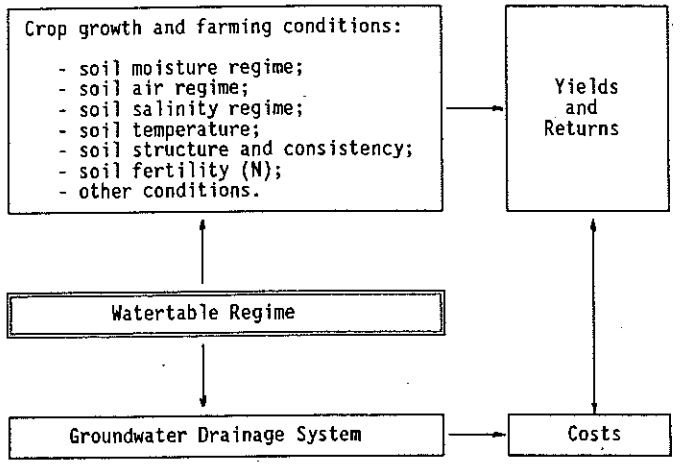
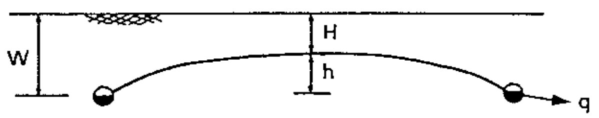


Figure 1 - Relationships to be considered in groundwater drainage design for agricultural land

Source: Lesaffre ed. 1990

Fig. 2-15 a



objectives	H (m)	q (m/d)	W (m)	h (m)	10^3 q/h (day^{-1})
leaching salinity control aeration subirrigation	1.00 1.75 0.50 1.00	0.002 0.0005 0.007 -	2.50 2.50 1.20 1.00	1.50 0.75 0.70 -	1.3 0.7 10.0 -
compromise for all objectives	1.0	0.002	2.0	1.0	2.0

Figure 4 - Groundwater drainage criteria for different watertable control objectives

Source: Lesaffre ed. 1990

Fig. 2-15 b

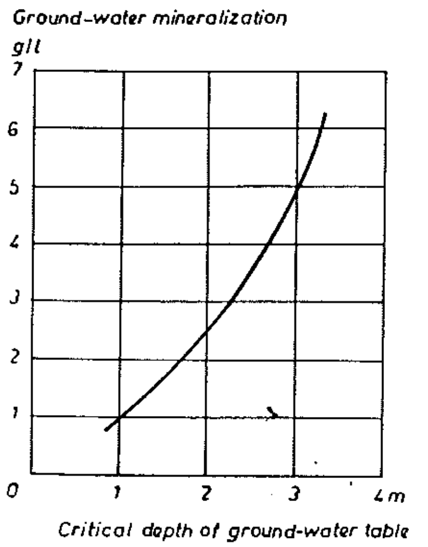


FIG. 16. Relation between ground-water salt content and the 'critical ground-water level'.

Source: Szabolcs 1979

Fig. 2-15 c

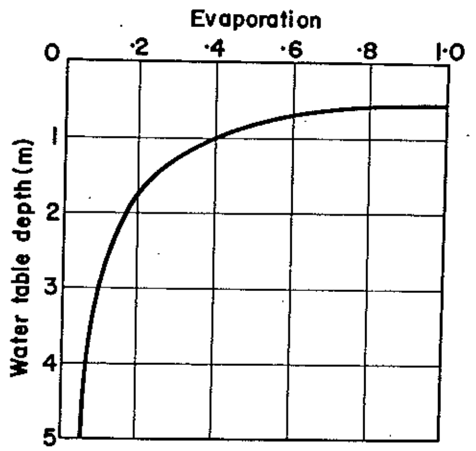


Figure 7
A schematic relationship between the depth of groundwater and relative evaporation rate from soil surface

Source: FAO (SB 39) 1988

The design of multiple objective watertable control in semi-arid regions may be formulated on the basis of the relationship shown in Fig. 2-14. For example, the main objectives are:

i) to control **salinity**: the watertable levels should be low enough to maintain a gradient for downward flow in the rootzone but otherwise no strict watertable level requirements apply; to limit dry season and post harvest upward salt movement, the upward gradients should be weakened by lowering the watertable, thus keeping the subsoil and groundwater out of reach of the upward pull; when there is no seepage influx, this lowering will occur passively as a result of the upward flow, although the active lowering of the watertable by a deep drainage base is preferred,

ii) to control **aeration**: adverse effects of waterlogging-induced air shortage are accentuated with rising soil temperature; hence, aeration control is essential if the growing season coincides with the warm season. The situation is complicated by fluctuating watertables within the growing season.

Various indices have been proposed, eg the SD30 and SW30 indices, respectively, measuring the total number of days with watertable within a 30cm depth from the surface and the product of the number of days by the height of exceedency of the 30cm depth level. Generally, these indices have not been found to correlate with crop yields because of the complex nature of factors which contribute to yields under field conditions (also Smedema in: van Hoorn 1988),

iii) **subirrigation**: under semi-arid conditions crops can satisfy a considerable part of their water requirements by capillary uptake from shallow watertables. This applies in particular to dry periods during and shortly after the rainy season. In an irrigation project in North Pakistan improved drainage has resulted in increased irrigation water demands, partly due to the lowering of watertable resulting in reduced opportunities for groundwater uptake by crops.

Source: Smedema in: Lesaffre ed. 1990

Ideally, watertables should be controlled that there is sufficient:

- depth during the leaching period to meet the leaching requirements
- depth during post harvest and fallow periods to minimise capillary salinisation
- depth and control during the rainy season and irrigation period to minimise damage due to poor aeration
- height during dry periods and times of irrigation water shortage to maximize opportunities for subirrigation.

Typical criteria for fine sandy or silty subsoils (moderately high capillarity) in semi-arid regions are indicated in Fig. 2-15:

The system intensity factor is indicative of the capacity of the system to control high watertables. High intensity factors are required especially for aeration control because most crops can stand only limited periods of waterlogging. The suggested compromise design is clearly not the most cost-effective design for each objective. It largely meets salinity control requirements, leads to some over-drainage which minimises subirrigation opportunities and ensures only limited aeration (Smedema in: Lesaffre ed. 1990).

To achieve 'best management practices' to minimise the off-site impacts of drainage water the following issues need to be addressed:

- drainage volume and time distribution of drainage water as a function of specific soil characteristics, water management alternatives and agricultural strategies,

Fig. 2-16

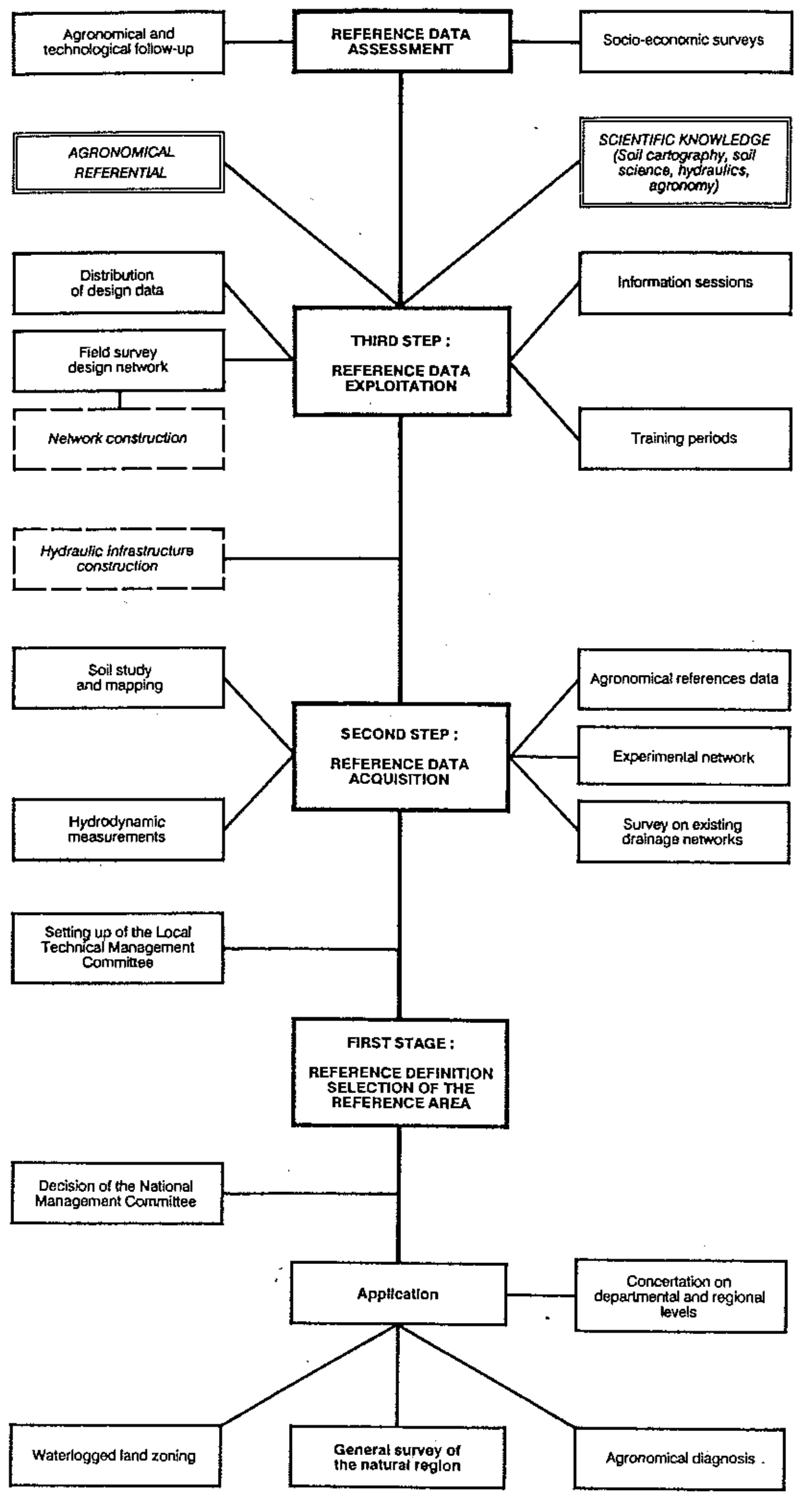


Figure 1 - The different steps of the reference area method

Source: Lesaffre ed. 1990

- determination of drainage water quality as a function of specific soil characteristics, water management alternatives and agricultural strategies,
- determination of the effect of controlled drainage and subirrigation on salinity and nutrient transport to groundwater.

Modified after Evans/Gilliam/Skaggs in: ICID 1990

Field experiments in the USA have revealed that significant decreases in nitrate and phosphate pollution can be obtained by controlled drainage (Evans/Gilliam/Skaggs in: ICID 1990). However, increased seepage may result from controlled drainage.

Formulas for '<u>ecological drainage criterion</u>' exist for drainage of non-irrigated soils:

> In conventional drainage systems, the relation (coefficient) between the necessary drawdown of the water level for keeping the design drain depth and the harmful drawdown up to the drainage base that occurs during the vegetation period is 1.0; in environmentally sound drainage systems it should be <1.0, the minimum being 0.6 (Kochev in: ICID 1990). Drainage systems with regulating valves may be advisable.

Some of these results may be transferable to irrigated farming but systematic research and evaluation of potentials for controlled drainage under irrigation should be addressed in future.

<u>Groundwater pumping</u> from shallow aquifers may be used as a feasible strategy to control water levels (see also Fig. 3-25 a). Disposal may be directly into a river or use for irrigation. A groundwater pumping/reuse management system exists for example in Tongola in Australia and in many part of Pakistan. The following variables must be determined for adequate design and operation:

- volume of groundwater that must be pumped to maintain safe water levels in various seasons
- volume of groundwater that can be safely used for irrigation regarding short-term and long-term impacts on the salt balance
- ability of neighbouring farmers to cooperate in achieving water table control
- effects on trade-off balance between pumping costs and economic benefits to individual farmers.

Source: Heupermann in: van Hoorn ed. 1988

2.4.4 Regional Drainage Planning

Drainage systems may be based on an individual farm approach or on a wider scale. A strategy for an operational approach for design and construction on a regional base is the '**Reference Area Method**' (Favrot in Lesaffre ed. 1990). The method includes two complementary parts:

- aquiring technical and agronomic recommendations for proper design, construction and operation of drainage systems
- organising the dialogue required between the various parties involved.

The different steps in the method are shown in Fig. 2-16.

Wetland buffer zones for drainage water disposal

Wetland areas may also be used to buffer the impact of agricultural drainage water. Conventional drainage systems are composed of collectors which discharge directly into natural systems. Wetland buffer areas may be marshland, wooded swamps or other vegetated land filter areas. They are expected to filter and remove nitrogen, phosphorus, sediments or toxic constituents of the drainage effluent (see Part I section 4.7). They also may attenuate peak flow rates before the drainage water enters river systems. Generally, two different types of buffers may be developed:

- **infiltration** (deep percolation) buffers where the drainage water is not directly discharged into the surface waters; these areas are similar to wastewater infiltration lands where the groundwater is recharged and it is assumed that backflow into the river systems is retarded and the polluted water is filtered
- **overland flow** strips where the drainage water is discharged into the surface water systems after passing a vegetated buffer strip. The primary mechanism for removal of nitrogen and phosphorus and sediments is sedimentation. Nitrogen is removed by denitrification, and the period of time that the effluent stands on the buffer area largely controls the efficiency of removal. Field studies in the USA have revealed that these buffers can remove 70% of P, 50% of N and 90% of the suspended load of the effluent. (Skaggs/Chescheir/Gilliam in: ICID 1990). However, serious wildlife problems due to drainage effluent are also reported from wetlands in the USA (see Part I section 2.3).

Soil requirements for wetland buffers are similar to those of wastewater treatment infiltration land (see sections 2.5 and 3.2.), ie soils must be permeable with high infiltration rates but also capable to adsorb toxic constituents, eg containing sufficient fine particles.

Sources: Favrot in: Lesaffre ed. 1990; Evans/Gilliam/Skaggs in: ICID 1990; Kochev in: ICID 1990; Skaggs/Chescheir/Gilliam in: ICID 1990; Lesaffre (ICID) 1990; Heuperman in: van Hoorn ed. 1988; Smedema/Rycroft 1983

Further reading: Lesaffre ed. 1990; van Hoorn ed. 1988; Smedema/Rycroft 1983; FAO (IDP 31) 1979; Dieleman/Trafford (FAO) 1976; vanSchilfgaarde ed. 1974; Eggelsmann 1973; ILRI 1972-74; FAO (IDP 16) 1973; FAO (IDP 6) 1971

2.5 Reuse of Sewage for Irrigation

Key words:

reuse objectives; impacts; reuse benefits; control methods; site evaluation; social acceptance; health protection; objectives of raw sewage treatment; design criteria; layout for tropical countries; layout-options; crop selection criteria; safety rules; irrigation methods; wild flooding; border irrigation; furrow systems; sprinkler and drip methods; human exposure, planning wastewater reuse; systems framework; monitoring;

Cross-references:

Part I sections 2.3; 3.6 and 8.1, Part II sections 2.2, 3.2.4, 4.1, 5.1

Main Reference:

WHO 1989; Mara/Cairngross (WHO) 1989; Feigin/Ravina/Shalhevet 1990; Biswas/Arar ed. 1988; Pescod/Arar ed. 1988; Shuval et al (WB) 1986

2.5.1 Potentials and Constraints to Development

Potential for wastewater irrigation still exist in many countries and with growing populations in urban centers, the availability of domestic wastewaters will rapidly increase. Nevertheless, it is estimated (early 1980s) that in 80% of the situations where wastewater is collected and water is an agricultrual development constraint, wastewater, either raw or treated, is already used for permanent or seasonal irrigation (Wright/Quicke in: Shuval et

al. 1986). The use may be direct via immediate use of the effluent, or indirect by using groundwater or surface water resources with effluent additions further upstream.

Wastewater reuse may have one or a combination of the following objectives:

- use of a **reliable water source** for irrigation,
- **fertilisation** of land, especially infertile sands,
- reuse of **scarce water resources** (especially in arid areas),
- **safe** disposal of wastewater to avoid surface or groundwater contamination by direct (unfiltered) inflow,
- **groundwater recharge,**
- safe disposal of wastewaters containing **toxic** concentrations of inorganic or organic chemicals.

Wastewater irrigation offers economic potential where water is a constraining factor to optimum growth, agricultural areas can be developed near the effluent source (thus conveyance costs are low), and profitable marketing is ensured by nearby cities.

General principles for use of wastewaters to reduce potential negative health and environmental impacts are:

- soils should not be contaminated with persistent toxic organic or inorganic solids or compounds (design variables are soil buffering capacity for heavy metals, rate and frequency of water applications, content of elements per wastewater unit),
- wastewaters should not be contaminated with excessive concentrations of pathogenic microorganisms (variables: rate and frequency of water application, number of pathogens per wastewater unit),
- water applications should be moderate to avoid temporary waterlogging and anaerobic conditions, except in the case of paddy; design variables are soil infiltrability, permeability, land drainage, aggregate stability, rate and timing of water applications,
- wastewater applications should not contain concentrations of nutrients, sodium, and trace elements/heavy metals in excess of that required for crop growth and the buffering capacity of soils (design variables are soil texture and mineralogy, actual nutrient status, buffer capactiy, total water application and content of nutrients per unit wastewater).

Wastewater reuse may have several benefits, among which are the following:

- reuse of water can be considered as an additional source of water for irrigation,
- the marginal cost of providing the same volume of good quality water is generally higher than the cost of producing wastewater under conditions of water shortage; wastewater will be produced irrespective of whether or not it is used since sewage treatment works are essential to prevent groundwater pollution, and hence, it makes sense to use it beneficially,
- properly planned use of wastewaters can reduce environmental and health impacts which have been observed with traditional wastewater disposal practices in developing countries,
- wastewater reuse can prevent or reduce eutrophication of water bodies, especially closed ones such as lakes, where uncontrolled disposal can contribute to nutrient overloading,
- wastewater can provide nutrients to soil and plants, especially N and P but also trace elements, and thus may reduce the need for fertilisation, which may increase the total economic return to farmers,
- salt water intrusion in coastal areas can be prevented by recharge of groundwater with treated wastewater.

Source: Biswas in: Biswas/Arar ed. 1988

Generally, irrigation with wastewater can be carried out on all soils which are suitable for irrigation, although associated risks differ for soil contamination or groundwater pollutions. Primarily, the specific suitability depends on site specific water qualities attainable with a given treatment and source and quantities available. (for criteria and guidelines on water quality see section 2.1).

The control or remedial methods include:

- **wastewater treatment**: to eliminate or reduce the concentration of pathogens or other potentially toxic constituents to acceptable levels.
- **disinfection** of wastewater-contaminated crops: disinfection of farm produce prior to marketing or in the home,
- improving the **occupational health** of sewage farm workers or farmers: protective clothing and/or other measures,
- **agronomic techniques**: restrictions on the type of crops grown or modifications and control of irrigation techniques and operations,

Source: Shuval (WB) 1990

Sources: WHO 1989; Mara/Cairncross (WHO) 1989; Pescod/Arar ed. 1988; Biswas/Arar ed. 1988, Shuval et al. (WB) 1986

2.5.2 Site Suitability

Suitability of locations depends on technical aspects:

- irrigation areas should be close to the treatment plant (effluent source) to avoid transportation costs, risks of exposure, unfavourable changes in water quality during transport (especially in pipelines) and maintenance problems in conveyance canals or pipelines,
- irrigation areas should be at a safe distance from settlements, usually >1 km to avoid odour nuisance and aerosol pollution of nearby settlements,
- irrigated areas should be close to markets to minimise transportation of goods,
- there should be non-irrigated areas in the vicinity which can be used outside the cropping season for safe disposal (rapid infiltration fields) or groundwater recharge, if no groundwater induced salinity problems exist; this applies also in emergencies for example in the case of treatment plant failure, if polluted water is released from the plant which does not meet quality standards for use in irrigation.
- size of irrigated areas must be adapted to the quantity of available water (or vise versa) to avoid over-irrigation and the conseuent contamination of soils,
- if effluent quality does not meet standards, the ability of mix it with freshwater (ground or surface water) must be ensured at the site; this mixing may be required necessary temporarily or routinely,
- for deep percolating water (unavoidable groundwater recharge) the quality standards of maximum permissible concentrations of chemical constituents (eg toxic heavy metals) must be met; if soil filtering capacity is too low, eg in sandy soils, then other sites must be selected if groundwater pollution would cause problems (eg if groundwater is used for domestic supply to the local population),
- water quality standards must also be observed for surface drainage outflow.

Site specific criteria are:

- suitability of the terrain for a specific irrigation method (topography, microrelief, general slope),

- climatic water balance and temperature, eg evaporation rates will affect the salt balance, and temperature and soil moisture regulate the transformation of constituents in the soil,
- soil properties regarding the insuitability to filter, buffer and transform inorganic and organic constituents of wastewaters (precondition to avoid pollution of groundwater),
- infiltration and permeability properties (precondition to avoid waterlogging in the rootzone and allow the movement of wastewater constituents; precondition for well aerated soils),
- adequate land drainage (precondition for sustainable irrigation to avoid waterlogging and salinity build up; either natural or artificial, or both),
- nutrient status (determines the acceptable level of additional nutrient supply),
- risk of sodicity and alkalinity (affects structure and mobility of elements).

It follows that most soils are suitable for wastewater applications but not all wastewaters are suitable for all soils if the above objectives are to be met.

Reference: Kretzschmar in Blume et al. 1992

2.5.3 Socio-Cultural Aspects

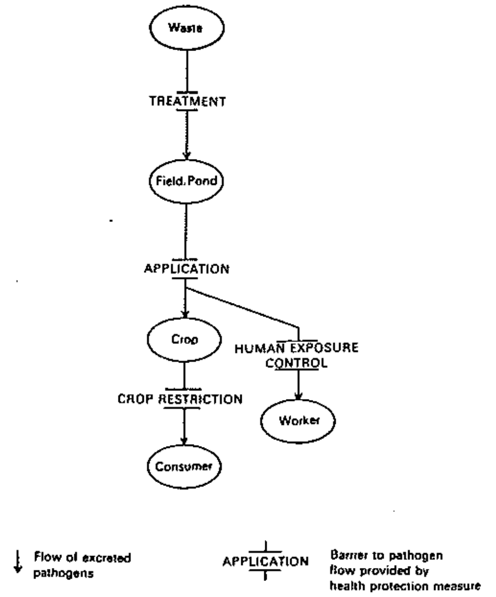
It is essential that the acceptance of excreta or wastewater reuse by farmers, farmworkers, consumers and people living in the vicinity is ensured before it is considered for irrigation. Socio-cultural studies or other information is required to ensure that there are no objections. Suitably designed information programmes may contribute to increased acceptance.

The introduction of human/animal excreta or wastewater use and the adoption of health safeguards related to wastewater irrigation may require changes in behavioural pattern. Human societies have evolved very different responses to the use of excreta, eg in many African communities it is regarded with disaffection whereas the use of excreta (or derivates) for fertilisation of soils and its use in aquaculture has been common in Asian communities for thousands of years (Mara/Cairncross 1989). Often, no distinction is drawn between products irrigated or fertilised with excreta or wastewaters; the reuse of wastewater is not often hampered by sociocultural disgust, although the possibility should be given serious attention.

Intensive cultivation practices which may evolve in response to the need to produce food for a rapidly growing number of people from limited land resources may contribute to a change in behavioural pattern and the acceptance of excreta and wastewater reuse, as it is dictated by survival economics. However, any attempts to alter a social and cultural preference are likely to fail if changes are not introduced stepwise and immediate benefits can be observed by the users. In Islamic culture direct contact with excreta is abhorred by Koranic verdict. However, its use is permitted after treatment, ie after composting or production of a waste material which has no visual or odorous connection with the original waste. The same applies to wastewater and after removal of all impurities the water can be used without any objection. Stabilization ponds usually deliver wastewaters with low contents of visible impurities which may contribute to their successful development in Islamic countries. Experiences in the Near East have shown that treated wastewater is accepted by most farmers (eg case studies in Biswas/Arar 1988; Pescod/Arar 1988).

Figure 7.1 Effect of health protection measures in interrupting potential transmission routes of excreted pathogens

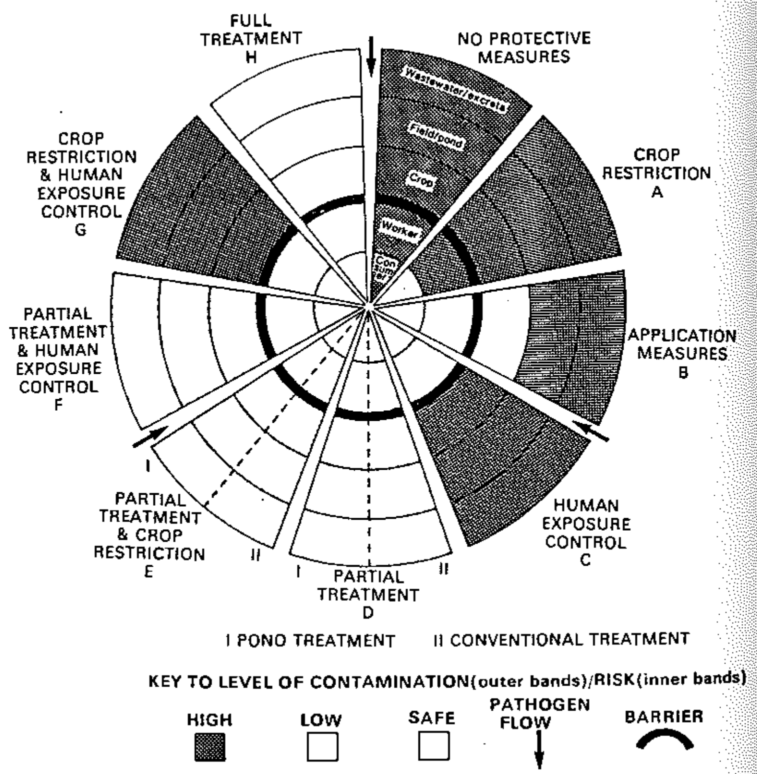
Fig. 2-17



Source: Mara/Cairncross 1989

Figure 7.2 Generalized model to show the level of risk to human health associated with different combinations of control measures for the use of wastewater or excreta in agriculture or aquaculture

Fig. 2-18



Source: Mara/Caircross 1989

Fig. 2-19

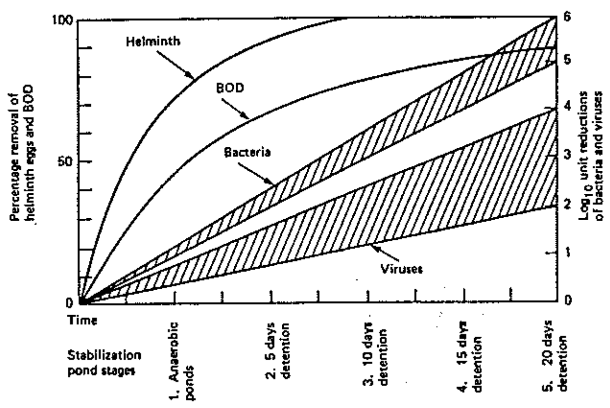


Figure 2.1 Generalized removal curves for helminth eggs, BOD, excreted bacteria and viruses in waste stabilization ponds at temperatures above 20°C

Source: Pescod/Arar 1988

2.5.4 Options for Health Protection

There are several methods and measures to reduce health risks to farmers, farmworkers and people living in the vicinity of treatment plants and irrigated areas. The points at which these measures can interrupt the potential routes of transmission of excreted pathogens (see section 4.1 and Part I section 8.1) are shown in Fig. 2-17. In most cases a combination of several methods is desirable to meet safeguard requirements without a full treatment of wastes, ie three stage treatment which is often needed in industrialised countries with chemically polluted wastewater. This multiple method concept is schematically shown in Fig. 2-18. The feasibility of any combination will depend on factors such as availability of resources (funds, land, manpower), existing social and agricultural practices and possibilities for changes to meet requirements, existing patterns of excreta-related diseases, and means for enforcement of standards.

2.5.5 Wastewater Treatment for Irrigation

Wastewater treatment is the most effective remedial measure in reducing health effects and soil contamination due to wastewater irrigation. The primary objectives in the following order of priority are:

- maximum removal of **helminths** (close to 100%),
- effective reduction in **bacterial** and **viral pathogens** (minimum 99 to 99.9 %),
- effective reduction of **suspended load** (site and irrigation type specific criteria),
- maintain **aerobic conditions**,
- production of **nuisance** and **odour-free effluent** which is attractive to users.

These specific design criteria differ from those aimed at reducing pollution from BOD and COD, and thus result in different optimal treatment strategies. Conventional multistage wastewater treatment plants utilising mechanical equipment, chemical amendments, filters and large energy inputs are not particularly effective in meeting these criteria, although they are generally recommended (WHO 1973), see Tables 2-50 and 2-51. In contrast, well-designed and well-operated stabilisation ponds can meet all four criteria in warm climates and wherever land is available at reasonable cost (Shuval et al. 1986; Mara/Cairngross 1989). Gravel bed hydrophonic (GBH) systems may be used for the secondary and tertiary treatment of effluents (Butler/Dewedar in: Wooldridge ed. 1991).

The advantages and disadvantages of various sewage treatment methods are shown in Table 2-52. The generalised removal curves for pathogenic microorgnism are shown in Fig. 2-19 and Tables 2-53 a-c. Specific perfomance of waste stabilisation ponds is shown in Tables 2-54 a-c. The ponds should be arranged in a series of anaerobic, facultative and maturation ponds with an overall hydraulic retention time of 10-50 days. The degree of bacterial reduction in a pond can be estimated from:

$R = 1 + Kt,$

where R is the ratio between the concentration of faecal coliforms in incoming and outflowing water, t is the retention time, and K is a factor respresenting the rate of die-off of faecal bacteria in maturation ponds at various temperatures: $K = 2.6\ (1.19)^{T-20}$. For facultative ponds die-off rates are slower.

Source: Mara/Cairngross 1986

A typical sewage treatment plant in tropical regions may have the following layout:

(i) Anaerobic ponds, at least two in parallel, with a minimum of 2 days total retention time: effects on helminths; BOD,

(ii) Facultative pond(s), usually 5-10-15 days total detention time (temperature-dependant) to reduce BOD, to remove bacteria by one or two orders of magnitude, and to serve as a security factor for helminth eggs carried over from anaerobic ponds,

(iii) Maturation pond(s) in series to achieve reasonably high bacterial removal; a standard unit for each location is recommended, ideally, a retention time of 5 days each.

Source: Shuval et al. (WB) 1986; an illustrative example is given on page 177., including cost estimates

There are a number of options to consider in the final selection of initial and final treatment systems (Shuval et al.1986):

The removal of **heavy metals** as well as removal of synthetic organic trace compounds (eg carbohydrates, organic acids, organic bases, polynuclear hydrocarbons (HC), halogenated HC, phenols, aliphatic and aromatic materials) are not primary objectives in developing countries, since waters contaminated with these industrial chemicals or metals should not even be considered as a source of irrigation water in developing countries (Wright/Quicke in: Shuval et al. 1986). Removal of metals requires more sophisticated secondary biological treatment stages, eg activated sludge, biofilters or algal ponds. These are complicated in design, difficult to operate and expensive in comparison with the pond system.

The **advantages** of ponds are: low costs for design, construction, operation and maintenance; no expenditures of energy (run by solar energy); high ability to absorb organic and inorganic shock loads; extreme simplicity of operations (fool-proof) and ability to treat a wide variety of different domestic wastewaters (Mara/Cairngross 1989). The main **disadvantage** of pond systems is the large area of land they cover. However, recent research has shown that increasing pond depth (from 1-2 m to 2-3 m) may be successful in metropolitan areas with limited land resources.

An efficient reduction of **COD** and **BOD**, aimed at minimising the potential eutrophication of surface or groundwater by effluents, is not a primary objective for wastewater treatment because the water is used on fields where biodegradation of organic materials (mainly C and N) takes place in the soil and many organic compounds and minerals are considered as useful agents to improve soil fertility and the aggregation of soils.

Disinfection, usually **chlorination**, of raw sewage can reduce the number of bacteria but it is, unlike chlorination of fresh water, a vastly more complex and unpredictable operation for wastewaters (Mara/Cairngross 1989). Except when high levels of operation and maintenance are guaranteed it cannot be recommended as a general treatment, because irregular or inadequate disinfection is of little use for health protection. Effluent chlorination may have, in addition to its costs, a number of detrimental effects: treated effluents, rich in nutrients but low in microbiological activity, are ideal for the growth of some surviving bacteria; secondly it may contribute to proliferation of simple or **complex chlorinated organics** (chloramines) that may be toxic to fish or carcinogenic and mutagenic (Pescod/Arar 1988); further, some solutions will react with emulsifiers, fertilisers and pesticides and reduce their effectiveness. Occasionally chlorination may be used to reduce clogging hazards in drip irrigation systems or if bacterial slimes and algae within the water transfer system pose serious problems (Feigin et al. 1991:186). Dosages are in the range of 0.5 to 1 mg/l to control algae, iron bacteria and slimes (Ayers/Westcot, FAO 1985).

Main sources: Shuval (WB) 1990; Mara/Cairngross (WHO) 1989; Shuval et al. (WB) 1986

Further reading: Feigin et al. 1991; Pescod/Arar 1988; Biswas/Arar 1988

2.5.6 Crop Selection

Crop selection should be based on the following criteria:

- suitability to general agronomic and economic criteria (eg climate, soils, markets),
- suitability to salinity and specific toxicity criteria (see sections 2.1 and 3.3),
- constraints to marketing imposed by public health concerns or regulations related to pathogens and toxic chemicals.

The most obvious problem related to health constraints is the contamination by wastewater of plants destined for human consumption without further processing, within a short time after contamination. The most effective precaution would be to irrigate only wood and fibre crops (eg cotton). Safety rules for the cultivation of food crops should observe:

- minimal contact between effluent and edible crop part, eg tall growing fruit crops and trees,
- preference for crops which are normally washed or treated before consumption, eg olives, citrus, avocados,
- crops which are exposed for some days (or weeks) to desiccation and ultraviolet radiation before being marketed, eg crops which are not irrigated for several weeks before harvest,
- low-growing but erect crops if grown in furrows, ridge-and-furrow or drip irrigation systems.

Source: Shuval et al. WB 1986

Toxic chemicals in the form of heavy metals may occur in soils or in irrigation waters; some of them are taken up and accumulate in plants. Toxic concentrations must be avoided in both fresh water and wastewater. Similar regulations are applicable for both waters (Table 2-55, see also section 2.1).

Guidelines for restrictions on types of crops irrigated with wastewater can be an effective remedial strategy. Crops can be grouped into three broad categories in increasing order of public health risk involved (Table 2-56). Regulations exist for example in the USA (1977) (Table 2-57). Guidelines for crop categories have been established by WHO (1973) (Table 2-58). They have been effective in some countries with efficient means of control. Other national guidelines are shown in Biswas/Arar 1988 and Pescod/Arar 1988.

Careful **cleaning** and **disinfection** of contaminated crops at the point of use (ie consumer) may be effective in industrialised countries where public health standards are high and high quality freshwater is available. It is not applicable on a larger scale for developing countries. Market disinfection stations (eg at vegetable markets) may be theoretically considered, especially for large scale, centralised irrigation schemes.

Sources: Mara/Cairngross (WHO) 1989; Shuval et al. (WB) 1986

2.5.7 Suitability of Irrigation Methods

All the commonly used irrigation methods can also be used for wastewater irrigation under appropriate conditions. The advantages/disadvantages of the four main irrigation methods in relation to disease transmission are listed in Table 2-59. Constraints may be mainly imposed by:

- possible effects of effluent properties, eg clogging problems,
- irrigation methods which favour large scale non-uniform water application and may contribute to ground- or surface water pollution,

- specific environmental health hazards caused by the irrigation method, eg sprinkler irrigation favours air pollution; wild flooding, large basins and border checks favour continuous contact of farm workers with wastewaters; with sprinkling there is contact of wastewater with consumable fruits or crop parts.

Wastewater reuses does not pose any additional technical factor to the design of an irrigation system. However, some precautions must be considered to minimise contacts between farmers and wastewater and close attention should be given to uniformity of field distribution to avoid unwanted deep percolation and/or tailwater losses which may contribute to ground- or surface water pollution from uncontrolled wastewater losses. Therefore, detailed **field tests** may be required to evaluate surface irrigation performance as the situation demands.

The use of standard figures such as hydraulics of open-channel flow and infiltration rates, should be avoided in the design of large scale wastewater irrigation projects where specific **site characteristics** should be taken into account. In addition the **labour situation** is to be considered seriously because the good surface irrigation performance requires technical knowledge and experience which cannot solely be transferred through formal training programmes. Surface irrigation with wastewater should only considered where surface irrigation is already a part of the farming tradition. Each site and each irrigation system has its own characteristics in this respect:

Wild flooding is sometimes practiced for forage crops, pastures or small grains. Water is supplied by temporary earth ditches and the periodic breaching of the ditch berm or placement of earth dams requires a considerable amount of manual labour, as does the handling of tailwater. This requires farmers to stand in water or mud and to move wet earth. All body parts, including the face, could be splashed or could otherwise come into contact with effluent.

Border and contour checks, typically 3-30 m wide and 100-400 m long, are practiced on very gentle slopes with a minimum amount of levelling and are suitable for many crops including row crops. Paddy rice terraces are essentially contour checks but require levelling. Typically, discharges are in the range of 10-50 m^3/h per meter of check width, and total discharges range between 50 to 300 m^3/h. A well designed and constructed border check system is probably the most efficient surface method available, giving reasonably good uniformity of water distribution and control over flow, with very low maintenance and operating costs. Water control at the lower end of a check is achieved either by collecting the tail water in a ditch, or by having the lower end closed to impound the water. Thus, no labour should be required and turnout structures can be operated manually without operator contact with the water. The system can also be adapted to automatically operated turnout devices. If the borders are made sufficiently strong and high to prevent breaching and overtopping, the method is clean, both from the point of view of human exposure and of environmental pollution (tailwater runoff losses).

To achieve uniform distribution, the smallest application is about 100-150 mm. For a number of reasons, the performance of border irrigation is less satisfactory in many irrigation projects in developing countries; consequently, most borders need frequent repair and water flow is manually operated in a similar way to wild flooding systems. Hence, in practice poorly designed and maintained border and contour checks will provide frequent opportunities for contact between farmers and wastewater.

Basin methods use smaller (3-30 m^2) units than border checks and they are completely level. Their size makes it easier to cover the entire field with water in a short time. In contrast to border checks, water distribution is little affected by a ditch at the end of the field. Water is delivered from small earth ditches, with the elevated ditch also serving as a border for every second row of basins. Basins require smaller discharges and it is possible to irrigate several basins simultaneously. The turnout structures are usually simplier, and often the ditch bank is breached. This makes the operation more labour-intensive than

border checks, and may involve more operator contact with wastewaters. The distribution of water may be improved by the use of small diameter syphons when water is delivered from a line-source (eg canal) instead of a point-source. However, frequent contacts with water occur during walking in wet soils and during priming the syphons.

Various technical options exist in order to minimise human water contacts, for example when basins are supplied with water from pipelines either on the surface or underground. The land grading and levelling operations for both border check and basin irrigation systems often require heavy earth-moving machinery and some special equipment for final smoothing, as well as trained engineers for design and construction for water distribution control structures. Thus, the utilisation of wastewater for these irrigation systems should present no problem in situations where these systems are common. However, in situations where the technical infrastructure and local farmers knowledge is not available, problems may be encountered in achieving the required standards in design, construction and operation which may result in poor system performance.

Furrow systems are well suited for row crops. The fact that the ridge tops are 10-25 cm above the water surface in the furrow is an advantage of this method with wastewater irrigation, since even crops with a low growth habit have no contact with the water, provided they have erect stems (pepper, tomatoes, eggplants). The furrow method is the most flexible of all surface methods in terms of length, slope limitations, and size of stream required. Furrows can be used on graded lands and even within boder checks under crop rotation.

Furrow irrigation is characterised by a unique wetting pattern, caused by lateral and upward flow paths from furrows into the ridges. This results in higher salt concentrations within the top of ridges. Salt accumulation may impair crop growth (see section 3.3 and Part I section 3.1) during the irrigation season and leaching must be provided either during the cropping period or outside the growing season by rainfall or additional leaching irrigations. Since sewage wastewater always contains more salts than the normal supply water, the question of water quality must be even more carefully considered if wastewater is applied under furrow irrigation.

Another characteristic of furrow irrigation is a tendency for over-irrigation fields. Most farmers feel that they must accomplish complete wetting of the ridges (wetting depends on the flux rate which, in turn, depends on soil properties and tillage practices) even though this is not required in very heavy (silty loam, clay) or light to medium textured (sand, loamy sand) soils. Especially in heavy soils with slow water flux and where ridges are high there is a tendency to over-irrigate; this may result in unnecessary deep percolation losses or uncontrolled tailwater losses and possible water pollution. The problem can be alleviated by compacting the ridges after construction to lower them and to decrease macroporosity, and by reducing row spacing and making wider furrows. During water supply to furrow heads the farmers may come into frequent contact with wastewater because repair work is often neecessary at the furrow entrance as a result of erosion.

There are various technical options for the supply of water to the furrow such as syphons, gates, temporary breaches, tubes, etc.. Selection should be made on the basis of minimising contacts between farmers and wastewater. Since it is very difficult to supply equal discharges to all furrows, and since shape, roughness, and soil properties (especially infiltration rate) are not uniform in a field, the rate of advance of water in the furrows is never uniform. As a consequence, the water in individual furrows will reach the downstream end of a field at different times and the depth of wetting is not uniform along the furrow. Irrigation must be continued with a reduced rate of flow (cut back). This is not practical for each individual furrow nor it is possible to cut back the discharge so as to exactly balance the infiltration losses over the entire length. Hence, some excess water will be unavoidable at the end of some furrows and this should be, whenever possible, collected in a ditch at the lower field boundary and led to another field for reuse. The control of tailwater may require some works at the checks and hence, human contact with wastewater is possible. Such tailwaters may pose additional problems if they are not reused or otherwise controlled but are conveyed immediately into the drainage system which eventually drains into surface waters where they create pollution problems.

Sprinkler irrigation relies on mechanical devices to distribute water droplets over the field and water must be delivered under pressure. Various types of sprinklers are classified according to portability criteria and delivery devices. Usually, the nozzle orifice diameter must be at least 5 mm and low-discharge impact spinklers are not suitable for wastewater irrigation. Sprinkler irrigation is well adapted to apply small amounts of water, does not require intensive land preparation, is well adapted to variable soil properties and shallow or sandy soils or shallow rooted crops. Major malfunctions may be caused by blockages, leaks at couplers or risers, and mechanical damage and improper operating conditions due to wind or pressure fluctuations.

A principle problem is associated with wetting of the canopy. Some crops and fruit tress are sensitive to chlorides, and fungal plant diseases may be enhanced. Sprinkler irrigation should only be allowed for consumable crops or fruits where it meets standards for health safeguards ("restricted crops"). Sprinkler systems have metal components which may be exposed to increased corrosion activity when corrosive wastewater is used (see section 2.1). Generally, the large-scale use of sprinkler systems for wastewater irrigation in developing countries does not currently seem to be a realistic alternative due to technical and managerial constraints.

The same applies to drip irrigation where additional clogging problems are encountered with the use of wastewaters and even sophisticated filter systems require continuous control which may not be achieved under average managerial conditions in most developing countries.

> Low rate application methods (eg drip) with a large number of emitters with small orifice diameters or narrow flow paths, operating under low pressure, are obviously very susceptible to clogging by suspended mineral and organic particulates, organic slimes and dissolved solids (eg Fe, Mn, Ca). Since clogging is greatly aggrevated when more than one agent is present in the water, there is no single standard for acceptable levels of clogging contaminants. A tentative evaluation was given in Tables 2-15 and 2-16. Suspended solids, responsible for clogging of sprinkler and drip irrigation and sedimentation in canals may reach 0.1 to 0.5%, and therefore, pretreatment is required, especially for drip irrigation systems. These may consist of filter systems (60 to 200 mesh) or other installations, such as sand and gravel pressure filters with backwashing arrangements (Shuval (WB) 1990). Recently developed bubbler systems are less vulnerable because of their larger orifices.

Nevertheless, drip irrigation has some unique advantageous features: there is virtually no contact between the farmer and the wastewater or equipment and only minimum contact between the crop and the wastewater; there is no airborne spray and waterlogging problems are rare; there is virtually no tailwater or deep percolation losses and aerobic conditions which accelerate the destruction of many pathogens and the degradation of chemicals are maintained (see also sections 3.2.4 and 4); also a low soil salinity level within the main rootzone can easily be maintained during the irrigation season.

> Source: Shuval et al. 1986; A detailed dsicussion of sprinkler and drip irrigation design for wastewater application is given in: Shuval et al. 1986, page 233 cont.

2.5.8 Reducing Human Exposure

Four groups of people can be identified as being at potential risk from irrigation use of wastewaters: farmers and agricultural field workers, crop-handlers, consumers, and those living near affected fields (Mara/Cairncross 1989; see also section 4).

Regarding on-farm risks, exposure to many parasites can be reduced by adoption of certain health safeguards, eg use of footwear. Rigorous health education programmes are needed to propagate meticulous personal hygiene.

Immunisation is not possible against helminth infections and control of other infections (eg typhoid and hepatitis) is not feasible on a large scale. Additional protection may be provided by the availability of medical facilities to treat diarrhoeal disease and by chemotherapeutic control of nematode infections.

Many risks can be reduced by strict personal, kitchen and food hygiene, eg by thorough cooking of vegetables, meat, milk, etc. Regular health education campaigns are required to improve standards, especially in societies with poor education.

Local residents should be kept fully informed about the location of irrigated fields, so that they may avoid entering them and also prevent children from doing so. Warning notices may be posted and fences may be erected.

2.5.9 Systems Approach to Planning Wastewater Reuse

While the interest in reusing wastewater for irrigation is increasing in many developing countries (especially in North Africa, the Near East and Latin America), many attempts made so far have generally been unsuccessful. Intentions to save water must be supported by proper planning of wastewater reuse, which will ensure that an optimal cost-effective process can be designed and maintained for each of the site-specific situations under consideration, consistent with environmental and health. A decision model for wastewater treatment for reuse and for setting local effuent standards is shown in Fig. 2-5.

Planning of long-term sustainable wastewater projects needs a systematic approach. A systems framework is shown in Table 2-60 where six major issues are addressed under the following headings:

- identification of the nature of development objectives and constraints,
- identification of legal feasibility,
- technical feasibility,
- political and social feasibility,
- economic feasibility,
- manpower feasibility.

The cacacity of agricultural soils to treat wastewater should be used to identify suitable areas for reuse under various options, namely under irrigation or land treatment (infiltration for groundwater recharge). Most emphasis is now being given to ensuring that the crops to be consumed do not pose and the farmers do not face undue health risks. Recently established effluent discharge standards (see section 2.1) are satisfactory and land treatment should follow those standards. Table 2-61 shows various requirements of land application of wastewaters in terms of its use under irrigation, groundwater recharge and overland flow. Cost estimates are given in Table 2-62.

> Case Study Kuweit. An example of the planning and implementation process is shown in Figs. 2-20 and 21. The procedures involved in preparing plans which enable optimum use to be made of the treated effluent are similar to those involved in land and water resources planning (see section 1).

Source: Biswas in: Biswas/Arar ed. 1988; Cobham/Johnson in: Pescod/Arar ed. 1988

Fig. 2-20

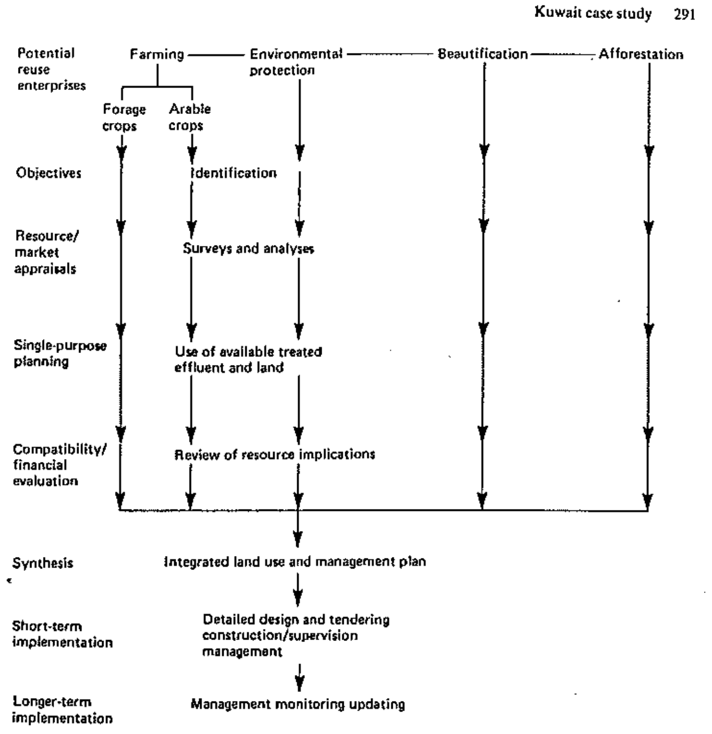


Figure 24.1 An outline of the resource planning and implementation processes

Source: Pescod/Arar 1988

Fig. 2-21

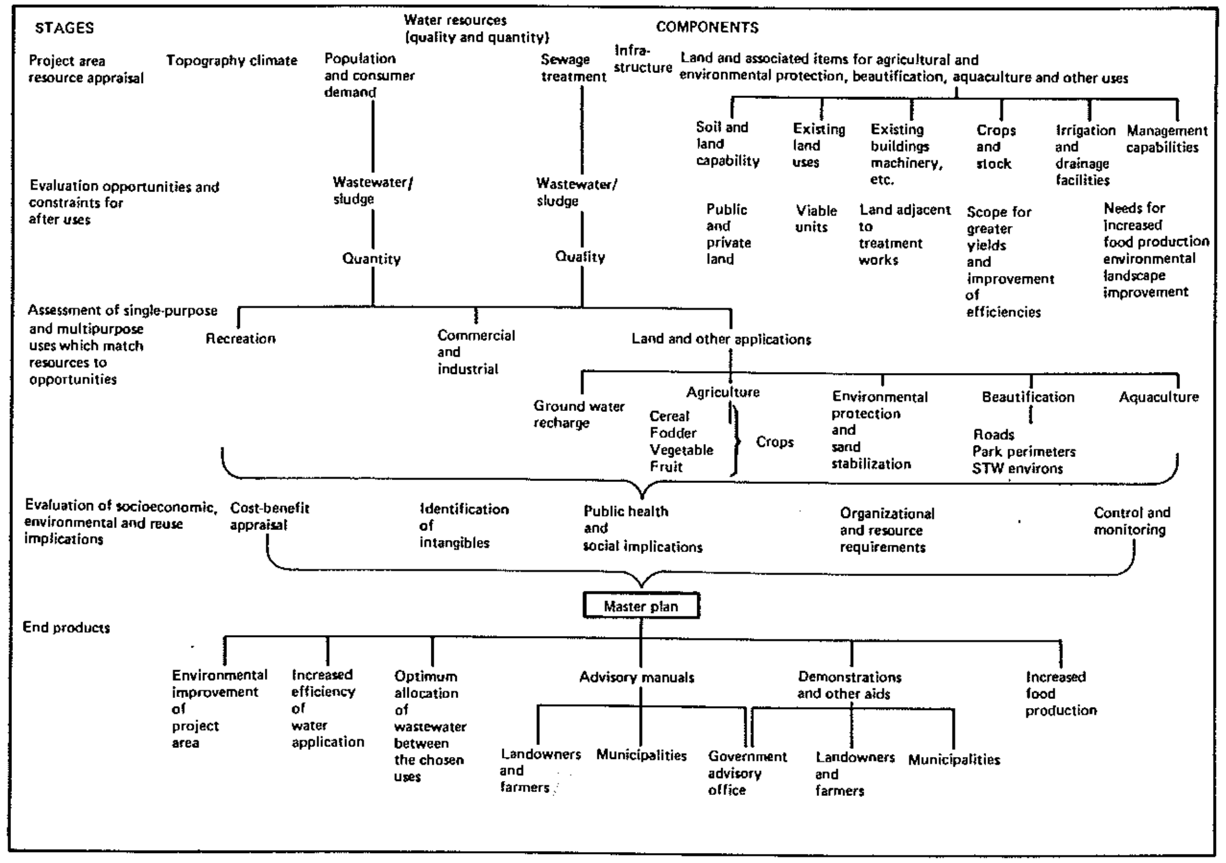


Figure 24.2 Main components of general planning guidelines for wastewater reuse

Source: Pescod/Arar 1988

2.5.10 Monitoring and Evaluation

Without regular and effective surveillance during project implementation, the anticipated benefits from the project will be endangered and there may be real possibilities that the project may contribute to the development of serious health and environmental hazards. Thus, a monitoring system should be implemented which focused on targeted outputs in terms of water quantity and quality, delivery of water to the irrigated area, quantity and quality of agricultural products, and compliance with health standards on the part of farmers, treatment plant workers, traders or consumers of irrigated crops. Since the aim of monitoring and evaluation is to achieve successful project performance, it should be an integral part of an effective management information system in order that:

- timely corrective actions can be taken to reduce the probability of occurrence of any environmental or health hazard,
- project assumptions are seen to be valid and can be verified,
- achievement of project objectives and impacts can be determined,
- lessons for other projects can be learnt for more effective planning and operation in future.

The major requirements for monitoring and evaluation systems (M & E) are:

- **timeliness:** most information must reach decision-makers promptly for immediate and appropriate decisions to be taken and implemented. Accordingly, management success will depend on the accuracy of data, the speed of analysis and interpretation and the form in which information is channelled into the decision-making process,
- **cost effectiveness:** financial resources are invariably limited in most developing countries and a sensible trade-off must be established between the depth and context of collected data, as well as between amount, relevance and accuracy. Thus, as as general rule, the value of collected data should exceed the cost of obtaining that information (see Fig. 2-22). However, the quantification of the 'value' of various data depends on perceptions and professional outlook,
- **maximum coverage:** the decission need to be made on which data should be collected, frequency of collection, spatial distribution of collection points; given the very high resource costs of manpower, instruments, and transportation, a decision has to be taken to restricted coverage to selected parameters which are necessary for adequate operation and management of the treatment plant and irrigation system, and then allocate remaining resources to obtain more detailed data on critical parameters in selected areas,

  Example: A comprehensive monitoring programme is outlined in do Monte (in Pescod/Arar 1988:338). The programme includes physico-chemical and microbiological analyses of wastewaters, soils and crops (Table 2-63).

- **minimum sampling and measurement errors:** close cooperation between the various disciplines is required because perceptions and views may vary amongst sanitary engineers, doctors, soil scientists, hydrologists, irrigation engineers, agronomists, agricultural engineers, analytical chemists, etc. Based on the ultimate use of data, standards and procedures must be established with the final decision being site-specific,
- **biases:** these may arise from a lack of coordination because wastewater treatment and reuse under irrigation spans several disciplines; for example, health specialists may attempt to monitor residual chlorine in effluents, even though the water is for restricted irrigation only, thus making both chlorination and data collection unnecessary.

Source: Biswas in: Biswas/Arar ed. 1988

Fig. 2-22

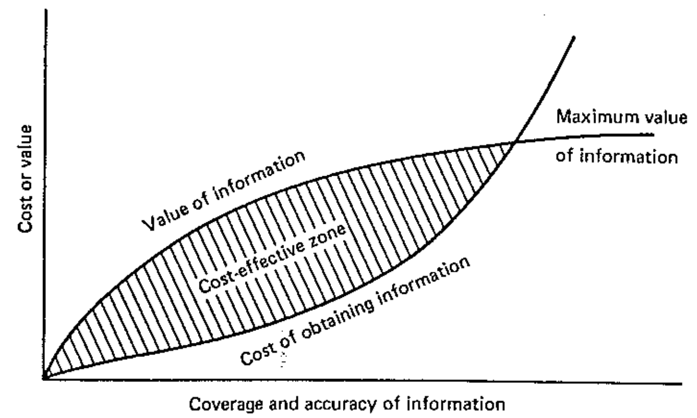


Figure 1.4 Cost-effectiveness of monitoring and evaluation information

Source: Biswas/Arar 1988

The political and institutional framework for monitoring and evaluation should be considered as an important factor. A large number of specific and specialised tasks have to be performed both concurrently and sequentially, in a planned and coordinated manner, by a variety of professionals, with an array of decisions being made by local, regional, national or even international institutions, which may exert a direct influence on projects. The differing interests and objectives of these institutions, and inter-institutional conflicts may complicate the process. Relevant activities for wastewater projects can placed in four interrelated groups:

- operation and maintenance of the treatment plant: monitoring at this level will focus on treatment facilities, including variations in quality and quantity of the final effluent,
- operation and maintenance of the irrigation project (agricultural institutions, probably an independant irrigation institution): monitoring will focus on data on crop production (area, yield), cropping pattern, effluent quality with regard to irrigated crops, fertiliser and pesticide applications; effluent characteristics in relation to soil properties as a filter, buffer and transformer; short- and long-term impacts (see section 3.2.4),
- operation and maintenance of the water supply system (probably an independant water resource institution): monitoring will focus on data on irrigation facilitites, including flow in effluent canals, losses in canals, factors related to groundwater discharge and water quality implications, eg surface or groundwater pollution,
- health and environment related issues (various institutions and authorities): monitoring will focus on concentration of pathogens contributing to health concern that may be present in the effluent, such as intestinal nematodes, bacterial organisms, viruses, nematode and cestode infections. In addition, it may be necessary to monitor heavy metals or other toxic chemicals present in the wastewater. The frequency and extent of contacts with farmers, farmworkers, children and people living nearby would also be examined.

Typically, these levels and their activities are neither discrete nor sequential and monitoring implementation must be site-specific.

Source: Biswas in: Biswas/Arar ed. 1988; further relevant reading Pescod, Hillman, Montgomery, Arar and Shende all in Biswas/Arar ed. 1988

Training and manpower development is probably the most important requirement for the successful development and management of wastewater irrigation projects in developing countries, including monitoring and evaluation. The projects are often designed by experts in industrialised countries which makes the need for experienced local managers and well trained technicians of various disciplines even more acute in order to operate wastewater irrigation projects successfully.

General Sources: WHO 1989; Mara/Cairngross (WHO) 1989; Feigin/Ravina/Shalhevet 1990; Biswas/Arar ed. 1988; Pescod/Arar ed. 1988; Shuval et al (WB) 1986

Further reading: Bouwer/Idelovitch 1987

3 Considerations for Soil Resources Conservation

3.1 Integrated Land use Planning for Irrigation

Key Words:

irrigation planning; limited resources; principles of efficiency, sustainability, equity; need for planning; levels and scales of planning; spectrums of irrigation system levels and status: system status, organizational status, technical level; procedures for land use planning; planning activities; functional versus resources procedures; comprehensive versus integrated plans; step-by-step approach; goals & targets; interdisciplinary ILRI approach for regional plans; planning activities; interdepartmental & intersectoral cooperation; policy orientation & tactical programmes; detailed design & incremental approach; strategies for integration of irrigation development; environmental quality assessment; landscapes & ecosystems; human land uses; alternative land uses; boundary conditions; land use planning models; suitability judgements; ecological compatibility; carrying capacity; succession & reliance; environmental performance standards

Cross References:

Part I section 4.

Part II sections 1.1, 1.2, 3.2,

Main References: FAO 1989; ADB 1989; van Staveren/Dusseldorp (ILRI) 1983;

3.1.1 Introduction

Planning for irrigation projects is a multidisciplinary task because irrigated agriculture consists of various interrelated technical, organisational and socio-economic activities, methods and implications. There are five main kind of activities which can be differentiated in irrigation planning and management:

- regarding supply of water for irrigation; water resources planning,
- regarding land use systems; land resources planning (soils, land, ecosystems),
- regarding technical structures; agricultural and civil engineering,
- regarding agricultural production; agronomy, soil & water management; extension
- regarding agricultural economics; farm economy; marketing.

These activities occur for all types of irrigated farming, regardless of whether plans are made by small subsistence farmers, private cash-crop farmers, centrally or decenetrally managed smallholder projects or a government-managed production scheme. In addition, especially in the case of larger smallholder projects or production schemes, there are general public and administrative interests and concerns of politicians, regional planners, administrators and economists, local elites, and public health authorities. Small subsistence farms and private cash-crop farmers are in most cases responsible for the allocation of resources, production and farm economics. Only in well organised and bureaucratic societies are these farmers also integrated into national plans (eg in USA, Europe, China).

Irrigation is a complex, highly productive agricultural system with manifold impacts on land use, soil and water resources. Hence, planning for irrigation should be embedded in a greater framework of regional planning (or environmental planning) to ensure sustainable development, regardless of the **extent** of an irrigated area. The extent to which natural resources are used and the actual or predictable future impacts on other resource users should determine the degree to which an individual project should be integrated into a national or regional plan. **In practice**, however, irrigation planning and management is often the result of

- **sectoral** interests, usually directed by agricultural economy policy or water resources policy goals at the national or regional
- **private** initiatives, completely independant from any national or regional plans, which are, however, liable to national regulations or laws (often water or land use laws).

It is obvious that such approaches and practices cannot guarantee the sustainable development of irrigation. A regional integrated planning approach is required for planning and managing irrigation systems where also other viewpoints are also considered, such as the wise use of scarce water and soil resources, environmental protection of ecosystems of special interest, optimal spatial distribution of various land uses on a national and regional basis, and the perceptions and needs of local people.

3.1.2 Concepts for Land Use Planning

Land use planning aims to make the most of **limited** physical and socio-economic resources through the use of principles of **efficiency, equity** and **sustainability** in a systematic manner. Land use planning is needed to:

- assess present and future needs as perceived by various groups or individuals
- assess present and future potential or constraints of physical resources
- assess socio-economic resources
- identify and resolve conflicts between competing present and future uses and various groups of human users
- identify sustainable uses (based on current technological and economic feasibility and socio-cultural acceptability) and elaborate on various alternative uses.

Planning is generally made at various levels and on different scales:

- at various levels: household, village, town, region, national, international
- on various scales: short-term or long-term scale; large or smale scale
- to the benefit of the nation or groups of nations or individuals
- for the exploition or conservation of natural resources.

Planning for irrigation projects (or projects with irrigation components) may be conducted for various types of irrigation systems which may be characterised as follows:

- low, medium or high **system status** (size of command area; number of individual units; number of operational/organizational levels): low/minor - medium - high/ large
- **organisational status** PO - CO - GO, ie individual or group responsibilities for operation & maintenance: this may be private (informal) - cooperative (by groups) - government/ water authority dominated (formal)
- high or low **technical level** employed, eg degree of automation and mechanization
- level of **management potentials**: low to high, depending on technical know-how, educational level, perceptions, organisational skills, administrative capacities, social security, etc.
- status of **production orientation**: market (local/regional/national/world markets) or subsistence oriented and intermediate status.

Land use planning for irrigation projects or projects with irrigation components in development aid is usually on the

- national level (system status high to medium; organizational status government organised, seldom community organised)

- local or community level (system status low to medium, organizational status: community organised, seldom private owned).

Decision making in land use planning

Decision making may apply to all **planning levels**: strategic, policy, programmes and operational (day-to-day). It should follow principles of equity, sutainability and efficiency:

Equity is based on

- ensure **protection** of other users and ecosystems
- provide **compensation** (adequate and timely) for those who are detrimentally affected by new developments
- ensure that all members of the target group have **equal access** to resources
- **counterbalance** regional imbalances by allocating funds to less developed areas.

Sustainability in irrigation development is based on

- management maintains or increases the **long-term productivity** of the area, with regard to soil and water resources
- preparation is made for actual or predictable future **hazards**, either human-made or natural
- **detrimental** direct or indirect impacts on other users are minimised
- **irreversible changes** are minimised, so as to maintain future development options under changed technical, economic and socio-cultural conditions.

Planned land use should be fully acceptable to all target groups, ie it must meet the perceived material and socio-cultural needs and it should be efficient, ie economically viable and technically effective. Regional planning should provide a balanced approach which overcomes possible conflicts between equity and economic efficiency, ie decisions on purely economic trade-offs must be avoided and aspects of the welfare economy (which is difficult to express in market values) should be equally considered.

Land use planning for irrigation should provide answers to the folowing questions:

- what is the present situation regarding resources and living conditions?
- is change desirable (in the eyes of various groups: perceived needs)?
- what can be changed?
- how can changes be made?
- what is the best alternative (regarding technical, economic and socio-cultural aspects)?

Sources: FAO 1989; Westman 1985

3.1.3 Procedures for Land Use Planning

A detailed methodology for land use planning is presented in FAO (1989) Guidelines for Land Use Planning (see Figs. 3-1 to 3-3). Recommended methods are also shown in Table 3-1. The contents of 'Land Use Plans' and the headings for descriptions of 'Land Use Types' are given in Tables 3-2 and 3-3, respectively.

Framework for planning

National plans and sectoral plans serve as a policy framework and as a legal basis for regional land use and water resources planning. **Regional** plans should provide a structure sufficiently detailed for the coordination and mutual adjustment of subregional plans and individual project plans. Those, in turn, should be based on the needs and ideas of **local**

Fig. 3-1

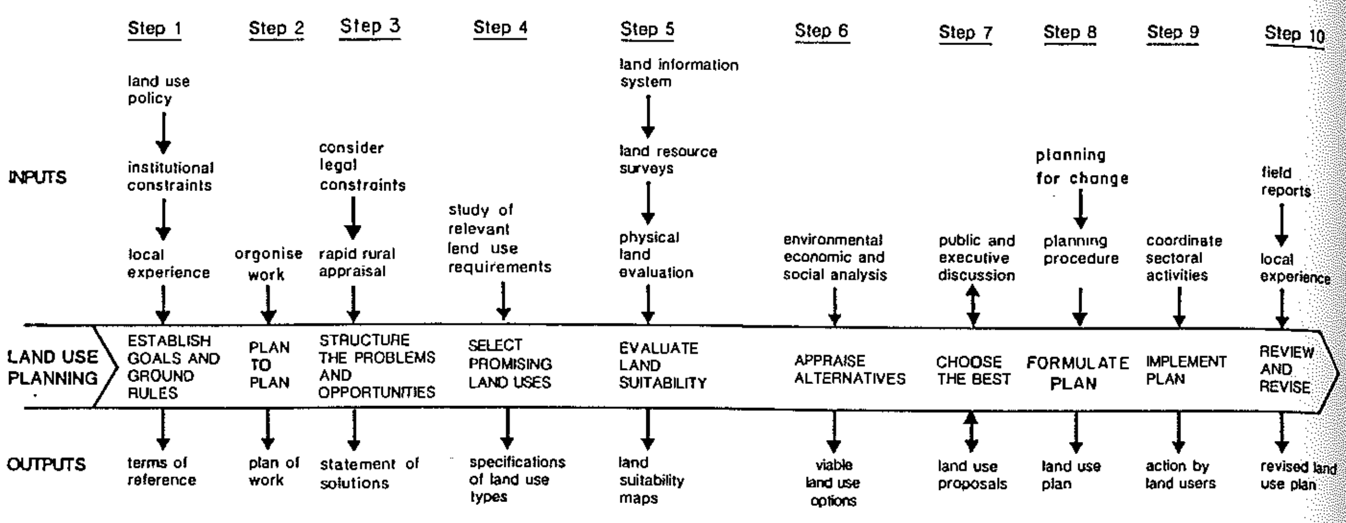


Figure 4
Synoptic view of the land use planning process
adapted from Dent and Ridgway 1986

Source: FAO 1989

Fig. 3-2

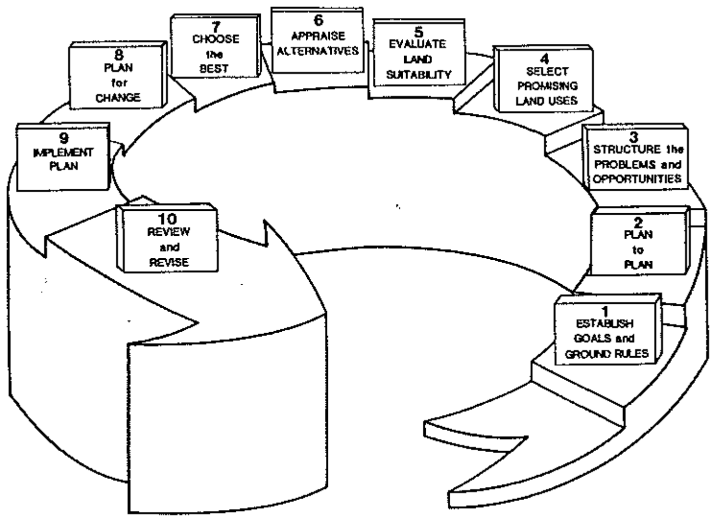


Figure 3. Steps in land use planning.

Source: FAO 1989

Fig. 3-3

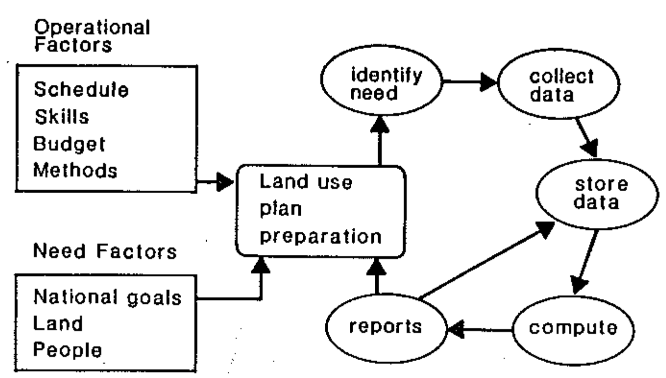


Figure 18 Elements of a land use planning information system

Source: FAO 1989

people and should mobilise the social potential for economic development which is sustainable and self-reliant.

There are two approaches in regional planning:

- the **functional** procedure is a top-to-bottom approach where national and/or sectoral policy defines the function of a given region to contribute to national objectives,
- the **resource-based** procedure is a bottom-to-top approach where planning is based on the on hand on physical (land, water, climate) conditions and on the other by the socio-economic resources and by development needs and potentials which should be identified jointly by policy makers, planners and the actual target groups.

In theory, both approaches should be harmonised for optimal allocation of scarce funds and optimum use of limited resources (physical and human). This can be achieved by plans which are:

- **comprehensive**, ie which analyse the physical and human resources of a specific area for sustainable development,
- **integrated**, ie plans which fit into the policy frameworks provided by national development plans, sectoral and regional programmes or by special laws.

In practice, however, the implemention of comprehensive and integrated plans to the benefit of both national objectives and the needs of local people are very difficult to achieve. In reality, large scale dam and irrigation projects often primarily serve national interests or they are to the benefit of influential groups. In addition, reality is usually too complex to allow for the establishment of comprehensive plans of sufficient detail, and changes happen often too fast for realistic follow-up. On the other hand, large development schemes have long-term influences on physical and human resources and they should be considered in a comprehensive and integrated manner before implementation commences (see Table 3-4). Therefore, for practical reasons, it may be best to subdivide planning procedures for irrigation projects into two categories:

- at a **national** (often sectoral) level, planning and implementation is based on predefined national strategic goals and the subsequent management of the project is left to the responsible water authority (or similar organisations). These plans usually have long to medium term perspectives; perceptions of target groups do not have a high priority nor do they they participate. For example, irrigation may be aimed at a high production level or to substitute for grain imports
- at a **regional** or local level a step-by-step or **incrementalism** approach should be used which considers both broadly defined long-term planning targets and the immediate perceptions and needs of local people, in a flexible and pragmatic planning way. Decicions are made at the local level. These plans usually have short to medium term perspectives.

With either approach, the formulation of goals and quantifiable objectives must be performed during planning and implementation

- goals are to be translated into **realistic** systems and time horizons; goals are defined on the needs perceived by target groups and decision makers
- data inventories should be based on a **dynamic** analysis (past, present, future developments),
- **alternative** strategies or policies should be developed to maximise potentials and eliminate constraints.

Iterative processes with frequent evaluation and re-adaption of proposals are probably the most important tool for sucessful planning. Successful implementation requires the participation of all involved groups at all levels.

The ILRI approach to regional planning

A comprehensive land use plan requires an outline of

* identified activities
* sequence of activities
* cooperation between disciplines and degree of responsibility.

Detailed guidelines for regional plans in rural areas are given by van Staveren/vanDusseldorp ed. ILRI, 1983. The general outline and the contents of a plan must be adjusted to

* the **sectoral** needs of irrigation projects
* the specific **regional** or local socio-economic circumstances
* the size and type of project, depending on the agricultural technology and hydraulic engineering works and environmental and social impacts and economic trade-off.

The interdisciplinary process of planning should use the network analysis where a large number of individual, clearly distinguishable but connected activites are systematically evaluated using a systems' approach. Such a functionalised (or classified) network is shown in Table 3-5. The activities are listed in Table 3-6. Further documents are:

- list of identified activities
- functionalised relation diagram
- definition of each disciplines' task and interdisciplinary function
- structured list of data to be collected per discipline
- overview of activities of each discipline
- overview of the organisational activities of key team members.

Source: van Staveren/van Dusseldorp ed. (ILRI) 1983, Annex I to IV

Activities and relevant data for the planning of irrigation projects are

Physical Resources

Climate: rainfall, evaporation, temperature, wind, air humidity, daylength, climatic water balance

Hydrology: legislation, water right, surface water resources (occurrence and availability characteristics), groundwater resources (roundwater levels, aquifer occurrence and yield characteristics), water quality, water resources development

Land and soils: land use characteristics, land and soil evaluation

Agro-Hydrology: on-farm land and water management practices, crop and farm water requirements, reclamation measures related to soil degradation, drainage needs, erosion control, flood control, organizational aspects of water management

Physical infrastructure: transport systems; public utilities, housing, health and education services, public administration services, agricultural services, banking, marketing, service centers

Production Systems

Crop production: present types of utilisation, farming systems analyses, cropping pattern, cropping techniques, crop protection, plant-soil nutrient balance, use of other farm inputs, extension service

Agricultural extension: existing organisations, existing extension programmes, present pattern of activities, availability of agricultural research messages

Irrigation infrastructure (civil and hydraulic engineering): existing structures, alternative developments, design and implementation of structures, operation and maintenance, costs

Social and Institutional Structures:

Demography and sociology: population size and distribution, population growth, social structure, communication pattern and mobility, cultural patterns and hopes for the future, pattern of decision-making and participation, social action programmes

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Fig. 3-4

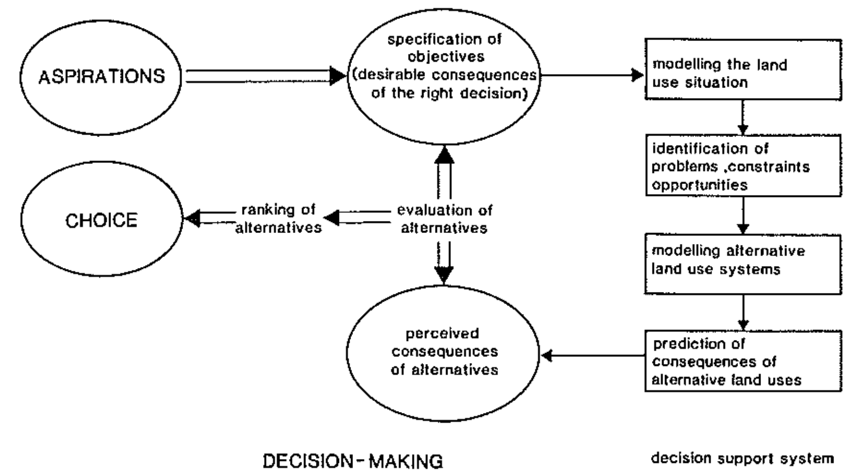

Figure 16 Schematic representation of decision-making

Decision-making is an information-processing task (Lewandowski 1987). The decision-maker must take account of a large and heterogeneous mass of information, much of poor quality. Problematic elements include:

- expert knowledge of the subject is needed;
- the effects of the decision on land use and its implications for the land and people of the whole planning area must be predicted;
- there are complex structural and logical relationships between the elements of land use, the decision undertaken and the response of land users;
- a degree of uncertainty is encountered in the decision-making process, and must be taken into account.

Lack of a priori knowledge, and the presence of uncertainty, can result in the rejection of a potentially good option at a very early stage of the process.

Source: FAO 1989

Health: health services and health statistics; economic aspects, socio-cultural aspects, environmental aspects, health services; cost elements, constraint analyses, development options, public health care programmes and plans

Institutional setting: agricultural administration, communication and cooperation pattern, informal structure, personnel issues, participation and representation pattern, planning activities at various levels, action programmes

Agricultural cooperatives: social and organizational viability, economic viability, potential role of cooperatives

Agricultural credit: socio-economic context, credit demand; credit supply, credit policy, loan policy, loan effects, formulation of action programme

Land tenure: government objectives, distribution of land and water, ownership of land and water, land tenure and tenancy arrangements, customary rights to land and water, resolution of land and water disputes, government organisations and actions concerning land and water

Economic Structure:

Agricultural economy: present situation: position in the national economy of sectors and subsectors, agricultural enterprises, present situation and potential situation, agricultural economic policy, potential situation, regional aspects of the agricultural development process, agricultural policy

Source: modfied after van Staveren/van Dusseldorp ed.. (ILRI) 1983. Further details in discipline checklists in Annex III, ILRI p.153 cont.

See also: Mann (BMZ) 1982

Table 3-1 provides a checklist of relevant information and methods. The comprehensive FAO system for land evaluation for irrigation is outlined in section 3.2.

3.1.4 Summary of Context and Shortcomings

By its nature, land use planning should be non-sectoral. But a land use plan has a history, ie it is usually **initiated** by a single governmental body, and its implementation is the responsibility of one governmental authority. In practice, programmes and actions are planned and implemented by **sectoral agencies** such as: Ministries of Agriculture, Water Affairs, Land Use, Local Govenerment, Works, etc. or by private (or other non-governmental) organisations, cooperatives or individuals. Hence, even good land use plans, developed by independant planners, may be difficult to implement because cooperation between various groups and interests is needed (see Fig. 3-4). A general experience is that many land use plans are either not used much or fully implemented. Often they are drawn up by planners with little local experience. Local involvement is generally limited and the socio-economic perceptions, needs and capacities of the local people are given inadequat attention. Planning at the village level may be hampered by land use plans which do not consider the needs and perceptions of local residents.

Once developed, land use plans can be very rigid and inflexible. Much depends on the approach used and the integration of various criteria as described above. Therefore, useful land use plans should be **policy oriented** and define a **range** of possible programme alternatives, but should leave the detailed design and operational aspects to be dealt with an incremental planning approach by regional or local institutions. This means the **decentralisation** of detailed planning and implementation.

Irrigation developments should be embedded in a 'Land Use Plan' or in a more broadly defined 'Regional Plan' for rural areas.(see sections 1.2 and 1.3). Land use plans and programmes for irrigation projects should primarily be aimed at:

- allocating land to different kinds of uses
- specifying management standards and inputs
- coordinating sectoral proposals, namely agricultural and water resources planning.

In practice, many irrigation projects are neither integrated into regional plans, nor into land use or water resources plans at a sufficient or appropriate degree of detail. Often

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Fig. 3-5

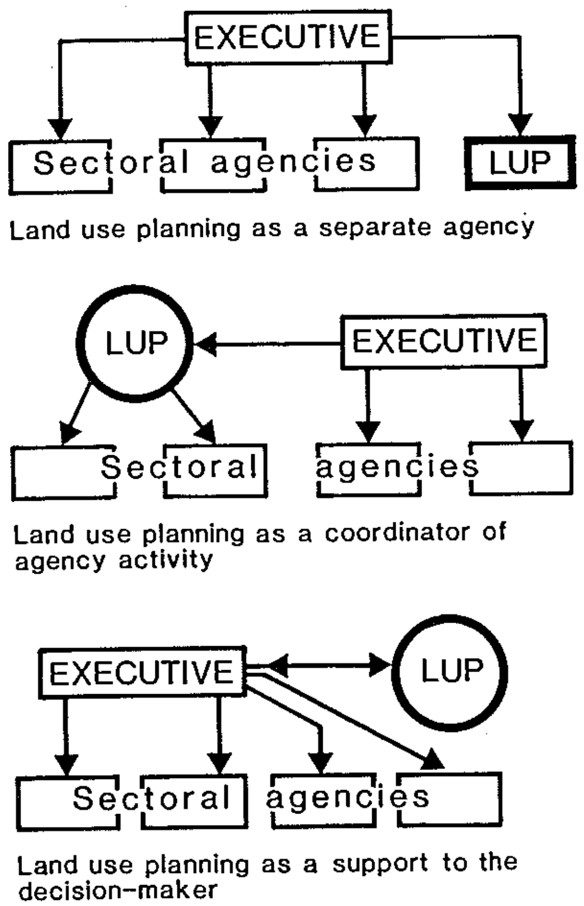


Figure 22 Alternative institutional structures for land use planning

Source: FAO 1989

projects are integrated into national or regional policy progammes which are, in turn, usually sectorally oriented. Few irrigation projects are embedded in 'integrated regional plans', eg. watershed management programmes. Experiences with integrated regional projects have not always been favourable, due to a lack of coordination and cooperation, and disputes over responsibilities at regional levels. The guidelines outlined eg by ILRI and FAO should be understood as optimum standards to aim for.

The Land Use Planning Unit may be located in the Ministry of Agriculture, Ministry of Planning, or Ministry of Local Affairs (eg Local Government). Irrigation planning and management may be located in the Ministry of Agriculture, Minisitry of Works, Ministry of Water Affairs, or may even have its own Ministry. Consequently, land use planning has to cut across these administrative hierarchies. Bureaucratic conflicts over responsibilities for coordination of sectoral activities are unavoidable and in most cases they are decided indirectly by sectoral budget allocations. There are only three proven strategies:

- the setting-up of a special **planning area** with its own budget and administration (eg New Valley Development Authority in Egypt; Tennessee Valley Authority in the USA; regional Municipalities in Libya),
- the setting-up of an independant **land use planning unit**, although this is just another sectoral body which competes with other departments
- direct support to the executive by a (steering) **committee** which should make recommendations on priorities, the allocation of resources, and the establishment, approval, and coordination of land development plans. These committees may be established on a national and regional level. It remains debatable whether such a body merely have coordinating functions at the administrative level or if it should be active at the technical level. Some experiences have shown that the involvement of technical staff is crucial (often allocated by the Ministry of Agriculture's Division of Planning), but steering committees should consist of technicians and administrators from various other sectoral agencies (see Fig. 3-5).

Main References: FAO 1989; van Staveren/van Dusseldorp ed. (ILRI) 1983; Mann (BMZ) 1982

Further reading: Rydzewski ed. 1987; Easter et al. 1986; Helweg 1985; Carruthers/Clark 1981; Jurriens/Bos in: ILRI 1980; FAO (SB) 1985; FAO (CG) 1986; FAO (CG) 1977

3.1.5 Ecological Criteria for Land Use Planning

Irrigation contributes to the destruction of **natural** ecosystems and to stress disturbances of individual beings (see Part I section 4). Environmental management aims to limit these negative impacts as far as possible (see section 1.1). The following section as an introduction to environmental quality assessment in the course of land use planning for agricultural development.

The following is a description of terms in landscapes and ecosystems

A landscape segment is typically composed of patches that are discontinuous in some physical and biological characterstics. A topographical variation, for example, through its effect on air, insolation, and water flow, can induce differences in soils, moisture conditions, and compositions of flora and fauna. These patches may be observed by using soil, vegetation and associated fauna, landform, or other static attributes as indicators. These distinguishing characteristics can be used in land use planning to assess the effect of human actions on landscape patches. Observations of such attributes take place in a framework which is discrete in time and space, ie processes of changes occur in a continual or episodic continuum. Atributes of landscape segments or ecosystems can serve as indicators of response to purposeful development or as indicators of vulnerability to impact.

For example, soils can be used as indicators of agricultural capability or as an indicator of vulnerability to the soil erosion process. Vegetation can be used as an indicator for a wide range of landscape conditions and biomass production capabilities.

Source: Westman 1985

Fig. 3-6

Mapping Landscape Characteristics 247

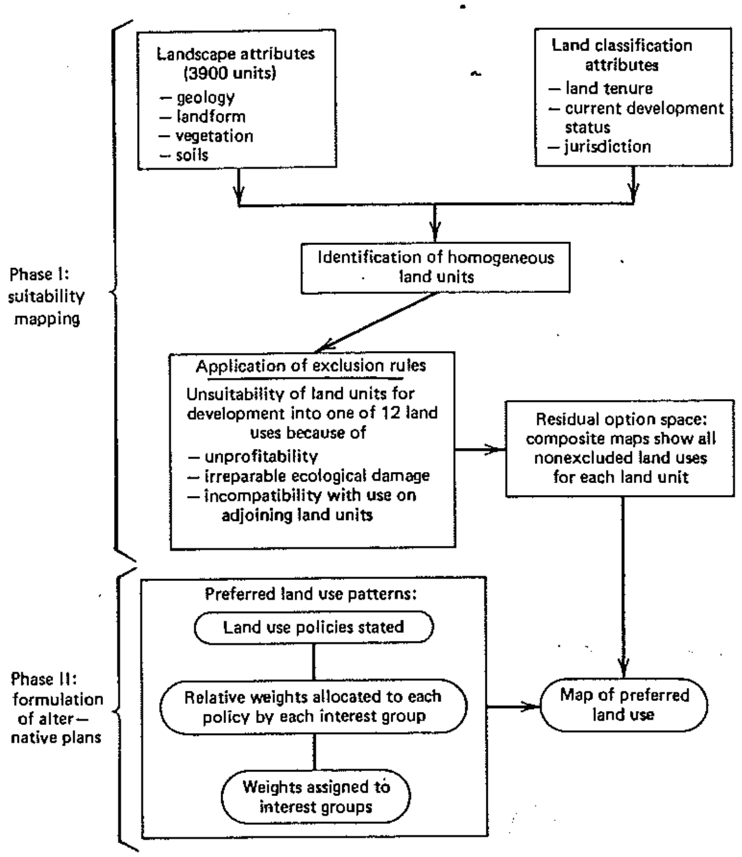


Figure 6.19. Steps in the CSIRO approach to land use planning (SIRO-PLAN), as applied to the south coast of New South Wales, Australia (from information in Austin and Cocks 1978).

Source: Westman 1985

Planning for irrigation development involves balancing the competition between irrigated agriculture other types of human land use. Land uses which are usually incompatible, include:

1) land uses for production or collection of human food or materials
   - crop production, eg rainfed farming, irrigation
   - rangeland
   - forestry
   - fishery
2) urbanisation including industries and transport and communication lines
3) recreation
4) mining of minerals
5) conservation: strictly reserved for non-human landscapes or ecosystems, although a transition to other land uses (rangeland, forstry and fisheries) may be possible. For example, protected areas under international or national legislation are: Wetlands under the Ramsar Convention, World Heritage Reserves, Biosphere Reserves, National Parks. Further categories are developed by IUCN (Lucas (IUCN) 1992; IUCN 1990, IUNC 1986, IUCN 1985).
6) residue assimilations: deposits of waste generated by human activities.

Evaluating alternative land uses by environmental modelling

Geographic information systems (GIS) are often used for land use assessments. The systems usually include economic, ecological, social and socio-cultural criteria which are linked into a process of scenario generation. Final plans must always be a compromise between conflicting criteria. For example, following the METLAND model (cit. in Westman 1985, chapter 6)

step I: choose land use options with the lowest development cost and greatest economic benefit; for example, options may be on several levels and include:

1. level: cropland or other land uses; if cropland, then:
2. level: irrigation - rainfed; if irrigation, then:
3. level: type of irrigation system, organization, cropping pattern, etc.

step II: various irrigation options are screened for ecological compatibility and economic feasibility (other critieria may be related to social impact analysis)

step III: alternative scenarios are evaluated by their potential for achieving three distinct community goals: landscape value, ecological compatibility, provision of goods and services.

Boundary conditions may be fixed by existing zoning, master plan restrictions or community group priorities (on various levels from national to village community). Explicit planning goals are usually pre-set in a more or less rigid manner so that the choice of a preferred scenario must occur with reference to explicit planning goals which include ecological, economic, and social goals, leaving the final choice to policy and decision makers.

Another land use planning model by CSIRO (CSIRO-PLAN or LUPLAN in: Westman 1985 Chapter 6) first uses ecological and economic criteria to reduce a range of possibilities to a smaller number of options. Subsequently, policy goals are used to select a single option by linear optimisation (Fig. 3-6).

Note: Further modelling approaches especially for water resources are given in Onta et al (1991), Harboe et al. (1990) and Biswas et al. (ed.) 1990)

Limitations in environmental modelling

Despite the potential for automatization of the entire process of scenario generation for land use planning, various limitations apply to all such planning models:

Typically, the data necessary to run such models are rarely available especially in developing countries, so that much 'soft' information is put into the data base. Due to further limitations on the accuracy of much hard or soft data, the resulting output is without strict bands of confidence. Furthermore, most data is compounded with other data on ordinal scales and then summed or combined nonlinearly. None of these mathematical operations are based on empirical relationships or they can be validated by empirical data. The evaluation of various parameters or results in monetary terms involves general assumptions, especially in relation to nonmarketed goods, which remain implicit in the valuation procedure of such models.

Hence, their use for rapid assessments for small projects with limited funds, time and impacts may be questionable, but various logical sequences (of palnning and decision making) analysis can be used in land use or water resources assessments and in environmental impact assessments (EIA) for small or medium scale irrigation projects.

Various types of suitability- judgements are possible for each landscape attribute:

- the **value** of the attributes as a resource for human use, such as source of water, minerals, land for agriculture, housing, or other essential human uses, source for recreational value, genetic resource for future development options, etc.,
- degree of **hazard**: air pollution, noise, water pollution, soil contamination, flooding, etc.,
- **suitability** for development, eg agriculture, housing, recreational activities.

The ecological compatibility of land segments/ecosystems can be assessed as follows:

- calculation of the existing biomass and the production/respiration ratio as strict criterion of ecological **productivity**,
- calculation of the biological **potential** based on soil capability, forest resources and solar radiation input; this yields the forest and crop potential indices which gives the combined **biological index**. In combination with the soil denudation potential (derived from soil erodibility, runoff potential, slopes), the **substrate profile index** is derived,
- the ecological **compatibility index** is derived from the substrate profile index and the ecological productivity.

Source: METLAND model in: Westman 1985

Aesthetic criteria may be applied in addition to economic and environmental criteria in evaluating the effects of development on a landscape resource. There have been various attempts at assessing the visual or scenic qualities of a landscape. Some mehtods idetify universally valued landscape elements (mountains, waterfalls, lakes, etc) or design elements (color, line, contrast, texture, for example a unique riparian forest within an open bushland savanna), while in others the process of evaluation is totally subjective, for example by examining public opinion on specific properties, using interviews with concerned or affected people. Also a mix of intrinsic beauty and individually pleasurable responses may be applicable.

Carrying capacity approaches are often used to evaluate a proposed project in relation to ecological goals. A true ecosystem carrying capacity derives from the interaction of soil/land, air, water and species elements in space and time. The capacity is defined as the ability of the natural ecosystem to support such levels of use (eg agriculture, irrigation) without adverse ecological effects. Subjective judgement is involved regarding what constitutes 'adverse' ecological effects. Environmental, perceptional and institutional as-

pects are typically all involved to set the carrying capacity of a region. For example, in irrigation development

> rainfall and low river discharge often limit agricultural production (environmental aspects); as the river is dammed and reservoirs are developed, irrigation is introduced. Now, living citizens living near by feel the environment is becoming too unnatural and some natural vegetation is destroyed (perceptional aspects). Eventually, the ability of institutions to raise funds, to supply abundant water to future domestic and irrigation users may eventually be exceeded. This progression has often occurred in many places and institutions are now struggling to find socially acceptable means to increase water supplies.

In fact, no model or concept has yet been developed in which the proposed land use or water development can be evaluated in terms of ecologically acceptable limits without the definition of either **boundary conditions** or policy assumption, eg by defining legal, regulatory or other threshold standards.

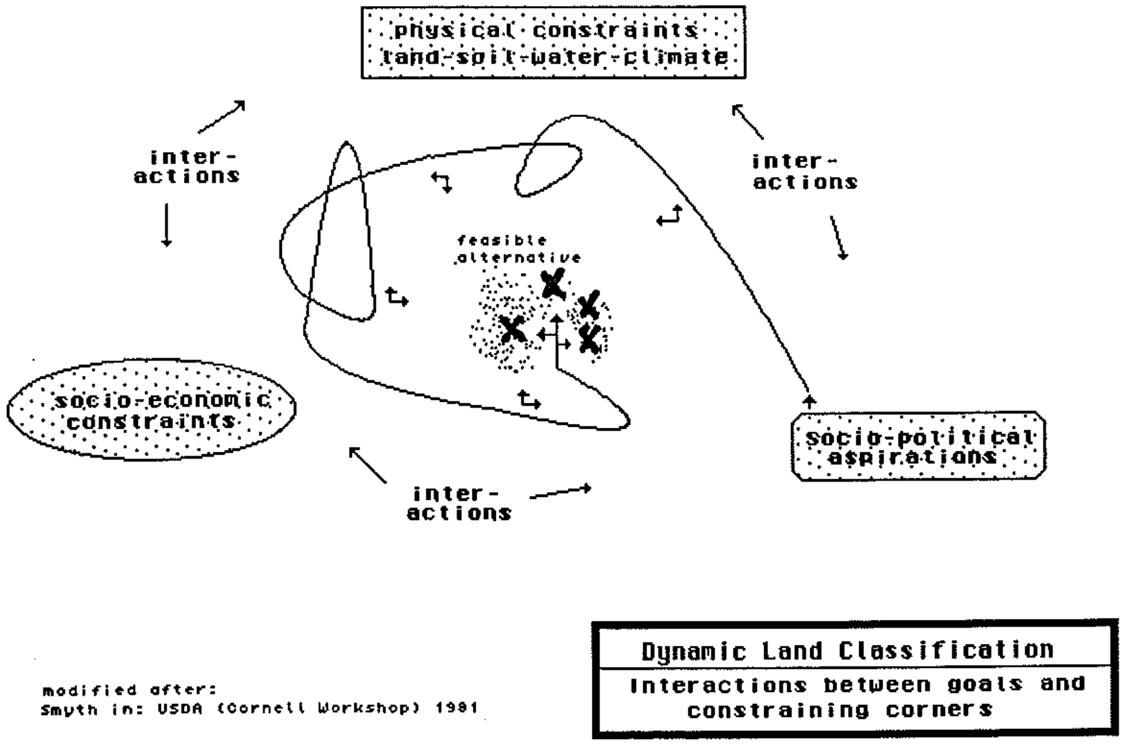
A strict **preservationist** view may assume that any development will exceed the carrying capacity. In any case, the succession and resilience of **ecosystems** and the consequences for specific species (humman, fauna, flora) must be considered when defining the carrying capacity. Also the **user's** point of view must be defined because the optimum use or threshold limits of ecosystems resources (see section 1.1) vary from one user to another. For example, habitat suitability indices (HSI) may be used as indicators for specific wildlife species, but due to niche differentiation in a multispecies community, habitat optima are typically different for a species in a community setting than when it exists in isolation. Consequently, HSI can only be established for individual ecosystems with site-specific parameters. In particular, the use of a single habitat parameter for establishing a limit to the carrying capacity of a particular species - to be used as the **grand index** - has **no basis in ecological theory**.

Another major problem with these approaches to aggregation is that they require extensive **empirical study** before the true nature of the relationship between parameters can be ascertained. It is also unlikely that all these relationships will be cumulative, or all compensatory. In addition, a general suitability index derived from cumulative interrelations with compensatory variables, exceed the current capacity of ecological knowledge. They may be applicable for precisely defined users of natural resources at specific locations, with narrow time scales and specific economic settings. Their general use is, however, questionable.

A more practical approach may be the **disaggregation** of the ecosystem into specific components. By this method, natural functions are identified which are limiting the carrying capacity or which define the limits for potential conflicts over resoruces. Environmental performance standards may be used, for example by stating that irrigation development may be permitted if 10% of the initial river discharge is not exceed. Such performance standards **limit the degree of change** from the initial natural status, which is (for simplification) assumed to represent the natural **carrying** capacity. A given performance standard can be combined with land suitability maps and water resources figures (for streams, groundwater quality/quantity) to indicate for a particular land unit or river section the scale of permissible development which will meet the given environmental performance standard. This is termed impact zoning. The METLAND or CSIRO-PLAN models have built-in user-applied performance standards. Nevertheless, the problem of the spatial interdependence of units remains and the system does not integrate ecosystem elements of soil, water, air and species.

Main reference: Westman 1985, further reading: IUCN 1986, 1992

Fig. 3-7



3.2 Land Suitablity Evaluation for Irrigation

Key Words:

Land evaluation; soil survey; objectives; shortcomings; soil qualities; physical & chemical soil analyses; paddy land considerations; soil suitability systems; land qualities & land characteristics; FAO land evaluation system; land utilization types; step-by-step approach; soil criteria for crops; soil standards; soils and selection of irrigation types; rice land classification; guidelines for soil protection: heavy metals and pesticides.

Cross References:

Part I sections (with regard to soil contamination) 1.2.3; 1.3.4; 1.3.5

Part II sections 3.1; (with regard to soil contamination) 2.1; 2.5; 3.1

Main References:

Landon ed. 1984; FAO (SB 55) 1985; USDA/SMSS 1981;

3.2.1 Land Evaluation Concepts and Procedures

Land evaluation is aimed at assessing the suitability of land for specific uses. It provides information and recommendations for land reclamation measures, agricultural practices and limitations for specific crops. In the process of land use planning it should provide general information on topography, climate, ecosystems, soils, and geology (see section 3.1). Particular data needed for irrigation projects are summarised in a checklist in Table 3-7.

Land evaluation may serve two general purposes:

- short-term planning, eg a suitable area must be selected for a specific irrigation project; the demand may be formulated by government policy (eg in Libya, Saudi Arabia), or by requests from villages or groups of farmers who would like to develop an area for irrigation
- long- or medium-term planning for either new developments in remote rural areas (eg in many semiarid areas), or in densely cultivated areas for purposes of identifying, appraising, and maintaining agricultural development.

The first type of land evaluation is rather specific in terms of goals, procedures and methods. A static approach of land suitability may be applicable in circumstances when the type of future land use is already fixed (eg smallholder irrigation with slightly saline groundwater, or large scale, commercial irrigation using sewage wastewater). Such surveys are also specific in terms of scale, ie very detailed surveys must be conducted.

The opposite applies to land evaluations conducted within the framework of national or regional development planning. Here, attention should focus on how to achieve an aim that is determined largely by human interests. This approach is dynamic; ie feasible land use alternatives (asterix in Fig. 3-7) lie within a 'field' determined by sociopolitical aspirations (desires or objectives of the people, politicians or administrators), socio-economic constraints, and physical constraints (land, climate, soil and water resources). None of the constraining corners are fixed, all can be changed, either by labour or capital. Land evaluation starts by establishing desired objectives which are examined in relation to physical constraints. These can also be changed by inputs that involve a change in socio-economic constraints. Finally, socio-political aspirations may also be modified and adapted.

Sources: Mitchell/King in: Rydzewski ed.1987; Breimer et al. (UNESCO-MAB) 1986; FAO (SB) 1985;

Further reading: Steiner 1983; SCS-USDA 1981; Laban (ILRI 28) 1981; Beek in: ILRI 27, 1980; Beek (ILRI 23) 1978; FAO (SB32) 1976; Maletic/Hutchings in:Hagan et al. 1967

3.2.2 Soil Surveys for Irrigation

Information on soils and the environment of soils (climate, water, fauna/flora) forms a major part in land suitability evaluation. Detailed guidelines on procedures and field and laboratory methods for soil surveys for irrigation have been developed by FAO and others. This section will highlight essential issues and address some critical issues related to soil surveys for irrigation.

Objectives for soil survey investigations for irrigation can be:

- indicating favourable **locations** for irrigation
- indicating susceptibility to soil **physical** deterioration,
- indicating susceptibility to **salinity** and **chemical** degradation,
- indicating soil susceptibility to **erosion** (wind- or water-induced),
- indicating needs for special erosion, salinity and sodicity **control** measures,
- indicating needs for **land development** (levelling, subsoiling, soil amendments),
- indicating measures to maintain soil **fertility** for sustainable cropping (eg fertilising),
- indicating soil **engineering** properties (drainage, structures, field lay-out etc),
- indicating soil constraints to **irrigation** (eg to specific irrigation systems; location of structures etc),
- indicating the best **agricultural** and **water management** practices.

Special features of soil surveys for irrigation are related to an assessment of the main **constraints** for irrigation and the expected **future changes** in soil properties under irrigation. This includes evaluations of future topography conditions after land development, alteration in physical (including waterlogging) and chemical processes (including salinity), alteration of microclimate and microbiological processes. Emphasis should be placed on

- **surface** properties, especially for surface irrigation, eg stoniness, microtopography
- properties related to the dynamics of **soil-water relations**, eg infiltration and moisture holding capacity, type of clay minerals, stratification, internal drainage (permeability) of topsoil and substratum; land drainage
- surveys for paddy rice cultivation requires special attention on physical properties related to the capactity of the soil to retain water on the surface.

Shortcomings in soil surveys may arise with

- inadequate soil survey intensity (see Tables 3-8 a-b) in areas with irregular soil pattern and in areas with problems in salinity/sodicity or potential waterlogging
- inadequate recognition of changes that will result in land drainage conditions
- sampling to inadequate depth (usually 1.2m is required, selected profiles down to 2.0m)
- inadequate attention to specific soil characteristics relevant for the specific type of irrigation and the intented agronomic development
- failure to interprete soil data in terms easily usable by system planners
- inadequate attention to cumulative effects of soil limitations (or soil plus other land limitations, or soil limitations in relation to anticipated or factual soil and water management practices under irrigation)
- inadequate consideration of efficiency of achievable soil and water management, ie efficiency of land reclamation and avoiding of soil degradation depend largely on the proper use of soil and water management measures; in other words, the potential risk to secondary salinization may be high in a given area. However, good soil and water management can avoid degradation, whereas poor management may lead to degradation even if susceptability is low. Hence, the evaluation must also consider soil management aspects.

Soil data inventory

Investigations and interpretations should be focused on the following soil qualities:

- sufficiency for water	soil texture, structure, depth, stoniness, salinity,
- sufficiency of oxygen	permeability, infiltration, land drainage, groundwater
- provision of good tilth	structure, aggregate stability, consistency,
- sufficiency of nutrients	actual and potential chemical fertility: macro- and trace nutrients; soil reaction,
- ease of water management	landform, slope, microtopography, soil pattern, infiltration, depth to groundwater,
- erosion hazard	soil texture, aggregate stability, slope,
- toxicity levels	salinity, sodicity, nutrient toxicity, toxic chemicals, pH, pathogens.

An inventory of important soil data is presented in Table 3-9.

Details on soil survey investigation methods are available in various handbooks. It is referred to the references which deal with the various field and laboratory procedures and methods of analyses. A summary on physical and chemical routine analyses is shown in Tables 3-10 a-b. Further details may be obtained from:

Landon ed. 1984. Booker Tropical Soil Manual. Longman. UK. (usefull summary)
FAO 1980. Soil and Plant Testing Analysis. Vol.1 and Vol.2. Rome.
McIntyre et al. (CSIRO) 1974. Methods for Analyses of Irrigated Soils. CSIRO. Canbarry. Australia.
Black et al. ed. (ASA) 1964. Methods of Soil Analysis. Vol.1, Vol.2. SSSA, Madison. WI.
Westerman et al. ed. (ASA) 1991: Soil Testing and Plant Analysis. SSSA, Madison. WI.

It is essential to screen out those data which are not immediately required for the land evaluation and to specify those which are later needed for detailed agronomic recommendations (eg fertilisation). Soil surveys are rather expensive, especially if laboratory analyses are involved. On the other side, recommendations and reclamation cost estimates can only be based on reliable data. Constraints for irrigation development should be identified as early as possible to avoid unexpected problems arising during implementation (eg soils unsuitable for unlined canals). From experience it can be concluded that most land development measures are more expensive when subsequently implemented, especially the installation of drainage systems.

The extend of field investigations, laboratory analyses and soil mapping cannot be generalised, ie they depend on size of project, type of irrigation, total investment costs, and local circumstances.

Special considerations for paddy lands

Ideal wet rice lands have several characteristics which differ from other upland irrigated crops. These are mainly caused by the intention to retain water on the soil surface. There are several physical soil properties, hydrological conditions, chemical characteristics, and operational needs which should be emphasized or de-emphasized in classifiying rice lands:

- land qualities slope, break in slope and contour, erosion, drainage,
- physical properties: hydromorphic qualtities, texture, permeability, water table, compactability, aggregate stability, conversion potential, soil depth,

Fig. 3-8-1

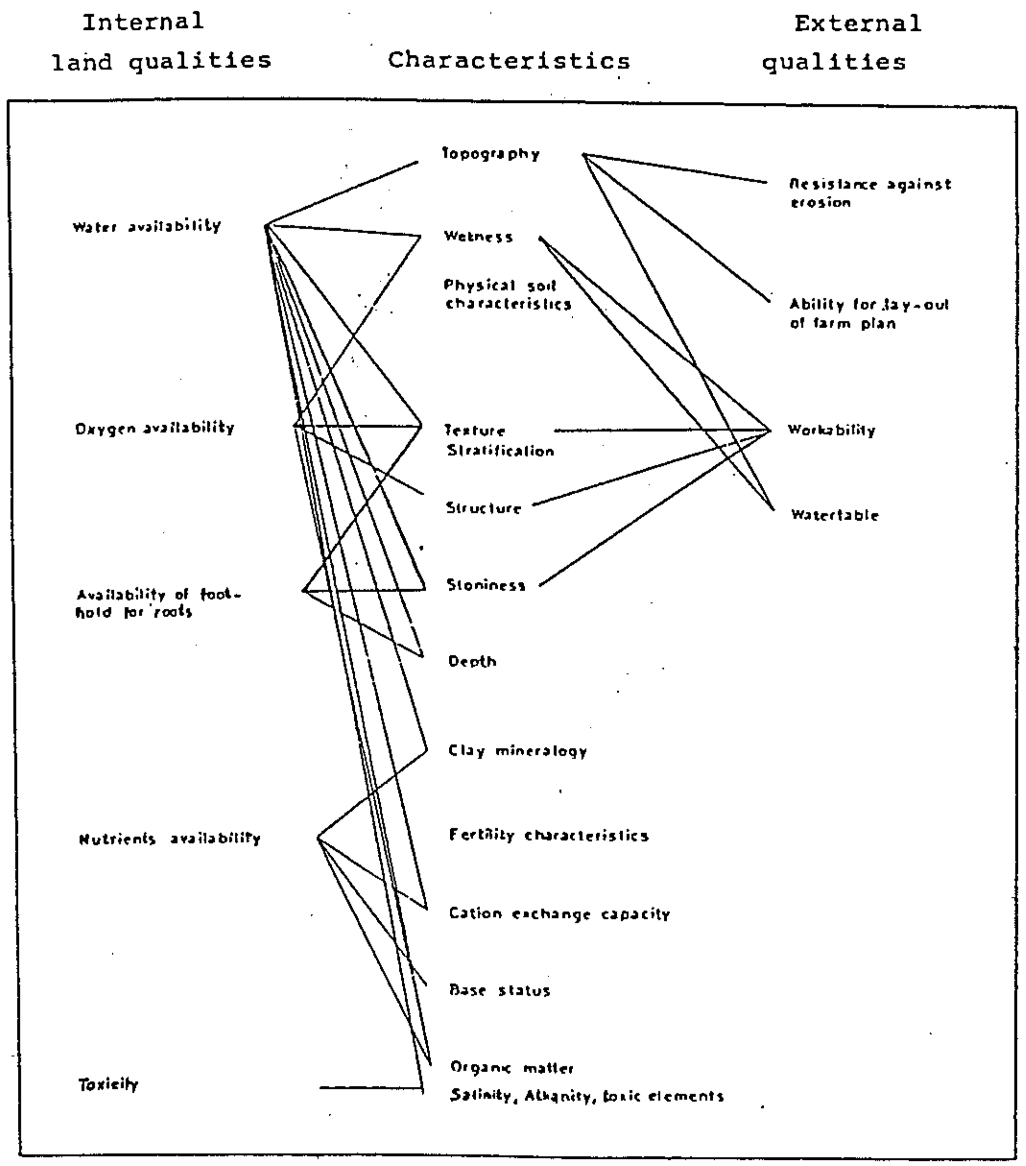


Fig. 9: Relation between Land/Soil Characteristics and Land Qualities (modified after Sys, 1978) ; Petermann

- hydrological condition: regarding natural conditions of an area: depletion neutral, overland enriched, groundwater enriched, seepage enriched, upwelling enriched, moderately flooded, deeply flooded; regarding irrigation: distance from the source, landscape inversions; induced upwelling,
- chemical properties: oxidation/reduction, soil reaction, salinity, sodicity, organic matter, organic soils, potential and actual fertility level, micronutrients, presence of toxic elements; further details are shown in Table 3-11.

Further reading: Landon ed. 1984; FAO (SB 42) 1979; Western 1978; Young 1976; McIntyre et al.. 1973
Rice soils: Tinsley in: USDA-SMSS (Cornell Workshop) 1981; Moormann/ van Breemen (IRRI) 1978

3.2.3 Soil Suitability Classification for Irrigation

Land evaluation for irrigated crops relies on predictions of future soil conditions. Therefore, the determination of pertinent characteristics is important to identfy the limiting properties for crop production. The changeable characteristics are determined to identify the need for reclamation and land development, based on technical, economic and managerial feasibility under given conditions. In addition, requirements and limitations are different for various crops, irrigation and cultivation practices. The soil suitability systems should meet the following requirements:

- applicable to the prospected management level,
- applicable to specific irrigation types and practices,
- specific to the crops, fruit trees, fodder crops to be cultivated.

On the other hand, the soil suitability classification should provide recommendations regarding (i) the type of irrigation and (ii) suitable crops.

Soil suitability classification systems

There are various qualitative, quantitative and economic classification systems developed for specific purposes. They are already well documented and some of them are mentioned in this section. There are parametric methods which assess the agronomic potential of soils for a specified land use and limitation threshold methods which define minimum criteria for important soil characteristics.

The physical land suitability may be expressed in terms of 'land characteristics' and 'land qualitites':

- **land qualitites** are for example, root penetrability, nutrient toxicity, nutrient availability and -fixation, nutrient reserves; water availability, wind erosion susceptibility, trafficability, workability, access,
- land **characteristica** are for example: salinity degree, profile depth to substratum, permeability rate, infiltration rate, pH.

A parametric system was established by Blume/Petermann 1979 for land evaluations in Libya and Egypt. Firstly, numerical valuations are used to separate soils and land characteristics (see Fig. 3.8/1) according to their relative significance. Subsequently, these valuations are combined to produce an overall index of suitability and to rank soils in order of their value for irrigation. Each rank is attributed to a suitability class. Subclasses are used to specify the most important limiting factors as:

w -limited water availability (water retention characteristics, effective profile depth)
o - limited oxygen availability (pore size characteristics, permeability, profile depth)
n -nutrient availability (nutrient reserves of N, P, K, B; total exchange capacity, pH)

t - toxicity (high salinity, boron, sodicity, high or low pH, Cl, $CaSO_4$, $CaCO_3$)
e - erodibility (texture, aggregate stability, slope)
a - in-field trafficability and accessibility
c - resistance to compaction
v - high level of vegetation removal required
l - high level of land grading and levelling irequired
i - drainage system required to avoid wetness

However, this parametric method is only semi-quantitative at best, because the rating of soil and land properties is usually not empirically derived from field trials or yield estimates. usually, only few observations (eg salinity to yield level) or generalised conclusions on soil characteristics for optimum growth are used for ranking (Remark: the same applies to the FAO Land Evaluation System).

The USBR-method designates six classes. The classes are essentially defined by limiting factors by establishing threshold values for important soil properties. Three systems for different land utilization types are shown in Tables 3-12 a-c:

* classification for smallholder irrigation schemes with a combination of sprinkler and basin irrigation systems and a mixed cropping system: grains, fodder, vegetables, fruit trees (desert climate; Libya, Egypt),
* classification for large scale center pivot production schemes, crops: wheat, beans (desert climate, Libya),
* classification for paddy rice cultivation; smallholder system, individual farmers (semi-arid climate, Ivory Coast).

Further systems are shown in FAO (SB 42) 1979 and FAO (SB 55) 1985.

Another classification system describes the 'actually limiting' and the 'development potential' characteristics of soils for a specific use. The classes may be defined qualitatively or may be quantified following the principles outlined before. The development potential considers reclamation- and operation costs (eg drainage maintenance, fertilisation) in relation to specific crop requirements. This system provides a rapid appraisal of

- actual limitations (salinity, waterlogging, reduced trafficability),
- potential limitations after technically and economically feasible reclamation and land development measures were conducted.

Table 3-13 provides examples for several soil units. Other systems are for example,

USBR classification; examples for special land use types are explained in: FAO (SB) 1979.
General classification for various types of rice cultivation: Sys (1986).
Thailand, FAO classification for paddy rice: Brinkmann (FAO (WSRR) 1978) p.36.
Indonesia: Land limitations for sugarcane production: Thompson (FAO (WSRR) 1978).
Near East: Classification of gypsifereous soils for irrigation: Mousli (FAO (WSRR) 1979.
Sudan: Suitability of Vertisols (clay-soils) for irrigation: vanderKevie 1976 (cit.in: ElTom/Ali in: FAO (WSRR) 1979.
Asia: Classification of land for lowland rice: Early et al. in: FAO (WSRR) 1979.

FAO land evaluation for irrigation

On the basis of previous documents and field experiences the FAO developed procedures for land evaluation for irrigation which are intended as optional guidelines to assist in evaluations of land and water resources (FAO SB 55, 1985). The procedures determine important criteria in a step-by-step approach:

i) deciding the land utilization types (LUT) to evaluate, eg irrigated rice (Table 3-14)

ii) developing land suitability class specifications; class determining factors are selected from following criteria (details see Tables 3-14 and 3-15):
   A) agronomic, eg crop requirements and limitations,
   B) management, eg. water application, tillage, mechanization,
   C) land development and improvements: clearing, flood protections, drainage, grading-levelling, amendments, leaching,
   D) conservation: long-term prevention of salinity-sodicity, long-term groundwater control, erosion hazards, other environmental hazards,
   E) socio-economic: farmers attitude to irrigation; other limitations 'critical limits' of suitability for individual requirements and limitiations are selected for five classes,
iii) field survey and mapping of provisionally-irrigable classes and subclasses
iv) determination and mapping of 'irrigable' land, including economically and financially viable project plans.

An example of rating in five classes is given in Table 3-17 a-b.

Further reading: FAO 1989; FAO (SB 55) 1985: Chapter 3 (Step-by-step guide); see also section 3.1.

The final classes are applied according to economic measures rather than simply on the basis of assessments of physical productivity. The FAO methodology employs the 'farm budget' analyses to confirm that, under current or expected market conditions, there are financial incentives for farmers to participate in a proposed irrigation development programme on a particular area.

Soil criteria for optimum growth of crops

The soil conditions requird for the optimum growth of crops may differ under various climatic conditions, but also differences between crop varieties may be significant. Nevertheless, important soil properties can be assessed by the definition of optimum or ranges of specific soil indicators (eg pH, EC, N-nutrient availability), whereas tillage and water management are responsible for the actual growth conditions on a given site.

* Summaries of available standards are given in Tables 3-18 a-d
* Malaysian standard for tropical crops: Table 3-19 (USDA 1981)
* FAO rating by Sys/Riquier for upland conditions and paddy rice Table 3-20 (Sys/Riquier FAO 1979)
* Growth limitating conditions for rice; Table 3-21 FAO (SB 55) 1985.

Land evaluation for the selection of irrigation methods

Land characteristics affect the application of irrigation systems and in some cases they may be the most limiting factor for the selection of an appropriate irrigation system. Land characteristics also affect the shape and size of fields, water application rates and intervals and the costs of moving pipes around obstacles.

The advantages and limitations of various irrigation methods in relation to land characteristics and other factors are summarised in Tables 3-22 a-b (FAO SB 55. 1985) and 3-22c. Optimum and limiting conditions for the use of sprinkler irrigation are outlined in Table 3-23.

Rice land classification

A specific land classification system for rice cultivation in hilly areas has been developed for rice irrigation in Sri Lanka. The system is based on four land categories, each with various determinants and components (Fig. 3-8/2). The land qualitites in the lowest cate-

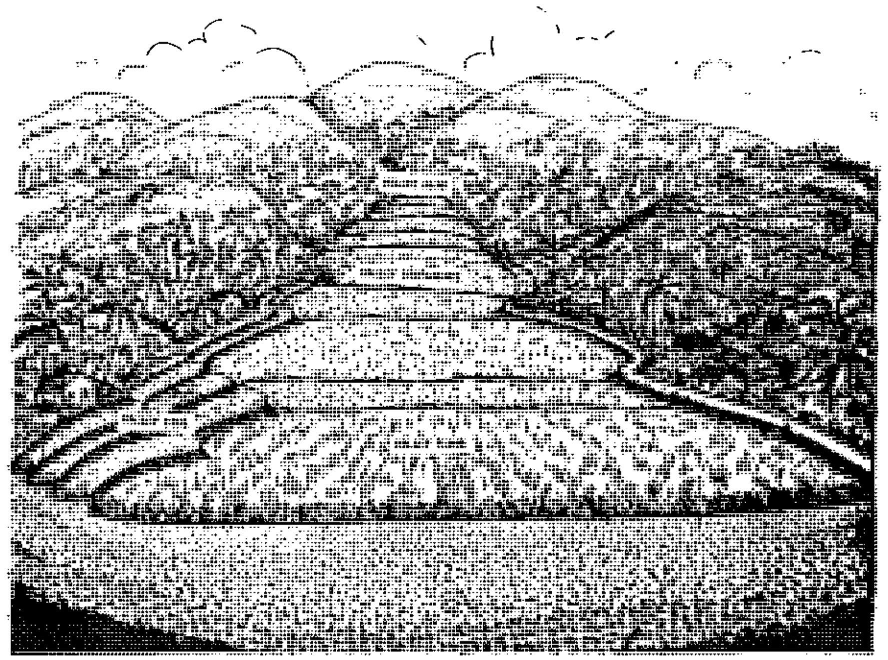


Figure 4. Land elements found in inland valley complexes.

Fig. 3-8/2

Table 1. Rice land classification scheme.

Land Category	Determinants/Components
I. SYSTEMS	Relief, Agro-Climate
II. SUB-SYSTEMS	Hydrology, Micro-relief Paddy/Upland Ratio Upland Soils Parent Material
III. RICE LAND COMPLEX	Individual Tracts —Inland Valleys —Terraced Slopes
IV. RICE LAND ELEMENTS	Inland Valleys —Valley Head —Valley Sides —Valley Bottom with Incised Drain —Valley Bottom without Incised Drain —Confluence Terraced Slopes —Concave Slope —Concave Contour —Straight Slope —Convex Slope —Convex Contour —Ridge Crest

Source: USDA-SMSS 1981

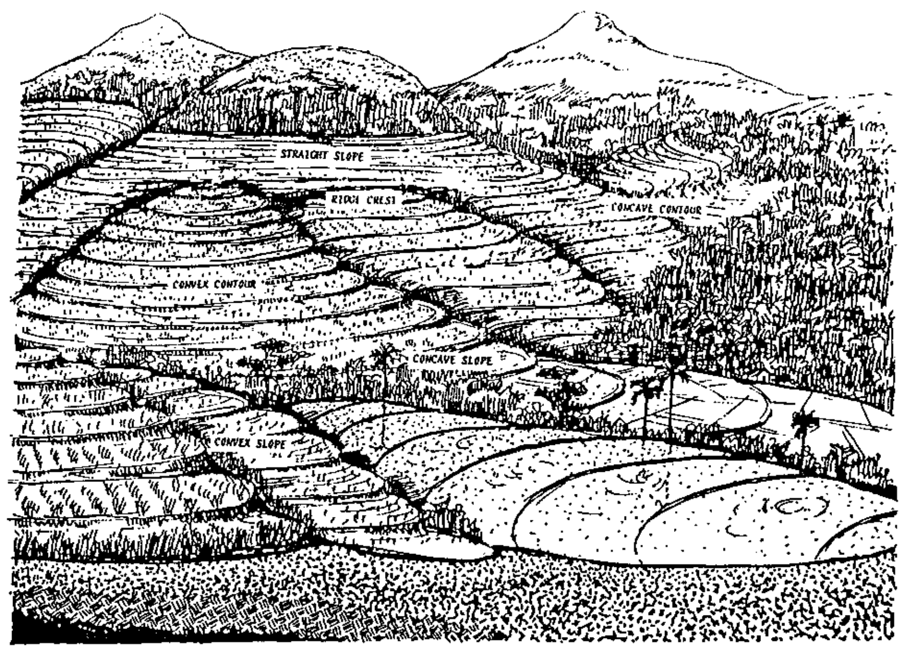


Figure 5. Land elements found in terraced slope complexes.

gory are highly specific and are defined in terms of biological responses and specific management requirements. The system provides guidance to the extension services and assists in improving their understanding of irrigation in terms of potentials, limitations, and variable management needs.

Source: Somarisi et al. in: USDA (Cornell) 1981

3.2.4 Soils as a Filter, Buffer, and Transformer of Pollutants

Soils are capable of immobilising pollutants, ie holding them in a fixed position and thus reducing their harmful off-site effects. The capacity of individual soils, however, differs considerably. This section evaluates the capability of different soils to immobilize heavy metals and pesticides. Tools for rapid assessments of risk potentials are given.

Soil protection with regard to heavy metals

The capability of a soil to retain and immobilise heavy metal ions so that uptake by plants or transport into groundwater or surface waters are minimised can be evaluated by a rapid appraisal method developed by Blume et al. (DVWK 1991; Blume ed. 1992). These guidelines may be used where increased natural metal contents are expected to occur because of special rock and soil conditions, where disposals of wastes or wastewaters are planned for agricultural purposes, where high-quality food stuff or medical plants are to be grown, and in assessing the need for detailed metal analyses.

Dissolved metals are transported in the soil by percolating water. The actual extent of dislocation depends on the filtering capacity of the soil and percolation rates, which must be separately assessed.

I) Data on metal contents frequently occurring in rocks and soils are given in Table 3-24/1

II) Guidance data for metal contents frequently occuring in soils and legal threshold values for sewage sludge are given in Table 3-24/2

III) Metal binding mechanisms, determined by the content of humus, clay and sesquioxides (oxides and hydroxides of Fe, Mn and Al) and applicable to well aerated soils with moderate acid pH, are given in Table 3-24/3. Competition between the various metals can reduce the binding; high salt concentrations are modifiers, too. In alkaline soils (pH >7.5) the mobility of any metal can be increased as a result of the formation of water soluble, metal-organic complexes. Moreover, for negative redox potentials (paddy soils) many metals form poorly soluble sulphides; the solubility of Fe and Mn is especially dependant on the redox potentials.

IV) Evaluation of relative binding strengt|h: The initial binding strength of topsoils (0-30 cm) is mainly a function of pH as shown in Table 3-24/4. Higher humus, clay and sesquioxide contents are modifiers, see Tables 3-24/5 to 7.

V) The danger posed to groundwater pollution should be evaluated by Table (4) and modified by humus, clay and iron oxide contents as shown in Tables 3-24/7 and 8. For strongly swelling/shrinking soils one must account for rapid and non-homogeneous infiltration patterns. The influence of the climatic water balance in groundwater free soils (GW deeper than 0.8 m) is shown in Table 3-24/9. Under irrigation, the balance may often be modified towards classes 1-2. The overall risk of groundwater pollution is shown in Table 3-24/10. It is influenced by the binding strength and the filter length, ie the depth to watertable level.

VI) The environmentally harmful mobility of heavy metal compounds increases with decreasing binding strength of a soil. Table 3-24/11 indicates recommendations for control procedures applicable when waste products are designed to be deposited.

Fig. 3-9

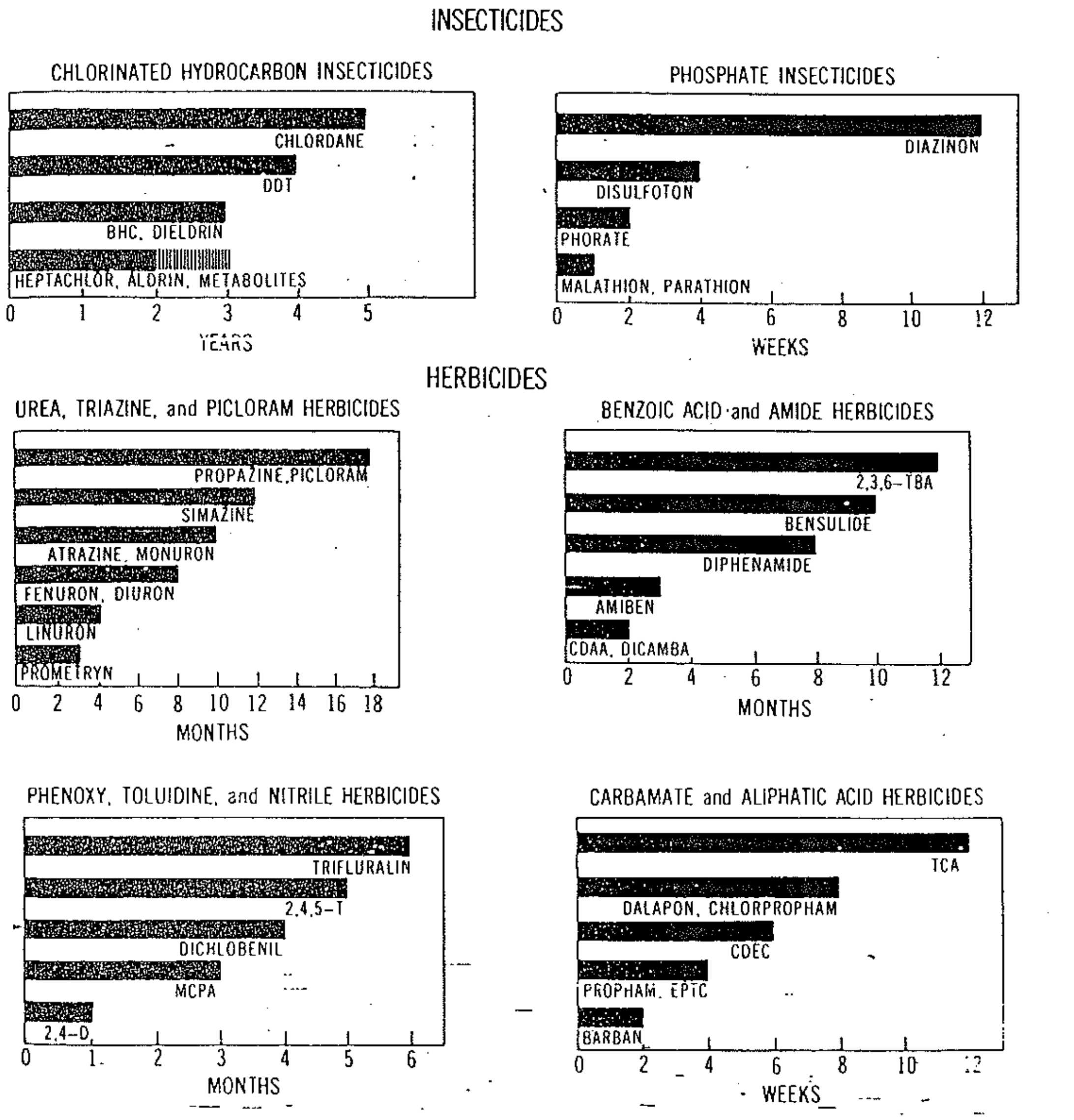


Figure 2 Persistece of certain pesticides in soils. The lengths of the bars represent the time required for loss of 75 to 100% of the biological activity under agricultural conditions with normal rates of application. The values were derived from a review of approximately 80 sources concerned with pesticide persistence in soils (CAST 1985)

Source: Kandiah 1990

VII) Measures to influence the binding strength of a soil include increasing pH of the soil, increasing the organic matter and sesquioxides and/or clay mineral contents, eg liming, addition of organic manures or crop residues, fertilising with ferric oxides and addition of clay materials, respectively.

Source: DVWK 1991

Soil Protection with Regard to Pesticides

Guidelines for a rapid assessment of the behaviour of soils with regard to pesticides have been developed by Blume/Brümmer (in Blume ed. 1990). The fate of pesticides and the efficiency of action on target organisms can only be evaluated in sophisticated trials and by analytical methods. However, for several pesticides important characteristics which determine the behaviour in soils are generally known: solubility, volatility, fixation/binding strength with humus, clay, and sesquioxides at given pH-values, aerobic/anaerobic degradation rates, and mobility (Table 3-25).

Based on soil and climatological data the negative side-effects of pesticides can be evaluated with regard to uptake by plants or animals (non-target organisms) and groundwater contaminations.

* The influence of soil properties on the relative fixation of chemicals is determined by the average humus content and the soil texture of topsoils (0-30 cm) according to Table 3-26/1. The mean pH may be a modifier, depending on pesticide characteristics. These determine the total fixation/relative binding strength; classes vary from 0 to 5.
* The rate of degradation is determined by the temperature and inherent chemical characteristics according to Table 3-26/2 a. Modifiers are waterlogging, high fixation strength and volatilisation as shown in Tables 3-26/2 b-d. The highest obtainable value of degradation rate may be 5.
* The risk of groundwater pollution depends on relative fixation, percolating water, degradation and depth to groundwater level. The transport of pesticides above the groundwater table is assessed from Table 3-26/3, using fixation (from Table 3-26/1), degradation (from Table 3-26/2) and the leaching fraction of irrigation plus rainfall. The given depth to groundwater classes in Table 3-26/4 and the mobility risk from Table 3-26/3 yield the risk class from 1 to 5.
* The overall risk of groundwater pollution, accumulation in soils and uptake by non-target organisms can be evaluated from Table 3-26/5 as being between class 1 and 5.

The **relative mobility** of pesticides in soils can be assessed on the basis of the information given in Table 3-27 (see also Part I sections 2.3 and 3.4). The **persistence** of some common pesticides is shown in Fig. 3-9 (Kandiah ed. (FAO) 1990).

Source: Blume ed. 1992, Further reading: NN 1985; Herzel 1987,

3.3 Control of Soil Salinity and Sodicity

Key Words:
reclamation; mechanical measures; adequate drainage; soil permeability; reclamation leaching; leaching requirements; leaching methods; leaching efficiency; salt balance control; conventional versus minimum leaching; high frequency irrigation; intermittent flooding; dual LR; boron leaching; leaching models; land levelling; grading; tillage & subsoiling; deep subsoiling; cultivation practices/ techniques; broadcasting; mulching; fallowing; manures and fertilisers; crop tolerance; crop selection; cropping patterns; irrigation methods; irrigation mangement; drainage and leaching; re-use of drainage water; sodic soil reclamations; Ca-requirements; amendments

Cross-references:

Part I sections 2.3; 3.1; 3.2;

Part II sections 2.1; 2.4; 2.5; 3.2, 5.1

Main References: Rhoades/Loveday in Stewart et al. ed. (ASA) 1990; Kandiah (FAO) 1990; FAO (SB 39) 1988; van der Molen/van Hoorn in: ILRI 1972; Shaw 1982

3.3.1 Control of Salinity

The long-term environmental viability of irrigation largely depends on mitigating on-farm, off-farm and basinwide (strategic) effects related to soil salinity and drainwater pollution. Most concern is with soil degradation on the farm and water pollution problems in downstream areas, which may eventually be associated with further soil degradation if the water is used for irrigation and impacts on other users.

Solutions to the problem of salinity under irrigation contribute to the efficient and sustainable utilisation of land and water resources. Irrigation economics, however, require the combined analyses of both soil salinity and moisture, since both affect crop growth and yields, and the relationship between these two factors is quite intricate. There may be difficulties in simultaneously controlling soil moisture and salinity as shown below, and various concepts and approaches to control salinity exist. Furthermore, soil and water management should not necessarily aim to control salinity at the lowest possible level, but rather to keep it within acceptable limits for sustainable production. **Crop, soil and water management** practices can be modified to achieve this and to prevent salinisation of irrigated lands.

The conditions that give rise to waterlogging and salinity are **complex** and so are the **means of control**. Principally, there are three reasons and sets of measures for reclaiming and controlling

- reclamation of salt affected soils (initial leaching and soil reclamation),
- regulation of the current salt balance (maintenance leaching),
- controlling the processes which cause salinisation (which may include alkalinisation) by preventive measures: soil management and agronomic measures, controlling irrigation water salinity, modifying irrigation methods and practices, and drainage design, maintenance and operation.

Appropriate measures and management techniques to control salinity are **site specific**. Both require an understanding of the sources of salts, the processes of salt mobilisation and redistribution within the root zone, the farm field, the irrigation command area, and the overall river basin. The predominant salt types and their characterstics are shown in Tables 3-28 and 3-29. Furthermore, the process of desalinisation cannot be treated in isolation and the possible hazards of alkalinisation caused by leaching cannot be ignored. Therefore, soil reclamation and salinity control must be understood as a **comprehensive**

approach to simultaneously control salinity, sodicity, alkalinity, waterlogging and groundwater tables (Kandiah ed. (FAO) 1990). Such an approach must be based on sound **resource evaluations** (monitoring of soil and water) from which **technical options** can be developed to control salinity with regard to water resources planning and agronomic- or water engineering measures. However, sustainable solutions will only be found if socio-economic and institutional potentials and constraints are also identified and if there is adequate allocation of funds (eg for drainage, training of farmers, monitoring systems, etc.), adequate water pricing, production goals, selection of technology, land consolidation, land tenure systems, and training and extension systems (FAO (SB 39) 1988).

Further reading: Kandiah (FAO 1990); Szabolcs 1989; FAO (SB 39) 1989

Initial Reclamation Process

Reclamation of saline soils is usually required

- if excessive salt loads have accumulated in irrigated soils over a longer period, especially under adverse permeability and drainage conditions, or if saline water or sewage effluent is used
- after the installation of a new drainage system or the rehabilitation of existing systems
- for the development of new areas, especially in arid regions where soils often contain a high level of salts.

The soil reclamation measures comprise **mechanical** methods, **chemical** amendments and **irrigation** well in excess of evapo(transpi)ration requirements. Mechanical methods are

- **removal** of salt crusts by hand or machines, which is suitable for soils with hard, compacted salt layers at the surface. The efficiency can be increased, if the soil is watered some time before removal of the crusts. Salts in deeper soil horizons may migrate and further concentrate at the surface upon drying, thus leaving the topsoil horizons less saline after reclamation
- **subsoiling** to destroy any compacted subsurface layers which impede drainage. This is suitable for large scale development schemes but requires technical and managerial skills for successful operation
- **ploughing** and **turning** to lift any compacted salt layer and subsequent removal or further destruction.

Chemical amendments are applied to enhance the process of leaching by creating or supporting a favourable, ie aggregated, soil structure which facilitates the rapid downward movement of water and salts out of the main root zone.

The removal of salts by crop harvesting is not an efficient method from removing salts from the soil. Crops usually remove less than 5% of the amount of salts present in the root zone and less than the amount which is usually supplied by the irrigation water (Hoffman 1980).

Reclamation leaching usually means the application of large water quantities in excess of potential evapotranspiration so that the excess water drains through the root zone (see section 2.4). Salt removal takes place as

- convective flow under high-velocity flow conditions in permeable soils, or
- convective and diffusion under moderate to low-velocity flow in less permeable soils and well structured or cracking soils, usually with a clayey texture.

Adequate **drainage** and favourable **soil permeability** properties are required, otherwise the process may worsen the situation. The amount of leaching water required and permissible depends on the following factors:

Fig. 3-10 a

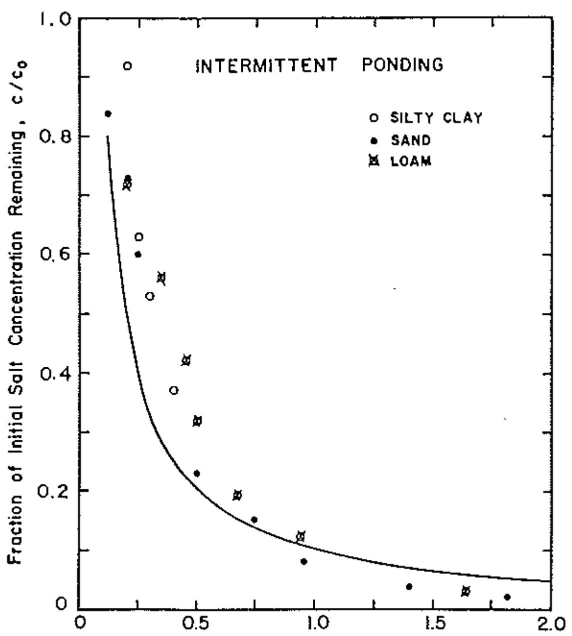


Fig. 36-13. Depth of leaching water per unit depth of soil required to reclaim a saline soil by ponding water intermittently. After Hoffman (1980).

Fig. 3-10 b

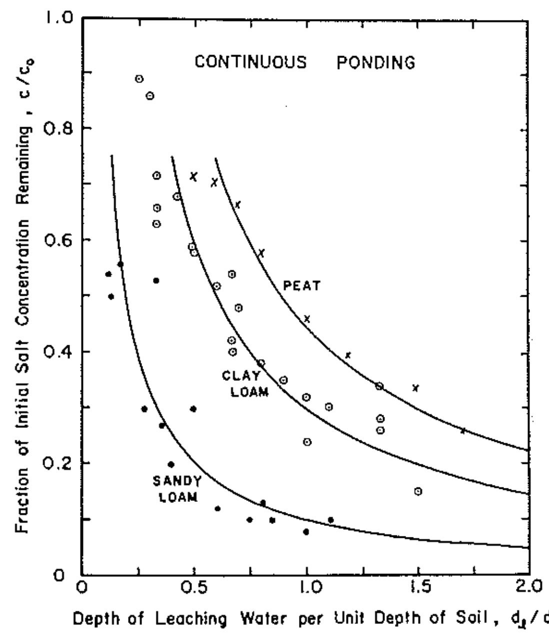


Fig. 36-12. Depth of leaching water per unit depth of soil required to reclaim a saline soil by continuous ponding. After Hoffman (1980).

Fig. 3-11 a

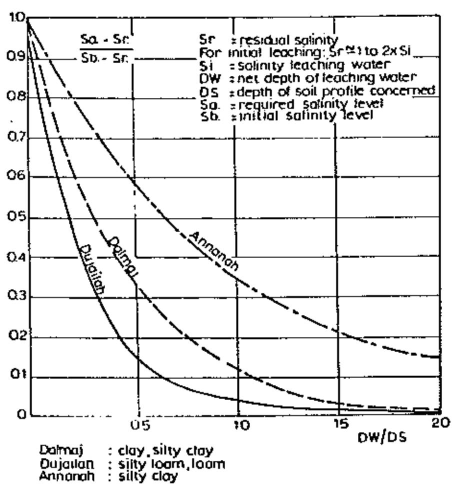


Fig. 5.3/1. Leaching curves of soils in Iraq

5.3.2 Reclamation of saline soil and leaching curve

In the event that the soil is too saline for cropping, de-salinization has to be carried out prior to cultivation. This operation is called pre-leaching or initial leaching. The depth of water required for pre-leaching depends on the depth and degree of de-salinization desired, the leaching characteristics of the soil and the salt content of the leaching water.

The leaching curve (Fig. 5.3/1) shows the relationship between the reduction of soil salinity and the depth of leaching water per unit of soil depth. The shape of the leaching curve is related to soil texture and soil profile. Leaching curves for different soils, given in Fig. 5.3/1, can be expressed mathematically as:

$$DW/DS = -C \log (S_a - S_r)/(S_b - S_r)$$

where
C=2·2 Annanah curve
C=1·1 Dalmaj curve
C=0·67 Dujailah curve.

For initial leaching S_r is about one to two times the salt content of the leaching water.

The S values refer to the salt content or EC values of the soil moisture at field capacity. These values can be related to salt content, the EC of the saturation extract or any other soil-water extract by using the proper conversion factor. For EC values of the saturation extract (EC_e) the factor 2 may be used:

$$S_b \simeq 2 \times (EC_e)b$$
$$S_a \simeq 2 \times (EC_e)a$$
$$S_r \simeq 2 \times (EC_e)r \simeq 1 \text{ to } 2 \times (EC)_i$$

The leaching curve or formula makes it possible to estimate the depth of leaching water required to bring down the salinity to the wanted level. For instance to reduce ($S_b - S_r$) to half its value a soil depth of 60 cm requires:

40 cm depth of leaching water for the Annanah soil
20 cm depth of leaching water for the Dalmaj soil
12 cm depth of leaching water for the Dujailah soil.

A rough guide for the pre-leaching requirement can be summed up as follows: X cm of water is needed to leach a soil depth of x cm.

Source: ILACO 1981

- initial level of salinity in the soil profile,
- final level of desired salinity within the root zone
- depth of soil profile to be desalinisated
- salinity level of irrigation water
- infiltration and permeability characteristics which affect the application rate
- drainage characteristics whcih affects the total water volume to be applied
- possible problems of sodification (high Na-concentation) or alkalinization (high pH) which affect the level of desalinisation possible
- method of water application.

The **reclamation leaching requirement** (RLR) can be ascertained by several methods:

- measurement of leaching effects in representative field **trials** after application of variable depths of water, and using the irrigation methods and application rates available under specific local conditions. This method will provide the best results, although it is time consuming, and it requires trained personnel and scientific supervision and expertise (eg from an agricultural research station),
- applications of a **any** given depth of water and direct measurement of desalinisation in **field trials**. This method is time consuming if properly conducted and requires careful monitoring of salinity. In practice, this is the least reliable method if conducted without field tests. When over-irrigation may occur, this method is probably the most common method of desalinisation.
- estimation of RLR by empirical **formula**, derived from research or field trials elsewhere. Numerous dynamic water-solution flux models conducted are now available, based on transport theory. However, most of them still suffer from the fact that they cannot quantitatively integrate and mathematically describe all the processes (pore bypass, dissolution, diffusion, hydrodynamic dispersion) which operate during the leaching process under heterogeneous and large scale field conditions (Bresler et al.1982; Shainberg et al. 1984). In an ideal porous matrix system (eg in many sandy soils) soil salinity should decrease in proportion to the concentration of applied water when the volume of water equals the pore space of the soil volume to be leached (ie equivalent to one pore volume, PV), assuming no dissolution of previously precipitated salts. Any leaching water in excess of one PV is required to replenish moisture in dry soils and to remove salts from the root zone. Total salt removal can be described by:

  (C/Co)(dw/ds@) = 0.8 ,where C = salt concentration of effluent, Co = initial salt content of soil water, dw and ds are depth of water applied and soil respectively, and @ is the soil volumetric water content. The term dw/ds@ is equal to the pore volume of leaching water applied. About 60 and 80% total salt removal occured with applications of 2 and 4 PV equivalents of leaching water, respectively, in sandy loam to clay loam soils (after Jury et al in: Shainberg/Shalhevet ed. 1984; Jury 1979),

  other experiments (Hoffman 1980) fit the relation

  (C/Co)(dl/ds) = k ,where C/Co is the fraction of the initial salt concentration remaining in the soil profile after application of the amount of water per unit depth of soil, dl/ds. The constant k varies with soil type and method of application. Representative values are: peat (0.45), clay loam (0.3), sandy loam (0.1); with continuous ponding k becomes equal to 0.3. Intermittent flooding may reduce k by about 30%; k may approach 0.1 with intermittent ponding or sprinkler irrigation (see Fig. 3-10 a-c). The irrigation water salinity (Ci) can be considered by substituting (C-Ci)/(Co-Ci) for C/Co

  A semi-empirical method to calculate the reclamation leaching demand, based on field experiments in Iraq, is given in Fig. 3-11 as a rough guide.

Fig. 3-11 b

5.3.5 Salinity control, salt balance and leaching requirements

Salinity control means that the renewed accumulation of salts must be removed through leaching. This requires the presence of adequate permanent subsurface drainage facilities; and in the second place this requires a regular supply of leaching water over and above the minimum crop water requirement. The minimum required monthly or yearly depth of leaching water for salinity control is called the leaching requirement (*LR*). *LR* is often expressed as a percentage of the monthly or yearly irrigation supply.

The leaching requirement can be derived from analysing the salt balance of the root zone resulting in:

$$LR = \frac{100\,D_d}{D_i} = \frac{100\,S_i}{f\,S_d-(1-f)S_i} \simeq \frac{100\,EC_i}{2f\cdot EC_e-(1-f)\,EC_i}$$

where
D_i = depth of irrigation supply over the period considered;
D_d = net depth of drainage from the root zone equal to the depth of leaching, over the same period;
S_i = salt content of irrigation water;
S_d = permissible salt content of the soil moisture at field capacity (equivalent to drainage water);
f = efficiency coefficient=effective fraction of the leaching water;
$1-f$ = ineffective fraction of leaching water (passage through holes and cracks etc);
EC_i = EC of irrigation water;
EC_e = permissible soil salinity in terms of EC saturation extract;
EC_d = permissible EC of soil moisture at field capacity. $EC_d \simeq 2EC_e$.

5.3.6 Application and interpretation of the salt balance and LR relationship

5.3.6.1 Leaching efficiency

The leaching efficiency is related to soil texture and structure and the method of water application. Tentatively the following values can be applied:

sandy soils (sand, loamy sand)	0·8–1·0
loam and silt loam soils	0·6–0·8
clay loam and clay soils	0·3–0·6

The lower the values for gravity irrigation the higher the values for sprinkling or leaching by rain.

Source: ILACO 1981

Fig. 3-12

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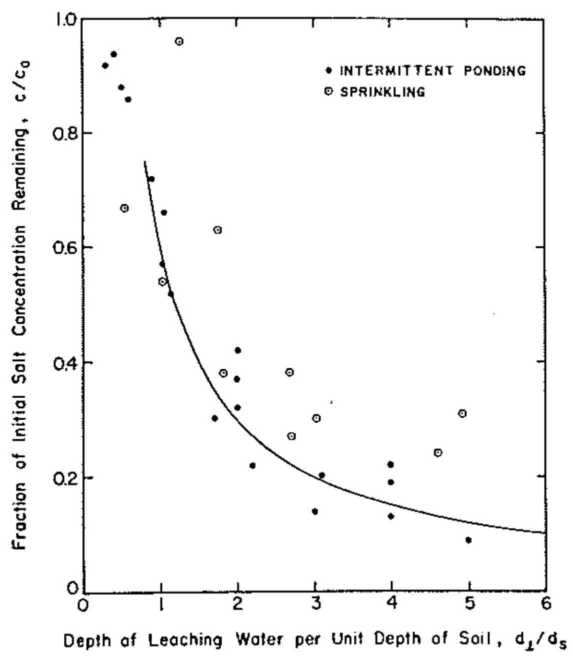


Fig. 36-14. Depth of leaching water per unit depth of soil required to reclaim a soil inherently high in B. After Hoffman (1980).

Source: Stewart ed. 1990

- as a general guide, it may be assumed that about 70% of the initial salts (eg easily soluble NaCl) will be removed by continuous ponded leaching of loamy soils. In terms of total pore volume PV, about 1.5 PV of water must pass through the soil (Hoffman 1980; 1984),
- leaching of **boron** salts requires higher application rates because boron is adsorbed by the soil matrix. Field studies showed that k is equal to about 0.6 and is less dependent on the method of application (see Fig. 3-12). In addition, periodic leaching may be required to remove additional boron released from mineral weathering or dissolution.

The leaching methods for reclamation purposes are essentially the same as for maintenance leaching (see also section 2.4). In impermeable, highly saline soils, however, **surface** leaching may be applicable, too. This involves five processes:

- irrigation at low application rates for moistening the root zone,
- leaving the area dry until most salts have accumulated in the topsoil through evaporation,
- flooding (ponding) the area (eg in basins),
- puddling of the soil to dissolve the bulk of salts in the standing water,
- immediate draining of the stagnant water by surface run-off (temporary open ditches).

Leaching efficiency may be increased by reducing the soil water content maintained during leaching because unsaturated flow conditions reduce large pore bypass (see below). This applies especially for ponding or continuous flooding leaching methods. Thus, cropping (eg with green manure) during or between leachings may be expected to enhance the efficiency of salt removal.

Because of their highly variable water and solute transport properties which result from the structural pore space (interpedal voids, planar voids, channels) which provide preferred pathways for flow, the leaching efficiency of well structured, cracking soils is less than in non-cohesive soils (eg sands). Hence, many parts of the soil material have limited or no contact with the percolating water even during saturated leaching (eg ponding). Intermittent flooding with smaller quantities of water allows diffusion processes to transport salt from relatively immobile to mobile regions so that less salt is bypassed. Best leaching results may be obtained by sprinkler and drip irrigation methods and application rates which result in low-velocity flow conditions.

Source: Rhoades/Loveday in: Stewart et al. ed. (ASA) 1990.

Leaching Requirement for Controlling the Salt Balance

Permanent agriculture under conditions of insufficient rainfall inevitably depends on water management so that excessive salts do not accumulate in the root zone. The removal of salts from the root zone to maintain the soil solution at a salinity level tolerated by the cropping system is referred to as maintainingthe salt balance. The fraction of infiltration water (rainfall, irrigation, surface inflow) that passes through the root zone is called the leaching fraction (LF), ie Ddw/Diw are the depths of drainage water and of irrigation/rainfall, respectively.

The LF can be estimated for steady-state conditions from the equation ECiw/ECdw, where ECiw and ECdw are, respectively, the electrical conductivities of the irrigation and drainage waters. A **general salt water balance** can be obtained by various inputs and outputs of salt to the soil water salinity (Ssw) in the rootzone. The resultant change in soil-water salinity is given by:

$$ViwCiw + VgwCgw + Sm + Sf - VdwCdw - Sp - Sc = d\,Ssw$$

Fig. 3-13

SALINITY IN IRRIGATED AGRICULTURE 1109

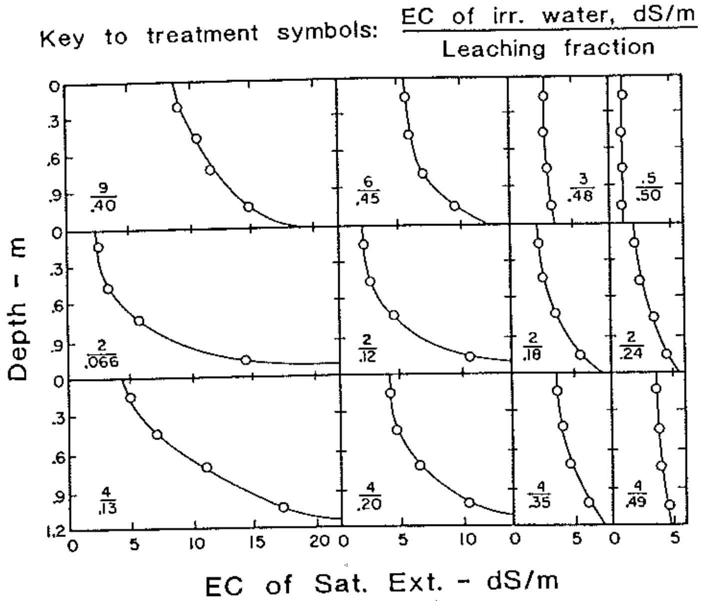


Fig. 36-5. Steady-state salt profiles expressed as electrical conductivity (EC) of the soil-saturation extract, as influenced by EC of irrigation water and leaching fraction. Key to treatment symbols: EC of irrigation water, dS/m per leaching fraction (Bower et al., 1969a).

Source: Stewart ed. 1990

Fig. 3-14 a

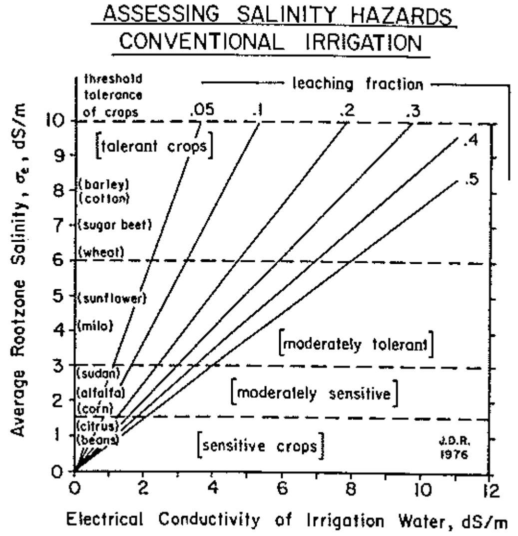


Fig. 36-10. Relations between average root zone salinity (saturation extract basis), electrical conductivity of irrigation water, and leaching fraction to use for conditions of conventional irrigation management (Rhoades, 1982b).

Fig. 3-14 b

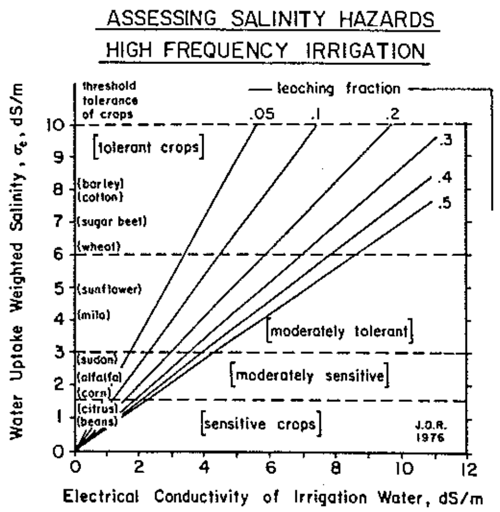


Fig. 36-11. Relations between water uptake-weighted salinity (saturation extract basis), electrical conductivity of irrigation water, and leaching fraction to use for conditions of high-frequency irrigation (Rhoades, 1982b).

Source: Stewart ed. 1990

where Viw, Vgw, Vdw and Ciw, Cgw, Cdw are volume and total salt concentration of irrigation, groundwater and drainage water, respectively (Rhoades/Loveday in: Stewart et al. 1990).

Vgw refers to that water which moves up from the water table into the root zone. Sm is the amount of salt brought into solution from weathering or dissolution, Sf is the quantity of soluble salts added by fertilisers, soil amendments and animal manures, Sp is the quantity of applied soluble salts in the irrigation/rainwater that precipitates in the soil after application, and Sc is the quantity of salts removed from the soil by crops.

Under steady-state conditions (no change in salinity and soil moisture), assuming no appreciable contribution of weathering and disslolution, or losses by precipitation, uniform areal water application, and insignificant capillary uprise from the water table into the root zone, the balance reduces to:

Ddw/Die = ECiw/ECdw,

where the equivalent depth of water D is substituted for volume, and concentration is replaced by EC.

Thus, by varying the fraction of water that is percolated through the root zone, it is possible to control the concentration of salts in the root zone, and hence, to control the average or maximim level of the soil water at a desired level (see Fig. 3-13).

Field experience (Rhoades/Loveday 1990) with conventional water management under steady-state conditions has shows that:

- salt contents of soil-water increases with depth in the root zone, except when low salinity waters (EC <0.2 dS/m) or high leaching fractions (LF >0.5) are used,
- soil water salinity near the soil surface is essentially uniform regardless of ECiw and LF, but increases with depth as the LF decreases,
- average root zone soil-water salinity increases and crop yields decrease as ECiw increases and LF decreases,
- at approximately equal ECiw/LF ratios, soil-water salinity is proportional to ECiw near the surface, but is almost independent of ECiw at the bottom of the root zone,
- the first increments of leaching (initial leaching) are the most effective in preventing salt accumulation in the soil-water of the root zone.

The irrigation interval affects the soil salt accumulation as it determines the degree to which the soil water is depleted between irrigations. To maintain a low salinity level in the topsoil it is essential that the soil is kept continously moist. The use of moderately or highly saline irrigation waters requires that the moisture level should be maintained at a continuously high level, ie well in excess of the water requirements for optimum growth conditions (Fig. 3-14 a-b), a comparison of conventional versus high frequency irrigation).

From the salt balance it is obvious that sufficient irrigation water (including effective rainfall) must be applied in excess of the potential evapotranspiration (PET) needs of the crops grown, so that there is excess water to pass through the root zone (usually up to 2 m depth) allowing salts to be carried away (leached) from the rootzone. This excess water is referred to as the leaching requirement (LR). Several methods to determine the LR exist (see also sections 2.3 and 2.4); they are either derived from general soil-water balance concepts or from field observations as empirical formulae.

* **Dual LR** concept by Rhoades 1982. The LR for salinity control is determined by using the following variables; tolerance of the crop, salinity of irrigation water and type of irrigation. Conventional irrigation means that the soil is allowed to dry out between applications. Fig. 3-15 shows the relation between LF and the permissible root zone concentration factor. The linear average salinity within the root zone is used for conventional irrigation. Water uptake-weighted factors related to the salinity within the root zone are used for high-frequency irrigation

Further reading: Bresler 1987; Smith/Hancock 1986; Ingvalson et al. 1976].

Fig. 3-15

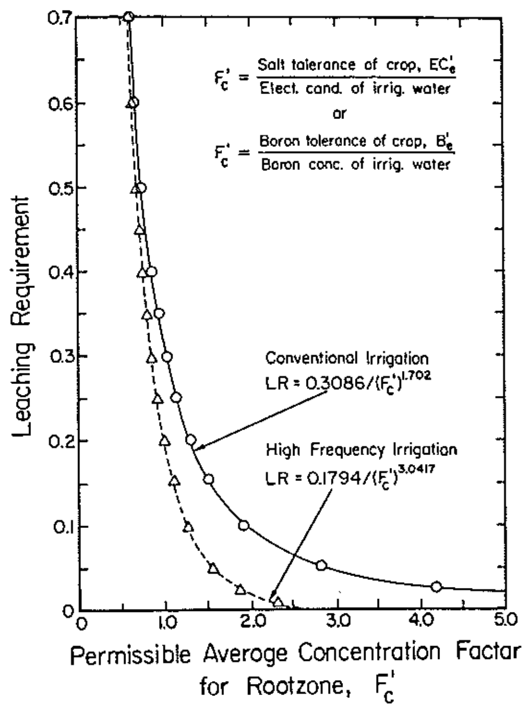


Fig. 36-9. Relation between leaching fraction and permissible root zone concentration factor for use in determining leaching requirement for conventional irrigation. After Rhoades (1982b).

Source: Stewart ed. 1990

Fig. 3-16 a

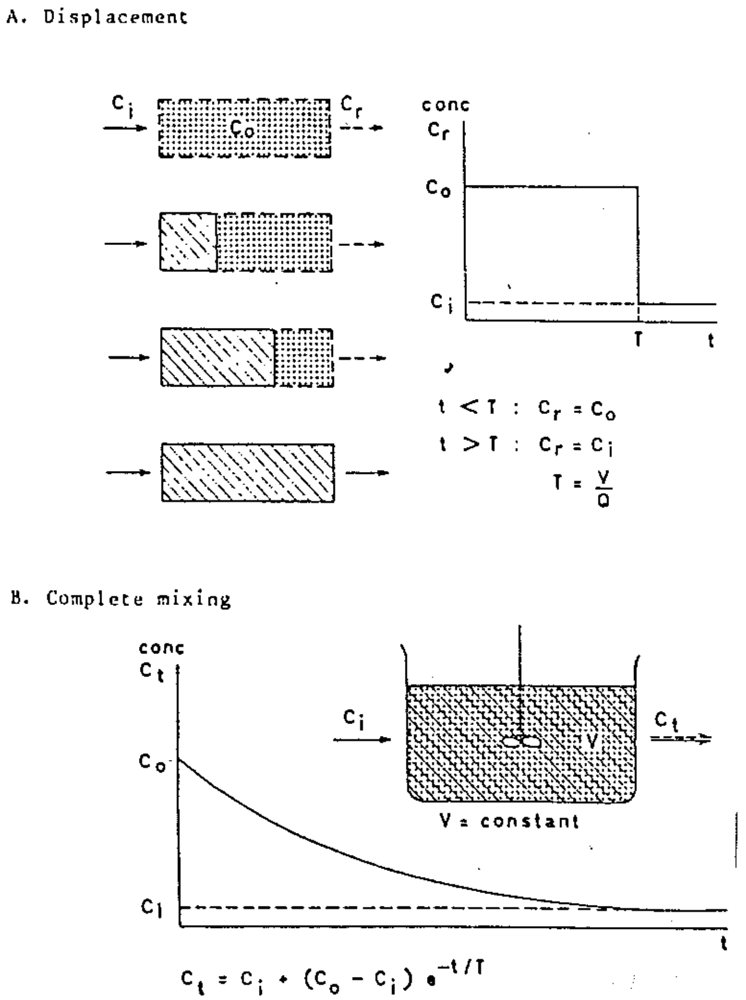


Figure 11. Desalinization of a reservoir.

Fig. 16 b

Source: van der Molen/van Hoorn 1979

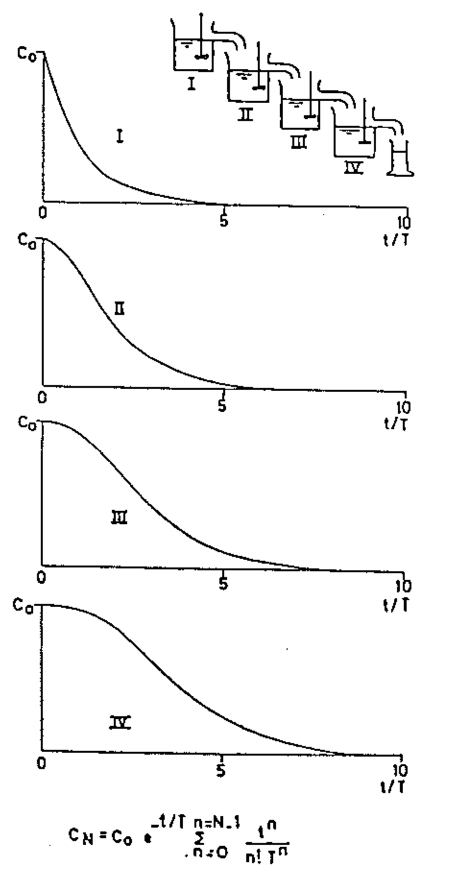


Figure 12. Desalinization of 4 reservoirs in series by rainfall.

* Analogously, Fig. 3-15 can be used for **chloride** and **boron** to determine the LR. Tolerances are calculated by converting the threshold values (given in terms of soil water content) from Tables 2-10 b and 2-11 a to a saturation extract water content basis: dividing by 2 for Cl; by 1.4 for B,
* a simple **empirical** relation is given by: LR = 100 ECi/ (2 f × ECe - (1- f) ECi),

  where ECi and ECe are water and permissible salt contents in dS/m and f is the soil specific leaching efficiency. Typical figures for f are: >0.8 in sandy soils, 0.6 to 0.8 in medium textured and 0.3-0.6 in fine textured soils (ILACO 1981),
* an **iterative** calculation procedure is given by van der Molen/van Hoorn (in: ILRI 1979) to be used for a series of soil horizons (Fig. 3-16 a-b)

The aim of the '<u>minimum leaching</u>' approach is to make maximum use for evapotranspiration of each volume of irrigation water applied so that minimum water quantities of drainage and salt return to receiving waters. Where groundwater can be intercepted, for example by tile drainage or groundwater pumping, it may be re-used in irrigation at least in fields of crops with a higher salt tolerance or in crop rotations (Rhoades et al. 1989). Minimising the amount of leaching from the rootzone, however, maximises the **precipitation** of salts in the soil, and it minimizes mineral weathering and dissolution of previously deposited salts.

Fields studies have shown that reducing the leaching fraction from 0.3 to 0.1 reduced the salt load leaving the root zone by amounts varying between 2 and 12 t/yr/ha for a range of irrigation waters (Rhoades 1985). Hence, under conditions where the salt load of drainage waters create conflicts with other downstream users, minimising L is clearly **beneficial** in environmental terms. A crop water management strategy that optimises these problems in technical terms must therefore consider possible conflicts over scarce water resources, crop management strategies and environmental conditions. Data on the water and salt mass balance in a landscape, land drainage, permeability properties of soils, chemistry of the drainage and receiving waters, and potential soil salinity problems must be known (Rhoades 1985; Rhoades/Suarez 1977).

Sources: Rhoades 1989; Rhoades/Loveday in: Stewart et al. ed. (ASA) 1990; Rhoades 1985; Shainberg and Shalhevet ed. 1984; Rhoades in: van Schilfgaarde et al. (ASA) 1974

Conclusions and open issues

Under saline conditions, whether soil- or water-induced, more water must be applied to irrigated fields and high irrigation frequencies are required. Generally, there are two methods by which leaching water can be applied:

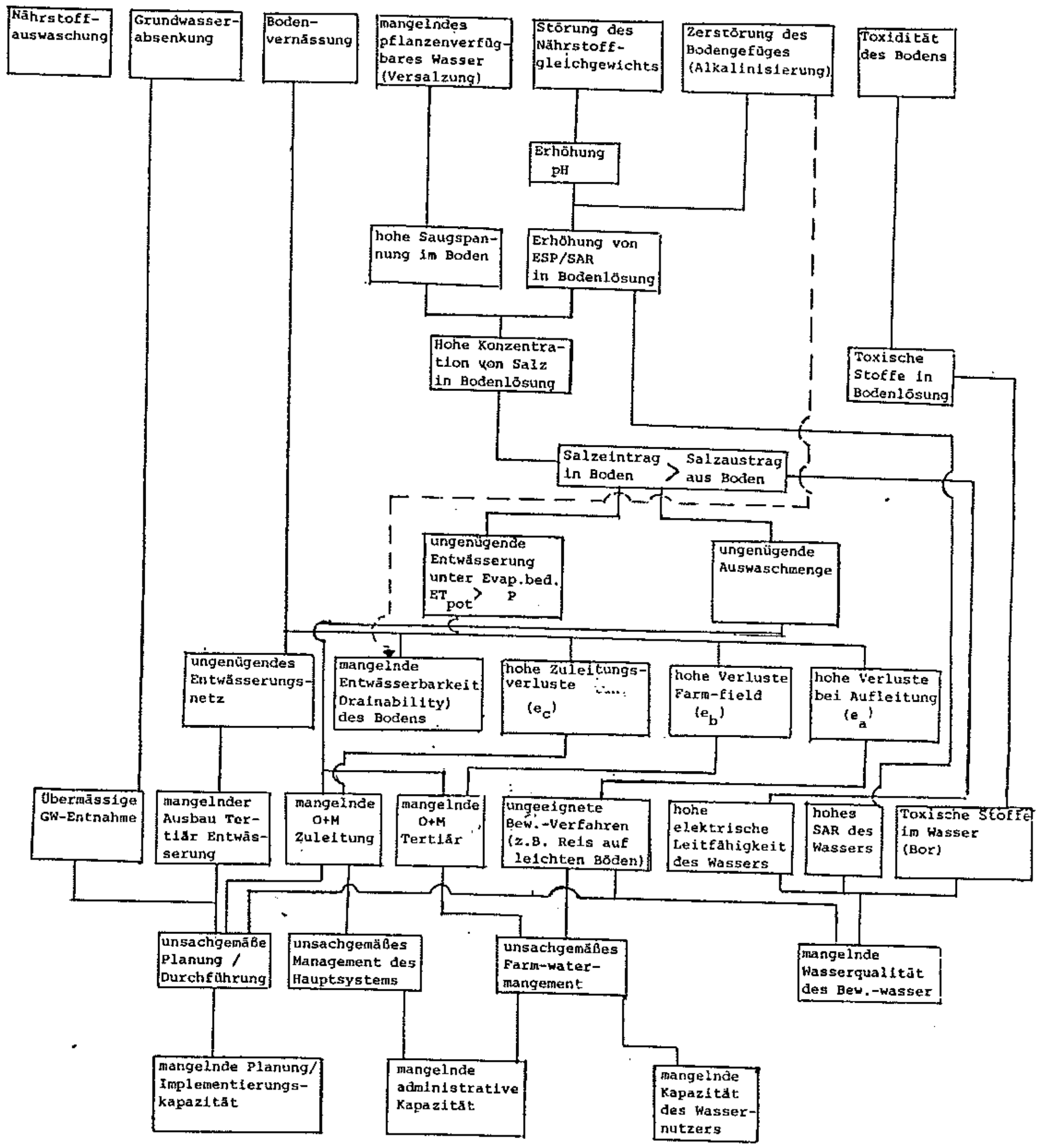
- applying sufficient water at each irrigation to meet the LR,
- applying, once or on several occassions, an additional 'leaching irrigation' sufficient to remove the salt that has accumulated from previous irrigations.

To control salinity, it is essential that infiltration and subsoil permeability rates are sufficiently high to allow for deep percolation. Furthermore, either natural or artifical drainage must be capable of conveying the drainage water (leachate) away from the subsoil, and the watertable should be kept below a critical depth, ie the lower rootzone should be above the capillary reach of the watertable (see section 2.4).

The relationships between salinity and irrigation and various environmental factors are shown in Fig. 3-17. A scheme of amelioration of salinised areas is outlined in Table 3-30. The methods recommended for the control of salinity and alkalinity in irrigated ares are summarised in Table 3-31.

Some important open issues in <u>salt control analyses</u> are:

Fig. 3-17



Source:

- Crop salinity tolerances may vary with the type of irrigation, ie there are indications that trickle and sprinkler irrigated crops have higher tolerances, probably due to typically higher water potentials achieved with high frequency irrigation methods, although an advantage of trickle irrigation is that salts are carried to the edge of the wetting bulb.
- Most leaching formulas ignore the chemical composition of the salts, interpreting the effects of salinity solely in terms of total salinity, measured as electrical conductivity (ECe). However, it is obvious that effects vary with the nature of the salts (solubility and toxicity).
- The crop-water production function (ie the relationship between crop yields and the seasonal amount of applied water), required to design irrigation systems and to plan irrigation management, assumes that the relation between yield and PET is independant of whether yields are primarily affected by matric stress (caused by soil water holding properties) or osmotic stress due to the salt content. All models ignore the chemical reactions occurring during irrigation and leaching.

Reclamation of heavy saline soils

Although heavy textured soils are often attractive for irrigated crop production, because of their high nutrient status, level topography, high moisture holding capacity, they pose various difficulties in managing the water regime which makes the prevention of a secondary salt build up difficult. Also the reclamation of native saline soils is extremely difficult and requires special water and crop management techniques. These may include a combined approach of tillage practices, adequate drainage, cropping pattern, and water management practices. Difficulties arise from the fact that the rate of salt removal is very low, the flux is limited to preferential routes through the clay ('bypass transport', eg Kamphorst 1988, 1989), and to specific water adsorption characteristics which require high water applications. Standard approaches for reclamation are inadequate and site specific measures are required, which consider also the management capabilities of the farmers. The improvement of soil structure, eg through tillage or horizontal drainage, is one applicable method, although it requires high inputs (Tanton ODU 1989 with several references).

Regional approach for salinity control

Regional approaches to control salinity in river basins are required in order to minimise the cumulative effects of salinity build up along the streams. This may apply to areas with native saline soils or to areas where irrigation contributes to a build up of soil salinity. In either case, the entry of saline drainage water into the river must be limited. Among possible salt disposal measures are the collection and evaporation of polluted water in ponds which is a practicable and feasible method in cases where water is not a scarce resource. Greater benefits may be gained by implementation of salt mitigating measures which may also include storage reservoir operations with seasonal restriction on diversion of highly saline effluents into the river system. A summary of suitable methods for a 10,000 km^2 watershed is given in Table 3-32 (Shiati 1991).

Generally, the control of soil salinity should always be seen in the strategic context of protection of groundwater from salt pollution. On a regional basis, the major categories of salinity control for groundwater protection (after Maletic in: Helweg 1985) are:

(i) point source control:

desalt; divert and evaporate; divert and special use,

(ii) natural diffuse source control:

collect and desalt; collect and evaporate; collect and special use; watershed management: vegetative conversions, forest management, structural measures, water harvesting, reduced sediment production,

Fig. 3-18

SALT BALANCE

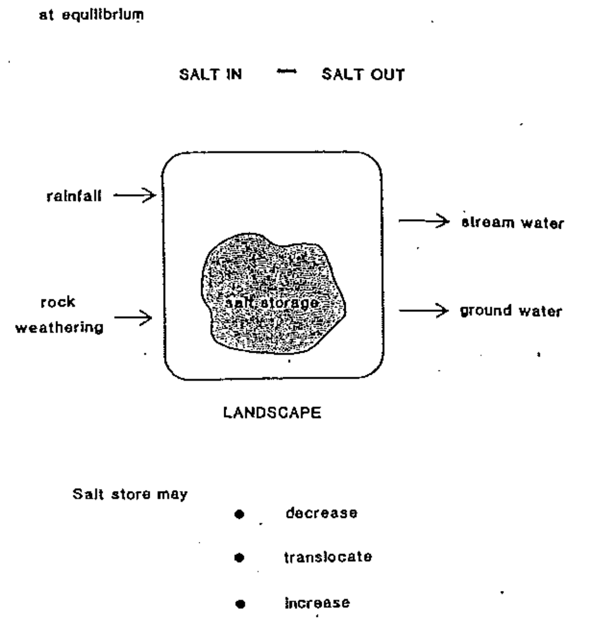


Figure 1 Conceptual model of a salt-balance in a landscape, from Shaw *et al.* (1987).

SALT MASS BALANCE

Utilisation of salt affected land for the medium to longer term requires that the management strategy is sustainable. This requires that the quantity of water and salt being imported to the salted area annually is in some quasi equilibrium with the exports of salt and water from the discharge area.

This can be expressed by the steady state mass balance equation ;

$$Q_i c_i = Q_o c_o$$

where Q_i quantity of water entering a system
Q_o quantity of water leaving the system
c_i concentration of input water
and c_o concentration of output water

This equation is the basis of the well known leaching fraction concept of USSL (1954). The equation can be expanded to take into account other processes in landscapes such as dissolutiou and weathering. Figure 1 illustrates a diagrammatic section through a catchment with most of the significant mass balance inputs and outputs. The symbols are explained below the figure and the range of nominally expected values given in Table 1.

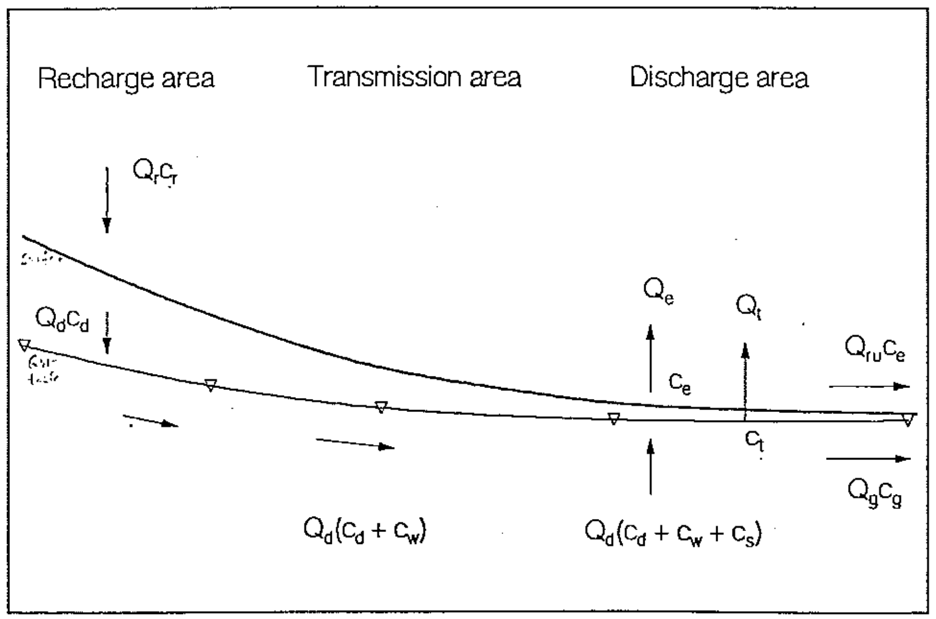


Figure 1 Components of the steady state water and salt mass balance in a salted landscape.

Source: Shaw 1992 b

(iii) irrigation sources (off-site effects):
- improved on-farm use: scheduling, increasing application efficiency,
- improved conveyance efficiency: pipes, canal lining, mechanisation,
- groundwater management; water table control; selective pumping; groundwater recharge
- return-flow management: reuse in downstream irrigation systems; collect and desalt; collect and special use.

(iv) river system management:
- alteration of time pattern of stream flow,
- alteration of time pattern of saline discharges,

(v) dilution:
- augmentation: desalting; wastewater reclamation; conservation practices,
- importation (large scale transfers).

Some of these methods will not be technically or economically feasible under certain conditions and the selection of proper methods must be based on site specific evaluations.

Guidelines for the regional control of salinity in semiarid areas should consider the recharge and discharge model, the salt accumulation process and the mobilization of stored salts (Shaw 1992a,b). The parameters required for estimates of a water and salt mass balance of a landscape are shown in Fig. 3-18. The model can be extended to include irrigation. Based on the salt balance concept, approaches to dryland salinity management are outlined:

In irrigated areas, which are typically located within 'discharge areas', it is essential to manage the water (and salt) balance so that the water table is maintained at or below the critical depth where upward flux is not sufficient to salinise the root zone (approximately between 0.7 and 2 m minimum). Then, average irrigation management with good quality water can maintain a favourable salt level within the root zone. Interception of groundwater in the transmission area is a measure to control salinity in lower lying (discharge) areas by reducing the volume of water flow into the discharge area.

Management options for dryland salinity are shown in Table 3-33. Similar management options need to be established for irrigated areas which are typically located within drylands. Such models, however, may also be used for rapid appraisals of **salinity risks** in a landscape, considering local hydro-pedological and climatic conditions and socio-economic values. Typically, the following factors can be modified within a landscape: irrigation (method and operation), leaching fraction, runoff, drainage, and groundwater flow. Selection criteria for management options in recharge and discharge areas are shown in Fig. 3-19 a-c. They depend on the size of the area, permeability characteristics, soil depth and stratification, and salt load estimates (Shaw 1992b).

General references to salinity: Shaw 1992; Rhoades/Mimeyato in: Westerman ed. (ASA) 1991; Rhoades/Loveday in: Stewart et al. ed. (ASA) 1990; Szabolcs 1989; Rhoades et al. 1989; Diestel 1987; Smith/Hancock 1986; Hoffmann et al. 1984; Kovda 1983; van Hoorn 1981; Hoffmann 1980; Rhoades/Suarez 1977; Diestel/Treitz in: Dregne ed. 1977

Further reading in: Shainberg/Shalhevet et al. 1984; Bresler et al. 1982; Dregne ed. 1977; FAO/UNESCO 1973; FAO (IDP 16) 1973; FAO (IDP 7) 1971

Journals with relevant articles: eg Agric. Water Management; Soil Technology; Irrigation Science

Fig. 3-19 a

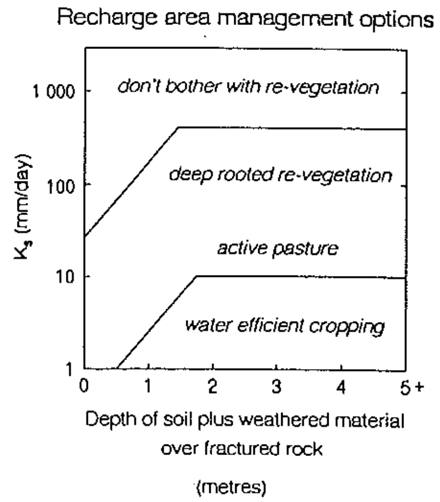


Figure 2 Potential dryland salinity control options for recharge areas based on the depth of soil plus weathered rock and saturated hydraulic conductivity K_s.

Source: Shaw 1992 b

Fig. 3-19 b

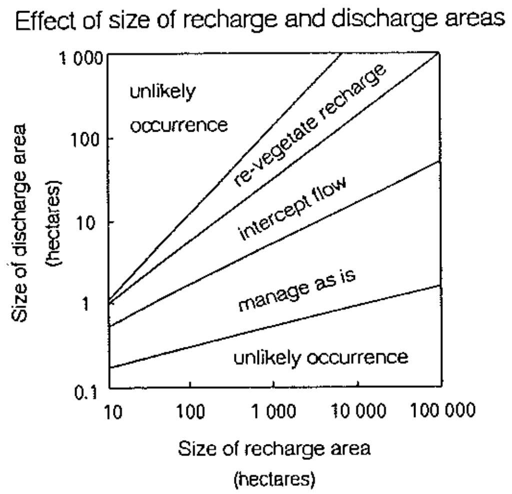


Figure 3 Possible dryland salinity control options based on the relative sizes of recharge and discharge areas. These options need to be considered in conjunction with the information in Table 2.

Source: Shaw 1992 b

Fig. 3-19 c

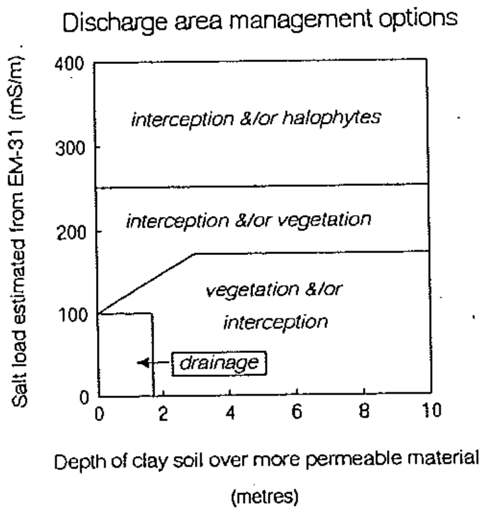


Figure 4 Possible dryland salinity control options for the discharge area, or by interception of water flow to the discharge area, based on the depth of soil and the estimated salt load in the discharge area.

Source: Shaw 1992 b

3.3.2 Soil Management and Agronomic Practices for Salinity Control

The effects of soil management and cropping practices on salinity and alkalinity are closely related to water management practices. For the control of salinity and alkalinity the following factors may have long duration effects and should be considered for an environmentally sound planning which, especially with regard to salinity and alkalinity control, is an important aspect of sustainable irrigation development.

Land Preparation and Soil Management

Land levelling and grading are important for efficient water distribution by surface methods and for run-off control, namely in newly developed areas. Levelling can change profile morphology and the distribution of salts. Large scale levelling can expose (or bury) saline soil horizons and may have significant influences on soil permeability by compaction (use of heavy machines) or creation of new stratifications which may impede vertical flow. An irregular micro-relief (<30 cm elevation) has a distinct influence on salinity patterns in irrigated fields, resulting in increasing salt contents on the raised spots and improved leaching in the dips if the soils are permeable. In slowly permeable soils the reverse may occur. Alterations during the course of levelling must be assessed for efficient initial leaching. Undesirable effects must be avoided by a close consultation between technicians and reclamation engineers prior to levelling.

Tillage operations are carried out for seedbed preparation, improvement of soil structure (increasing or decreasing permeability) and other agronomic means (eg weed control). The relation between tillage and soil salinity depends on the following factors:

- vertical distribution of salts
- depth of tillage and soil stratification
- soil moisture at time of operations, timing of tillage (soils should not be too wet or too dry during tillage operations)
- tillage equipment.

Tillage can - if executed at the proper time and with adequate machinery - accelerate desalinization by mixing saline surface layers into the subsoil, loosening the topsoil and/or subsurface horizons and mixing amendments. Chisel ploughs are more useful for loosening, whereas mouldboard ploughs are better for turning activities. If improperly timed, tillage may cause the reverse effect: turning up saline layers/soil horizons, destroying a favourable structure (thus reducing permeability), and creating compacted, less permeable plough horizons below the ploughing depth. Poor tillage may favour erosion, waterlogging and temporary inundation of low lying spots. This may result in local sedimentation.

Subsoiling (deeper than 0.4 m) can be very efficiently employed for disturbing compacted saline or non-saline layers and deep loosening to enhance percolation during leaching. Furthermore it can be used for deep mulching and turning of various layers. However, due to the large scale of operations the potential damage can be immense if operations are not properly planned and executed. Optimum soil moisture conditions must be observed. Serious damage to soil structure can occur especially in sodic soils if soils are cultivated when too wet.

Amendments are an ameliorative measure to reduce the negative effects of salinisation and especially alkalinisation (see section 3.3.4). Typically amendments enhance the development of favourable soil structure which increase infiltration and permeability rates. Amendments may be applied on the surface or incorporated into the soil. They may also be applied to waters at lower concentrations and for continuous application, eg by the placement of gypsum stones in tanks or canals. In alkaline soils or water having a high SAR-value the following amendments can be used: increasing Ca by adding gypsum or

Fig. 3-20 a

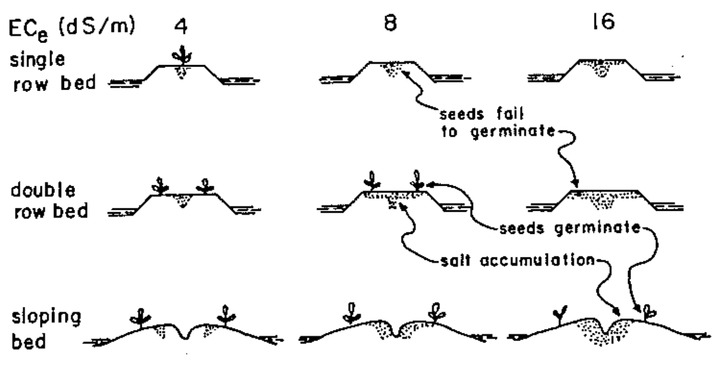


Fig. 36-2. Pattern of salt buildup as a function of irrigation management, bedshape, and level of soil salinity. After Bernstein et al. (1955).

Source: Stewart ed. 1990

Fig. 3-20 b

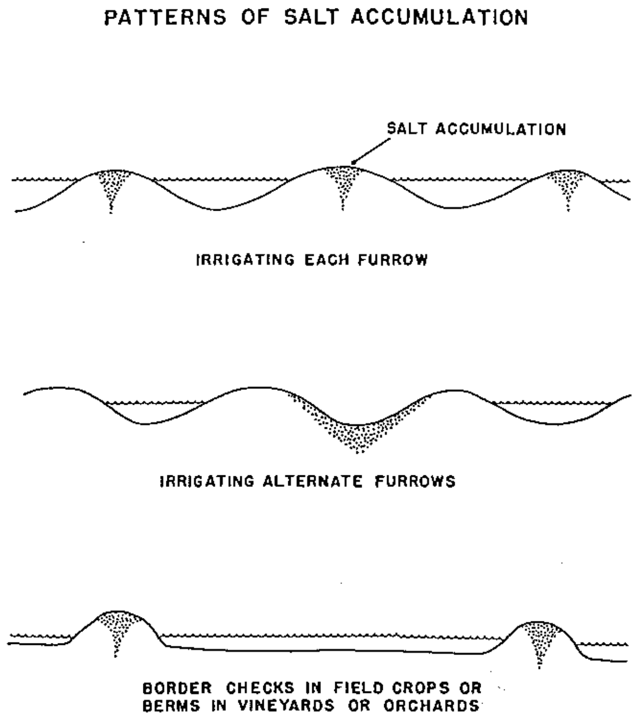


Fig. 2-4. Irrigation management can affect salt accumulation.

Source: Western Fertilizer Handbook 1980

other soluble Ca-salt and reducing HC_3 by adding sulphuric acid, sulphur dioxide or other acidifying amendments.

Mulching. The reduction of moisture losses by limiting evaporation from the soil surface has an immediate effect on the salt balance of the topsoil. Any disruption of capillary continuity restricts moisture rise and consequently reduces salinity build up in the topsoil. Surface tillag and placement of coarse crop residues or other materials on the soil surface (eg gravels around trees) may be applicable measures to prevent topsoil salinisation. Surface tillage must be done before the soil is completely dry. Minimum or no-tillage may be used to conserve soil moisture.

Agronomic Practices

Fallowing. Irrigated land may be left fallow if water is scarce or may be followed under a farm management plan. If irrigation is practiced in order to supply water in addition to rainfall, then fallow land may be left to replenish soil moisture during one season (requires normally at least 200 mm rainfall). Cropping may continue the next season when crops will benefit from a better water supply. Measures are, however, required during fallowing to reduce evaporation from the bare surface, eg mulching, weed control. The effectiveness of fallowing increases with deeper water tables (below the critical depth). In general, summer (hot-dry season) fallowing is less recommended. Fallow areas should be practiced in groups in order to avoid capillary uprise from neighbouring (irrigated) fields. Fallowing may have detrimental effects when practiced for a longer period (two or more seasons, depending on climate and soil conditions), as it may lead to a build up of extreme salinity/alkalinity due to the continuous uprise of soil moisture.

Planting techniques and positioning of crops can be an effective means to reduce the detrimental effect of soil salinity on crop yields (Fig. 3-20 a-b). For saline soils and furrow crops, the crop stand can be improved (FAO 1976)by

- planting on top of a single row bed
- planting near the edges of a double row bed
- planting on the side of a sloping bed
- planting in irrigation furrow (if no crusting).

Manures as well as providing plant nutrients, can also improve physical conditions of the soil and therefore enhance leaching of salts and the drainage of wet soils. Some manures, however, have high salt contents which must be considered especially under arid hot climates where higher application rates (or frequent applications) of manures are required to maintain a beneficial effect (eg Palaniappan 1992).

Broadcasting or drilling seeds on level land, immediately followed by irrigation and then maintaining short irrigation intervals during establishment may also be practiced to overcome salinity effects during germination. If soil crusting is a problem which is often the case in saline soils, measures are required to loosen the surface. Under alkaline conditions row crops are planted on high beds to reduce the effects of waterlogging. The quantity of seeds required for planting on salt-affected soils is higher than usual, due to a toxicity effect and often a delay in emergence is to be expected.

Fertilisers differ in their beneficial or detrimental effect on the control of salinity according to their chemical composition, solubility, rate of release, fixation, and time and method of placement. A proper diagnosis of site specific factors is a prerequisite for efficient recommendations. In general, most fertilisers add salts to the soil. The use of fertilisers with a low content of additional salts are therefore advantageous, namely most K-fertilisers (eg K_2SO_4). Unfortunately, these fertilisers are often not available in developing countries, or they are more expensive than salt-rich fertilisers.

Fig. 3-21

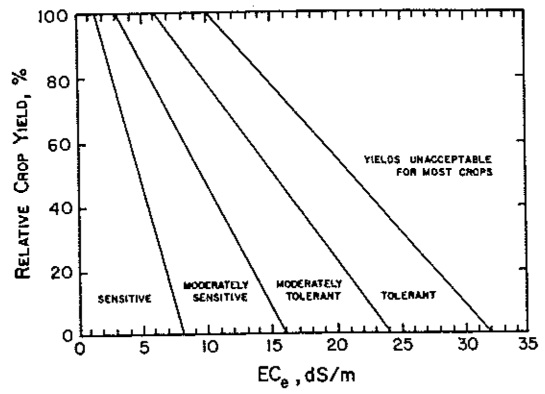


Fig. 36-1. Divisions for classifying crop tolerance to salinity. After Maas (1986).

Source: Stewart ed. 1990

Fig. 3-22

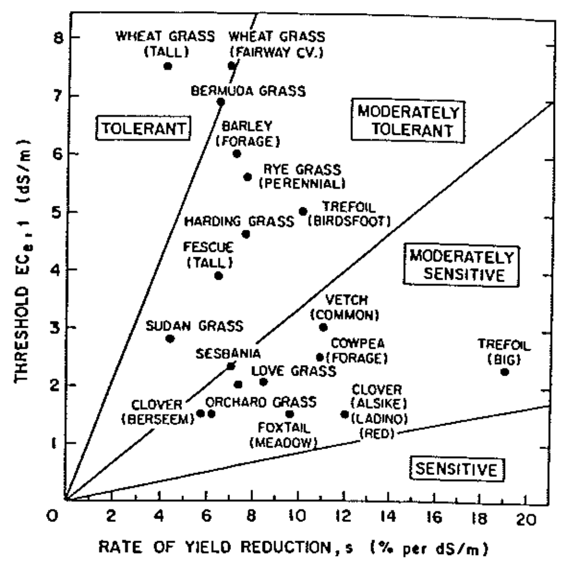


Fig. 3.7 Salt tolerance (threshold EC_e and % yield reduction with increasing salinity) of forage crops (Maas 1986)

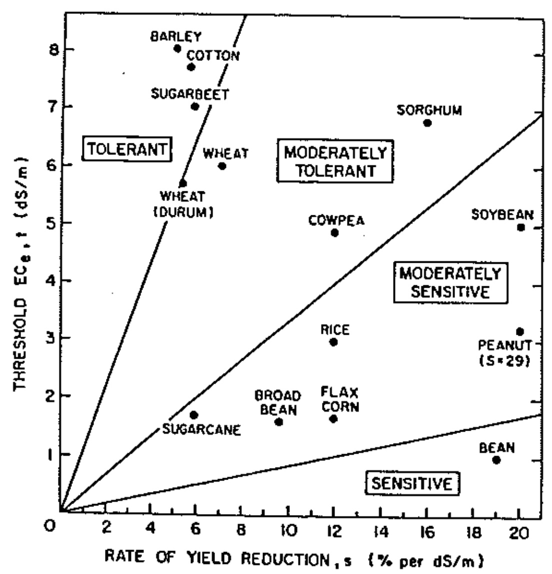


Fig. 3.6 Salt tolerance (threshold EC_e and % yield reduction with increasing salinity) of field crops (Maas 1986)

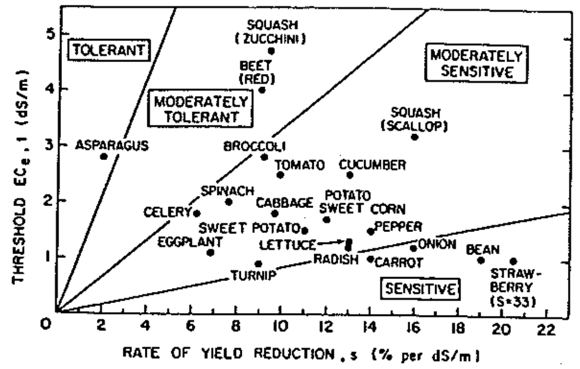


Fig. 3.8 Salt tolerance (threshold EC_e and % yield reduction with increasing salinity) of vegetables (Maas 1986)

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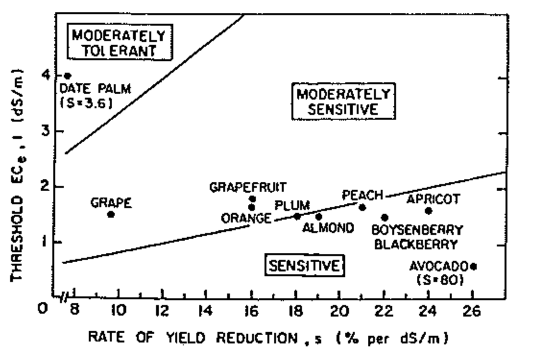


Fig. 3.9 Salt tolerance (threshold EC_e and % yield reduction with increasing salinity) of trees (Maas 1986)

Source: Feigin et al. 1991

On the other hand, fertilisation can control the detrimental effects of nutrient imbalances in the saline soil where direct or indirect shortages of K, Ca, and trace elements are often found. N-fertilisation may increase the formation of protein in plant tissues and thus inactivate excessive chlorides. Potassium fertilisers are known to be beneficial in saline soils because they counteract ionic imbalances, namely Na+/K+, because they reduce Na-uptake (Härdter 1992). Mg-rich saline soils may be deficient in Ca - even in calcareous soils - and therefore require Ca-additions either as Ca-rich fertilisers, Ca-amendments or by Ca-leaf applications.

In alkaline soils (pH >8) the availability of many trace elements is reduced (Finck 1991, 1992). Fertilisation and soil amendments may assist in reducing the pH. Acid fertilisers are recommended for alkaline soils, eg ammoniumsulphates.

Selection of Crops and Crop Rotation

When selecting crops for problem soils, the sensitivity of crops to salinity/alkalinity and the availability of water can be more important considerations than the level of economic return. In arid regions legumes or grasses are usually grown for one or more seasons until the salinity level in the rootzone is reduced to an acceptable level for other crops. An indirect benefit is the development of a favourable soil structure especially under grass which improves leaching and root growth for the following crops.

Under conditions that encourage salinisation or alkanisation of soils the specific crops (or varieties) should be selected on the basis of the irrigation water quality, their salt tolerance and their effects on the accumulated salt balance. For example, given a low water quality, then low water consumptive use, short a growing season, high up-take of minerals, development of a dense, deep root system are favourable, but with good quality water longer growing seasons and high water demands may be tolerable. Crops requiring continuous or frequent irrigation (eg rice, fodder) are better adapted for use in saline soils because the soil is kept continuously moist, and hence salts do not accumulate within the rootzone.

Under alkaline conditions the tolerance to specific sodium ion effects and the susceptability to adverse physical soil conditions (waterlogging, crusting) should be considered.

Salinity effects will differ under various crop rotations. For example, salinity will be higher after a rotation of cotton-cotton-fallow than after fodder-cotton-beans or cotton-fodder-rice. Crop rotations with long periods of dry fallow and a long duration of evapotranspiration can cause salinity levels to rise in the rootzone unless there is adequate leaching.

Crop management also implies the selection of types and varieties of crops which are best adapted to the prevailing conditions of salinity/sodicity/alkalinity. Plant density may be increased to compensate for the smaller plant size that usually exists under saline conditions.

Detailed information about salt tolerances of various crops is given in Figs. 3-14 a-b; 3-21 and 3-22 and Tables 3-34 a-b and 3-35 a-b.

Crop rotation with the alternate cultivation of salt tolerant and more sensitive crops is an effective method for irrigation with saline waters, eg during re-use of drainage water (see 'minimum leaching approach' in section 2.4). For example, a method to avoid the maximum build up of salts which would occur during continuous irrigation with saline water is:

- preplant and initial irrigation of a salt tolerant crop with water of low salinity to keep the topsoil salinity low during emergence
- irrigation pf the tolerant crop with more saline drainage water (maximum salinity is reached in the root zone)
- subsequent cropping with less sensitive crops using water of a low salinity.

Fig. 23 a

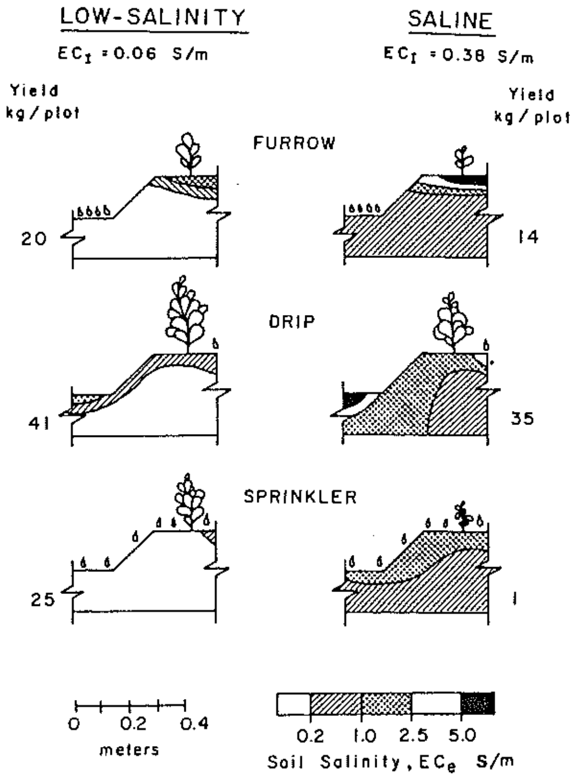


Fig. 36-3. Influence of the irrigation system on the soil salinity pattern and yield of bell pepper (*Capsicum anuum* L.) at two levels of irrigation water quality. After Bernstein and Francois (1973).

Source: Stewart ed. 1990

Fig 23 b

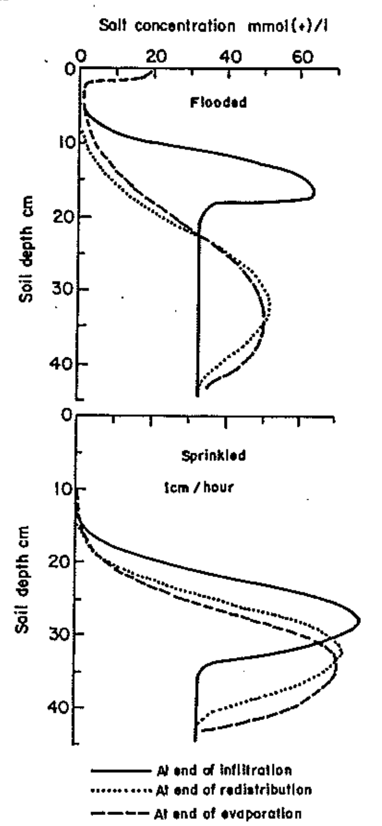


Figure 3
Effect of method of irrigation (flooding vs. sprinkler) and water redistribution following irrigation[2] and evaporation[3] on the salt concentration profiles (Bresler and Hanks, 1969)

Source: FAO (SB 39) 1988

Fig. 23 c

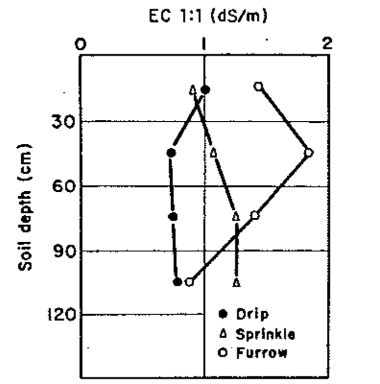


Figure 12
Salinity profiles in sweet corn under drip, sprinkler and furrow irrigation methods (Goldberg et al., 1976)

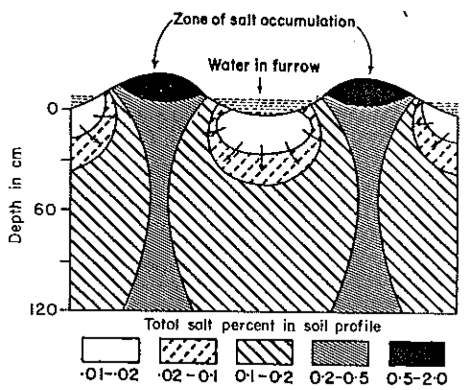
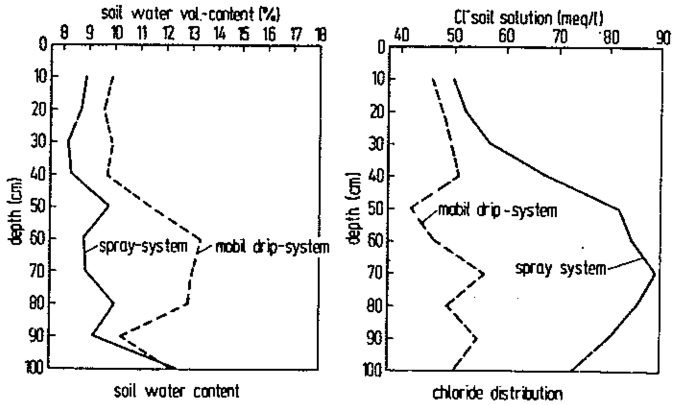


Figure 13
Direction of salt flow and salt accumulation in furrow irrigation. The zone of maximum salt accumulation is in the top of the ridges

Source: FAO (SB 39) 1988



Sourell in ICID 1991

Sources: El-Guindi/Abu Bakr in: ICID (STS-C16) 1991; Rhoades/Loveday in: Stewart et al. ed. (ASA) 1990

Irrigation Methods and Practices

The method of irrigation and irrigation practices determine the salt movement in irrigated soils (see Figs. 3-23 a-d). Soluble salts move in the direction of water movement. In areas of large scale frequent flooding or sprinkling, salts are usually leached downward. Salinity is often most limiting to crop production during crop establishment, especially under surface irrigation systems (especially furrows) even if the average salt content in the soil is relatively low. During seedling establishment most plants are more sensitive to salts (Table 3-36). In addition, seedlings may be exposed to locally excessive salt concentrations that tend to develop in topsoil layers.

Movement and concentration of salts along **furrows**, beds, border checks or berms in orchards commonly occur. The accumulations are highest in single-row, flat-topped beds. Planting on the shoulder of the bed or planting in two rows on a wide bed so that salts will be pushed to the centre of the bed and away from the seedlings (or seeds) may help to reduce crop damage in saline soils. If the soil (or irrigation water) is slightly saline, irrigation in alternate furrows is advantageous. With double-row beds, under moderately saline conditions, most of the salt is carried into the centre of the bed, leaving the shoulders relatively free of salt. Sloping beds are best suited for saline soils because the seedling can be established on the slope below the zone of maximum salt concentration.

Planting in **furrows** or **basins** is often favourable for salinity control but it may create problems for many row crops because of crusting and poor aeration. Excessive salts may accumulate in the tops of beds during pre-irrigation, especially where animal manures have been used. Permanent berms in rows (eg in orchards) may also accumulate excessive salts over a few seasons. Berms should be removed or levelled to disperse the salt and then be rebuilt.

Temporary **sprinkler** irrigation or **drip** lines (pre-emergence with frequent applications) are advantageous in saline soils until seedlings become well established and surface methods can be used. Special temporary furrows can also be used during seedling establishment. Drip irrigation is most advantageous because it can be designed to establish a continuous flow (even at low rates), thus keeping the emitter surroundings continuously moist (eg around trees), and allowing the salt to accumulate at some distance at the moist-dry boundary of the wetting bulbs. Salts may be removed from time to time either manually or by leaching through flooding or movable sprinkler systems, if rainfall is insufficient.

Although sprinkler irrigation is used efficiently to control salt-induced root damage, it can be unfavourable, especially when highly saline waters are used: crops may suffer from foliar salt uptake and burn caused by direct contact of leaves with the spray (see Tables 2-19 and 3-37). The actual degree of foliar injury also depends on salt composition, climate (eg temperature), size of sprinkler droplets, crop type and growth stage. The following recommendations to minimize crop injury by sprinkler irrigation are given by Meiri (in Kandiah 1990):

- reduce wetting of the foliage of sensitive crops; for example, irrigation below the crop canopy is possible in orchards with mini-sprinklers
- infrequent heavy irrigation is preferable to frequent light irrigations
- intermittent wetting by slowly rotating sprinklers that allows drying between cycles is unfavourable because it would increase injury levels
- moving sprinkler systems downwind will wash of the salt accumulated on leaves from salt drift
- changing to water of good quality before terminating irrigation
- night time sprinkling should be practiced to reduce evaporation losses

- sprinkling during daytime, hot, dry and windy periods should be avoided.

Sources: Rhoades/Loveday in: Stewart et al. ed. (ASA) 1990; Maas 1985, 1986 Bernstein/Francois 1973, Rhoades/Oster 1986

Under irrigation the root zone salinity varies in time and space according to changes in soil moisture following irrigation as water is used by crops, and lost by evaporation or deep percolation. Because salinity effects are predominantly water stress effects, there are obvious implications for irrigation management. For example,

- plants can tolerate higher levels of salinity under conditions of low matric stress resulting from high frequency irrigation, eg by drip/trickle or sprinkler (see Fig. 3-14b),
- deleterious effects of high salinity in the lower rootzone can be minimised by adding low salinity water to the upper rootzone to satisfy the plants' evapotranspiration needs, and to prevent plants extracting water from the lower, saline rootzone.

<u>Irrigation Management</u>

The best means of controlling soil and water salinity is the provision of efficient irrigation with adequate but minimum leaching and a drainage system that maintains the **net flux of water downward** over time. This can be achieved by **frequent** irrigation applications.

The <u>delivery</u> system and field irrigation <u>practices</u> can contribute to controlling salinity, too:

- water **supply canals** often allow considerable seepage losses which are a major cause of the development of high water tables within irrigated lands; such losses can be reduced by compaction of the canal bottom and walls or by lining them with impermeable materials. Concrete lining and pipelines are the most efficient means to reduce conveyance losses,
- for efficient control of the supply system, the water volumes passing **critical points**, including farm outlets, must be known. Flow measuring devices are required to identify sections with high losses and to avoid over- or under-irrigation on-farm,
- many irrigation systems encourage **over-irrigation** due to a **fixed** delivery system, which supplies water in fixed quantities or at fixed times, irrespective of actual requirements. Such systems may facilitate easy operation of the system, but they do not encourage sound management of scarce water resources. Ideally, water delivery should be **on demand**. Hence, compromises are required between systems operator and farm operators to allow for sound water management and efficient salinity control,
- concepts and techniques for scheduling irrigation should be adapted to salinity control, eg by providing the **appropriate amount** of water at the **appropriate time** with a **high uniformity of application**. Ideally, soils should be kept continuously moist to prevent increasing salinisation between irrigations. To achieve such a system the volume of water replenishment must be known as well as potential evapo(transpi)ration rates. Well designed, operated and maintained drip irrigation systems may come close to these ideal conditions, as they maintain high water contents, move salts out to the periphery of the wetted (root) zone, and allow for high uniformity of application. Good volume control and uniformity may also be achieved by sprinkler systems, but these suffer the disadvantage of tending to produce drop impact-induced soil crusts,
- in surface irrigation systems efforts must be exerted to increase the uniformity of applications, eg by means of precise levelling, and reducing furrow or strip length.

<u>Conclusion</u>

A summary of expert recommendations to control soil salinity and water quality is shown in Table 3-38, related to management on the farm, crop, water, fertility, soil, irrigation system, and basin levels (Kandiah ed. (FAO) 1990).

Further reading: Kandiah ed. (FAO) 1990; Rhoades/Loveday 1990; Rhoades 1985; van Schilfgaarde/Rawlins 1980; van Schilfgaarde in: FAO 1976

3.3..3 Drainage for Salinity Control

Control of the depth of the watertable is essential in areas without adequate natural drainage in order to prevent capillary uprise of salts towards the surface (Fig. 3-24; see also section 2.4). The importance of drainage is illustrated in Fig. 3-25 where the evolution of salt-affected areas and depth to watertable are shown for a project in China.

> Before irrigation started on 40,000 ha some 6,800 ha were originally salt affected. Some five years after irrigation commenced the water table rose to 1.5 m below the soil surface and the salt affected areas increased to some 19,000 ha. Irrigation was suspended on some 60% of the total command area of 40,000 ha. Since 1967 an improved drainage system has been in operation in combination with 6,000 tubewells, supplying about 30% of the total irrigation water. Watertable levels are kept below the critical level at some 3 m and the salt affected area has been reduced to some 3,900 ha, ie less than before irrigation started. (Zhang in: Lesaffre ed. 1990)

However, the processes of leaching and drainage within the command areas are **'necessary evils'**, since they are the causes of the salt load (ie pollution) of the waters receiving the drainage.

> A bias in maintaining soil fertility in the irrigation area exists: the removal and disposal of salt accumulations by leaching means to add salts to the river basins and it may add or cause serious imbalances at other points.

There is no permanent benefit from leaching without efficient natural or technical drainage effluent. **Drainage efficiency** can be analysed in terms of systems' capability to convey groundwater which percolates beneath the irrigated land towards areas outside the command area so that no water table can develop within the critical groundwater depth. Without such drainage, groundwater may eventually rise to levels that allow salts to accumulate within the root zone, and the root zone may become waterlogged. Percolating water includes

- leaching water from irrigated lands (vertical percolation)
- canal seepage (lateral flow from conveyance systems)
- natural watercourse seepage (eg lateral flow from rivers or channels)
- lateral seepage from elsewhere (eg other irrigated lands, lakes)
- excessive rainfall in the area.

<u>Management practices</u> that reduce these contributions also reduce the volume of drainage water and the degradation of the waters that receive it and, hence, off-site water pollution. Such practices include

- increased irrigation efficiency (eg irrigation on demand)
- adopting the concept of 'minimum leaching'
- increasing interception (eg by plants)
- re-use of tail water for irrigation

Fig. 3-24

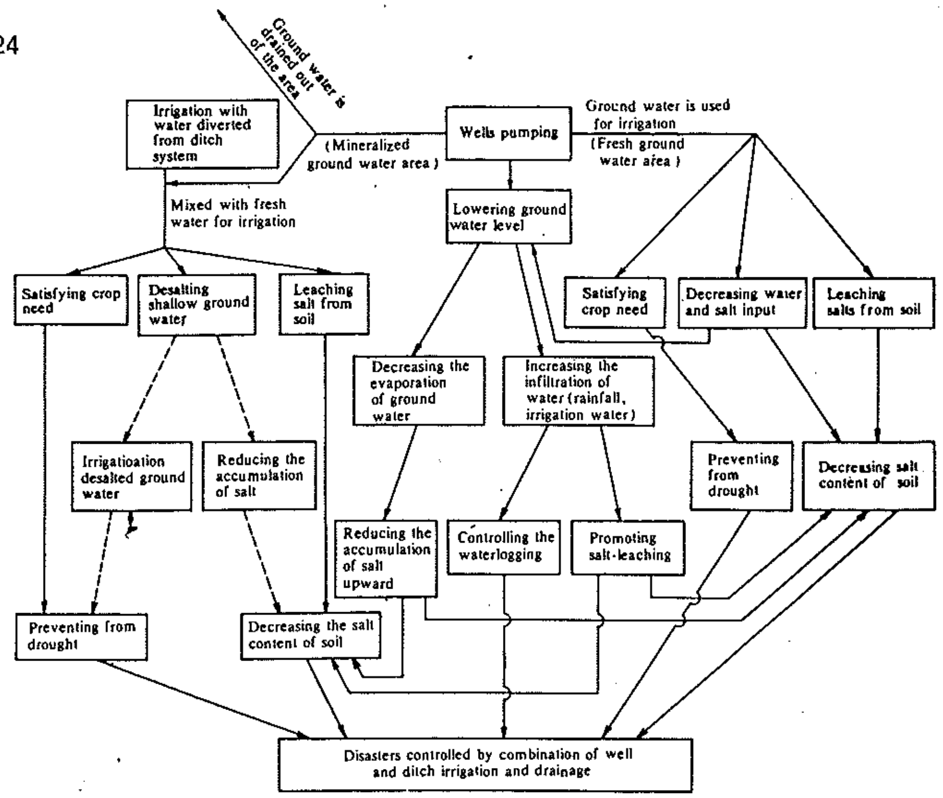


Figure 34
Schematic diagram of the effect of pumped well irrigation and drainage on control of drought, flooding, salinization and sodication (You and Wang, 1983)

Source: FAO (SB 39) 1988

Fig. 3-25

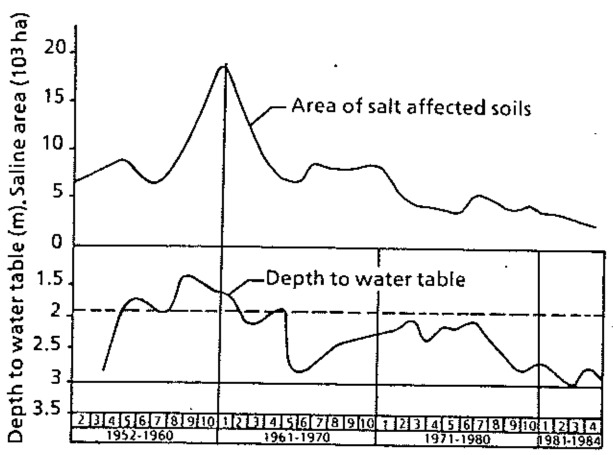


Figure 2 - Evolution of the area of salt-affected soils and of depth to watertable in the People's Victory Canal Project

185

Source: Lesaffre ed. 1990

- re-use of subsurface drainage flows for irrigation
- re-use of open ditch drainage water for irrigation
- diversion of drainage flow to appropriate waste sites (lakes, treatment, depository facilities)
- isolation of polluted saline groundwater from other fresh water resources (eg rivers used for domestic supply).

Re-use of drainage water or use of saline waters for irrigation

- selection of salt tolerant crops,
- crop rotation with alternating sensitive and tolerant crops grown with water of low and high salinity, respectively
- dilution of saline ground/surface waters with water of low salinity and use of the blend for irrigation (this also occurs under natural conditions when drainage water moves by diffuse flow back to river or groundwater aquifers).

There are several **problems** (or shortcomings) involved with the reuse of saline drainage water:

- suitability for irrigation is reduced since only plants tolerant to the specific salt level can be grown,
- irrigation demand and leaching requirements (LR) increase with the use of saline water because plants can only extract soil water (to meet transpiration requirements) up to its tolerance limit of salt concentration, the remaining water is unavailable and must pass once again out of the root zone, and secondly, the LR increases with increased salt concentration in the irrigation water
- increased water demands and the need for a highly flexible system typically requires higher investment costs (hydraulic infrastructure) and operational costs (energy) and good operation practices are essential (see also section 2.3).

Further reading: Tanji/Hanson in: Stewart ed. 1990; Bhuiyan in: ICID 1989; Westcot in: van Hoorn ed. 1988; Boumans et al. in: van Hoorn ed. 1988; Smedema in: van Hoorn ed. 1988; Oosterbaan in: van Hoorn ed. 1988; Lesaffre ed. 1990; Bernstein in: Yaron ed. 1981; Yaron in: Yaron ed. 1981; Bouwer in: vanSchilfgaarde ed. 1974; ILRI 1972

3.3.4 Reclamation of Sodic Soils

The main purpose of reclaiming sodic soils is to produce a stable and favourable soil strucure which provides adequate porosity for water percolation and storage throughout the root zone. This usually requires increasing the Ca-level on the cation exchange complex at the expense of Na-ions and subsequent leaching of excessive Na. The following factors must be considered:

- desired extent of reclamation (level of accepted ESP, SAR); often an ESP of 5-15 is considered an acceptable level for sensitive plants (see Fig. 2-1, section 2.1),
- rate of reclamation,
- required depth of soil reclamation: often 0.4 m, but between 0.2 and 1.0 m is acceptable,
- physico-chemical soil properties,
- amount and quality of irrigation water available,
- source and method of application of Ca-supply,
- costs involved, mainly depending on the desired rate of reclamation and the costs of available Ca sources.

Source: Rhoades/Loveday in: Stewart et al. ed. (ASA) 1990; FAO (SB 39) 1988

Fig. 26 a

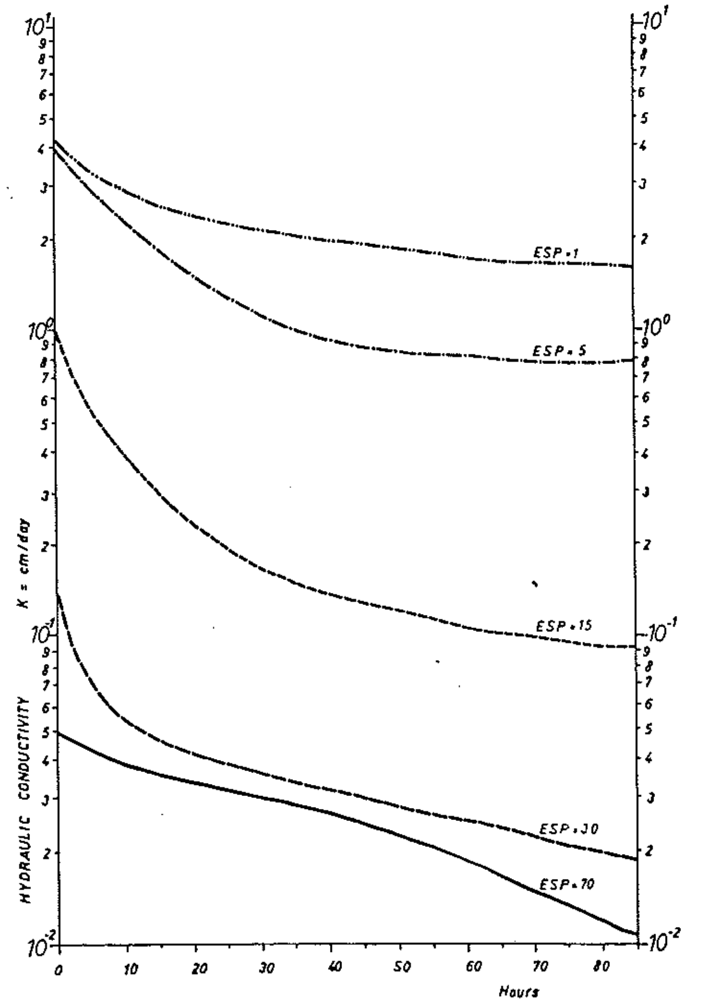


FIG. 55. Hydraulic conductivity of a chernozem soil saturated with sodium to various degrees.

Source: Szabolcs 1979

Fig. 26 b

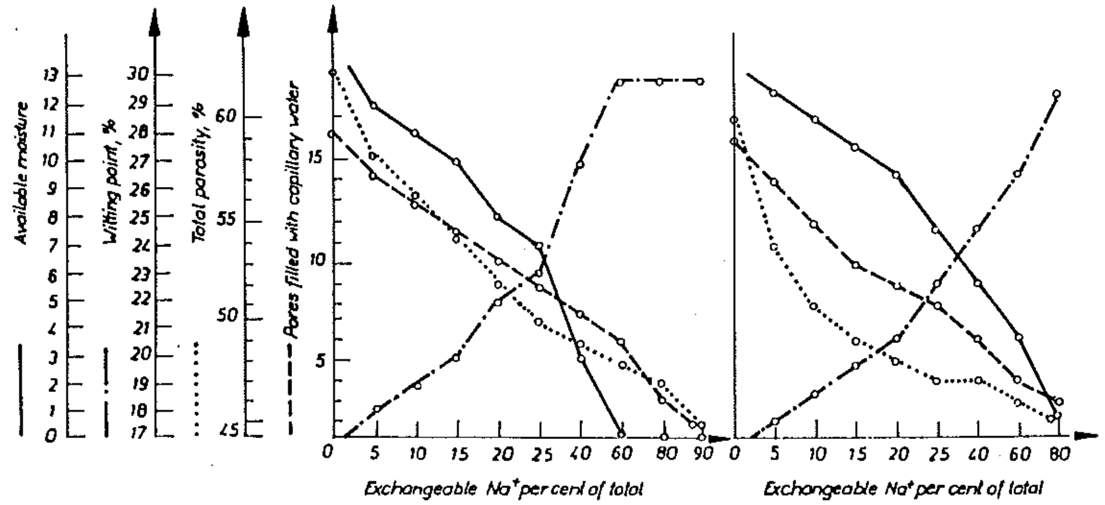


FIG. 54. Exchangeable cations and water properties of a soil according to a ratio of (Ca⁺ + Mg⁺) to Na⁺ in sandy and clayey soils.

Source: Szabolcs 1979

In practice, sodicity problems are often related to the use of water of poor **quality**, ie water with high SAR values (see also section 2.1). In permeable, light to medium textured soils the soil exchange complex will soon reach an equilibrium with the sodium and divalent cations in the irrigation water. Management practices for the efficient use of water likely to cause soil sodicity problems are:

- application of **amendments**: increasing the Ca-status of the water and to neutralise the bicabonate and carbonate; gypsum can be applied to the soil or lumps of gypsum can be suitably placed in the tanks or canals to dissolve gradually; sulphuric acid can be used as amendment to waters, although corrosion problems may occur
- mixing with an alternative source of water with a better quality
- **irrigating** more frequently: frequent applications with smaller volumes are effective to manage sodicity, especially in slowly permeable soils to avoid waterlogging
- growing **crops** with low **water requirements**: each volume of water applied to the soil will add to the sodicity problem; growing outside the peak evaporation season is recommended
- growing **tolerant crops** and crops which are better suited to waterlogged conditions
- **manuring** and **organic matter** applications: dressings of manures, regular incorporation of crop residues, mulching, organic materials (rice hulls, sawdust, sugar cane byproducts such as molasses), etc. counteract the adverse effects of sodicity problems.

Source: FAO (SB 39) 1988

In some situations, sodicity (high Na) and alkalinity problems (high pH values over 8.5) are associated with inherent soil properties. Common reclamation methods appropriate to different conditions are summarised as follows

Reclamation Methods for Sodic Soils (after Rhoades/Loveday 1990)

soil condition	recommended amelioration method
saline-sodic, with soluble Ca in topsoil	leaching
sodic B horizon; Ca-carb. or sulphates	subsoil profile mixing, followed by leaching
calcareous sodic soils	acid or acid formers (S, fertilisers)
moderately sodic soils (ESP < 25%)	gypsum
strongly sodic soils	$CaCl_2$, H_2SO_4, saline water applications

Generally, it is recommended to test effciency and adequacy of the selected method during field experiments before larger areas are treated with amendments and other measures. To achieve leaching, soil permeability and drainage facilities must be adequate which is often not the case in sodic soils. Soil porosity and permeability should be improved by tillage practices, but often it subsequently declines rapidly with the presence of excessive Na-ions unless the total salt concentration is maintained at high levels (see Fig. 3-26 a-b), which on the other side can be adverse to plant growth, too.

In developing countries, the costs involved for reclamation are often beyond the economic capacity of a single farmer. In government schemes the situation can be different and large scale treatments are often applied. In either case, smaller applications may often provide immediate permeability effcts and some initial exchange of Na which can be built upon by later applications over several seasons. This gradual, incremental reclamation is probably more adapted to conditions found in developing countries.

Sources of calcium include:

- soil parent materials as $CaCO_3$, silicates, evaporites (eg gypsum, anhydrite); acid or acid-forming amendments can be used to produce Ca from $CaCO_3$,
- **gypsum** may be used in moderately sodic soils (ESP 10-30); it is often easily available, available at low costs, and offers easy handling; in highly sodic soils (ESP > 30%) it does not provide sufficient salts to maintain adequate permeability for leaching; the solubility of various gypsum amendments is variable; phosphogypsum (byproduct of superphosphate production) is soluble at significantly higher rates than natural gypsum; differences occur also in particle sizes and in most cases a combination of various sizes is recommendable to maintain solubility level constant over time; surface applications are suitable to improve infiltration and reduce crusting tendency; otherwise, mixing into the surface is used; deep subsoil mixing can be applied during subsoiling (see agricultural practices) and mole drainage installations; dissolution of gypsum in the irrigation water (either sprinkler or surface systems) reduces costs of applications; possible leaf injuries must be observed; occasionally waste deposits rich in gypsum are available; however, security standards of other elements in wastes must be observed
- **calcium chloride** is usually too expensive for applications in developing countries, yet reclamation can be rapidly achieved; the high solubility provides high initial electrolyte levels, which favours favourable soil structure development,
- **calcium carbonate** is usually not efficient due to its low solubility; it may be beneficial at moderate ESP values < 20% (Shainberg/Gal 1982),
- high **salt water dilution** can be used if the irrigation water contains enough divalent cations; large quantities of water volumes are required to substitute Ca for Na at the soil's exchange complex (Rhoades/Loveday 1990),
- **fertilisers** which contain Ca-salts or other Ca-additions and which react neutral or acid may be used especially to accelerate solubility of amendments and to reduce extremely high pH-values, often associated with high sodium contents.

The rate of amendment application is calculated by the 'gypsum requirement':

kg gypsum/ha = (8.5)d × db × Ec (RNai - RNaf),

where d = depth of soil considerd, db = bulk density of soil (g/cm^3), Ec is cation exchange capacity (mmolc/kg); RNai and RNaf are initial and final Na-adsorption ratios, respectively. A common factor to compensate for inefficiencies in the cation exchange process for gypsum is 1.25 (USDA). Soils rich in Mg might need further adjustments.

Equivalent amounts to gypsum are given in Table 3-39 for other amendments.

In practice, local experience and economic considerations determine the application rates and methods. A common practice for reclamation of sodic soils is to apply about 10 t/ha of gypsum in the first year and use about 1.5 m of leaching water. In the subsequent three years, an additional 4 t/ha/a are applied, with some leaching (Rhoades/Loveday in: Stewart et al. ed. (ASA) 1990)

Methods of reclamation of sodic soils are summarised as reclamation programmes in Tables 3-40 a-b.

Further reading: Kandiah (FAO) 1990; Keren/Miyamoto in Tanji ed. 1990; FAO (SB 39) 1988; Szabolcs 1989, 1979; Loveday in Shainberg/Shalhevet ed. 1984; Bresler et al. 1982;

3.4 Control of Soil Erosion

Key words:

soil conservation methods; furrow irrigation; sprinkler irrigation; wind ersoion control methods

Cross-references:

Part I sections 3.3; 5.3.4

Part II section 3.2; 5.3

Main References:

Hudson (FAO SB 57) 1987; Carter in Stewart ed. 1990; Morgan 1986; Breburda 1983; ASA 1982 and various FAO-documents: eg FAO (SB 44) 1985; FAO (CG 13); FAO (CG 14), FAO/UNEP 1983

Erosion contributes to water and air pollution and is a major cause of soil degradation. Therefore, remedial measures to control erosion on-farm may have beneficial in reducing water pollution downstream. Most technical, agronomic and other measures are applicable to both irrigated and non-irrigated agriculture, and a separate treatment of interrelated impacts and effects is not necessary.

3.4.1 Control of On-Farm Soil Erosion

The design of strategies for erosion control under irrigation must be based on a thorough analysis of the mechanics of detachment and transport of soil particles by natural rainfall, irrigation-induced runoff and wind (Part I section 3.3). Conservation measures should involve:

- protection of soil from raindrop impact (rainfall or sprinkler droplets)
- minimising overland flow velocity during surface irrigation applications as far as possible
- avoiding run-off under sprinkler irrigation
- increasing the infiltration capacitity of the soil
- increasing the roughness of the soil surface
- protection of agricultural lands from strong winds.

These remedial measures can be grouped under the headings of mechanical, agronomic and irrigation techniques and soil management. Agronomic techniques and soil management influence both detachment and transport, whilst irrigation techniques and mechanical measures mainly influence transport processes (Table 3-41). A combination of measures is usually required and their adequacy must be balanced against technical feasibility, management needs, costs involved, and defined needs for sustainable irrigation. Planning for new projects should include aspects of erosion hazards and erosion control (section 3.2).

Methods of soil conservation for agriculture are already treated in textbooks and field manuals (eg Hudson 1987, Morgan 1986). A summary of common knowledge is shown in Figs. 3-27 and 3-28 and therefore, special emphasis is given here to irrigation.

Control of furrow erosion and associated soil loss may include:

- **sediment retention basins**: basins constructed in drainage ways to temporarily intercept irrigation run-off and serve as a sediment trap to prevent the suspended load being transfered to reservoirs, canals or rivers. The sediment removal efficiency depends on flow rates, sediment concentration, particle sizes, and time available for deposition. Basin sizes may be larger than 1 ha. More often, minibasins are excavated in drain ditches. If each basin has an outlet into a separate drainage ditch, sediment removal efficiencies range from 65 to 95%. If water is allowed to pass thro-

Fig. 3-27

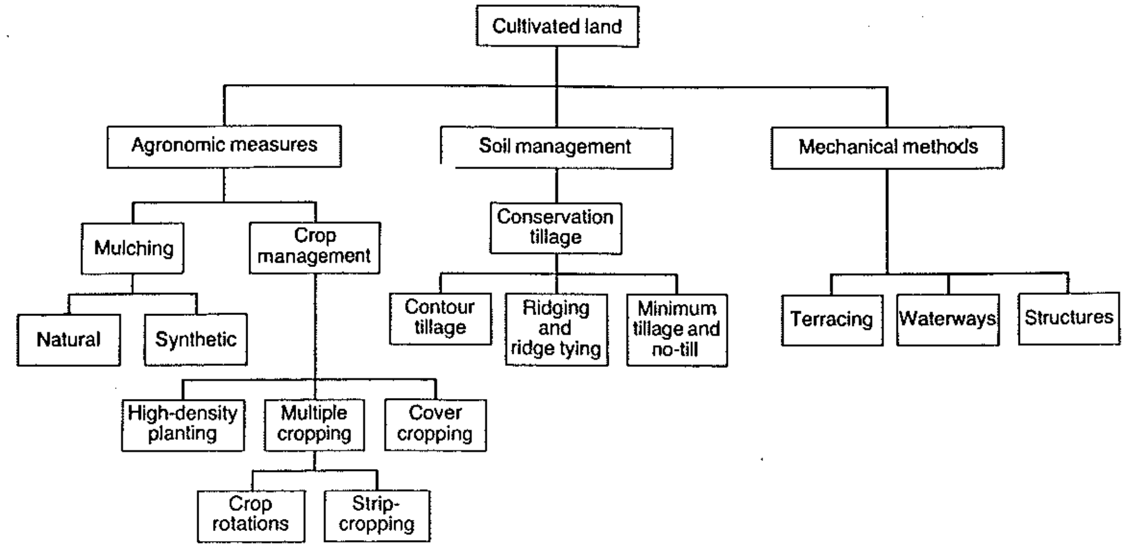
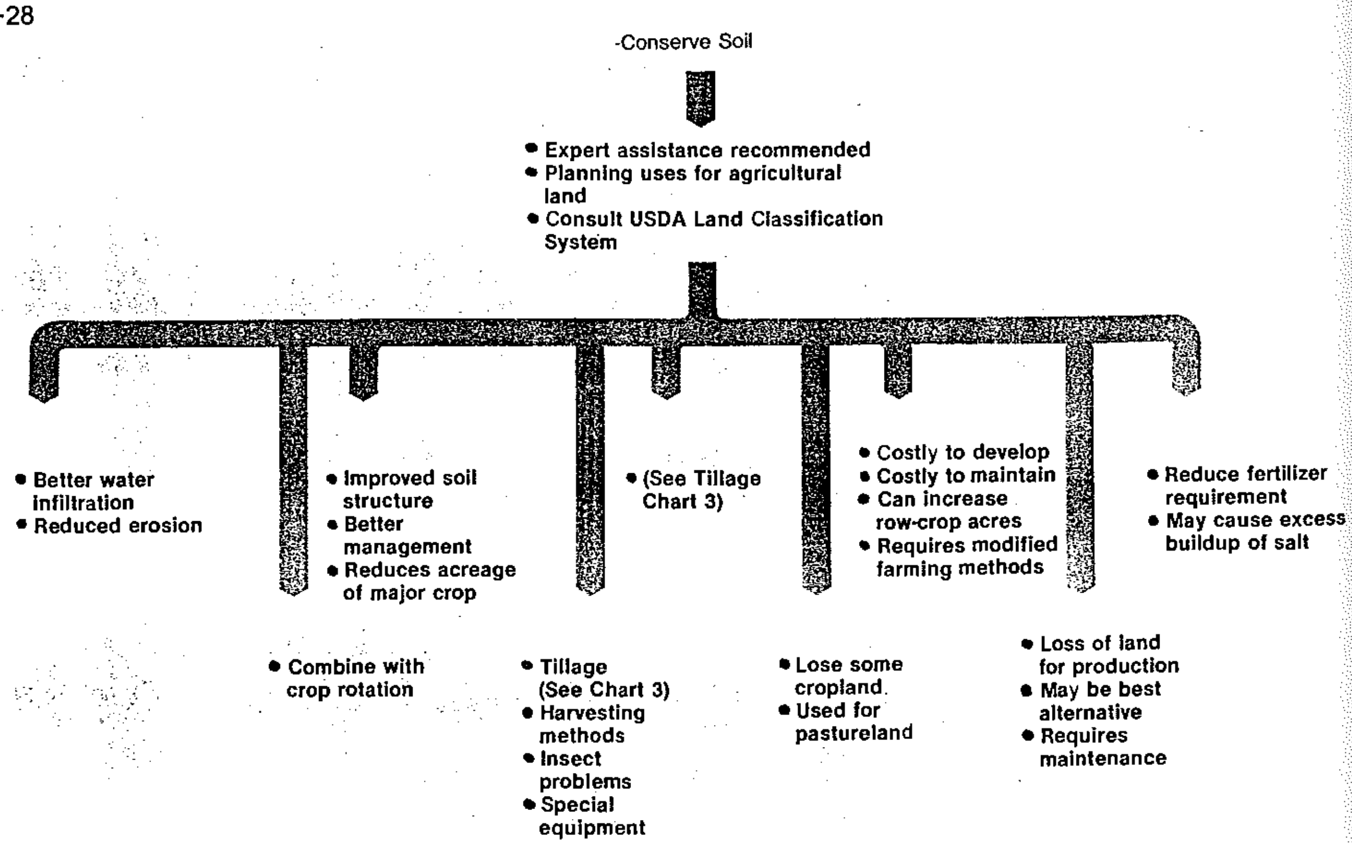


Fig. 7.2 Soil conservation strategies for cultivated land (after El-Swaify, Dangler and Armstrong, 1982).

Source: Morgan 1986

Fig. 3-28



Source: Hughes 1980

ugh a series of basins, each successive basin becomes less effective, although more sediment is removed generally. Regular cleaning and shape maintenance of all sediment retention basins is a common disadvantage because of high maintenance costs,

- **buried pipe systems** have vertical inlets at intervals to correct the erosion problem at convex field ends; the pipe replaces the tailwater drainage ditch, and the vertical inlets serve as individual outlets for minibasins formed by earthen bunds across the convex portion of the field; as the minibasins fill with sediment, their efficiency decreases, but erosion rate decreases on the convex end, too. Drainage water is carried away through the buried pipe, preventing water ponding at the field end. Sediment removal efficiency may reach 80 to 95%, and after filling it decreases to about 70%,
- **vegetative filters**: inexpensive erosion and sediment loss control may be achieved by planting a strip of grain crops, grass, or fodder along the lower end of a field of row crops. They may remove 40 to 60% of the sediment load from furrow runoff water. The filter should be planted close to a drainage ditch and irrigation furrows should extend about one-half of the way through the filter strip. About 2 m should be left between the furrows and the ditch to allow water to spread through the filter,
- placement of **crop residues** in furrows: straw or other residues can be placed in irrigation furrows to reduce flow rates and thus erosion and increase infiltration. Thes are most effective when placed in the steepest sections,
- **irrigation management**; the smallest possible stream should be applied. The required stream size is determined by the infiltration rate, slope along the furrow, and the furrow length. Reducing length may be the best alternative. Another option is to compact furrows to reduce infiltration on upper furrow sections allowing a longer application. Surge flow is another manual or automated cut-back system approach at lower discharge.
- **conservation tillage**, including no-tillage or minimum tillage systems can be applied successfully to rainfed farming. Only recently has experience been gained from irrigated farming; furrow erosion and sediment loss may be reduced by 80 to 90% with no-tillage and by 50 to 80% with minimum tillage systems (production costs may decrease by 10 to 30%). However, these systems often require intensified weed control (by herbicides) and careful cleaning and regrading of furrows before irrigation. Conservation tillage is applicable especially where irrigation furrows are small, eg using 'corrugates',
- **structural treatments**, similar to conservation treatments in rainfed farming, eg bench terraces. These have high investment costs (some US $ 400-1000/ha in Indonesia) and high maintenance requirements. Designs must be site-specific to accomodate the engineering properties of soils and the rainfall pattern (eg ensuring adequate soil stability, providing adequate drainage to accommodate peak overland flows, minimising subsoil exposures).

Sources: Carter in: Stewart et al. ed. 1990; Broner in: ICID (STS-C8) 1991

Erosion control under <u>sprinkler irrigation</u> can be achieved by reducing the energy of water drops, maintaining infiltration, reducing overland flow, and protection against sheet and rill erosion. The following practices may be used:

- irrigation management: the application rate should not exceed the base (final) infiltration rate of the soil. Consequently, sheetflow is minimised and only raindrop (splash) erosion may occur. Usually center pivot systems require better management practices for correct operations than hand or machine moved units. Nozzles or heads should be designed to distribute water drops at the lowest possible kinetic energy,

- conservation tillage practices can be applied similar as those developed for non-irrigated crops. Tillage operation should aim at leaving crop residues on the soil surface to provide a porous and aggregated surface.
- reservoir tillage is most effective in the form of micro-water storage basins in the soil surface to catch and temporarily store water until it infiltrates. Reservoirs function best when small depressions are formed by scooping or pressing rather than being formed by earthen dams (bunds) in furrows, becasue those tend to collapse when depressions are filled with water. Reservoir tillage is usually done in the same operation with planting or after planting. Runoff can be prevented even when the water application exceeds infiltration rate. Furthermore, it is effective to intercept heavy rainfall.

Source: Carter in: Stewart ed.1990

Further principles of erosion control under irrigation are:

- the design of basins or furrows with reduced length of run allows for smaller flows which are easier to control
- furrows should follow the contour or be constructed across the slope (<2 to 3%),,
- contour irrigation may increase wetted subsurface areas further apart from furrows,
- contour irrigation is well adapted to crops that require ridging,
- technical devices to control and measure flows are required for efficient control of water application; such measurements require trained farmers,
- initial flow (with surface irrigation), which is required to get the water to the end of the field, should not be excessive because severe erosion occurs early in irrigation,
- the smallest stream that will irrigate to the end of the field (or furrow) is better for uniformity of application and for erosion control; if more water is needed, the number of furrows or the duration of irrigation can be increased,
- it is more efficient for erosion control to irrigate thoroughly and less often, but this may contradict sometimes with efficient salt control,
- alternative furrow irrigation may help reducing labour and minimising erosion; each application requires the double water volume as in the case where every furrow is irrigated; soils with sufficient lateral water movement are required (eg loamy sands).

Source: Mech/Smith in: Hagan et al. ed. 1967

3.4.2 Control of Wind Erosion

Measures to control wind erosion should consider the effects of

(i) **vegetation and organic matter**: a good cover of crops or vegetative residue provides the most effective protection from wind erosion. Organic matter ploughed under usually provides no effective protection. Aggregate stability is increased during the process of decomposition but after straw/stubble is decomposed aggregating effects are weak, and the best protection from wind erosion while fallow is obtained by keeping vegetative matter anchored on top of the soil. Favourable conditions under irrigation stimulate growth of both the planted crop and volunteer growth from crop residues or weeds. Such volunteers should be allowed wherever possible.

(ii) **use of water**: timely applications of water for wind erosion control allows for growth of vegetation and creates moist conditions. Moist soil has a threshold wind velocity considerably higher than that for dry soil, caused by stronger cohesion between particles. The best wind erosion control may be achieved either by daily irrigation (maintaining a continuously moist surface) or by larger irrigation intervals which avoid a frequent pulverization from regular overland flow. The impact of raindrops or sprinkler irrigation tend to break these clods and under sprinkler irrigation the surface roughness decreases rapidly.

Clods also tend to slake down during sheet flow (surface irrigation), and furrow irrigation is best suited to prevent smoothening and surface crusting because wetting is confined to furrow depressions; .

(iii) **tillage practices**: tillage is a very efficient method of increasing the surface roughness by forming rough, cloddy aggregates, but effects are temporary under irrigation (see above). Special tillage may be considered for erosion protection outside the cropping season and if vegetative cover does not exist; ridging is probably the most effective seedbed preparation. However, some tillage practices for the control of wind erosion which are advisable for non-irrigated agriculture may not be applicable for surface irrigation systems; the orientation of tillage operations should consider the wind directions prevailing when protection is desired.

(iv) **wind barriers**: shelterbelts and windbreaks are effective in protecting agricultural lands from strong winds and erosion; they absorb and deflect some of the wind force and provide sedimentat traps and thus may protect crops from corassive action. The effectiveness of a windbreak depends on wind velocity and direction, and the orientation, shape, width, height, length and porosity of the barrier. In general windbreaks consist of rows of conifers interrupted by fast growing short-lived deciduous shrubs or fast-growing eucalyptus trees. For best protection (within 10 to 20 times the height the belt), porosity of the belt should be 50 to 60% (see Figs. 3-29 and 3-30). However, the areal extent of protection is limited and the land losses and additional costs of irrigation water must be considered in arid areas. In large smallholder irrigation schemes in Libya the water demand of shelterbelts may reach 15% of total irrigation demand with windbreaks covering some 10% of the irrigated area. With drip irrigation water savings and improvements in the uniformity of water distribution may occur.

(v) **seasonal protection cover**: in some areas it may be advisable to grow a crop (fodder crops or fodder grasses) to provide seasonal protection outside the main cropping season. However, the economic viability must be analysed.

(vi) **selection of crops**: some crops are susceptible to wind damage, eg some fruit trees and vegetables. Selection of protected sites (eg close to windbreaks) or avoiding seasons with high wind speeds can be taken to minimise damages.

Source: Mech/Woodruff in: Hagan et al.1967

Details of sand dune stabilization and shelterbelts for irrigation schemes are presented in FAO Conservation Guide 10 (1985).

Further reading: Rochette (GTZ) 1989; Hudson (FAO SB 57) 1987; Morgan 1986; Breburda 1983; ASA 1982; Morgan ed.1981; Schwab et al.1980; Kirkby/Morgan ed.1980; FAO (CG1) 1977; FAO (SB33) 1977; Hagedorn ed. (GTZ) 1977; Weidelt ed. (GTZ) 1976; Hudson 1971; FAO 1960, 1965

Fig. 3-29

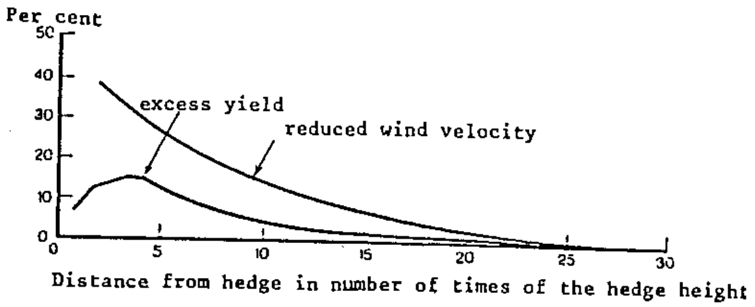


Figure 4

Relation between wind velocity and yield. The chart shows the average reduction of wind velocity in the growing season with a screen, and the measured yield of clover. The maximum yield appears in the area 1 to 5 times the screen height, where the shelter is optimal.

Source: FAO (CG 10) 1985

Fig. 3-30

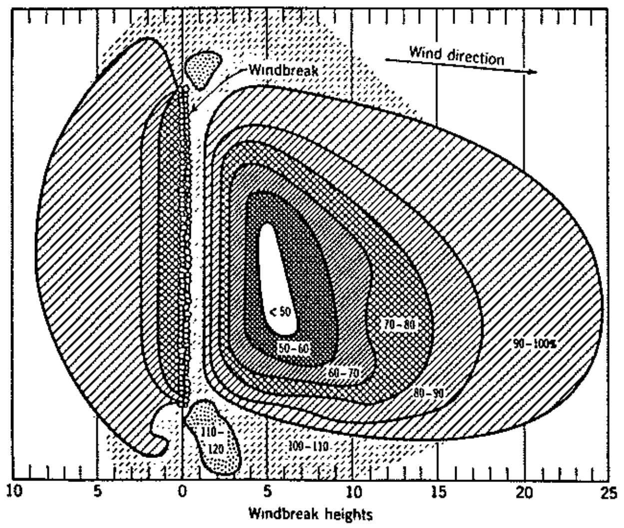


Fig. 6.7. Percentage of normal wind velocity near a windbreak having an average density of 50 percent. (Redrawn from Bates, 1944.)

Source: Schwab et al. 1981

4. Measures to Reduce Health Risks

Key words:

categories of diseases; sewage reuse potentials and risks; technical measures; health care programmes; reuse monitoring; forecasting health implications; community vulnerability; environmental receptivity; vigilance of the health service; hazard and risk assessment; assessment worksheets; health safeguards; environmental management; engineering controls in reservoirs; river flushing; engineering controls in irrigation schemes; drainage; irrigation canal design; canal maintenance; canal operation; farm water management; biological and chemical control; environmental impacts of health control measures; evaluation matrix. monitoring; evaluations

Cross-references:

Part I sections 8.1 and 8.2; 2.3.7; 3.4

Part II sections 2.5; 3.2.4; 5.2

Main Reference:

Birley (PEEM) 1992; Feigin et al 1990; Oomen et al (ILRI) 1990; WHO 1989; Mara/Cairncross (WHO) 1989; WHO 1989; Pike 1987; Shuval et al. (WB) 1996; Mather/That (FAO) 1984; WHO 1980

4.1 Introduction

Inevitably, the need for water for irrigation leads to the construction of reservoirs, networks of conveyance canals, flooded fields, and waterlogged disposal areas which provide ample habitats for the transmission of water related diseases (Fig. 4-1) (see also Part I section 8). Only recently, the potential implications for public health have been fully realised and new approaches are required to reduce the potential risks from irrigation and related waterworks (Fig. 4-2). Furthermore, it must be realised that engineering alone can never provide a complete solution to the problem. An integrated approach between planners, engineers, supervisors, farmers and public health institutions is needed to meet the challenges.

There are four categories of diseases which are associated with water:

(1) diseases prevented by washing and bathing,

(2) diseases prevented by clean water supply and sanitation,

(3) diseases acquired by professional or recreational water contact (depending on intermediate hosts; vectors),

(4) diseases acquired from insect bites.

Diseases in categories (3) and (4) are typically adversely affected by irrigation development projects (Fig. 4-3) (see also Part I section 8). However, careful planning and design of hydraulic infrastructure, irrigation methods, techniques and operating schedules, agronomic measures, and observation of water safeguards can help to prevent or reduce transmission of most of these diseases. This can be achieved by reducing the number of vectors and/or contacts with water. It is recognized that preventive health care measures can be introduced into water development projects without impairing their efficiency, and there is a distinct possibility that such measures will increase production efficiency and, hence, increase the general living standard which ultimately will lead to improved standards of rural health.

Sources: Birley (PEEM) 1989; Hillman in: Rydzewski ed. 1987; Hunter/Rey/Scott (WHO) 1980

Fig. 4-1

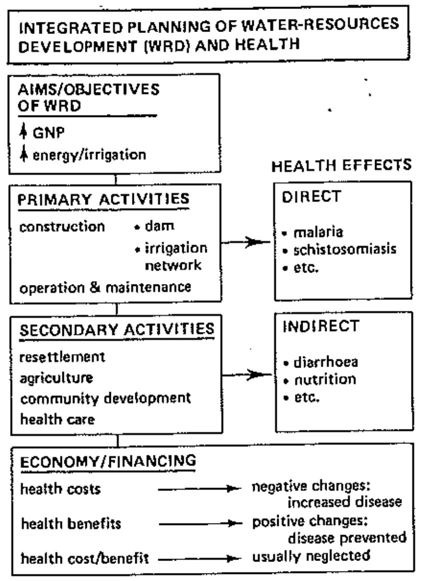


Figure 1.1 Integrated planning of water-resources development and health

Source: Oomen et al. 1990

Fig. 4-2

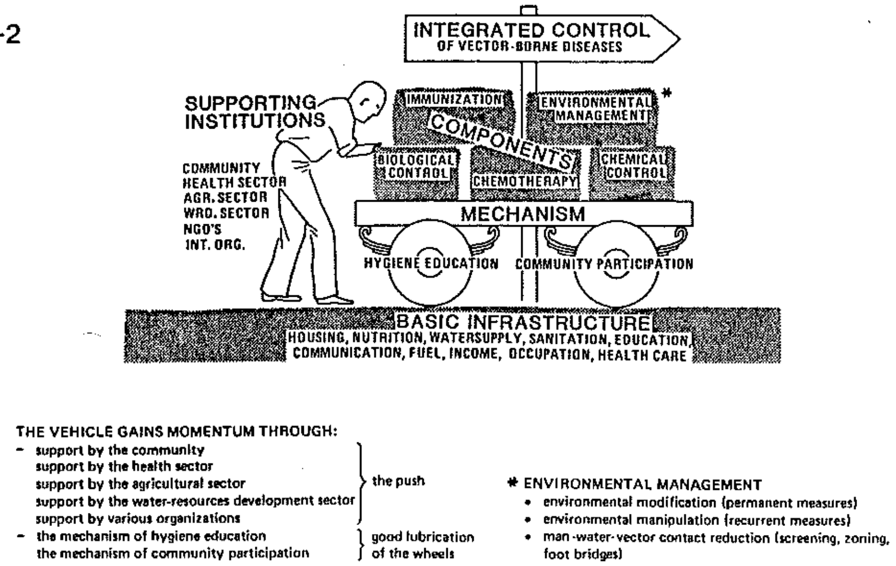


Figure 1.4 Integrated control of vector-borne diseases

Source: Oomen et al. 1990

Fig. 4-3

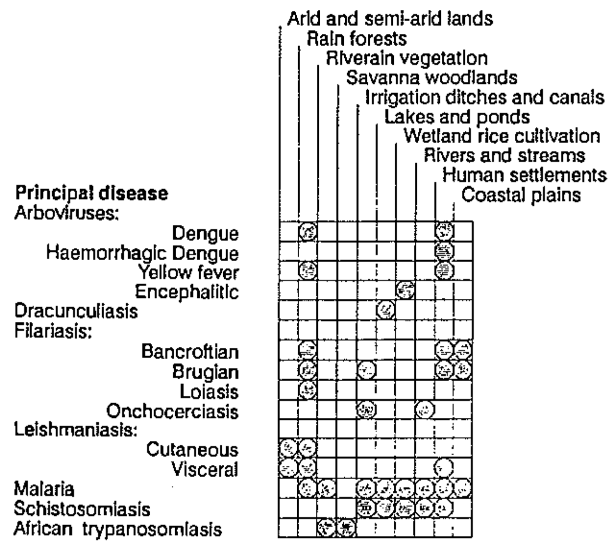


Table 2-3
The principal diseases associated with water in relation to the principal habitats of the vectors.

Source: Birley 1992

4.2 Reducing Health Risks in Wastewater Irrigation

4.2.1 Introduction

Where water resources are limited the reuse of municipal or agricultural wastewaters is an important water development option (see sections 2.2 and 2.5). Many societies have practiced excreta and effluent reuse successfully for decades, eg in rice irrigation in China (eg FAO (SB 40) 1978). Apart from conserving water, reuse of wastes provides a solution to the problem of disposal and it provides nutrients and trace elements to soils which are necessary for improved plant production (see also sections 2.1, 2.5 and 3.2).

Further reading: Shuval (WB) 1990; Hillman in: Pescod/Arar ed. 1988

Sewage comprises waste liquids including faeces and urine to which various amounts of industrial effluents may have been added. It has therefore a great potential for the transmission of diseases (pathogenic organisms and/or hazardous chemicals) and the rapid spread of infection within the community. Types of diseases, sewage treatment options and on farm management options to minimise health hazards have been already outlined elsewhere. It is vital that planners, engineers and public authorities fully evaluate the potential risks to public health of any proposed reuse project prior to its implementation.

Usually, the risks and costs involved in appropriate protection measures can be minimised and reuse can prove to be cost-effective. However, it is probably in the area of health education that some reuse projects have failed in the past. The wastewater treatment plant operators and the farmers must understand the importance of procedures which are designed to limit the risk they face and to limit the threat to the general public. The reuse of untreated sewage poses too many risks and existing night-soil collections should be stopped.

Whatever standards are applied (see chapter 4.17), enhanced monitoring programmes are required regarding:

- routine surveillance of the **quality of crops**,
- improved monitoring of **wastewater quality**,
- **health education** programmes to promote hygienic measures,
- continuous monitoring of **disease prevalence**.

However, lessons drawn from comparing the diverse approaches in various countries are that there is no single standard or best strategy which should be adopted. The situations and needs of each country and locality should rather be viewed on their own merits and the appropriate strategy be chosen accordingly (Strauss 1989).

Source: Hillman in: Rydzewski ed. 1987

Further reading: Feigin et al 1990; Mara/Cairncross (WHO) 1989; WHO 1989; Strauss 1989

4.2.2 Technical and Policy Options for Remedial Measures

Measures that reduce or eliminate potential health hazards and economic burdens resulting from unregulated irrigation with wastewater include:

- **agronomic measures**: restriction of crops, modification of irrigation practices,
- **disinfection** of farm produce,
- protection of **occupational health**: for example, use of protective clothing,
- **medical treatment**: prophylactic and/or chemotherapeutic treatment of the exposed population,
- **wastewater treatment**: to reduce the concentration of pathogens and chemicals.

Generally, integrated and site specific combinations of these measures are preferred to single or standardised programmes. Further details are given in section 2.5. In the following, programmes related to public health care are outlined.

* improving **occupational health** of farmers or sewage farm workers by reducing exposure to infection: the main diseases affecting farmers (hookworm, ascaris, bacterial diseases) can be reduced by proper clothing (shoes, boots) and attention to personal hygiene such as washing after work and before eating; among farmers with a higher educational level and improved socio-economic conditions, educational programmes aimed at achieving such goals may have some impact. Such programmes are often especially effective in centrally organised projects with a supply of clothing and adequate washing facilities. In marginal smallholder wastewater farms, such programmes are often ineffective,
* **prophylactic** and **chemotherapeutic** medical treatment: such treatment for the control of endemic enteric diseases in areas where transmission cannot be easily controlled due to poor personal hygiene and sanitation. During the initial stages of projects it may be effective as an interim measure to reduce environmental exposure and reinfection. **Immunisation** has been effective against a number of diseases (typhoid fever; polio; smallpox; and cholera to a lesser extent) but no simple solution exists for various helminth and protozoan infections; mass immunisations against potential enteric viruses are not a likely prospect, except for a few diseases such as infectious hepatitis and possibly retrovirus disease. **Chemotherapy** can be used in mass deworming campaigns with broad-spectrum antihelminthic drugs. Under endemic conditions of poor sanitaion and continuing reinfection this strategy is not widely accepted as a substitute for improving hygiene and other preventive measures due to the high costs involved. In addition, administering drugs regularly to large population groups may pose problems (vigilance of health services) and some drugs may have side-effects which require control. However, regular chemotherapeutic treatment for control of severely debilitating hookworm infections among selective groups of highly exposed individuals is an option,
* supply of additional **nutritional supplements**, such as iron: such pelliative remedial programmes may help to alleviate anaemia of highly exposed persons suffering from hookworm diseases.

Source: Shuval (WB) 1990; Shuval et al. (WB) 1986

Table 4-1 lists the official health protection measures which are currently being followed in some major wastewater reuse irrigation schemes.

4.2.3 Monitoring

If new wastewater projects are promoted, legislative action may be needed for establishing monitoring systems. Four areas deserve attention:

- creation of new institutions or allocation of new powers to existing institutions,
- roles of and relationships between national and local government institutions,
- right of access to and ownership of wastes, including public regulation of their use,
- public health and agricultural legislation.

In particular, the following critical issues must be addressed:

(i) type and kind of data:

continuous records should be maintained of the pevalence of various diseases in exposed groups: these can be generated for example, from a regular seasonal stool survey for intestinal parasites and surveillance of diarrhoeal diseases: bacteriological examination, serological survey (typhoid);

continuous records of crop and/or water quality with regard to microbiological and chemical properties such as helminth eggs, faecal coliforms, pH, EC, SAR, N-P-K, B and heavy metals should be kept (various WHO guidelines define the criteria WHO 1981, WHO 1983, WHO 1984, WHO 1989),

(ii) responsibility for data collection: interval of data collection; provision of financial, laboratory and personnel resources,

(iii) responsibility for examination and evaluation of data: by operating institution, by local or national health institutions, or independant health institutions,

(iv) responsibility for action programmes: this requires sets of standards to which the results can be compared,

(v) responsibility for execution/implementation of routine or special programmes (related to water treatment or to health services),

(vi) responsibility for the monitoring of such control programmes.

Source: Mara/Cairngross (WHO) 1989

A complete monitoring and control system therefore needs

(i) guidelines and/or standards,

(ii) monitoring or surveillance to assess compliance,

(iii) institutional arrangements for feedback or enforcement.

Sources: Mara/Cairngross (WH) 1989; Hillman in: Pescod/Arar ed. 1988; Shuval et al. (WB) 1986

Further reading: Shuval (WB) 1990; Feigin/Ravina/Shalhevet 1990; WHO 1989, WHO 1984, WHO 1983, WHO 1981

4.3 Control of Other Water-Related Vector-Borne Diseases

4.3.1 Introduction

The incorporation of disease-control measures in irrigation projects is a multi-faceted task in project identification, design, construction and operation. During early project planning objectives are formulated, and development potentials or constraints are identified and evaluated. This includes (for example within the course of environmental appraisals) the rapid assessment of health risks associated with the planned water development project.

Typically, such evaluations are a part of pre-feasibility studies (see Fig. 4-4) or project appraisals (GTZ). Guidelines for water resources development are given by PEEM (WHO/FAO/UNEP) Guidelines 2 (Birley 1992); the procedures are explained in the following section. More detailed epidemiological studies may be required for health planning for large scale projects or if a need for major interventions is identified during the course of the rapid health assessment. Further details are presented in Oomen et al (ILRI) 1990.

PEEM is the Panel of Expets on Environmental Management for Vector Control, World Health Organization, Geneva

4.3.2 Forecasting Health Implications

Preliminary health impact assessments include situation specific information on

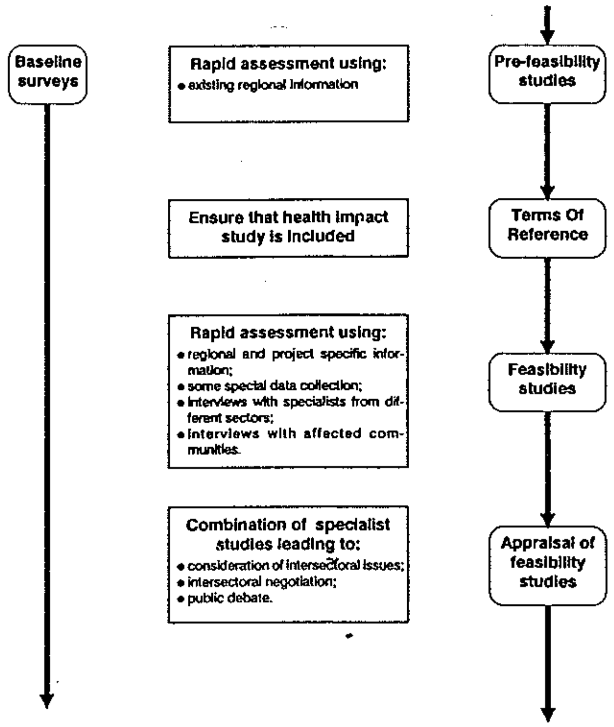
- type of vector-borne diseases in the region,
- their relationship to water,
- capacity of the existing health service to implement control programmes.

Source: Birley (PEEM) 1989; a detailed checklist and a questionnaire for informal interviews during baseline surveys are shown in Birley, Annexes A and B

Fig. 4-4

Figure 1

HEALTH IMPACT ASSESSMENT AND THE PROJECT CYCLE



Source: Birley in Wooldridge ed. 1992

A rapid assessment procedure for identifying health hazards in small scale irrigation schemes is shown in Bolton/Imevbore/Fraval 1990. The document includes a questionaire and guides for interpretation

The detailed assessment procedure developed by PEEM is shown in Fig. 4-5 a-b. Flowcharts and worksheets provide a focus and structure within which data are gathered and interpreted for each disease and each project phase. Descriptive scores are assigned and much of the procedure is aimed at justifying the assigned scores. The information are compiled in a Worksheet which indicates whether the hazard associated with each vector-borne disease is likely to be reduced, to remain the same or to be increased by the activities of a specific project phase (Table 4-2/1 to 6). The assessment system has three main components:

(I) **Community vulnerability**: the disease situation depends on the prevalence of infection in specific subgroups such as male/female, adults/children, farmers/other workers, hunters/farmers, etc. It also depends on proximity to areas where disease occurs, general health status, and the potential effect of an influx of migrants. Three scores are used:

'low vulnerability': communities who are unlikely to be exposed to a parasite,

'moderate vulnerability': the disease is present at restricted foci at or near the project site; relatively few people are susceptible or engaged in behaviour which places them at risk of exposure,

'increasing vulnerability': the population is largely susceptible to infection, there is little protection or immunity or little experience of the disease or exposure is expected to occur on a large scale. The community may be moving to an area with high prevalence, or changing its major occupation, or infected immigrants may be joining the community.

(II) **Environmental receptivity**: the transmission potential is determined by the abundance of vectors, degree of human contact with vectors or unsafe water and other ecological or climatic factors favouring transmission. Ranking includes:

'no receptivity': transmission is possible, but is not occurring; the vector is present in small foci but there is no human contact or the environment discourages vector breeding at present although this could change,

'moderate receptivity': transmission is easily resumed; the vetor has been eradicated but recolonisation is likely if vigilance were to be reduced, or as a result of development,

'high receptivity': there is likely to be an explosive increase in infection; the project will create or enhance either vector breeding sites or opportunities for human contact with vectors or unsafe water sources.

(III) **Vigilance of the health services**: describes the management effectiveness for adequate control and treatment programmes; it includes vaccination campaigns; detection of imported or relapsed cases; drug provision and delivery; hospital facilities; sufficient and trained personnel and vector control. Two components must be considered separately: prevention and cure. Ranking includes:

'very good': the health service includes effective preventive measures (vector control, chemoprophylaxis) and effective treatment (trained personnel, access, case detection, drug supply),

'effective preventive measures only': there may be a good residual spraying programme but no supplies of curative medicines or trained health service personnel,

'effective treatment only': there may be good supply of medicines and access to trained personnel, but no vector control measures,

Fig. 4-5 a

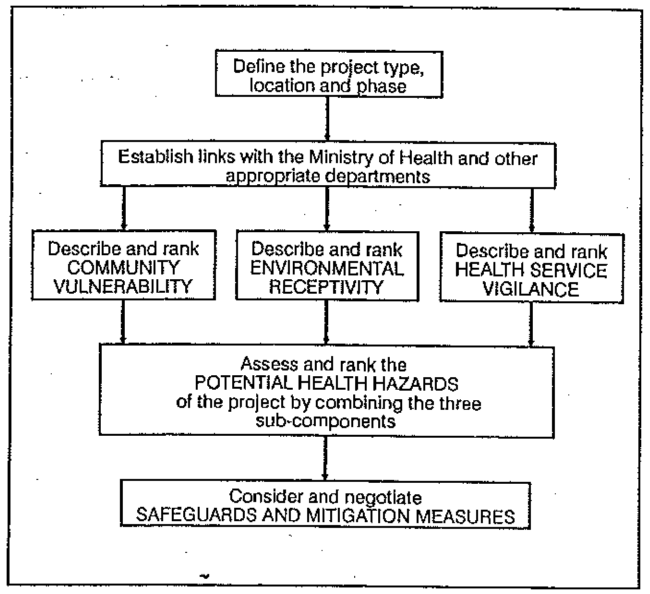
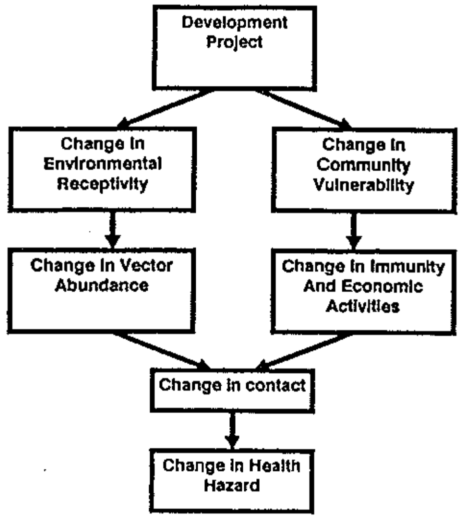


Figure 1-3. An overview of the assessment procedure.

Source: Birley 1992

Fig. 4-5 b



Source: Birley 1992

Fig. 4-6 a

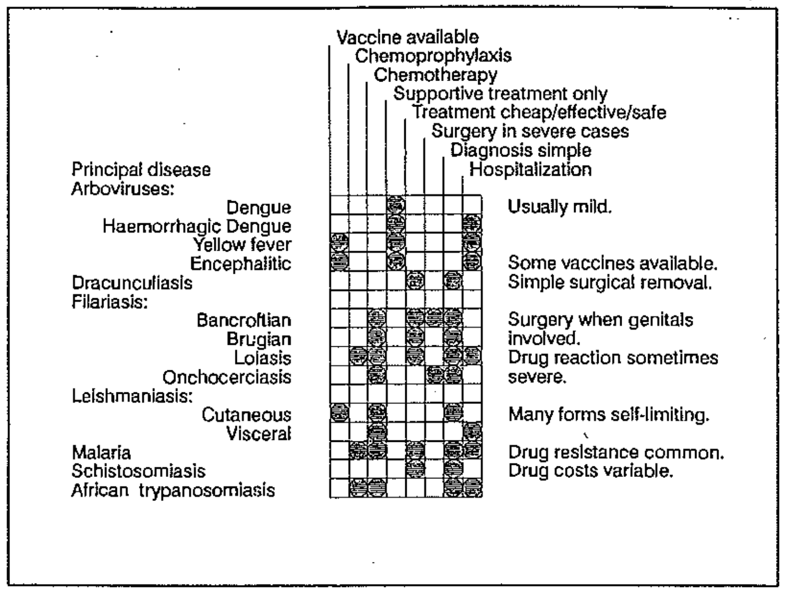


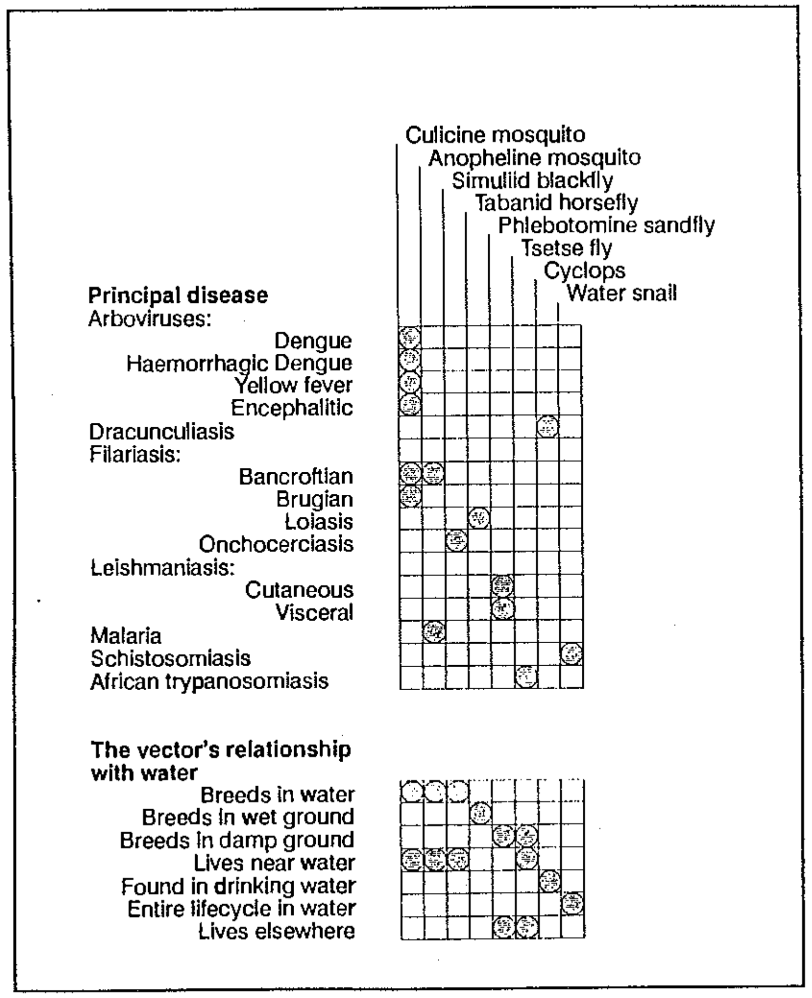
Table 1-7

A broad indication of the factors affecting medical treatment of vector-borne diseases. There are many additional complications. See references for additional texts.

Source: Birley 1992

Fig. 4-6 b

Table 2-4
Association between vector, disease and water.



Source: Birley 1992

'none': no effective health service of any kind because there is no infrastructure or the available services are under-supplied, unaffordable or inaccessible.

The **total health risk** faced by a community must be ranked as low, moderate or high or as likely to increase/decrease as a result of the project. There is no simple system for combining the ranks ascribed to the three components. For example, the risk of malaria may increase because there is no effective health service or because there is more opportunity for vector contact. Whatever rank is chosen must be justified by a written explanation (see Table 4-2/1 Assessment and Explanation)

Three flowcharts list the issues which need to be addressed in order to complete the Worksheet (Table 4-2/2 to 5). The questions may be answered by examination of relevant information (eg PEEM Guidelines), interviewing health specialists, or making an informed guess based on knowledge and experience. In most developing countries guesses may be unavoidable due to limited availability of basic data (or restricted access to data), but when made they must be clearly indicated.

Further details and discussion on community vulnerability and the vigilance of health services are given in Birley (PEEM) 1989. A broad indication of factors affecting medical treatment of vector-borne diseases is given in Fig. 4-6a.

The association between vector, disease and water is shown in Fig. 4-6b. Some basic issues which influence or determine environmental receptivity to transmission are mentioned in the following:

abundance: vector numbers usually vary over quite small distances and between wet and dry seasons; many vectors depend on water for their breeding sites; the contact may also vary seasonally

bounding in time and space: the extent of health hazards may be linked to certain project cycles, for example construction and operation. Vector-borne diseases may be grouped according to the rate at which disease manifestations occur in the exposed community. Some diseases may depend on a gradual build-up of vectors and intensity of infection; fast-spreading diseases tend to be caused by protozoa and viruses and the pathogen proliferates in the human host with immediate effects and only a few contacts: eg malaria, leishmaniasis, dengue and Japanese encephalitis; control is aimed at reducing incidents. Examples of slow-spreading diseases are schistosomiasis, filariasis and dengue haemorrhagic fever which require porolonged and repeated exposure to infections.

colonisation: most vectors can colonise and recolonise breeding sites; flying insects can migrate over substantial distances. Snails are adapted to seeking passive transport on floating materials in rivers, the legs of animals or on vehicles (construction equipment). Local movements and migratory distances are indicated in Table 4-3.

breeding sites: development activities may have a dramatic impact on the abundance, distribution and classes of potential breeding sites. Each vector has its own preferences for breeding sites. Most oportunities for environmental management in irrigation projects include features which discourage the breeding of harmful vectors (see later in this chapter). Relevant experiences regarding geophysical and biotic environments which influence the availability of breeding sites are listed in Table 4-4. A classification of relevant human activities which have effects on vector incidence is given in Table 4-5.

human settlement design: contacts with vectors or unsafe water can occur on irrigated fields, within settlements, at water supply sites or along farm roads; contacts near the domestic environment may be prevented by eliminating potential breeding sites; settlements should be located at least 2 km from irrigated fields (for mosquito control) and adequate sanitation should be provided; contact with unsafe water is prevented by ensuring that safe water points are more convenient to use for various activities (see Part I section 8.2)

contact associated with vector behaviour: each species has different habits which determine when, where and under what conditions it is associated with people. Important differences include preferred breeding sites, preferred time and location of feeding and preferred blood (animal or human); there will often be other species which are far less important under current conditions but whose importance will increase as a result of the irrigation development. Contact can be reduced by reducing the abundance of vectors (or their breeding sites) or by changing human behaviour

contact associated with human behaviour: people come into contact with unsafe water through three broad categories of activities: recreation (eg swimming), occupation (irrigation, fishing, crossing water) or domestic (washing, cleaning, bathing).

animal reservoirs: some diseases are associated with animals, eg rodents (see Part I section 8.2). Fig. 4-7 indicates also those parasites which have non-human hosts.

Source: Birley in: Wooldridge ed. 1991; Birley (PEEM) 1989

4.3.3 Safeguards and Mitigating Measures

Safeguards are interventions which are intended to prevent health hazards from developing. In contrast, mitigating measures are interventions which are intended to make health hazards less severe. Changes in health conditions which are caused by water development projects (eg irrigation) habe already been explained in Part I section 8.2, namely

(i) changes in vector and water contact,

(ii) changes in terrestrial and aquatic breeding sites.

Various options for interventions, aiming at eradication or reduction of hazards, are available with any of these changes. They must be identified and evaluated on the basis of type, magnitude and durability of beneficial or detrimental effects, their costs and their effect on non-health related factors, such as agricultural productivity, and soil and water resources. Since environmental management for health control may pose detrimental environmental impacts for example on water pollution by insecticide use.

Health safeguards can be incorporated into projects during the **early design phase**, that is before health hazards have developed. A forecast of project implications should be developed for the case with no special safeguards and then for each alternative group of safeguards. Various types of potential project impacts should be considered. During the **construction** and **operation** phases various inter-sectoral mitigating measures should be planned and executed. These require appropriate institutional arrangements in which responsibility for health is clearly defined.

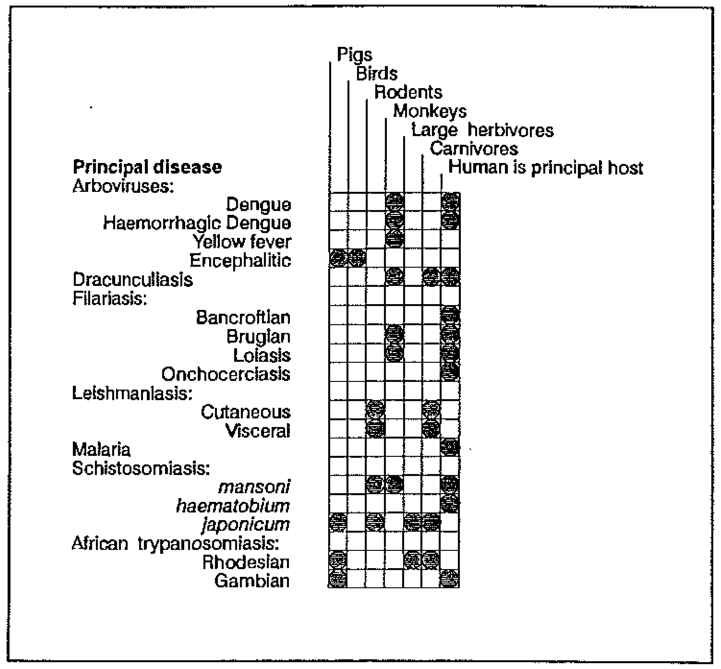
Special reading with regard to inter-institutional cooperation: Tiffen 1989

It is important to bear in mind that seldom is one single intervention adequate to control vector-borne diseases in large populations of people. The complexity of disease transmission and the difficulty of maintaining any single method require a rational and integrated approach which should consist of a mixture of careful siting, high standards of engineering design and construction, maintenance, and appropriate and effective institutional arrangements which aim to integrate available control measures. Any environmental management for disease control must be seen in relation to epidemiological factors and other control methods. For example, Fig. 4-8 a shows the natural and man-made factors that determine the epidemiological situation of malaria. Environmental management refers to:

- **water management** for vector control which aims to reduce areas of surface water or modifying some water management characteristics which reduce the emergence of adult vectors (vector density and vectorial capacity),
- **screening** of houses,

Fig. 4-7

Table 2-5
The main animal hosts of vector-borne diseases.



Source: Birley 1992

Fig. 4-8 a

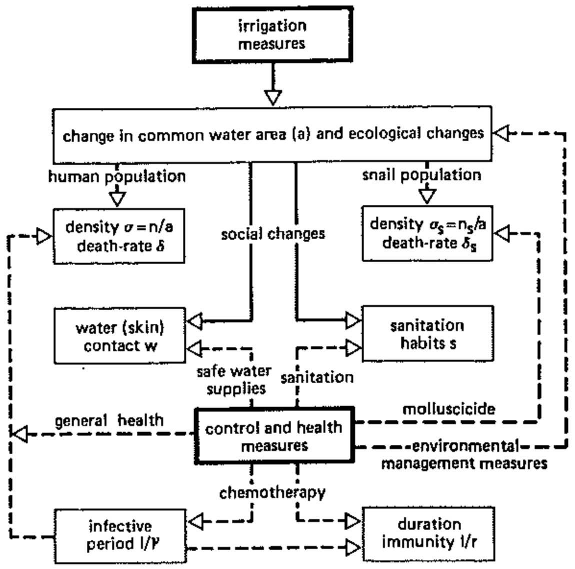


Figure 2 Irrigation, health, and control measures, and the nine parameters in the model that can be changed by these intervention measures

Source: Oomen et al. 1990

- **siting** of houses,
- destruction of larvae (**larviciding**) and adult vectors which can be done mechanically, biologically or chemically (insecticides, molluscicides),

Sources: Oomen et al. (ILRI) 1990; Birley (PEEM) 1989

Also regarding **schistosomiasis**, various parameters can be modified by different irrigation practices (Fig. 4-8 b). Some major intevention and the group of vectors on which they may have controlling impacts are summarized in Fig. 4-9. They are based on the classification of environmental measures given by FAO (FAO 1980):

(i) **environmental modification**: large scale or permanent alterations to the environment aimed at preventing, eliminating or reducing potential vector habitats; some of them need proper operation and maintenance to maintain efficiency,

(ii) **environmental manipulations**: any planned recurrent activity aimed at producing temporary conditions unfavourable to vector breeding or their habitats,

(iii) **modfication** or **manipulation of human habitation or behaviour**: intended to reduce contact with vectors or unsafe water.

Source: Birley (PEEM) 1989

In Zimbabwe, a pilot project was initiated in 1984 for the development of comprehensive guidelines to control the risk of schistosomiasis transmission by adapted design and operation of small irrigation systems (Mushandike Irrigation Project). Experiences include the formulation of criteria for schistosomiasis control; implementing these criteria in design, construction and operation of the system; establishing regular human parasitological surveys and treatments; and snail population and cercarial density surveys for monitoring of vector numbers. The control methods were tested: water source and main canal (with partial lining), reservoirs within the scheme, infield works with innovative control structures, water scheduling; village location, domestic water supply, sanitation, and drainage. First results indicate that the most efficient engineering options are canal lining to prevent seepage, innovative control structures, and irrigation scheduling. The package of control measures is aimed at interrupting the life cycle of the schistosomiatis parasites by:

- minimising man-water contact,
- trying to prevent faeces or urine, from entering the water
- diminishing the number of snails.

Source: Chimbari et al. in. Wooldridge ed. 1991; Bolton 1990 with further references

4.3.4 Engineering Control Measures in Large Reservoirs

Characteristics of large lakes (eg Lake Kariba, Lake Volta, Aswan High Dam) make it unlikely that environmental management methods, such as water-level fluctuations, application of chemicals, will be feasible for the control of vectors. In contrast, smaller reservoirs or networks of reservoirs in the same river system are well suited to management options for vector control due to a higher operational flexibility. **Water-level fluctuations** can be used for example for malaria control within the reservoir but also in the downstream river section. This may be aimed at eliminating the shoreline plants, stranding floating debris and flushing out of downstream sections when vectors are dislodged or exposed. In a reservoir the intersection line (for malaria control) or the iluminated shoreline (for bilharzia snail control) are of most importance in vector control.

In smaller reservoirs or larger irrigation canals the effect of flushing is limited in time and space which requires high flushing intervals. At least one flush per week and a velocity of some 0.5 m/s are required for control during the peak production period. This also applies to (larger) unlined irrigation canals where weed control is not feasible and water flows continuously: then, a flushing requirement should be considered during operation

Fig. 4-8 b

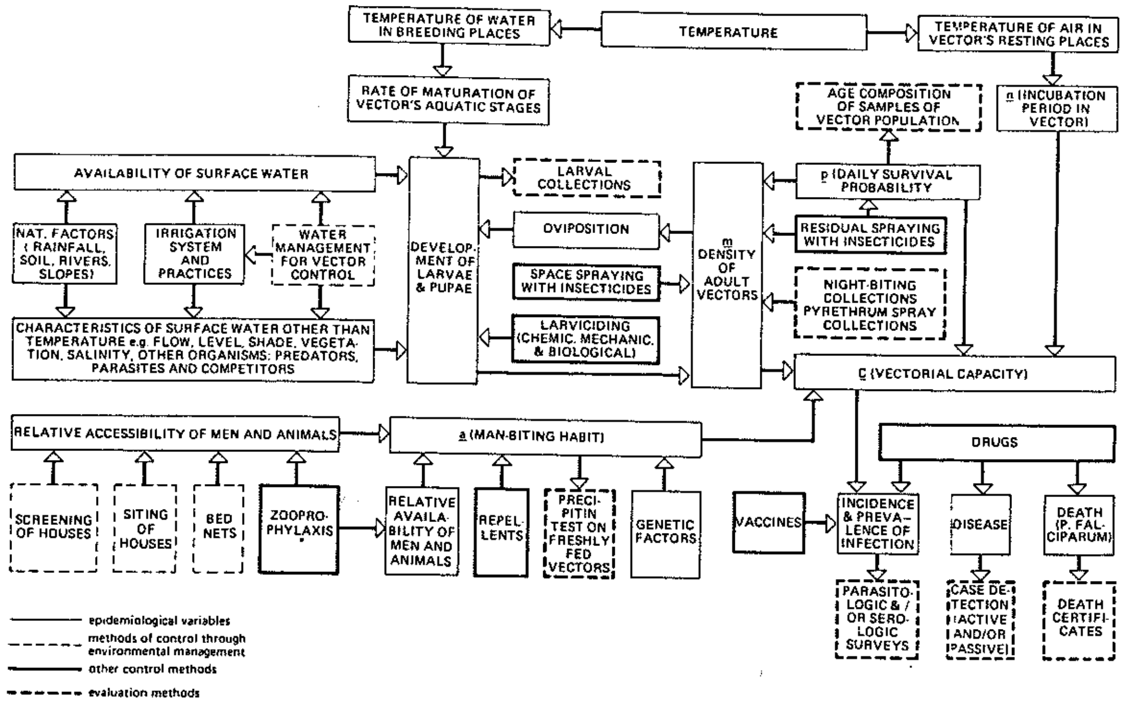


Figure 6 Malaria: natural and man-made factors, control measures, and evaluation methods, with particular reference to environmental management

Source: Oomen et al 1990

Fig. 4-9

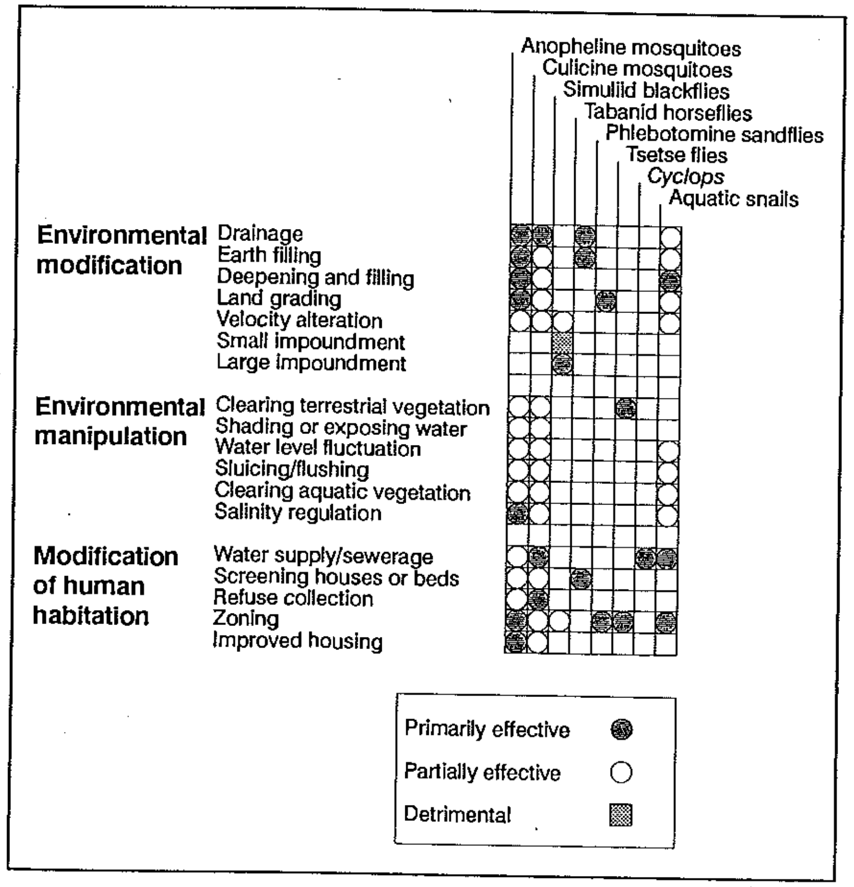


Table 2-11
Examples of interventions which are designed to control vectors and the vector groups which may be affected (WHO, 1980).

Source: Birley 1992

with average velocities in the range of 0.3 to 0.6 m/s (Jobin et al. 1984). Gated check structures at appropriate distances are required for efficient operation: these are closed during normal design flow and opened to produce the flush discharge.

Other means of control in medium or smaller reservoirs are:

- **shoreline modifications**: applicable to malaria and bilharzia control; it consists of straightening irregular edges by grading and improving drainage by ditching and filling,
- **biological control**: for example with other snails; see later in this chapter,
- **shoreline vegetation control**: aquatic vegetation provides food and shelter for many vectors; clearing can be done in the vicinity of settlements,
- **chemical control**: insecticides, molluscicides; however, these methods are usually too expensive for long-term application and control in reservoirs.

An example of integrated bilharzia control measures for two Lakes in Puerto Rico is given in Oomen et al. (ILRI) 1990; other examples in Oomen et al. (ILRI 1988) Vol.2, Annexes 2 and 3.

An example of efficient river flushing in Tanzania is given in Fritsch (in: Wooldridge 1992): impound run-off during the dry season in areas upstream of important breeding and transmission sites in order to release the accumulated water volume in the form of a flood wave. This artificial run-off regime extents the natural flushing effect during the rainy season and prevented the recovery of snail populations. Most important was that flushing started at the end of the rainy season before snail population densities reached critical levels. Controls were achieved within downstream stretches up to 1,300 m from the weir with mean velocities in the range of 0.7 to 1.1 m/s. Low frequency and low level flushings achieved positive but unsustainable effects: 60-80% reductions in snail numbers, but the area was repopulated 2.5 months.

Source: Oomen et al. (ILRI) 1990; Grubinger/Pozzi 1985

Further reading regarding bilharzia control in reservoirs: Pike 1987; regarding flushing: Jobin et al. 1984

4.3.5 Engineering Control Measures in Irrigation Systems

Irrigation systems with their network of canals, regulating structures, intermediate storage points, and complementary drainage networks have become important aquatic habitats for vectors and foci for disease transmission. Experience has shown that disease can be prevented through appropriate canal design, crop selection, water management, location of housing, and canal maintenance.

Drainage of impoundments, canals or other wet areas is the most effective measure against **mosquitoes. Blackflies** do not usually breed in such areas. For snails, drainage can suppress the population and can limit the extent of snail populations. The survivial period of snail adults is affected by temperature, humidity, the speed of drying (rapid drying is very effective), and by predation from rodents, birds etc.

The design time for drainage systems aimed at controlling the breeding of mosquitoes is the time between the deposition of eggs and the emergence of the flying adult form. The maturation time is generally about one week at high temperatures (>300C) and two weeks at lower temperatures (20-250C). The drainage system must be operated repeatedly during the season. Care must be taken to ensure that the drainage systems also dry out; this can be ensured by efficient collector drains.

The high resistance of snails to drying requires much longer dry periods to control bilharzia: typically, *(Bulinus globulus)*, requires at minimum 5 to 10 weeks to reduce the number to 50% of the original population. Other species may require up to 20 weeks or more. In most cases, after wetting the snail population will usually revive in sufficient numbers to replenish the habitat.

4.3.6 Irrigation Canal Design

Canals should be kept dry for as long as possible, especially during breeding periods (in seasonal climates). This may have effects on crop rotation, land allocations and land arrangements. Crop rotations should be arranged so that a minimum of channels are flooded for several successive months at a time.

Canal design should be based on the following principles:

(i) obtaining the **maximum velocity of flow** since many vectors can be destroyed or dislodged by flowing water:

bilharzia snails: most snails cannot populate areas with velocities above 0.55 m/s; they are immobile at velocities of some 0.3 m/s

mosquitoes: aquatic stages (eggs, larvae, pupae) can be destroyed or dislodged by flowing water; the design figure used for devices that flush the mosquitoes in natural streams is 0.5 m/s; in irrigation canals this figure is >0.1 m/s; optimum is 0.4 m/s

blackflies favour high velocities: aquatic stages are typically found attached to submerged trailing grasses, but may also occur on rocks, concrete, wood, or metal structures over which fast-flowing water is passing; velocities are in the range of 0.8 to 3.0 m/s, often 1.0 to 1.5 m/s.

It is obvious that **canal lining** provides the best results for maintaining high flow velocities and reducing maintenance problems with sedimentation, weed control and seepage; unlined canals may be acceptable if flow velocities are high enough to prevent snails from colonising, seepage is controlled, and the crop rotation plan allows canals to be in service no longer than for some three consecutive months,

(ii) designing canals to be capable of being **drained** dry when they are not in use

(iii) ensuring that **changes in canal direction** tare restricted to smooth curves, thus avoiding sharp bends and angles, stilling boxes, standing pools etc.,

(iv) smoothening water flow through **structures**, and avoiding short or long closed lengths at junctions; typically snails will assemble in pockets of still water at the corners of weirs, regulators, and other structures; these micro-habitats need to be avoided; in earth canals, particular attention must be given to the downstream side of orifices, weirs, drop outlets, etc. These structures should be given a solid invert; upstream faces should slope upwards to the crest,

(v) preventing growth of **vegetation** in irrigation and drainage canals that will remain flooded for long periods; aquatic vegetation increases evaporation, reduce canal velocity and discharge, and provides shelter, food and habitat for many vectors; low levels of field fertiliser applications will reduce potential weed growth in drainage canals,

(vi) preventing **siltation** in canals through effective canal maintenance: sedimentation usually reduce hydraulic gradients and increases the resistance to flow due to increases in aquatic vegetation, causing the velocity to drop (see above),

(vii) use of closed **conduits** if possible and economically feasible,

(viii) facilitating the process of **mollusciciding**,

(ix) **mechanical screening** of water intakes against snails; bridged crossing points,

Sources: Oomen et al. (ILRI) 1990; Pike 1987; Grubinger/Pozzi 1985

Further reading: an example from Zimbabwe is given in Chimbari et al. in: Wooldridge ed. 1991

4.3.7 Maintenance of Canals

Canal maintenance is essential to control sedimentation and aquatic weeds. Programmes for silt removal and weeding are required to maintain the functioning of canals and for health hazard control. **Weed control** methods include mechanical control such as harvesting or cleaning by hand or machines, chemical control with herbicides and biological control:

Chemical control may cause various problems related to water pollution, such as toxicity to aquatic organisms, accumulation and persistence (depending on type of herbicide) in water or organisms with long-term effects on food chains and influence on the biotope of aquatic organisms. In addition, the selectivity of various herbicides may enhance growth of other plants, eg control of floating plants like water-hyacinth may cause accelerated growth of submerged species. Some herbicides have molluscicidal or insecticidal properties as well, such as acrolein (aqualin), paraquant, diquat, and several carbamates, eg Ziram. It should be a pre-requisiste that chemicals should be not be toxic to fish and decomposition should be rapid (see also sections 2.2, 3.2.4 and 5.2).

Biological control: selective agents which attack one or only few weed species should be used; the effect is often the same as that of selective herbicides: one weed replaces another. Typically, water-hyacinth and blue-green algae are controlled by biological means. Polyphagous organisms which reduce the growth of all or most weed species, eg the mammal *Trichechus* (seacow) may also be used. Others include birds, reptiles and herbivourous fish, for example *Tilapia species*, grass carp, silver carp, and bighead. Recent research has been focused on insects, mites, snails, fungi, bacteria and viruses.

Source: Oomen et al. 1990

4.3.8 Operation of Canals

Other means of vector control are related to the operation of canals. There are various options such as intermittent flow (such as surge irrigation, see section 2.5) and flushing which have already been discussed elsewhere in this section. Essential means of control are temporary drying of canals and avoiding unnecessary canal flow. Scheduling for health control requires cooperation among various farmers or between farmers and the water authority in large irrigation systems which can only be achieved if farmers are aware of the beneficial health implications.

Associated Structures and Infrastructure

Structures such as access bridges, weirs, intakes, spillways/culverts, syphons, chutes etc. always change water velocities and therefore may create breeding sites. The same applies to roads and associated borrow pits. Management measures should be focused on minimising effects by hydraulic shaping of regulation and operation structures systems, regular flushing, maintenance, and avoiding creating uncovered borrow pit areas.

Stepwise Health Planning Approach for Irrigation Systems

A 10-step approach for the design of irrigation systems is proposed by Oomen et al. (1990), for areas where the risk of disease is severe. This stepwise planning approach should lead to a rational combination of preventive design measures and post-construction control programmes. Both the health and agricultural costs of canal and drainage design should be recognised early in the planning stage:

(1) first design, based strictly on agricultural needs, but paying attention to providing adequate drainage and control of aquatic weeds and sediments,

(2) estimate of annual costs and benefits of the initial design, including maintenance,

Fig. 4-10

Table 6.8. Fictitious example of matrix for comparing annual costs of Alternative Designs with First Design of canal and drain network in proposed irrigation system, giving consideration to health as well as to agricultural costs and benefits.
Goal: No additional disease – prevalence remains at original level (e.g. a low prevalence of 12%).
Fictitious annual costs are given in millions of U.S. dollars

Design alternatives	First Design	Alt. 1	Alt. 2
Project cost for First Design	10		
New prevalence of disease without program for disease control	75%	50%	25%
Cost of post-construction program for disease control	6	2	1
Additional irrigation system costs beyond the costs for First Design	0	1	2
Cost of lost agricultural productivity compared with First Design	0	1	3
Total cost for health and agricultural components	16	14*	16

* Alternative 1 at $14 million is thus cheaper than the First Design, which costs only $10 million for the irrigation system, but which requires a subsequent health expenditure of $6 million

Source: Oomen et al. 1990

(3) adjust to circumstances or accept the health imperative: aim for no additional disease due to the system; ie the prevalence should not increase after implementation (to be elaborated together with health specialists),

(4) estimate the increase in prevalence to be expected after the initial design is in operation,

(5) plan operational control programme and estimate the annual cost to maintain disease prevalence at the accepted level (see 3),

(6) using the annual cost of this programme as an upper limit, redesign canals and drains to decrease transmission by one or more alternative designs that may include various combinations of: higher flow velocity; increased longitudinal gradients, perhaps the elimination of night storage in canals; intermittent drying of canals and drains; changes in crops, cropping pattern or rotations; changes in irrigation practices to allow for periodic drying of canals; increased capacity of drainage system; increased silt and weed removal; flushing; fluctuations of pond levels, etc.,

(7) estimate disease prevalences that may result from each of the alternative designs,

(8) for each alternative design, estimate the additional costs of disease control programmes to maintain the accepted level of prevalence (see 3),

(9) for each of the alternative designs, estimate the additional costs of construction, operation and maintenance, as well as losses in agricultural productivity due to lower production or decrease in net irrigated areas,

(10) compare the annual costs for each of the alternative designs with the costs for the first design. Select the optimum design, reflecting both health and agricultural parameters (see Fig. 4-10).

Source: Oomen et al. (ILRI) 1990

A detailed checklist of major steps for the prevention and control of vector-borne diseases in each phase of water resources development projects is included in Table 4-6 (WHO 1980).

Further reading: WHO 1980; WHO 1982; WHO 1983

4.3.9 Control Measures in Farm Water Management

There are several components which contribute to vector control. One is the overall irrigation efficiency. Low efficiencies in the range of 20 to 80% are indicators of numerous impoundments, seepage, overtopping of canals or other poor water management practices. Increased water surfaces, however, provide additional habitats suitable for potential vectors. Consequently, anything that helps to increase irrigation efficiency may contribute to vector control, too.

A major factor is flow control at the intake structure and at gates to prevent overirrigation or standing water in canals.

Field irrigation should apply two basic guidelines: each flood period should not last for more than a few days, and after the withdrawal of water the fields should be allowed to dry for at least one day; and secondly, surface irrigated fields, especially basin, contour check and border strip should be frequently levelled and graded to ensure an even and uniform surface that will not produce pools with stagnant water after irrigation.

Other irrigation methods which have distinct impacts on vector control are related to irrigation scheduling. Rotational delivery and intermittent inundation of rice fields may be one efficient method to reduce water demand and control vectors. Also the rotational delivery of water in the conveyance or tertiary canals may be used to reduce vector transmission. Rotational delivery typically reduces losses between conveyance canals and tertiary sy-

Fig. 4-11

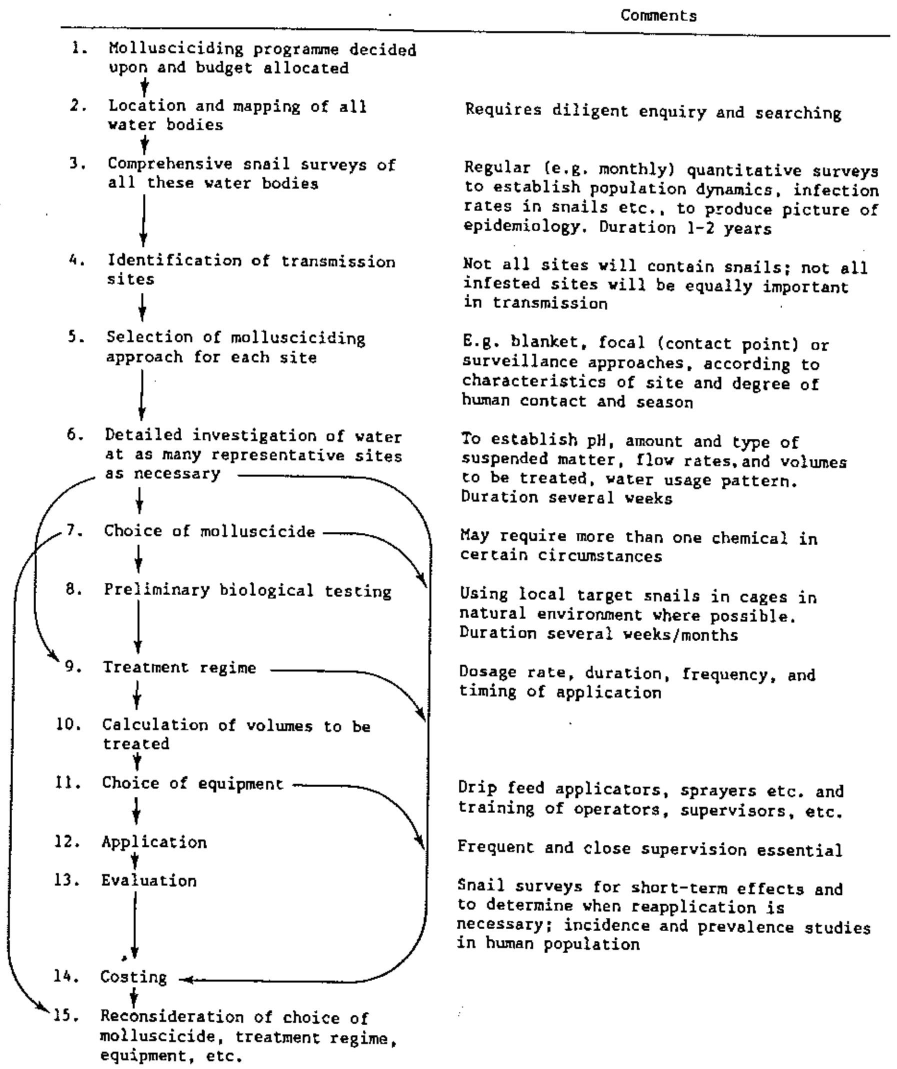


Figure 8.4 Sequence of events in a molluscicidinq program (after Jewsbury 1985)

Source: Oomen et al. 1990

stems and losses within field distribution systems. Rotational irrigation provides stream sizes suitable for flushing and promotes equal distribution of water to users. It increases the efficient use of rainfall.

Further reading regarding special health controls in rice irrigation: Mather/Ton That (FAO) 1984

Night storage reservoirs have various advantages for the operation of irrigation systems. However, they provide excellent breeding sites for many vectors, especially with siltation and growth of aquatic weeds. Risks can be reduced by using fewer, but larger sized reservoirs, and emptying them completely during daytime operation or at regular intervals. The reservoirs should be fenced to restrict human contact, and the design should facilitate easy maintenance and snail control.

Exposure to vectors can be reduced by avoiding field operations during periods when vectors are active. Some anopheles mosquitoes, for example, bite during evening hours only. Local conditions and experiences should be observed for scheduling of operations.

4.3.10 Other Measures

Other techniques and measures may involve ditch **maintenance**, drainage of all kinds of on-farm **impoundments**, drainage of nearby **swamps**, and clearing of natural **outflows**. **Land-use restrictions** may also be a useful tool to reduce human-vector contacts. The depopulation of areas declared as buffer zones, usually associated with the development of large reservoirs, is considered as an option by WHO (1980). The concept of 'dry belting' of wet rice cultivation areas, where a buffer zone surrounding the village is restricted to dryland crops, is based on land-use restrictions.

Sources: Oomen et al. (ILRI) 1990; FAO 1980

A WHO checklist summarising major environmental interventions designed to reduce health risks in water development projects is given in Table 4-7 (WHO 1982).

4.3.11 Biological and Chemical Control

Biological controls may be capable of eliminating vector snails within a few years. They involve the introduction into a snail habitat of either some other species of snail, or some kind of bird, fish, or insect that will prey upon the vector snails, their eggs or cercariae. Biological controls which must be under the strict supervision of a biologist and the responsible national authorities because complex ecological studies are required before these agents are introduced into a new ecosystem, and a continuous monitoring programme is required to avoid harm impacts on the ecosystem.

> Biological control is successfully carried out with a large aquatic snail (*marisa cornuarietis*), which eats the smaller bilharzia snails and larvae and competes with them for food. Other snails are currently being tested for their effectiveness. Biological control by fish raises the danger of introducing new species into an area. Most research trials with various species have not yet progressed far enough to allow for large scale propagation.
>
> Sources: Oomen et al. 1990; Pike 1987

Molluscicidinq is the most usual form of intensive bilharzia snail control. The snail hosts of bilharzia are extremely adaptable to various environments which makes it virtually impossible to lay down hard and fast rules for the application of molluscicides which will be suitable for all situations. In any programme, a sequence of events is followed, which is outlined in Fig. 4-11. Typically, comprehensive preliminary investigations over more than two years are required in order to establish an efficient control programme. Variables in-

Fig. 4-12

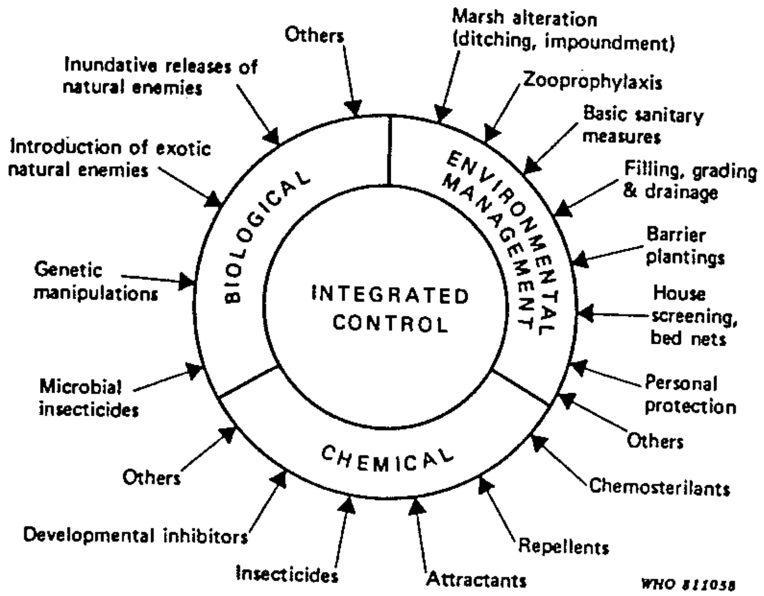


Fig. 6 Diagram of the components (environmental management, chemical, biological) and their potential constituent methods to be considered in an "integrated control" approach to mosquito control (Adapted from Axtell 1979)

Source: Mather/Ton that (FAO) 1984

clude optimum dosage rate and duration of application, timing, and frequency of application. Various types of molluscicides are shown in Table 4-8 together with a comparison of programme costs in Table 4-9.

Sources: Oomen et al. (ILRI) 1990; Pike 1987

4.3.12 Transferability and Situation Conformity of Control Measures

Measures to reduce or prevent health risks induced by irrigation require a package approach which conform to local situations regarding community vulnerability, environmental receptivity and health service vigilance. Sustainable blue print approaches do not exist and they would not reflect the complexity and location-specific character of disease control measures. Methods and techniques which can control vectors under specific conditions at one location may be less successful or not economically feasible at another location. Namely, vector biology and transmission routes may vary considerably with predominant vector species and site specific biotic and geophysical conditions. In addition, socio-economic conditions must be considered and the general health status of the farmers may affect the risk exposure of an individual.

Most important, however, may be the development of disease control packages which include socio-cultural issues in health education programmes. These should consider the people's beliefs about diseases, their attitudes and their behaviour in the choice for control of water based diseases. Collaboration between various the development institutions involved (from disciplines such as water engineers, land use planners, agriculturists, social workers, biologists, public health administrators, doctors) and the active participation of the farmers are preconditions for sustainable health care programmes (Tiffen 1989). Typically, centralised organisations may have some advantage in establishing and implementing such programmes when compared with small, indivudual communities spread over large areas and with shared responsibilities between various institutions.

Further reading: Tayeh/Cairngross in: Wooldridge ed. 1991; Bolton 1990; Tiffen 1989

4.3.13 Environmental Impacts of Health Control Measures

The application of environmental modifications and manipulations for health control will also affect environmental resources. The issue which deserves probably most attention is the application of pesticides for vector control. The same principles outlined in sections 2.2, 3.2.4 and 5.2 regarding agricultural pollution of water, soil and air resources are valid, regardless of whether the chemicals are used for health protection or for increased agricultural production. Another critical issue is the need for drainage which may reduce the area of impoundments or swamps in the vicinity of agricultural lands or villages. The diminishing of wetlands, however, contributes to the reduction of biological diversity (see Part I section 4).

In order to minimise the potential negative impacts which arise from the use of chemicals an integrated approach to the control of health hazards becomes even more important (Fig. 4-12). The evaluation of impacts resulting from health control measures can be assessed by the use of a matrix developed by FAO for rating both magnitude (extent of impact in space, time and affected population) and importance (intensity or relative impact) of effects (Table 4-15).

4.3.14 Monitoring and Evaluation

Monitoring refers to the measurement and collection of pre-selected data sets that allow evaluation within the planning, implementation and operation processes. Health status monitoring (surveillance) requires an integrated system for obtaining information on environ-

Fig. 4-13

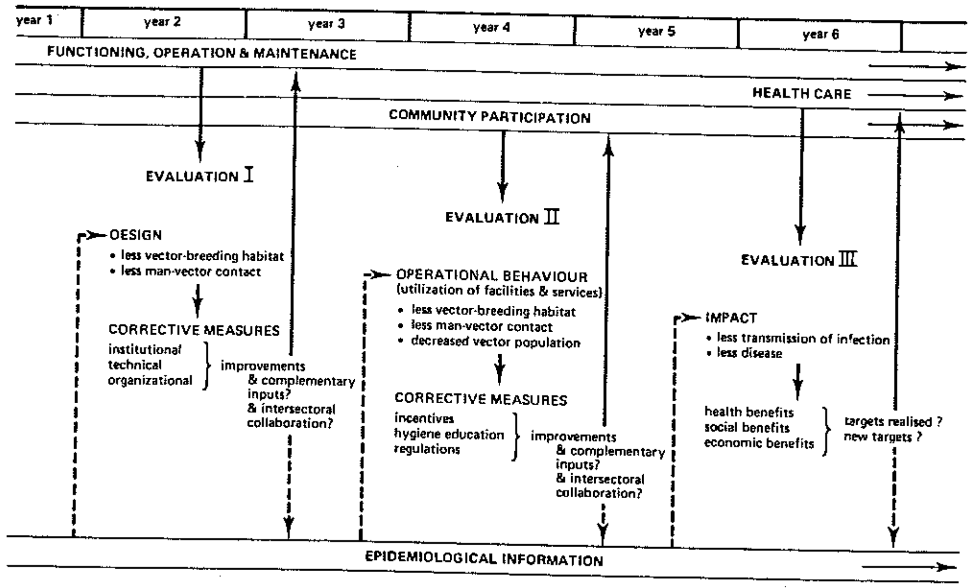


Figure 4.4 A schematic representation of monitoring and evaluation in the integrated control of vector-borne diseases

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Source: Oomen et al. 1990

mental factors and health conditions, and of examination of these data for the specific purposes of protecting and improving health. Monitoring is an action-oriented activity.

For irrigation project **rehabilitation**, it is important to re-assess the current state of disease transmission, prevalence and incidents (see above). Three distinct types of evaluations have been established:

Type I Evaluation involves examining various vector-control measures and their efficiency; corrective action can be modified in design and operation

Type II Evaluaion involves examining modified participatory behaviour of the community towards environmetal management measures. Corrective action may be aimed at increased utilization of these and other measures

Type III Evaluation involves examining the efficiency and effectiveness of the overall control strategy, and health, social, and economic benefits obtained from it. This can only be achieved within the framework of a complete project evaluation. Corrective action can change the control strategy, or make provision for complementary inputs.

Source: Oomen et al. (ILRI) 1990

Figure 4-13 shows the three types of evaluation within scheduled project development. For each type of evaluation, the monitoring system should provide relevant information on dependent and independent factors. The latter concern the technical, organizational, administrative, and resource features of the project, whereas dependent factors concern the epidemiological situation (Table 4-10).

A practical approach to monitoring during project operation was developed by ILRI in Sri Lanka (Zone 2 of System C of the Accelerated Mahaweli Development Programme). It was designed to identify those features of irrigated agriculture which could lead either to the introduction of water-related diseases or to an increase in their prevalence. It makes use of three matrices:

Matrix I: specific mosquito vectors in relation to potential breeding places (classes A to G); the bland matrix and the classification of breeding places is presented in Table 4-11

Matrix II: based on information on phases of seasonal irrigation and crop cycles, locations in the irrigation system in relation to potential breeding places (classes A to F). Matrix II indicated the relative importance of the irrigation system as a whole for potential vector breeding in the area. It singles out those elements of the system that give rise to the greatest risk (Table 4-12)

Matrix III: establishes the relationship between location of breeding places and those features of water management and irrigation engineering that promote them. It focuses on hydrology, design, construction, operation, maintenance, as well as on farm water management and crop husbandry. (Table 4-13).

Source: Oomen et al. 1988

A monitoring programme for small scale projects is given in Chimbari et al (1991). The programme included human parasitological surveys and treatments, snail surveys and surveys on cercariometrial density in water. The following parts of the irrigation scheme were observerd at regular intervals: nigth storage ponds, natrual drainage streams, main canal, secondary canalas and infield works.

General Sources: Birley in: Wooldridge ed. 1991; Bolton/Imevbore/Fraval in: Wooldridge ed. 1991; Chimbary/Chitsoko/Bolton in: Wooldridge ed. 19991; Tayeh/Cairngross in: Wooldridge ed. 1991; Oomen et al (ILRI) Vol. 1, 1990, Vol 2, 1988; Birley (WHO) 1989; Hillman in: Rydzewsli ed. 1987; Pike 1987; WHO 1980; Hunter/Rey/Scott (WHO) 1980;]

Articles: Mistry in: ICID 1990; Grubinger/Pozzi (ICID) 1985

Further reading: Wooldridge ed. 1991; Listori (WB) 1990; Mather/Bos (PEEM) 1989; Chanlett 1973

4.4 Control of Health Risks from Drainage Effluent or Surface Runoff

High fertiliser concentrations, pesticides and toxic trace element residues in drainage or surface runoff effluent may pose a health risk to downstream users if, after dilution with fresh water, the health advisory levels (HAL) are not observed (Table 4-14). Some elements are essential to human health at appropriate concentrations but at elevated concentrations cause damage to vital organs and symptoms of toxicity.

Most important are those metals which (bio-)accumulate in the food chain and thus in the human body or other organisms. Important issues regarding chemicals in wastewaters are also addressed in sections 2.1, 2.5 and 3.2.4. The same guidelines regarding quality standards are applicable for drainage effluents from agricultural lands.

Further reading: Hornsby in: Stewart ed. (ASA) 1990

5 Agronomic and other Measures for Environmental Management

Key words:

Soil and Crop Management Practices; plant manipulation; soil and crop mangement techniques for water conservation; soil tillage; crop types, varieties and cropping patterns; pollution and degradation; public intervention; nutrient management; pest management practices; heavy metal pollution; air pollution control;

Cross-references:

Part I sections 2.3; 9.1-4

Part II sections 1.3; 2.2; 2.3; 3.3; 3.4

Main Reference:

Lal ed. 1991; ISTRO 1991; Pereira 1990;

Irrigation is aimed at *mitigating drought effects* in agricultural production. Thus irrigation technology and water management practices must be seen in the context of agricultural production, and crop management must be seen in the context of land and water management techniques and options. The following chapter gives an outline of new trends in agriculture related to mitigation of drought or water stress, crop modelling in relation to water stress, soil management for soil and water conservation, and crop management in irrigated agriculture.

5.1 Soil and Crop Management Practices

There are various agronomic management options which increase or stabilise soil productivity and yields (Table 5-1). These include:

crop modelling, crop management, conservation tillage, crop rotations, improved drainage, residue management, water conservation, terracing, contour farming, organic and chemical fertilisers, pesticide use, and improved nutrient cycling.

Some of them are outlined in the following sections.

5.1.1 Crop modelling

Drought (water stress) affects the most important growth and metabolic processes of plants (Table 5-2). Understanding these processes has led to an improved recognition of the mechanisms of stress escape, avoidance and tolerance and of the related morphological and physiological characteristics (Table 5-3).

Crop modelling of water stress and water management can be an important tool in interpreting natural processes or to be utilised in irrigation scheduling:

- modelling physiological processes,
- modelling flux of water, solutes and assimilates, and quantifying the related resistances on roots, stems and leaves; this allows, for example, recognition of water stress avoidance and prediction of impacts from flux losses (eg groundwater pollution),
- modelling growth processes to manage crops and simulate the consequences of crop management options,

- modelling relationships between water use and yield, including models of agroclimatic influences, energy balances, soil-plant-water fluxes, transpiration, etc.

Source: Pereira 1990

Progress made in modelling has practical implications on agronomic (and irrigation) research and should provide the scientific background for irrigation planning and design and agronomic extension packages. Some of these models have already been treated in detail in sections 2.3, 2.4, 3.1 and 3.2.

Progress in breeding new rice varieties which transpire less **methane** into the atmosphere or produce less methane in the rizosphere are mentioned in Part I section 5.3. Efforts have also been made to breed new varieties which use **fertilisers**, namely nitrates, more efficiently, thus reducing water pollution risks and reducing nitrous oxide emissions (see Lantin 1992; Scharpenseel et al. ed. 1990; Boumans ed. 1990; Kimball ed. 1990).

Although beneficial effects may arise from genetic plant manipulation the potential negative impacts should be clearly seen. Such impacts and risks are still under debate and solutions must be found at the policy level for research activities. It will be essential to follow stricly the safety guidelines before new varieties are introduced at the field level.

5.1.2 Soil and Crop Management Techniques for Water Conservation

Conservation tillage and other soil conservation measures have positively affected the hydrological status of irrigated and rainfed fields and whole watersheds, minimising water shortage and reducing erosion in advanced agricultural farming. Some of these methods and techniques are also incorporated in 'ecofarming', a sustainable agricultural production system with low lewels of external inputs or other appropriate types of site specific farming systems in the developing countries.

A review of current options and their benefits is shown in Table 5-4, covering the following soil management and soil improvement techniques which are aimed at increasing:

- water retention on the surface and control of runoff,
- water yield and water spreading,
- water infiltration and soil storage volume,
- water retention in the soil profile.

The review shows that chemical modification of soil to improve water storage or decrease evaporative and seepage losses, faces important limits. Tillage techniques have a large potential despite small or contradictory effects for some problem soils (alkaline, saline, sodic, acid-sulphate, etc.).

In agricultural systems of semiarid and subhumid regions, options for irrigation or the adoption of drought management techniquesmay may often exist. Such options imply the needs to an economic perspective because modification of a crop system to avoid or minimise the risk of crop failure sometimes implies that farmers accept for some time a lower income although soil fertility is maintained or water resources are preserved in the long-term. Nevertheless, crop management options (Table 5-5) should be evaluated and some available techniques can be adopted in irrigated farming in order to achieve water savings in addition to water saving irrigation techniques (see section 2.3):

- drought risk management (or reducing water demand for irrigation),
- management for controlling the effects of water stress,
- cultivation techniques.

Sources: Pereira 1990; Pereira 1989. Further reading: Kotschi et al. (GTZ) 1989; Cleq/Dupriez 1988

5.1.3 Soil Tillage

Tillage forms an important component of agricultural production technology (Fig. 5-1). Tillage is aimed at preparing the desired seedbed, controlling weeds, managing crop residues, mixing fertilisers or other amendments or pesticides into the soil, improving aeration, alleviating compaction, and optimising soil temperature and soil moisture conditons. Thus, soil tillage plays an important role in achieving agricultural sustainability through its short- and long-term effects on soil processes, eg soil structure, soil organic matter content, rate and capacity for supplying or retaining water and nutrients to crops and also through impacts on soil degradation, and ground and surface water pollution. Consequently, soil productivity, economic profitability and environmental impacts are influenced by tillage operations. Adoption of appropriate tillage systems and techniques of soil surface management can facilitate attainment of agricultural sustainability by reversing degradative trends and restoring the productive capacity of soils.

Note: Aspects of labour saving through mechanisation are beyond the scope of this review.

Soil tillage techniques for improving water use efficiency and increasing nutrient use efficiency may vary for different agro-ecological zones as indicated in Table 5-6. Such technologies are based on principles of soil and water conservation (see above), preventing or minimising degradation (or over-use) of soil and water resources, restoring degraded lands (eg compacted, saline, alkaline soils), and often on reducing dependence on off-farm purchased inputs while enhancing or stabilising the productivity and profitability of the farming system.

The exact nature of tillage operations is soil and crop specific and is related to various farming systems and irrigation water management practices. Specific examples of tillage based technological packages for small and medium sized farms are listed in Tables 5-7 a-b, respectively.

Specific components relevant for irrigation include:

- mulch farming,
- minimum or no-tillage which can reduce the soil degradation which occurs with mechanical tillage in most rainfed agricultural systems; its effect under irrrigation is less clear and much depends on appropriate tillage packages and proper timing of operations; pest problems may be aggravated under no-tillage,
- soil inversion by ploughing, deep subsoiling,
- ridge tillage, raised beds, tied-ridges,
- land clearing.

Source: Lal in: Lal ed. 1991

The following regional reviews of current tillage systems and their impacts on soils are available:

Latin America - Alegre/Cassel/Amezquita (in: Lal ed. 1991),

West Africa - Aina/Lal/Roose (in: Lal ed. 1991). A regional guide to tillage methods is shown in Table 5-8,

Semi-arid African tropics - Hulugalle/Maurya (in: Lal ed. 1991),

Semi-Arid Tropics in general - Laryea et al. (in: Lal ed. 1991),

Conservation tillage in semi-arid tropics - Unger et al. (in: Lal ed. 1991).

The choice of an appropriate tillage system is a function of the natural resource endowments (soils, topography, climate, irrigation), expected crop yields, actual and anticipated erosion rates and net return. Tillage systems in turn affect the types and amounts of inputs required, as reflected in operating costs for materials, labour, and machinery. Tillage

Fig. 5-1

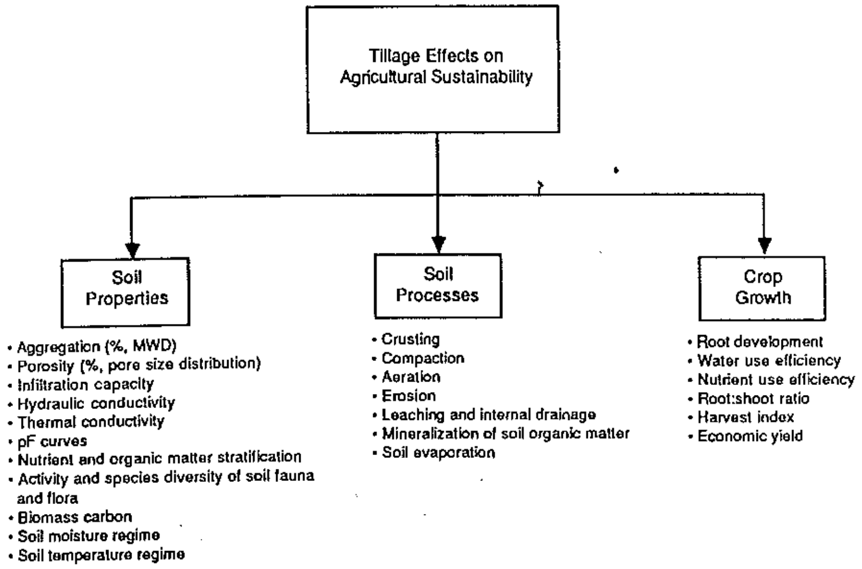

Fig. 2. Tillage effects on agricultural sustainability.

Source: Lal ed. 1991

Fig. 5-2

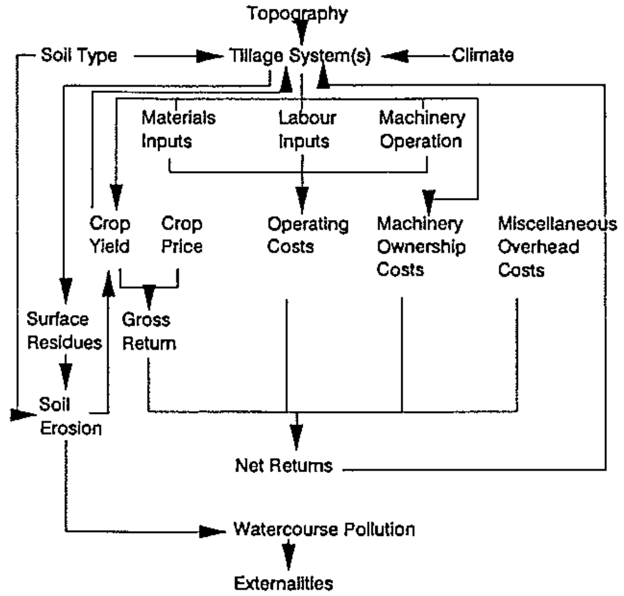

Fig. 1. An overview of the framework for economic analysis of tillage alternatives.

Source: Lal ed. 1991

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Fig. 5-3

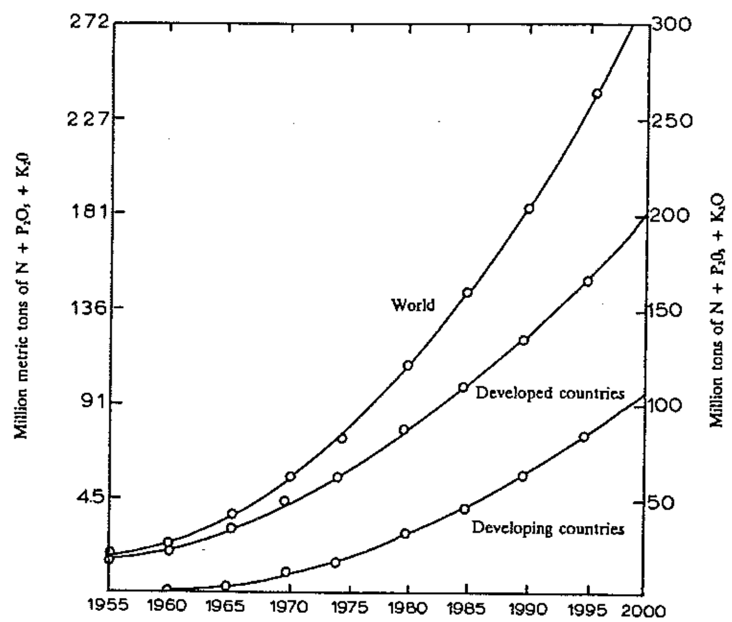


Figure 1. World fertilizer consumption, 1955-1974 (actual) and 1975-2000 (estimated) (Edwards, 1985).

Source: Edwards et al. 1990

choices are also influenced by ownership issues and types and usage rates of different tillage equipment and power units (hand, animal or tractor) available to draw them. Crop yields are a function of crop variety, tillage systems, soils, water management, climate, and management skills. These diverse interrelated factors are shown in a framework for economic analysis of tillage alternatives (Fig. 5-2).

Sources: Stonehouse in: Lal ed. 1991; Lal in: Lal ed. 1991; Laryea et al. in: Lal ed. 1991; van Doren/Triplett in: Lal (IITA) 1977

Further reading in: ISTRO 1991; Lal (IITA) 1977

5.1.4 Pollution and Degradation: Case of Public Intervention

Where there is little or no economic incentive to implement soil and water conserving measures to reduce off-farm impacts and on-farm soil degradation processes, rational farmers should not be expected to adopt conservation tillage methods. On the other hand, where such on-farm incentives do exist or they are realised by farmers, such techniques are typically adopted. External incentives may include government subsidies or mandatory controls and regulations. It has recently been recognised in industrialised countries that off-farm costs from watercourse pollution far exceed the on-farm costs, so that the expenditure of public funds as part of the intervention package would be justified. Such a targetted approach to offering financial assistance to farmers would be superior to a universal approach, and any subsidy programme should be combined with other elements such as education, extension assistance, and, if necessary, controls and penalties. However, such programmes are difficult to introduce in most developing countries due to budgetary restrictions and different perceptions or priorities. Development aid may assist to enforce such programmes in areas where control measures are required (see also sections 2.3, 2.4, 3.3 and 4.).

Source: Stonehouse in: Lal ed. 1991

5.2 Reducing Risks from Uses of Agro-Chemicals

5.2.1 Nutrient Management Practices

The use of mineral fertilisers is steadily increasing in both industrialised and developing countries (see Fig. 5-3 and Table 5-9; see also Part I section 2.3).

> During the period 1973 until 1986 the total application of N-fertilisers increased from 18 to 33 M t in developing countries, mainly caused by increases in Asia with the use of high yielding varieties (FAO 1987). Further increases in the range of 4-5 % can be expected (in some countries the increase may be in the range of some 10%, eg in China and Malaysia) and a larger proportion is often used under irrigation. For example, the production of rice increased from 256 M t (1969) to 467 M t (1985) in the Far East.
>
> The average figures of fertiliser uses in Asian countries are shown in Table 5-10.

It is expected that by 2000 the total consumption in developing countries (except CIS-states) will exceed 100 M t of N-P-K fertilisers, which is equivalent to the consumption of industrialised countries in the early 80s. Therefore, side-effects of the fertiliser use must be carefully monitored in future.

Agriculture is - with regard to salt, nutrient and sediment loads - a main polluter of groundwaters and surface waters which eventually results in the eutrophication of surface waters (see Part I section 2.3). Nutrients are derived from fertiliser applications, either as mineral or organic fertilisers, or from wastewater applications (see Part I sections 3.5

and 3.6). Some nutrient losses, either to waters or the atmosphere, are unavoidable and should be regarded as part of the natural cycling of elements. Environmental concerns are related to excessive non-productive losses of plant nutrients from the soil, particularly N and P. Although firm evidence of widespread impairments in developing countries are - to date - rare, the following losses may occur:

> **Nitrogen** - leaching of nitrates, production of ammonia and nitrious oxides by volatisation and denitrification, soil acidification,
>
> **Phosphorus** - leaching is minor, but run-off losses of soluble P and especially the transport with sediments during erosion can be of importance.

Other side-effect are related to **impurities** in fertilisers, especially those derived from the widespread use of rock phosphate. Impurities of cadmium (Cd; see Table 5-11) and lead (Pb) are known and gaseous fluoride (F) impairments occur especially during the manufacturing process. Under normal conditions and applications, these impairments do not create serious health risks to farmers, although close monitoring is recommended if such fertilisers are in use (McLaughlin 1991).

The **indiscriminate** application of fertilisers (and pesticides) in connection with over-irrigation or poor surface irrigation water management leads to the leaching or surface run-off of applied chemicals into downstream waters. There is a widespread opinion that the large scale increase in fertiliser use may be justifiable because the cost to individual farmers is less than costs for other means to increase yields. Research has revealed, however, that increased fertiliser rates are closely related to water pollution than to increased yields (Holy 1980). This indicates that it would be sensible to combine the application of mineral and organic fertilisers with other measures aimed at raising soil fertility, eg by reducing soil erosion, improving tillage practices, crop demand oriented irrigation practices etc., and that fertiliser rates should only be increased after all other agronomic techniques having less or no adverse environmental impacts had been utilised (see Fig. 5-4 a).

It is obvious that nutrient management is probably the most effective measure to prevent soil contamination and water pollution (Fig. 5-4b) with the same applying to pesticides. The easiest method, besides low application rates, is to prevent **soil erosion** and to prevent **excessive leaching** into surface and groundwaters. In irrigation it is unavoidable that some fertilisers and chemicals are leached into the deeper soil horizons or layers (see sections 2.2, 2.4 and 3.3). However, this seems less dangerous than their direct transport into the hydrological system through runoff, especially in paddy systems with continuous flow. In soils many chemicals are buffered, filtered and most of them are transformed after some time. Hence, leaching at low rates after this interactive period is less hazardous to the water system.

Major concern should be given to improving the efficiency of utilisation; for example, it is estimated that only 30-35% of the N applied to lowland rice is utilised (Uexkull/Beaton 1990). Some major management decisions to be made in the use of nitrogen fertilisers are as follows:

- selection of a realistic target yield,
- selection of the N-rate to meet this target,
- use of split applications,
- timing of N-application,
- precision placement (eg banding) especially deep placement of urea in rice fields,
- history of manure use and rate,
- history of legumes in the rotation,
- source of fertiliser N to use,
- use of nitrification inhibitors (to slow conversion of NH_4-N to NO_3-N),
- avoiding an imbalanced nutrient supply which restricts the net use of N,

Fig. 5- 4 a

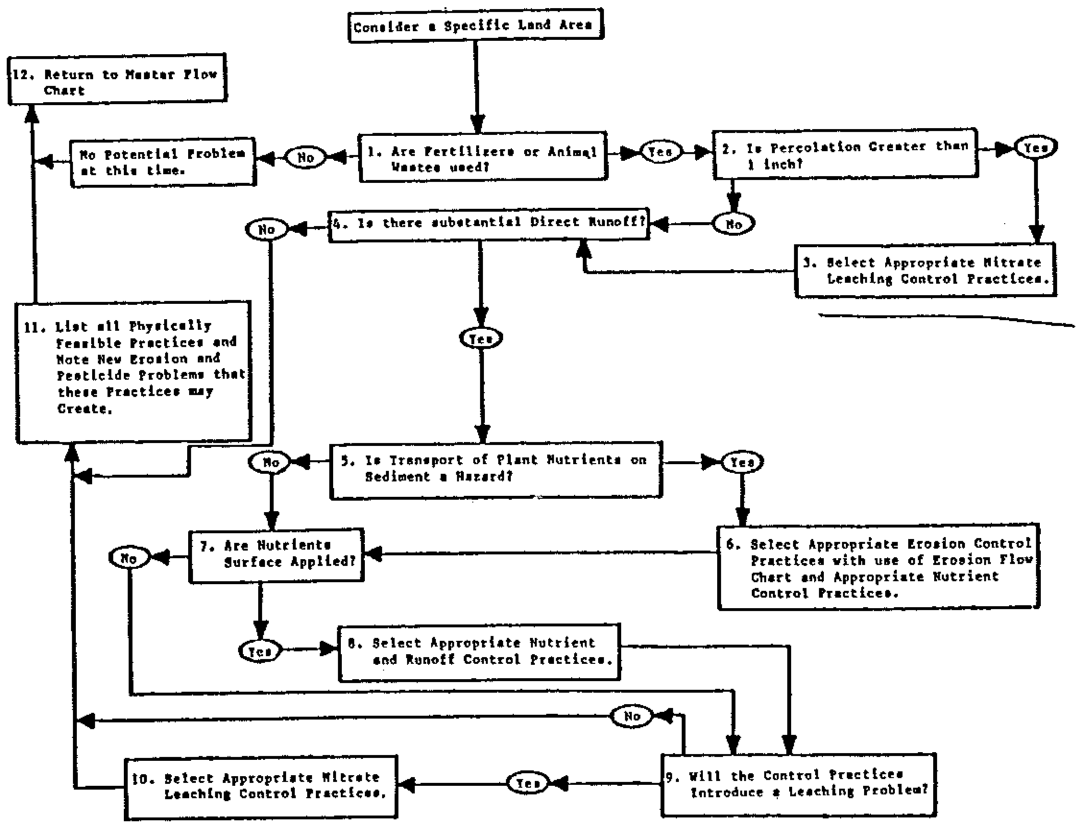
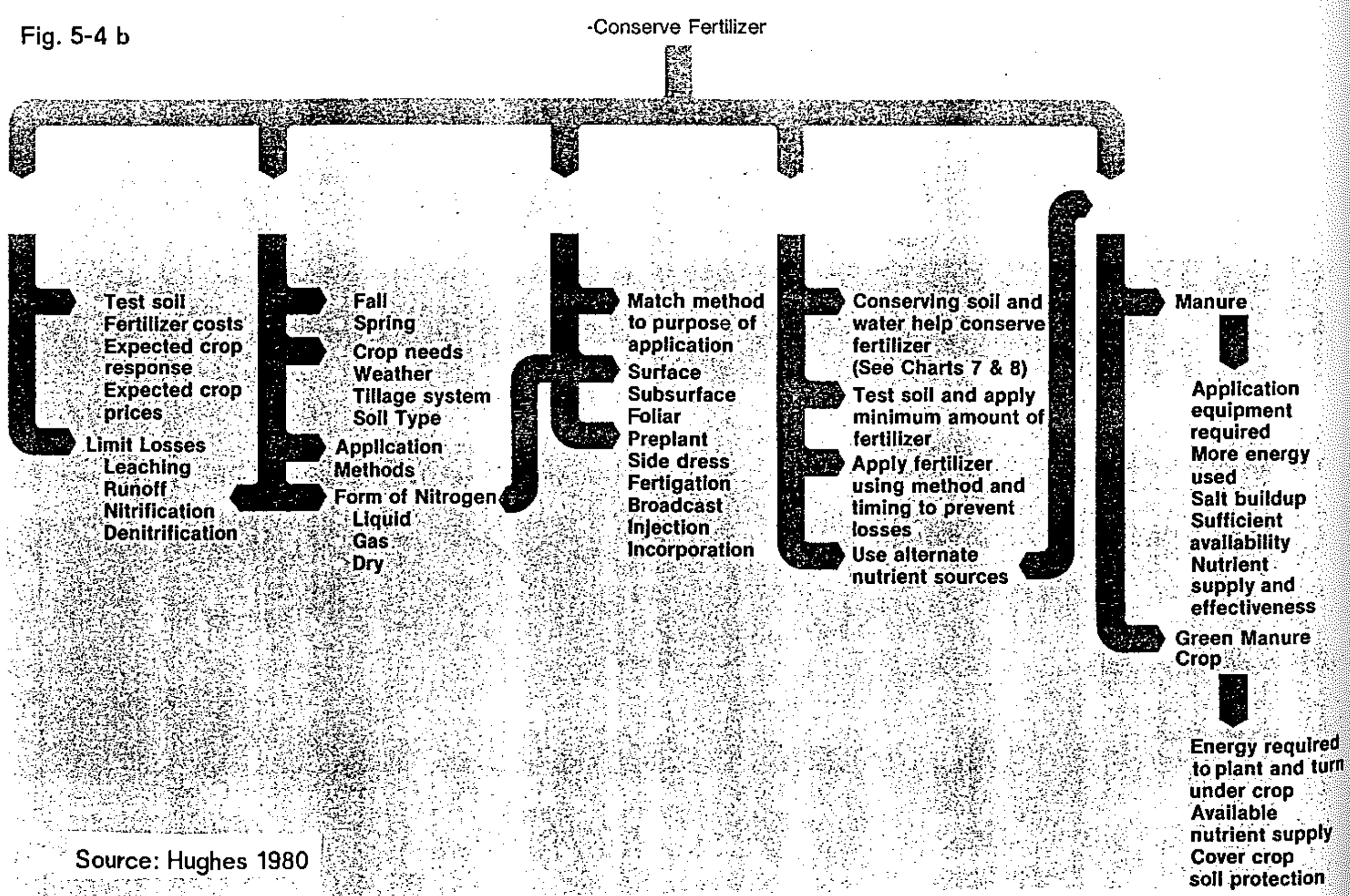


Figure 24: Flow Chart for Assessing Nutrient Pollution Problems and Controls (Frere, et al., 1977)

Source: Canter 1986

Fig. 5-4 b



Source: Hughes 1980

- avoiding unnecessary fertilisation due to incorrect diagnosis of plant deficiency symptoms,
- ensuring healthy and dense crop stands which make use of the fertilisers applied at design rates.

Source: Anderson in: USDA 1988; for rice irrigation: De Datta/Buresh 1989; further reading: Finck 1992, 1991

Various policy measures may also be applicable (see policy options; next section). To summarise, a number of agronomic practices will reduce direct runoff and erosion and, thus, reduce nutrient transport into surface waters or excessive gaseous losses. In irrigation leaching control by water management and associated agronomic methods which can control deep percolation may be used to reduce nutrient losses to the groundwater and surface water systems. A list of common practices is given in Table 5-12.

Sources: Anderson in: USDA 1988; Canter 1986; Holy 1980

Further reading: Stoy/Sattelmacher in: Blume ed. 1990; Conway/Pretty 1988; Kohlmeyer in: Nieder et al. 1987

5.2.2 Pest Management Practices for Pollution Control

Irrigation permits crops to be grown where it is not possible to grow them otherwise and it increases total biomass production, but at the same time it provides conditions conducive to high rates of population development of various pest species. Hence, the use of pesticides is typically high in irrigated agriculture, if other measures of pest control are not undertaken.

The use of pesticides to control pests is still rising sharply in most developing countries. Due to the rather indiscriminate and often inadequate use of pesticides in many localities in developing countries, potential (on-farm) environmental and direct health risks are higher (fatal incidents) than in many industrialised countries (see Part I sections 2.3, 4.3 and 8.3).

The demand for pesticides is predicted to rise from the present level of $ 2,550 M to about $ 5,000 M within a decade. It is likely that the usage of insecticides in Latin America will be 55% of the overall use in developing countries by 1993, and that of herbicides will rise from $ 730 M to $ 1,845 M over the same period. The equivalent fungicide market is likely to rise from $ 368 to $ 1,165 M over this period. The pattern of both regional and national demands, by class of pesticide and by the type of crop, will probably change very little over the period, with a few exceptions, including great increases in Africa.

Sources: Edwards 1987

Fig 5-5 shows a steady increase in the use of pesticides in both industrialised and developing countries. However, figures are often inconsistent and an UNIDO report (1987) shows that there was no increase in the use of pesticides in all developing countries between the period from 1975 to 1985 (Brader in: DSE 1989):

		total	insecticides	fungicides	herbicides	unit
global	1975	2,073	567	844	661	1000 MT
	1985	2,425	483	988	953	"
developing countries						
	1975	533	283	194	57	"
	1985	507	232	201	75	"

Fig. 5-6a shows that there are marked regional differences in the use of various pesticides (fungicides, insecticides, herbicides). In developing countries, insecticides are more important than herbicides, whereas herbicides are widely used in industrial

Fig. 5-5

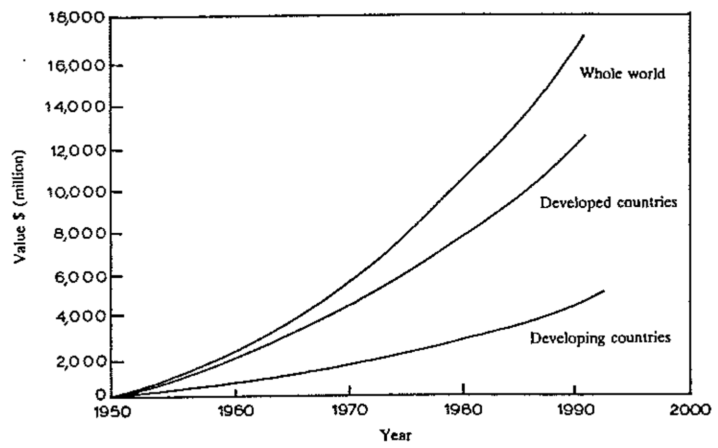
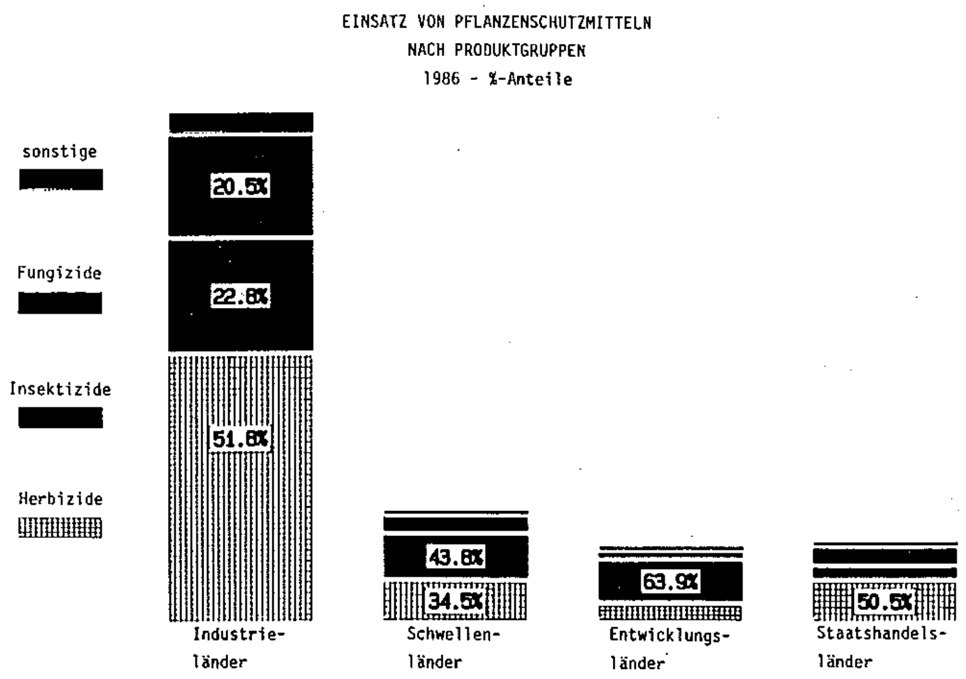


Figure 2. Predicted world pesticide use (Edwards 1986).

Source: Edwards et al. 1990

Fig. 5-6 a



Source: DSE 1989

Fig. 5-6 b

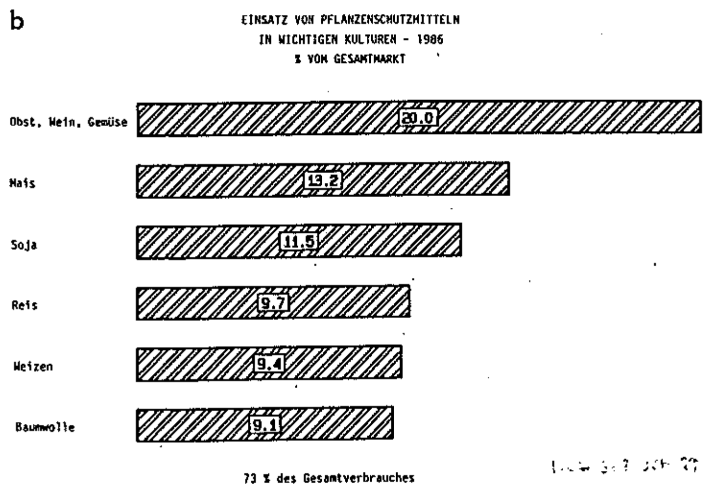


Fig. 5-6 c

- Wichtige Kulturen -
Einsatz von PSM nach Produktgruppen
% vom Gesamtverbrauch
1986

Herbizide	Soja	10.3 %
	Mais	10.3 %
	Weizen	6.8 %
	Obst, Wein	4.7 %
	Reis	4.1 %
	restl. Getreide	3.8 %
	Zuckerrüben	2.4 %
	Baumwolle	2.4 %
Insektizide	Obst, Gemüse, Wein	7.1 %
	Baumwolle	6.5 %
	Reis	3.5 %
	Mais	2.9 %
Fungizide	Obst	3.2 %
	Wein	2.6 %
	Gemüse	2.1 %

73 % des Gesamtverbrauches

countries and Eastern Europe (including CIS). These differences are also caused by different cropping patterns. Pesticides are often used for orchards and vegetables (Fig. 5-6 b), followed by maize, soyabeans and rice. The use of different pesticides for different crops is shown in Fig. 5-6c. Most pesticides in developing countries are probably used for rice cultivation (Hüttenbach in DSE 1989).

The average figures of pesticide uses in Asian countries are shown in Table 5-10.

On the other hand, there are reports from Indonesia about the successful introduction of country-wide integrated pest management practices in rice cultivation. The use of pesticides fell and rice production steadily increased at a reasonable rate (Table 5-13). The programme gives first priority to the use of non-pesticide agents for pest and disease control. For example, this involve taking into account the time of planting, the timing of irrigations, the farming pattern, the amount of fertiliser used, hand weeding, land sanitation measures, and the use of pest restistant varieties. Under such a system, insecticides are applied when the population of insects reaches a pre-dertermined limit or biologigal threshold. The number of pesticide applications per season fell from 4.5 in 1986 to 0.5 in 1988 (FAO cit. in Reus 1992) There are also measures such as mechanical, physical and biological pest control. Thus, mechanical controls seek to eliminate pests by hand, traps or by other equipment. Physical pest control uses high or low temperature, moisture, light or sound waves. Natural pest predators are used in biological pest control.

Source: Kasryna et al. in: OECD 1991d (Eröcal ed.)

The systems description of pesticide-soil-water-plant relations gives an indication about management options (Fig. 5-7). Although the transport into surface water is typically less than 1% of the total application, some agro-chemicals are extremely toxic to fish and other aquatic life so that even a small level of transport from irrigation return flow into the surface water system should be avoided or minimised. There are three general (policy) means to control soil contamination and water pollution by pesticides (and fertilisers):

- reducing **intensity** of agriculture: eg using taxes on fertilisers and pesticides; changing extension messages,
- changing **land use**: using only fertile soils for cultivation and establishing land use zones according to soil properties,
- special **restrictions**: on handling of fertilisers and pesticides; spatial restrictions on pesticide use within protected zones.

Fig. 5-8 indicates how to assess the pollution and associated problems. Generally, there are three strategies to controlling pests in agriculture to ensure that they are kept below the damage threshold:

- ensuring that the pest does not get into the field (sanitation),
- ensuring that the pest has little chance to multiply,
- eliminating the pest: mechanical methods or curative chemical or biological control.

Main advantages of most chemical control methods are speed and effectiveness of controls, flexibility in timing, easy application in comparison with many other methods, and the possible economy of control (eg if manual weed or insect controls are costly).

Main disadvantages are related to possible human health risks and environmental contamination, high costs of safe storage and disposal of containers, requirement to use special equipment for safe and efficient application and especially that the application requires technical skill which is often not available in developing countries. Local conditions must be known in order to assess risks involved in pesticide application in a given project.

Several agronomic methods are applicable for pest control which can be summarised under the headings: improved pesticide use, biological pest control techniques and integra-

Fig. 5-7

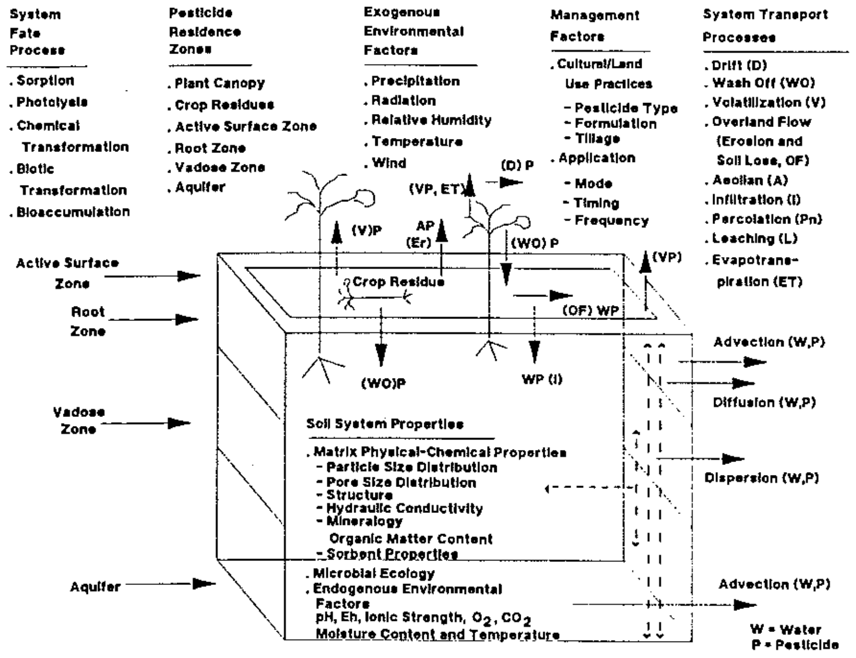


Fig. 14-1. System description of pesticide-soil/porous media-plant interactions.

source: in Cheng ed. 1990

Fig. 5-8

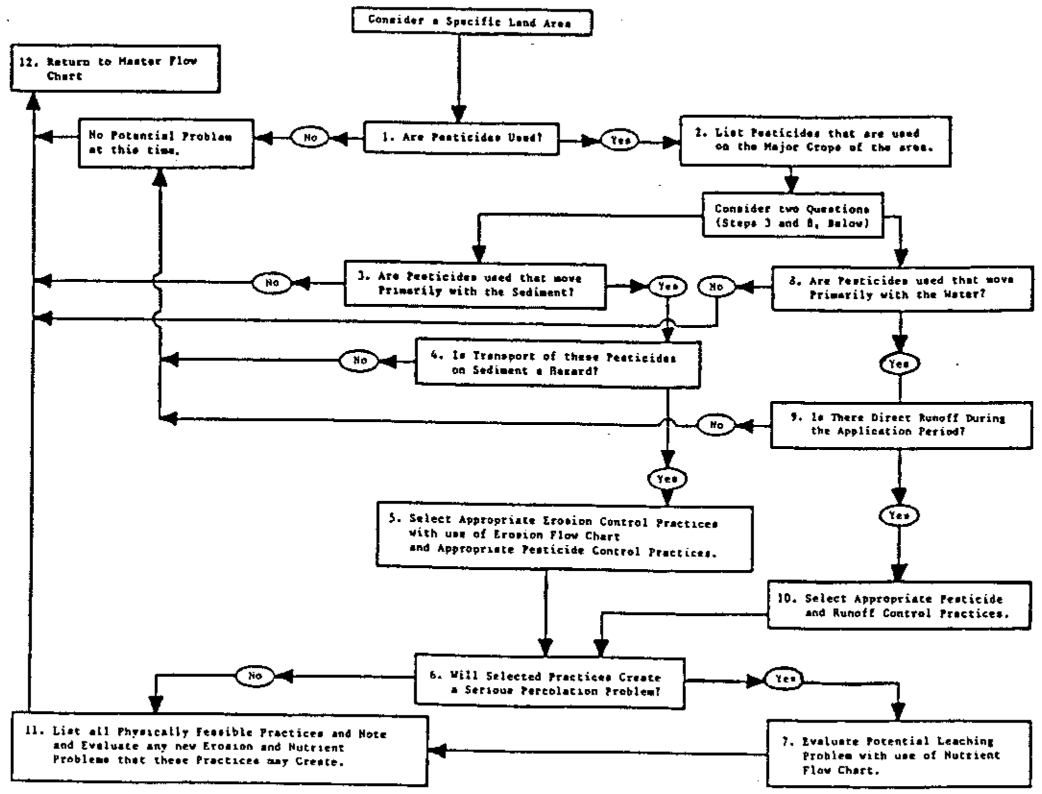


Figure 25: Flow Chart for Assessing Pesticide Pollution Problems and Controls (Frere, et al., 1977)

Source: Canter 1986

ted pest management, including cultivation methods (see also Fig. 5-9). Some important control measures are:

- adoption of **agronomic production techniques** that use methods other than agro-chemical for pest control, eg ecofarming
- strict legal **restrictions on aerial spraying,**
- use of **alternative pesticides** that are not water soluble or less toxic or less persistent and which do not accumulate: for example, use of organophosphates or carbamates instead of organochlorines; avoiding mercurial fungicides, arsenicals, highly toxic organophosphates etc.,
- use of pesticides **specific** to particular pests or groups of pests so as to have minimum side-effects on non-target species,
- optimisation of **pesticide formulation,** eg use of slow release formulations,
- treatment of **infected spots** only and avoiding **excessive treatments,**
- optimisation of application **times** and use of lower application rates,
- **biological control:** use of microorganisms or microbially produced pesticides (eg avermectins; however, the use of biotechnology/genetic engineering is controversial); use of semiochemicals (many pheromones and attractants for pests have been identified and active ingredients isolated for field use, eg in cotton); controlled use of predators and parasites of pests,
- **integrated pest control** and management: this includes any suitable technique to decrease pest populations and maintain them at levels below those causing economic injury (this differs from 'supervised control'): forecasting; scouting; use of crop varieties resistant to pest attack; use of varieties with shorter growth periods; timing of crop sowing/planting and harvesting to avoid pest attack; depth of sowing/planting; careful disposal of plant residues by grazing, burning or ploughing under,
- **cultivation methods** that increase diversity of habitat, flora and fauna: changes in cropping pattern; frequent crop rotations to avoid carrying over of pests; mixed or strip cropping etc..

Sources: Canter 1986; Edwards 1987
Further reading on integrated pest management: eg CON 1990, DSE 1987
Biological control methods are shown in Yaninek/Heren ed. 1989.

The following measures may be used to minimise <u>fungicide</u> use:

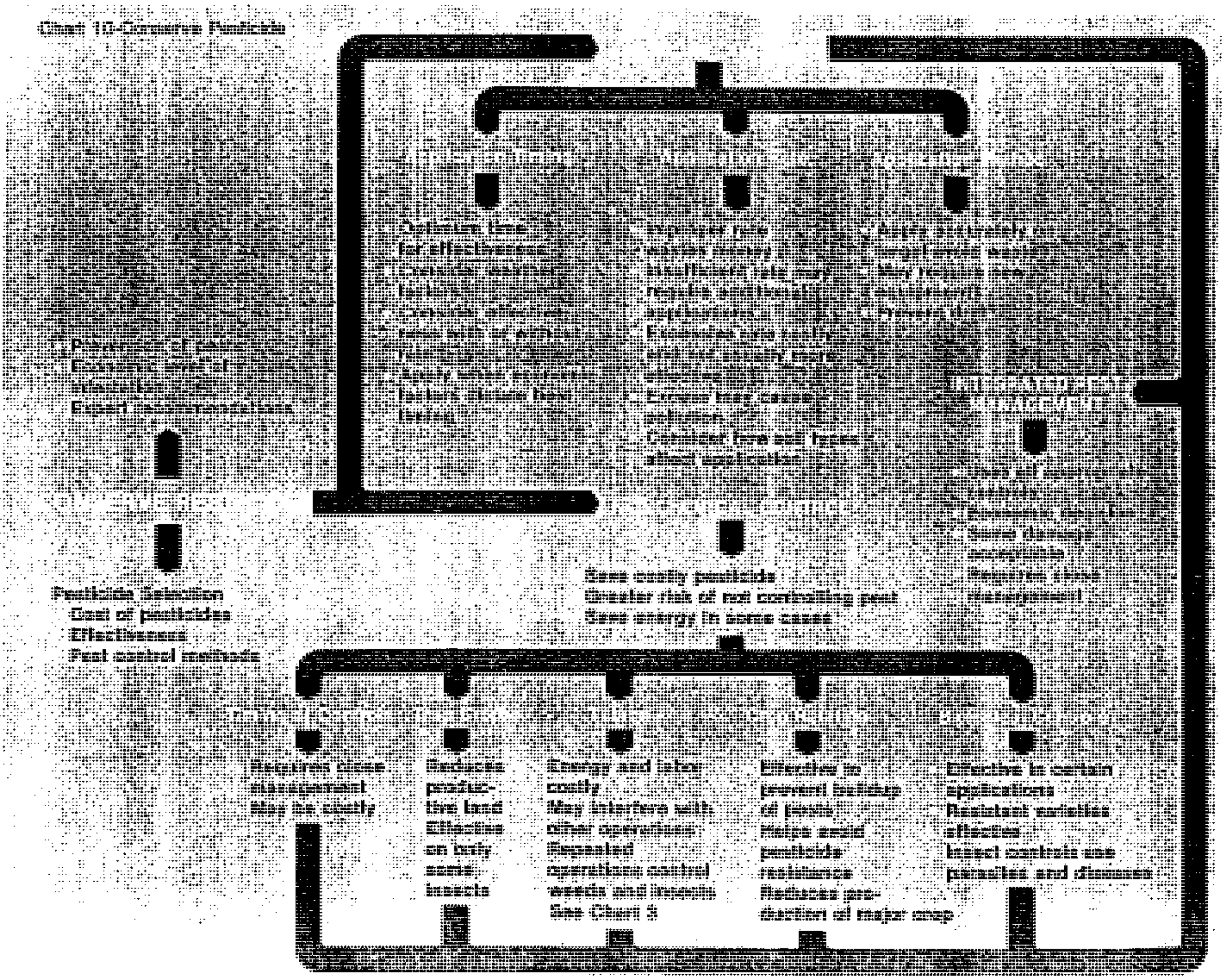
- use of minimal amounts of fungicides based on disease forecasting methods
- use of crop rotations to minimise disease attack,
- better application techniques for fungicides using small amounts and better palcement,
- timing of crop sowing to avoid the disease incidence period or climatic periods favourable to development of the disease,
- use of disease antagonists; eg a number of microorganisms inhibit growth of plant pathogens,
- use of crop varieties that are tolerant or resistant to disease,
- leaving stems dry during irrigation (eg furrow irrigation).

Source: Edwards in: Edwards et al. ed. 1990

Alternative measures for <u>weed control</u> other than herbicides may include:

- preventive measures prior to planting,
- thermal destruction of weeds prior to planting,
- mechanical measures: tillage practices for weed control; row spacing,

Fig. 5-9



Source: Hughes 1980

- agronomic measures such as crop rotation to minimise weed seed germination, or selection of uncontaminated seeds and plant materials; cover cropping to minimise weed seed germination,
- mulches to provide soil cover and inhibit weed seed germination,
- irrigation scheduling to hamper weed growth,
- use of mycoherbicides,
- release of pests of weeds,
- rotation of weed control methods.

Further reading: Loop in: Blume ed. 1990; Edwards in: Edwards et al ed. 1990; FAO 1986

A detailed list of common crop protection practices is given in Table 5-14. Any method which reduces surface runoff (soil erosion) is also effective in reducing pesticide losses into surface water (see Fig. 5-8 and Part I Fig. 3-17).

Major concern should also be given to the increase in on-field delivery efficiency. Present spray technologies are **inefficient** and do not conform to principles of spray physics. New delivery technologies must be based on efficient delivery to the target. With herbicides, control of spray drift is of overriding importance. Major components of pesticide losses in spray processes are assessed as:

- delivery losses are about 60-80%: directly to the soil and the peripheral foliage,
- primary volatilization losses to air some 3-10%: depends on volatility,
- primary particulate drift losses in the air amount to some 3-5% of most sprays.

Source: Himel et al. in: Cheng 1990

Irrigation can also be used to increase the pesticide's **efficiency** and thereby decrease the amount applied per unit of surface area, and to minimise its transport below the root-zone, thereby preventing leaching of the chemical into the groundwater. Irrigation becomes a tool in the control of pesticide **behaviour** in the soil environment (Yaron/Gerstl/Spencer 1985). This potential, however, can only be fully exploited under advanced **water mangement** systems and it requires a basic understanding of the fate of pesticides in soils (see Part I sections 2.3 and 3.4). Both preconditions are probably not yet met under prevailing conditions in many developing countries.

Irrigation may also be used to control pests by manipulating the pests' habitat. Well planned flooding and drying out for local pest control may be used prior to planting (eg rice caseworm). Temporary ponding with about 100 mm of water may also be used for weed control. On the other hand, water stress during the growing season makes most crops susceptible to a number of diseases (eg CON 1990).

Eficacy. Further improvements in the application of pesticides are also related to attempts to evaluate efficacy under field conditions. Guidance for such biological evaluations are for example given in FAO paper 'Guidelines on Efficacy Data for the Registration of Pesticides for Plant Protection' (FAO 1985b) and the FAO 'Code of Conduct' or other relevant FAO -guidelines. Other national institutions and international organisations (eg CON 1990, CTA 1989; Alebeek (CTA) 1989; GIFAP 1983) have been producing documents on the safe and effective application of pesticides.

Registration. In addition, the potential environmental risk of a given pesticide should be assessed separately for the agronomic, managerial and environmental conditions under which the pesticide is used. These conditions may differ significantly from those in industrialised countries where most pesticides are being tested for their environmental effects. **National registration authorities** and **research institutions** are urged to evaluate environmental risks implicit in the proposed use by conducting field observations and test programmes to supply specific information on application and use pattern, the fate and possible occurence of residues in relevant parts of the environment, and the effects of predicted exposures on non-target species. Such programmes and monitoring activities are outlined in FAO 'Guidelines for the Registration and Control of Pesticides' (FAO 1985a: chapter 8.5).

Waste disposal. Special attention should also be given to the handling of waste pesticides on the farm. Recommendations for methods of safe disposal are outlined in FAO 'Guidelines for the Disposal of Waste Pesticide and Pesticides Containers on the Farm' (FAO 1985c). Since most farmers in developing countries are layman in terms of handling chemicals and understanding chemical reactions, **educational and training programmes** for safe handling, application and disposal are essential to minimise soil and water impairments, biological imbalances and to reduce health risks.

Further reading: Loop in: Blume ed. 1990;

Monitoring. The adequate management of pests in irrigated agriculture requires a monitoring programme. Pest surveillance, a process that collects, analyses and interprets data for pest management decision-making is best suited to ensure that adverse impacts of pesticides on users, consumers and natural resources are avoided or minimised. Such a system, established by the **agricultural extension service**, should train farmers on the identification of pests and their natural enemies so that regular field surveys can be used in decision making on control methods by identifying economic pest thresholds levels (an example from Thailand is given in GTZ 1982; other project examples are in DSE 1987). Joint projects by UNDP/FAO and national plant protection agencies have produced documents to train the extension staff (eg the UNDP/FAO Plant Protection Project in Botswana).

Rapid assessment methods for potential hazards from pesticides to soil contamination and water pollution are shown in section 3.2.4.

5.2.3 Heavy Metal Pollution of Agricultural Lands

Most emphasis to date has been given to the conditions of disposal of sewage sludge and wastewater, but the principles involved can also apply to other metal-containing materials deposited on agricultural lands or effluents coming from agricultural lands. Guidelines for regulatory control may comprise:

- experimental approaches: need for a sound experimental base which integrates such factors as composition and application rate with agronomic and irrigation practices; evaluation of long-term effects on plants and soils must be included,
- legislative approaches: restricting applications; controlling application; defining maximum permissible contents; controls of heavy metal contents of foodstuff; combinations of these with restrictions related to land use and crop type.

Sources and further reading: Blume ed. 1990, Tiller 1985

The assessment of the behaviour of soils with regard to heavy metals is treated in section 3.2.4; further information on the reuse of sewage for irrigation is given in section 2.5.

Sources: Blume in: Blume ed. 1990; Brink in: Lessafre 1990; Himel et al. in: Cheng ed. (SSSA) 1990; Edwards 1987; Canter 1986

5.3 Control of Air Pollution

Control of emissions from irrigated agricultural lands can be achieved by several measures:

- reduction of gaseous emissions from fertilisers by careful selection of suitable N-forms, application rates and application methods,

- control and reduction of gaseous emissions during pesticide applications (eg avoiding windy days; use of low pressure spray nozzles) and selection of pesticides which are less volatile (specific information from suppliers and extension services),
- use of crop varieties which emit less gas or which are suitable to modified water management practices which allow reduced methane emissions,
- use of soil cultivation and water management methods which reduce methane and nitrous oxide emissions, especially in paddy rice,
- prohibiting burning of organic debris (by direct regulations or laws),
- prohibiting or restricting burning during land clearing activities,
- restriction of burning to limited periods (daytime/nightime or seasonal restrictions, periods with favourable weather conditions, regarding wind, temperature and humidity), or establishment of distance requirements between residents and open burning areas; or other regulations,
- control of emission standards from farm vehicles (application of control devices, regular inspections and maintenance, proper use of vehicles).

Control of emissions can be achieved by changes of individual behaviour, supported by training and information or regulations, which may be either direct or act as nuisance or hazard regulations.

Control or reduction of dust pollution can be achieved by several methods which reduce wind erosion and dust produced during tillage operations:

- use of soil preparation methods and practices which stabilise soil structure, eg aggregation,
- practicing tillage operations when soil surfaces are moist,
- cropping practices which reduce wind erosion (eg continuous cropping, strip cropping, stubble mulching),
- keeping soil surfaces moist during periods of strong winds (eg preventive watering),
- control of wind erosion on farm fields thorugh the use of windbreaks/shelterbelts,
- control or reduction of particulate pollution by crop processing and grain handling,
- all measures to prohibit or control biomass burning (see above).

Outlook. If current trends continues, a considerable increase in air pollution from fertiliser emissions is to be expected over the coming decades. Despite the fact that agricultural (and thus irrigation) pollution contributes to emissions on a global scale (eg methane, nitrous oxide, dust) it is agreed that

* their importance with regard to global warming should not be over-emphasised, eg methane and nitrous oxide respectively contribute 2.4% and 4.2% to the current mean world temperature (Schönwiese/Diekmann 1989)
* the growing world population requires the development of new agricultural land and air pollution will increase with the intensification of agriculture and increased livestock numbers. Regulations on other avoidable or unnecessary emissions of gases resulting from non-agricultural sources, especially in industrialised countries are of more importance in controlling the greenhouse effect (Schönwiese/Diekmann 1989).

Therefore, environmentally sound planning - regarding air quality - should be mainly focused on the reduction of emissions at the local level. However, there are again problems resulting from the scale effect: generally, each individual emission only contributes marginally to the overall impact. Thus, individual control measures also contribute also only marginally to improve air quality. Also, in many cases those resposible for emissions do not suffer directly from the pollution which makes progress difficult; it can probably only be achieved by changes in individual behaviour. This, in turn, depends on changed perceptions towards the protection of the environment.

Fig. 5-10

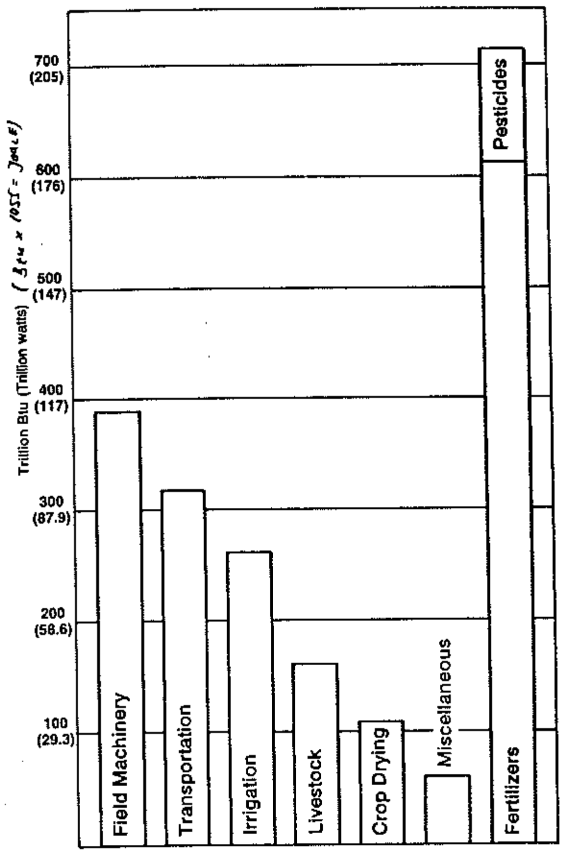


Fig. 6 — Energy use on farms

Source: Hughes 1980

Fig. 5-11

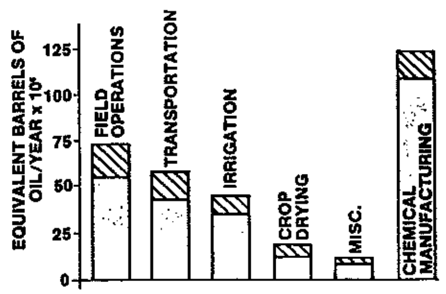


Fig. 24 — Potential for conservation of energy in crop production. Cross-hatch area indicates amount of energy that could be conserved without seriously affecting yield.

Source: Hughes 1980

Some measures can reduce costs or avoid health risk, eg in the proper use of fertilisers and the safe use of pesticides. Control measures may be possible in these fields, whereas regulations, eg regarding field burning, are often difficult to enforce by law even in industrialised countries. Therefore, efficient reduction or control of pollution from agricultural sites will remain a long term aim which should also be seen in the context of a continuous increase in irrigated areas. Some contributions to reduce air pollution may also be expected from agricultural research, especially in paddy rice cultivation where techniques are to be developed to reduce methane and nitrous oxide emissions.

5.4 Energy Conservation and Use of Non-Conventional Energy Sources

5.4.1 Irrigation and Energy Resources

Conservation of resources includes conserving on-farm energy. Irrigation is one of the main consumers of energy in modern farming systems in industrialised countries. Energy use for irrigation on farms in developing countries may even be considerably higher in relation to other activities. Direct on-farm energy use is mainly related to mechanised production, pumping of groundwater or surface water, operation of pressure systems (sprinkler, drip), transportation and post harvesting activities. An important indirect form of energy use is application of fertilisers and pesticides.

Typical energy uses on US-farms are shown in Fig. 5-10.

In China, irrigation and drainage systems account for about 5% of total electrical consumption and 25% of agricultural diesel oil consumption for the whole country (Z.Xiaoying). However, solar power in agriculture is developing in China and the use of solar power is promoted (Xin Muigyi 1991)

Irrigation may influence the demand for on-farm energy in three ways:

- intensification of agricultural production: it is obvious that irrigated agriculture is a highly intensive and specialised form of agriculture. Intensification usually implies the increased use of farm inputs, such as machines for tillage operations, weed control, application of fertilisers and pesticides, and harvesting, but also machines for post harvest operations,
- energy used for lifting water and field distribution of water,
- drainage machinery systems used for construction and maintenance works.

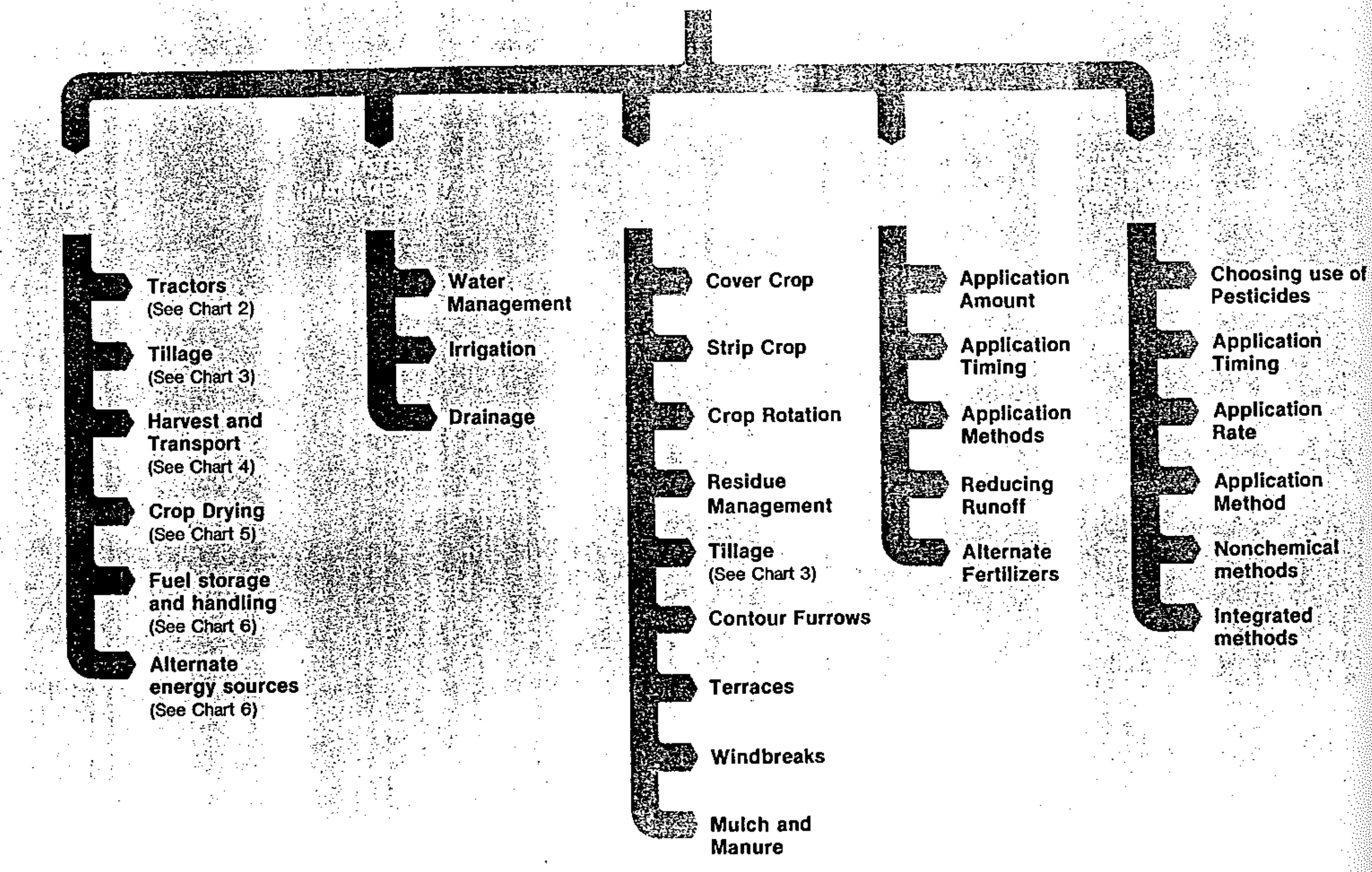
5.4.2 Energy Conservation

It is estimated that in the USA, the use of energy for irrigation alone can be cut by some 25% without seriously affecting production (Fig. 5-11). Energy audits (ie studies to measure energy use on farms) for developing countries are not at hand. For China, the utilisation ratio of agricultural energy sources and the efficiency of irrigation and drainage equipment are assessed to be low compared to international standards:

	China	other countries	
utilization ratio of agricultural energy	23	40-50	in %
irrigation/drainage - pump stations	36 *	60-65	in %
irrigation/drainage - motor pumped wells	27 *	60-65	in %

Source: Z.Xiaoying 1991 * Chinese standards for diesel engines are 54 and 45% respectively

Fig. 5-12



Source: Hughes 1980

Potentials for energy savings that reach national standards would make up about 1% of consumed electricity for the whole country.

Energy conservation measures must meet the following requirements to be accepted and applied by farmers:

- they should be cost efficient, ie costing less than current expenditures on fuel, gas etc. and the benefits should be immediate not only relaised in the long-term,
- they should be neutral to labour demand, ie a new water lifting method should not impose considerable additional labour requirements,
- they should be balanced: a new technology should not save energy at the expense of increased demands for other operations (ie switch of costs),
- they should be at least neutral to the efficiency and reliability of operations, eg sufficient wind energy must be available at times when it is needed for lifting given quantities of water.

In order to conserve energy the following measures and techniques should be adopted (see also section "conserve energy" in Fig. 5-12 and detailed Charts in Table 5-15):

(1) utilise technologies that require less on-farm energy:
  - more efficient use of chemical fertilisers and pesticides,
  - switch to crops which require less energy for production, eg during harvesting, post harvesting storage and drying,
  - more efficient use of water by increasing efficiency of conveyance systems and avoiding over-irrigation,
  - more efficient use of machines during cultivation, harvest and transport; proper maintenance of machines,
  - use of tillage systems which require less mechanization and machine operations,

(2) adoption of technologies that use renewable resources: eg for water lifting (wind power, photovoltaic power, bio-mass fuel) and drying (solar heat) etc.,

(3) use of an irrigation and drainage machinery system which has a high device efficiency index.

There are many variations and combinations of these options and an interested reader is referred to documents dealing with such systems in detail (eg Kenna and Gillet 1985).

Because labour substitution is often not a primary goal in agricultural development, a general option regarding agricultural mechanisation may exist in developing countries. For example developing animal drought power instead of introducing on-farm machinised operations or to the combined use of non-mechanised and mechanised operations.

5.4.3 Planning for Energy Conservation

An energy conservation plan may be established for an individual farm or for an entire project. The plan may, for example, be established for new farms to assess pump power requirements for various alternative lifting devices and irrigation methods. The following five steps should be undertaken:

- conducting an **energy audit** to identify the best targests for conservation efforts and to provide a basis for evaluation of the conservation effort,
- planning of the **conservation programme**; this includes general decisions about the type of water lifting device(s) to be used on the farm. After selection of the conservation target, the approach must be determined,

Fig. 5-13

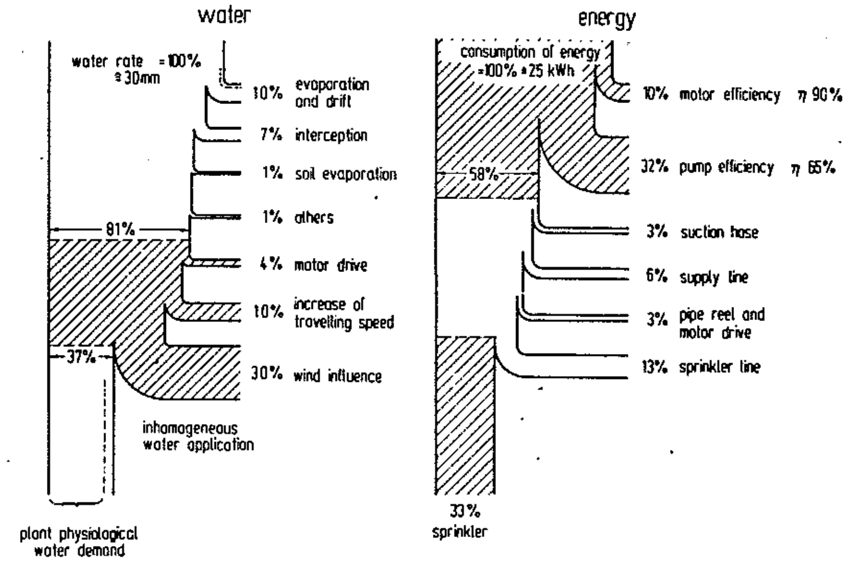


Figure 2. Water and energy balance for mobile irrigation machines

Source: Sourell in ICID 1991

Fig. 5-14

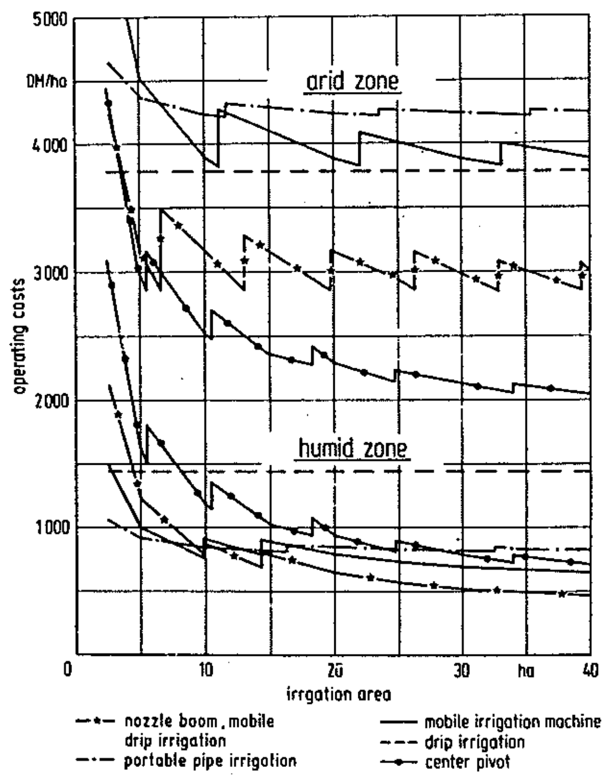


Figure 8. Variation of operating costs of the different irrigation systems depending on the irrigated area. For the calculation of water lifting and transportation costs partnership conditions are assumed.

Source: Sourell in ICID 1991

- **implementing** the plan with repeated evaluation of performance and discussion with all people involved,
- **evaluation** of effectiveness of conservation efforts at regular intervals (eg half-yearly or seasonally). The interpretation must consider that many factors, some of which are beyond the control of the individual farmer, affect energy use, for example emergency activities,
- **reassessment** of the efforts and repeating the steps above if required, for further improvements.

Source: Hughes 1980

The required power by a pumps depends on the pump and the power source: the discharge rate, vertical lift or head, and the efficiency of the motor pump combination. Energy conservation in pumping may be achieved by installing fuel-efficient power plants, reducing operation time by efficient water use, and by keeping the head as low as possible (eg by conjunctive use of ground- and surface waters, or the use of gravity-fed or low-pressure irrigation systems).

Increasing the device efficiencies of irrigation systems (including prime movers, transmission, water pumps, pipelines) would require the following steps during

measurement - regular calibration - calculation of energy efficiencies - analysis of the technical condition of the device - technical transformation - verification.

Measures of technical transformation are explained in ICID 1991 (STS p.262-270). Transformation programs in China resulted in the overall efficiency rising from 27% to 40% within a period less than one year (Z.Xiaojing 1991).

Energy losses in pipeline systems (ie friction and system losses) can also be greatly reduced, eg by designing various systems in undulating topography, optimum allocation of elevation differences, and the selection of optimum pipeline diameters. Energy-efficient system designs may be drawn up by linear programming or the cost potential method (Mitsuno 1991)

Possibilities for energy savings in sprinkler and drip systems are determined by increasing reducing the pressure requirement and increasing water distribution effectiveness. Pressure losses in mobile sprinkler systems are caused by water transportation and pressure requirements (42%), friction losses in delivery hoses (25%) with the remainder being lost at sprinklers (33%) (see Fig. 5-13).

A mobile drip irrigation system which combines the advantages of both drip irrigation (high water application efficiency and low operating pressure) with mobile irrigation machines (lower capital and labour requirements per unit area; higher operational safety compared to stationary drippers) proved to be cost efficient thorugh savings in water and energy. Fig. 5-14 compares fixed and variable charges for a number of systems (Sourell 1991).

Intake works for medium and minor irrigation projects can also be designed for energy saving.

A successful example is reported from China: hydraulic flap gates retain water, creating head differences between upstream and downstream sides, and driving turbine pumps which rise water directly onto the river bank (Xionghan/Xuannian 1991 in: ICID (STS-25 1991).

Sources: T.Mitsuno in: ICID (STS-B22) 1991; Zheng Xiaoying in: ICID (STS-B21) 1991; Y.Xionghan and G.Xuannian in: ICID (STS-B25) 1991; Hughes (DEERE) 1980

Further reading: FAO (EEP 5)1985; Kenna/Gillet 1985

Table 1-1

Table 9-10

ENVIRONMENTAL MANAGEMENT: CONFLICTS IN THE HUMID TROPICS

Agricultural Activity	Conflicts Within the Agriculture Sector	Conflicts with Other Sectors	Solutions
Utilization of fertilizers and pesticides for more intensive agriculture.	Loss of predator-prey equilibria; disease and insect resistance to pesticides require increasingly-expensive control.	*Fish/Wildlife* - Direct and indirect effects because of increasing levels of biocides in the water. *Water* - Potential contamination of drinking water. *Livestock* - Potential contamination of meat and milk products. *Forests* - Reduces the need to clean forests for agriculture.	Investigation of integrated pest management techniques. Establishing regulations controlling pesticide use with training, extension services, and enforcement. Evaluation of crop mixtures and agroforestry systems to increase production and to minimize problems with weeds and plagues. Pesticides need to be properly used for both economic and health reasons.
Increasing cultivation on marginal areas because of spontaneous cultivation.	Continued subsistence production levels and standards of living because of low yield.	*Fish/Wildlife* - Habitat loss because of forest destruction. *Water* - Accelerated sedimentation, increased water volumes in rivers, water quality is adversely affected by rapid runoff and reduced infiltration. *Forests* - Additional losses due to clearing. *Social Problems* - Rapid marginalization of small farmers near new settlements and limited development potential of occupied areas.	Encouragement of intensified agriculture on the best soils, evaluation of sustained agricultural production systems adapted to the humid tropics. Emphasizing the rehabilitation of abandoned fallow lands and of degraded pastures before new forest land is cleared.
Underutilization of land resources (planting of fertile soils in grass instead of more intensive uses).	Loss of profits obtainable from more intensive uses, need for utilizing marginal lands for intensive cultivation of annual or high-value crops.	*Fish/Wildlife* - Indirect loss due to continued clearing of forests. *Water* - Indirect conflicts due to continued agricultural activity on marginal soils in watershed highlands. *Forests* - Utilization of forest lands for agricultural use; loss of forest resources.	Evaluation of land use, considering climatic, soil and economic limitations, land tenancy, market conditions, and cultural characteristics.

Source: OAS 1987

Table 1-2 a

Table 16-1

NATURAL GOODS (RESOURCES) AND SERVICES

I. Goods/Products (Resources)
1. Surface and ground water for drinking
2. Surface and ground water for industry
3. Surface and ground water for irrigation
4. Biomass for lumber
5. Biomass for firewood
6. Biomass for construction materials (posts, vigas, etc.)
7. Ornamental plants (indoor, landscaping, dry)
8. Vegetable fibers
9. Medicinal plants
10. Food for human consumption (fruits, chicle, honey, sap, shoots, etc.)
11. Plant chemical substance (dyes, stains, waxes, latex, gums, tannings, syrups, drugs, etc.)
12. Fish for human food (crustacians, finfish, mollusks)
13. Fertilizer (guano, other dung, fish meal)
14. Aquatic plants for human food (algas)
15. Aquatic precious/semiprecious materials (pearl, coral, conchas, mother of pearl)
16. Materials for artisan work (rock, wood for carving, fibers for basketmaking, etc.)
17. Metallic minerals (bauxite, ores, nuggets, etc.)
18. Non metallic minerals
19. Construction materials (sands, clay, cinders, cement, gravel, rocks, marble)
20. Food materials (salt)
21. Mineral nutrients (phosphorus)
22. Material for mineral dyes, glazes
23. Hides, leather, skins
24. Other animal materials (bones, feathers, tusks, teeth, claws, butterflies)
25. Other vegetation materials (seeds, pods)
26. Live fish (ornamental, aquaria)
27. Live animals for pets, zoos
28. Live animals for research (medical, other)
29. Fossil fuels (oil, gas, coal)
30. Other fuels (peat, other organic matter dung - biomass)
31. Livestock forage
32. Food for livestock (fish meal)
33. Pulpwood

II. Ecosystem Maintenance Services
1. Nutrient cycling
2. Nutrient storage
3. Nutrient distribution
4. Photosynthesis-Respiration (biomass-succession)
5. Population control (predator/prey)
6. Flooding
7. Sediment transport
8. Habitat for local finfish
   - feeding
   - breeding
   - nursery
   - resting (refuge)
9. Habitat for migrating finfish
   - feeding (including transient food source)

II. Ecosystem Maintenance services (Cont.)
   - breeding
   - nursery
   - resting (refuge)
   - migration route
10. Habitat for crustacea
   - feeding
   - breeding
   - nursery
   - resting (refuge)
   - migration route
11. Habitat for mollusks
   - feeding (including transient food source)
   - breeding
12. Buffering

III. Non-tangible Goods and Services
1. Windbrake
2. Shade
3. Recreation use of water (swimming, boating, waterskiing, sailing)
4. Zones for scenic tourism
5. Zones for recreation tourism
6. Zones for scientific tourism
7. Scientific values
8. Spiritual values
9. Historical values
10. Cultural values
11. Sport hunting and fishing
12. Early warning system
13. Moisture modification (humidity)
14. Temperature modification
15. U.V. filtration
16. Endangered species (fauna)
17. Endangered species (flora)
18. Gene resource (fauna)
19. Gene resource (flora)

IV. Economic Services
1. Hydroelectric power source
2. Other energy sources (wind, sun, tides)
3. Dilution of contaminants
4. Decomposition of contaminants
5. Oxidation of contaminants
6. Transportation of contaminants
7. Airshed (dilution of air contaminants)
8. Erosion control
9. Sediment control
10. Flood control
11. Groundwater recharge
12. Space for urban, industrial, agriculture, occupation, roadways, canals, airports, waste storage
13. Physical support for plants
14. Pollination

Table 1-2 b

Table 16-2

NATURAL GOODS PRODUCED BY PROTECTED AREAS IN THE AMERICAN HUMID TROPICS[a and b]

Goods	National Parks (I-II)	National Reserves (VIII)	National Sanctuaries (III-IV)	Historic Sanctuaries (V)	Protective Forest (VI)	Wildlife Areas (VIII)	Reserved Zones (VI)	Native Reserves (VII)
Water	VI	VI	S	NS	VI	S	VI	NS
Genetic bank (Flora)	VI	I	I	NS	I	S	VI	NS
Genetic bank (Fauna)	VI	I	I	NS	I	I	VI	NS
Goods from fauna		VI			I	VI		VI
Goods from fishing		I			S	NS		VI
Non-lumber vegetative goods					VI			I
Lumber vegetative goods					S			S

a. The Roman numbers (I-VIII) indicate management categories adapted by IUCN (1978).
b. VI: Very Important; I: Important; S: Significant; NS: Not Significant.

Sources: OAS 1987

Table REM 2: Goods and services available to the molapo system

Table 1-4

A Biophysical Resources (water, land, air)

inputs = floodwater, land, soils, dung from cattle/wildlife, energy/sun, nutrients from floodwaters, sediment transport from wind erosion, rainfall

outputs = crops; grazing areas for cattle; seasonal fish ponds; waterponds for cattle; birds and domestic water supply; occasionally grazing areas for wildlife; food for birds (crops).

B Ecosystems Services

B1 Physical Resources: water/land/soil/air

inputs:
- land as habitat for plants and animals (biotic functions)
- land as buffer for soil moisture (flood recession farming)
- land as filter, buffer, transformer of toxins
- land for crop production and for grazing

outputs:
- filter and storage for groundwater aquifers
- filter for air pollution (chemical spraying for control of animal health, quelea birds and public health)
- filter for soil contaminants (agro-chemicals, future uses)
- soil degradation: chemical fertility, physical status, salinity, soil phases)

B2 Biotic functions

inputs: pest predators (invertebrates, reptiles, birds, mammals), microinvertebrates, other soil fauna to control biological balances; nutrient supply (marginal importance)

outputs: potential damages due to the indiscriminate uses of agro-chemicals; impacts on forestry, wildlife, livestock, public health, biotic imbalances.

C Immaterial services

currently no special functions

Table 1-5

NATURAL SERVICES PRODUCED BY PROTECTED AREAS IN THE AMERICAN HUMID TROPICS[a]

Services[b]	National Parks (I, II)	National Reserves (VII) (VIII)	National Sanctuaries (II, IV)	Historic Sanctuaries (V)	Protection Forests (VI)	Wildlife Refuge (VIII)	Reserved Areas (VI)	Common Reserves (VII)
Recycling of Atmospheric Contaminants	VI	VI	S	NS	VI	I	I	NS
Maintenance of the Local Precipitation Regime	VI	VI	NS	NS	VI	S	I	NS
Buffering of Local Climate	VI	VI	NS	NS	VI	S	I	NS
Regulations of the Water Regime	VI	VI	NS	NS	VI	S	I	NS
Maintenance of Supply of Quality Water	VI	VI	NS	NS	VI	S	I	S
Soil Conservation	VI	I	NS	NS	VI	S	I	S
Protection from Landslides, Floods and Other Hazards	VI	I	NS	NS	VI	S	I	S
Maintenance of Genetic Diversity	VI	I	VI	NS	I	S	I	NS
Maintenance of Natural Diversity	VI	I	VI	NS	I	S	I	NS
Reservoir for Species which Offer Biological Control of Plagues	VI	I	I	NS	I	I	I	S
Reserve for Species of Interest to Science	VI	I	VI	NS	I	I	I	NS
Reserve for Species of Interest for Domestication	VI	VI	S	NS	I	I	I	NS
Genetic Bank for Future Improvement of Domesticated Species	VI	VI	S	NS	I	I	I	NS
Scenic Beauty	VI	S	I	S	I	S	I	NS
Area for Hunting	-	VI	-	-	VI	VI	-	VI
Area for Fishing	-	VI	-	-	I	VI	-	VI
Area for other Recreation	VI	I	S	I	VI	I	S	S
Area for Tourism	VI	S	I	I	S	I	S	NS
Conservation of Natural and Historic Scenery	I	NS	-	VI	NS	-	-	-
Conservation of Cultural Patrimony	I	S	VI	S	S	S	S	-

a. The Roman numerals (I-VIII) indicate equivalent management categories adopted for IUCN (1978).
b. VI: Very Important, I: Important, S: Significant, NS: Not Significant, -: Not Applicable.

Source: OAS 1987

Natural Risk Assessment for Molapo Farming

Table 1-6

elements	occurence	significance
Water		
seasonal/annual shortage of floodwater	40%	+ +
extreme variability of floodwater	predom	+ +
flooding of cropland (untimely, prolonged)	25%	+ +
low saltload (for irrigation ?)	predom.	-
Soils		
low fertility and moisture storage capacity	50% area	+
irregular pattern of soil mosaics	predom	+
partly high wind erodability	40% area	O
low infiltration rates (danger of waterlogging)	40% area	+
Air/Climate		
high windspeed causing wind erosion/moisture stress	irregular	O
heavy rainfall intensity causing erosion, pools	irregular	+ +
high erratic seasonal rainfall	regular	+ +
occurence of dry spells within rainy season	regular	+ +
Biotic risks		
vector-borne diseases	frequent	+
plant pests (birds)	40% years	+ +
pests (other)	often	+
wildlife damage to crops/structures/dangerous animals	occasional	O
weeds as competition for crops	predom	+
other		
earthquakes	frequent	O

predom = predominant, occuring in most years; percentages refer to areas or years
significance: O not or minor important; + moderately important; ++ very important

Source: Petermann

Table 1-7

Table 16-5

EXAMPLES OF NATURAL GOODS AND SERVICES PROVIDED BY TWO HYPOTHETIC ECOSYSTEMS AND THEIR USE IN CONFLICT IDENTIFICATION

	Ecosystem a	Ecosystem b
Land for Agriculture	X	
Land for Industry	X	X
Land for Grazing	X	
Wildlife Habitat	X	
Underground Water for Irrigation		X
Underground Water for Domestic Use		X

Table 1-8

Table 16-6

INTERSECTORAL MATRIX IDENTIFYING POTENTIAL CONFLICTS BETWEEN SECTORAL ACTIVITIES

	Rice Cultivation	Vegetable Cultivation	Livestock Production	Forestry
Rice Cultivation	1	2	3	4
Vegetable Cultivation	5			6
Livestock Production	7			8
Forestry	9	10	11	12

Sources: OAS 1987

Table 1-9

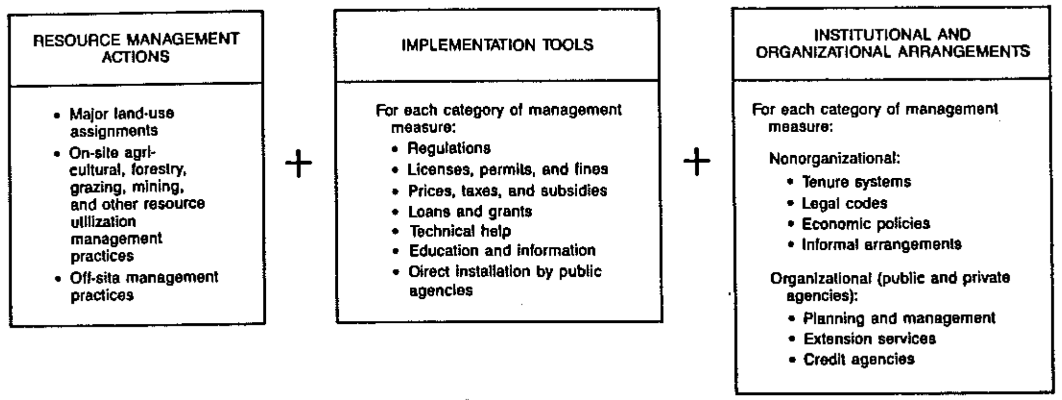


Figure 2.2
Watershed management as a planned system.

Table 1-10

Table 2.1
The three major activities of watershed management

Panel 1. Divide watershed into major land uses

- Agriculture
  Irrigated
  Rain-fed
- Grazing
- Horticulture
- Agroforestry
- Forestry
  Commercial
  Mixed use
  Preservation
- Mining
- Transportation
- Urban
- Lakes, reservoirs, stream channels, and wetlands

Panel 2. Develop set of resource utilization and management practices for each operating unit within each major land use

Irrigated Agriculture		Commercial Forestry	Agroforestry	
• Types of crops • Rotation of crops • Quantity and timing of water, fertilizer, pesticides, labor, animal power, and machinery inputs • Methods of tilling (e.g., contour plowing)	• Methods of application of water, fertilizer, and pesticides • Installation and maintenance of buffer strips, grassed waterways, terraces, on-farm check dams	• Types of tree species • Rotation and spatial distribution of tree crops • Quantity and timing of inputs • Methods of tree planting, thinning, and fertilizing • Harvesting methods, erosion control practices, road siting, construction and maintenance	• Types, spatial distribution, and rotation of tree and row crops • Quantity and timing of resource inputs • Methods of tilling and tree cropping • Methods of application of water, fertilizers, and pesticides	• Installation and maintenance of erosion control measures and road siting, construction and maintenance

Panel 3. Develop set of downstream management practices

- Stream bank protection by reserve buffer strips, revegetation, and riprapping
- Debris removal
- Channel dredging
- Harbor, estuary dredging
- Treatment of intake water
- Wastewater treatment
- Cheek dams

Table 1-11

Table 2.2
Examples of watershed management tasks required at the planning stage, classified by management activities and management system elements

Management Activities	Management System Elements: Resource Management	Implementation Tools	Institutional Arrangements
Land-use assignments	• Land capability analysis • Land suitability analysis • Formulation and benefit-cost analysis of alternative land-use plans	Planning for • Regulation • Economic incentives • Education	Planning for • Ownership/tenure systems • Public regulation systems • Organizational changes
On-site resource utilization and management practices	For agroforestry • Agronomic, forestry, and economic analyses of types, distribution, and rotation of tree and row crops • Planning for methods of tilling, methods of cropping, erosion control practices	Planning for • Education • Technical help • Economic incentives • Marketing assistance • Regulation	Planning for • Extension services • Credit/financial aid • Ownership/tenure systems • Soil conservation agency
Off-site management practices	Planning for • Stream bank vegetation, protection, or revegetation • Channel dredging • Riprapping • Intake water treatment	Planning for • Education • Technical help • Economic incentives • Public installation and maintenance	Planning for • Extension services • Credit/financial aid • Soil conservation agency

Source: Easter and Hufschmidt 1985.

Sources: Easter ed. 1986

Table 1-12

Table 2.3
Examples of tasks involving implementation tools, classified by stages of the management process and management activities

Management Process \ Management Activities	Land-use Assignments (1)	On-site Resource Utilization and Management Practices (2)	Off-site Management Practices (3)
Planning		Content, magnitude, and timing of • Education • Technical help • Economic incentives • Marketing assistance • Regulation	
Design		Detailed design of programs for • Education • Technical help • Economic incentives • Marketing assistance • Regulation	
Installation		• Establish special extension team • Technical help for crop planting, fertilizing, irrigation, harvesting, and erosion control practices • Economic incentives, set cost-sharing levels for practices • Marketing assistance, identify potential markets • Regulation, determine undesirable practices	
Operation		• Extension problem census and problem-solving meetings • Monitoring of performance • Technical help on changes in utilization plans • Economic incentives, adjust cost-sharing levels for practices • Marketing assistance, provide information on commodity prices by market • Regulation, check compliance	
Maintenance		• Technical help, economic incentives, and regulation for maintaining productive plant and facilities	

Sources: Easter ed. 1986

Table 1-13

Environmental Ratings of Top Ten Trends and Associated Practices: Nonirrigated Production (Unger, 1977)

Panel Rank	Trend and Subtrend
1	Runoff & Erosion Control a. Contour farming or contour strip-cropping b. Terraces and grass waterways c. Optimizing time of operations d. Narrow rows
2	Improvement of Seed and Plants a. Weather resistance b. Salt resistance c. Production efficiency d. Disease resistant crops e. Insect and nematode resistant crops
3	Conservation Tillage a. No-tillage b. Reduced tillage
4	Using Scouting and Integrated Controls a. Surface scouting b. Remote sensing scouting c. Using integrated controls
5	Developing New Biological and Chemical Pesticid a. Micro-encapsulated pesticides b. Systemic pesticides c. Surfactants for herbicides d. Bio-degradable pesticides e. Alternative formulations f. Juvenile hormones g. Pheromones h. Sterile males i. Predator and parasites
6	Improving Soil-Plant Analysis
7	Merhods of Nutrient Applying a. Foliar fertilization b. Multiple applications c. Fall application d. Liquid fertilizers e. Aerial and floater application f. Improved nutrient placement
8	Wind Erosion Control a. Strip-cropping b. Barrier row c. Windbreaks

Source: Canter 1986

Table 12: Description of Environmentally Related Trends and Developments: Irrigated Cropland Production (Unger, 1977)

CROP MANAGEMENT TRENDS

CONSERVATION TILLING - general reduction in cropland soil disturbance

a. No till plant: seeding without pre-planting tillage
b. Reduced tillage: weed control and soil breaking with a limited soil inversion

CROP SEQUENCING - cropping patterns

a. Mono-cropping: successive planting of one crop on the same plot of land
b. No-meadow: eliminates pastures or meadows from rotation sequence
c. Relay cropping: planting the second crop before the first crop is harvested
d. Double cropping: planting the second crop after the first crop is harvested in the same growing season

SEED/PLANT IMPROVING

a. Weather resistance: plants genetically developed to withstand winds, drought, etc.
b. Salt tolerance: developing plants capability to produce in a saline environment
c. Production efficiency: genetic development of plants which utilize nutrients and sunlight more efficiently and have desired growth characteristics of root development, growth and maturity.

SOIL WATER MANAGEMENT TRENDS

RUNOFF AND EROSION CONTROLLING

a. Contour farming: farming operations are performed according to the land elevations
b. Terracing: soil embankments which slow the downhill flow of surface waters
c. Cover crops: stubble mulching and grassed waterways to slow runoff flow
d. Optimizing time of operation: performing farm operations to minimize the time period that the soil is bare
e. Narrow rows: reducing the distance between adjoining rows of seeded crops
f. Chemical erosion-control: chemical agents applied to reduce soil erosion

Table 12: (Continued)

WIND-EROSION CONTROLLING

a. Strip cropping: dividing the field in alternate narrow bands of crop and fallow land
b. Barrier rows: use of taller crops to act as wind breaks
c. Wind breaks: planting trees and shrubs to reduce the effect of the wind and soil loss

SPRINKLER IRRIGATION -- application of water to crops dispersing droplets through the air

USING DRIP OR TRICKLE IRRIGATION -- application of water to crops by dispersing through subsurface delivery systems

REDUCING WATER APPLICATION

a. Furrow basins: small earth dams used to impound water in furrows
b. Sprinklers: dispersing irrigation water droplets through the air
c. Limited application: reducing irrigation frequency to eliminate over-irrigation
d. Recycling and controlling tailwater: using irrigation water runoff for application to other crops and improving irrigation water management

DIRECTLY MONITORING IRRIGATION NEEDS

a. Measure soil moisture content: direct field probes
b. Remote sensing of plant and water stress: by using satellite information

NUTRIENT MANAGEMENT TRENDS

IMPROVING SOIL-PLANT ANALYSIS (crop logging) - monitoring nutrient uptake, soil nutrients available, and plant condition to provide information to adjust fertilizer rates, timing, and cultural practices

METHODS OF NUTRIENT APPLYING

a. Foliar fertilization: applying fertilizer as a spray so that nutrients are taken up through the leaves of the plant
b. Fertigation: fertilizer application through irrigation systems
c. Multiple application: fertilizer is applied more than one time to realize optimum growth and crop production
d. Aerial and floater application: fertilizer is applied via airplane, helicopter, or by ground machines equipped to traverse wet or dry ground with limited soil compactions

Source: Canter 1986

Table 1-14

Table 12: (Continued)

e. Fall fertilization: application of fertilizer during the fall season prior to the crops primary growing season
f. Liquid fertilizer: application of nutrients as a liquid to enhance crop production

USING ALTERNATIVE NUTRIENT SOURCES

a. Animal wastes: solid and liquid wastes from livestock feedlots contain nutrients and organic matter
b. Municipal treatment plant wastes: use of municipal wastes as a source of nutrients
c. Green manure crops: crops grown for the intended purpose of incorporating immature plants into the soil structure

DEVELOPING BIOLOGICAL NITROGEN-FIXATION SOURCES

a. Legumes: plants capable of fixing atmospheric nitrogen and accumulating it in root nodules
b. Non-legume: soil microbacterial populations that are able to fix nitrogen from the air

DEVELOPING IMPROVED FERTILIZERS

a. Controlled-release: chemical inhibitors to delay nitrification, leaching etc. are added to fertilizers
b. High nitrogen content: use ammonia to supply a high concentration of nitrogen
c. High phosphorus content: use of polyphosphates to increase phosphorus content about 50 percent more than ordinary fertilizers

PEST CONTROL TRENDS

USING SCOUTING

a. Surface: determine types of pests and potential crop damage by visual inspection
b. Remote sensing: insect populations and locations are determined by satellite information

IMPROVING PESTICIDE APPLICATION METHODS AND TIMING

a. Aerial application: new methods to decrease pesticide drift during application by increasing an homogeneous particle size
b. Floater vehicle: can be used on wet soil for timely application
c. Dual application: herbicides, pesticides, and liquid fertilizer simultaneous application
d. Pesticide placement: using the most effective and efficient manner for applying pesticides

Table 12: (Continued)

DEVELOPING RESISTANT CROPS

a. Disease resistant: genetically developing plant species capable of resisting diseases
b. Insect and nematode resistant: genetically developing plant species capable of resisting selected insects and nematodes
c. Bird resistant: genetically developing plant species that are less accessible to feeding bird populations

DEVELOPING NEW PESTICIDES

a. Micro-encapsulated pesticides: pesticides in micro-capsule form that slowly release the pesticide over a longer time period
b. Systemic pesticides: pesticide compounds that are absorbed by the plant which make it toxic to pests
c. Surfactants: chemical materials which enhance the adsorption and absorption properties of herbicides
d. Bio-degradable pesticides: chemicals which are effective against pests and are decomposable by the environment with limited persistence
e. Alternative formulations: different methods combining chemicals which are effective against pests

DEVELOPING BIOLOGICAL CONTROLS

a. Juvenile hormones: hormonal compounds capable of preventing normal development and maturation of insects
b. Pheromones: chemical compounds containing organophosphorus insecticide used to selectively attract insects
c. Sterile males: release sexually sterile insects to decrease or control insect population
d. Predators and parasites: use of natural enemies, fungi, viruses, bacteria, to control insect populations

DEVELOPING INTEGRATED CONTROLS - integrating chemical, biological, and mechanical treatment methods to achieve desired control over cropland production

RESOURCE USE TRENDS

USING INCREASED RATES AND AMOUNTS OF CROP PRODUCTION INPUTS - increasing demands for cropland production will affect the quantity of fertilizer, animal and municipal wastes, chemicals, energy and land used for food production

Table 1-14 cont.

Table 13: Environmentally Related Trends: Irrigated Cropland (Unger, 1977)

TRENDS	Potential Contribution to Pollution--Major Pollutants: Surface Water						Ground Water			Air		Land				
	Sediment	Nitrogen	Phosphorus	Pesticides	Inorganic salt and minerals	Biodegradable organics	Nitrates	Pesticides	Inorganic salt and minerals	Gases	Particulates	Soil erosion	Salinity	Heavy metals	Pesticide residues	Biodegradable organics
CROP MANAGEMENT TRENDS																
CONSERVATION TILLING	+	+	+	-	0	-	-	-	0	0	+	+	0	0	-	-
a. No-tillage	+	+	+	-	0	-	-	-	0	0	+	+	0	0	-	-
b. Reduced tillage: chisel plowing undercutting, chemical	+	+	+	-	0	-	-	-	0	0	+	+	0	0	-	-
CROP SEQUENCING	-	-	-	-	0	0	0	-	0	0	-	-	0	0	-	0
a. Mono-crop sequencing	-	-	-	-	0	0	0	-	0	0	-	-	0	0	-	0
b. No-meadow crop sequencing	-	-	-	-	0	-	+	-	0	0	-	-	0	0	-	-
c. Relay cropping	+	+	+	+	0	-	-	-	0	0	+	+	0	0	-	-
d. Double cropping	+	+	+	+	0	-	-	-	0	0	+	+	0	0	-	0
SEED/PLANT IMPROVING (GENETIC DEVELOPMENT)	+	0	+	0	0	-	0	0	0	0	+	+	0	0	0	-
a. Weather resistance	+	0	+	0	0	-	0	0	0	0	+	+	0	0	0	-
b. Salt tolerance	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
c. Production efficiency	+	+	+	0	0	-	-	0	0	0	+	+	0	0	0	-
SOIL WATER MANAGEMENT TRENDS																
RUN-OFF & EROSION CONTROLLING	+	+	+	+	0	+	-	-	-	0	+	+	0	0	-	-
a. Contour farming: contour planting, contour-strip cropping	+	+	+	+	0	+	-	-	-	0	+	+	0	0	-	-
b. Using terraces & grass waterways	+	+	+	+	0	+	-	-	-	0	+	+	0	0	-	-
c. Using winter cover crops	+	+	+	+	0	+	-	-	-	-	+	+	0	0	-	-
d. Optimizing time of operation: tillage, planting	+	+	+	+	0	0	+	+	+	0	+	+	0	0	+	0
e. Using narrow rows	+	+	+	+	0	-	+	+	0	-	+	+	0	0	+	-
f. Using chemical erosion-control agents	+	+	+	+	0	0	-	-	-	0	+	+	0	0	-	0
MOISTURE CONSERVING (STORAGE)	-	0	-	+	-	+-	+	-	+	-	-	-	0	0	-	
a. Fallow cropping: moisture storage, salt-seeps	-	0	-	+	-	+	-	+	0	+	-	-	-	0	0	-
b. Using evapo-transpiration reducing agents	+	0	+	0	0	0	-	0	-	0	+	+	+	0	0	0

TRENDS	Potential Contribution to Pollution--Major Pollutants: Surface Water						Ground Water			Air		Land				
	Sediment	Nitrogen	Phosphorus	Pesticides	Inorganic salt and minerals	Biodegradable organics	Nitrates	Pesticides	Inorganic salt and minerals	Gases	Particulates	Soil erosion	Salinity	Heavy metals	Pesticide residues	Biodegradable organics
SPRINKLER IRRIGATION	+	+	+	+	+	0	+	+	+	0	+	+	-	0	-	0
USING DRIP OR TRICKLE IRRIGATION	+	+	+	+	+	0	+	+	+	0	+	+	-	0	-	0
REDUCING WATER APPLICATION	+	+	+	+	+	0	+	+	+	0	+	+	-	0	-	0
a. Furrow basins	+	+	+	+	+	0	-	-	-	0	+	+	-	0	-	0
b. Sprinkler	+	+	+	+	+	0	+	+	+	0	+	+	-	0	-	0
c. Limited application	+	+	+	+	+	0	+	+	+	0	+	+	-	0	-	0
d. Recycling and controlling soil water	+	+	+	+	+	+	-	-	-	0	+	+	-	0	-	0
DIRECTLY MONITORING IRRIGATION NEEDS	+	+	+	+	+	0	+	+	+	0	+	+	-	0	-	0
a. Measure soil moisture content	+	+	+	+	+	0	+	+	+	0	+	+	-	0	-	0
b. Remote sensing	+	+	+	+	+	0	+	+	+	0	+	+	-	0	-	0
METHODS OF NUTRIENT APPLYING	+	+	+	0	0	0	0	0	0	0	+	+	0	0	0	0
a. Foliar fertilization	+	+	+	0	0	0	+	0	0	0	+	+	0	0	0	0
b. Fertigation	+	+	+	0	0	0	0	0	0	0	+	+	0	0	0	0
c. Multiple application	-	-	-	0	0	0	-	0	0	0	-	-	0	0	0	0
d. Aerial and floater application	+	+	+	0	0	0	+	0	0	0	+	+	0	0	0	0
e. Fall fertilization	+	+	+	0	0	0	-	0	0	0	-	+	0	0	0	0
d. Liquid fertilizer	+	+	+	0	0	0	0	0	0	0	+	+	0	0	0	0
USING ALTERNATIVE NUTRIENT SOURCES	+	-	-	0	0	-	-	0	0	-	-	+	0	0	0	0
a. Using animal wastes	+	-	-	0	0	-	-	0	0	-	-	+	0	0	0	0
b. Using municipal treatment plant wastes	+	-	-	0	0	-	-	0	0	-	-	+	0	-	0	0
c. Using green manure crops	-	+	+	0	0	-	-	0	0	+	-	-	0	0	0	0
DEVELOPING BIOLOGICAL NITROGEN-FIXATION SOURCES	+	+	0	0	0	-	+	0	0	0	+	+	0	0	0	-
a. Developing legume sources	+	+	0	0	0	-	+	0	0	0	+	+	0	0	0	-
b. Developing non-legume sources	+	+	0	0	0	-	+	0	0	0	+	+	0	0	0	-

Source: Canter 1986

Table 13: (Continued)

TRENDS	Potential Contribution to Pollution--Major Pollutants: Surface Water						Ground Water			Air		Land				
	Sediment	Nitrogen	Phosphorus	Pesticides	Inorganic salt and minerals	Biodegradable organics	Nitrates	Pesticides	Inorganic salt and minerals	Gases	Particulates	Soil erosion	Salinity	Heavy metals	Pesticide residues	Biodegradable organics
DEVELOPING IMPROVED FERTILIZERS	0	+	+	0	0	0	+	0	0	0	0	0	0	0	0	0
a. Developing controlled-release fertilizers	0	+	+	0	0	0	+	0	0	0	0	0	0	0	0	0
b. Developing high nitrogen content fertilizers	0	-	-	0	0	0	-	0	0	0	0	0	0	0	0	0
c. Developing high phosphate content fertilizers	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
PEST CONTROL TRENDS																
USING SCOUTING	0	0	0	+	0	0	0	+	0	0	0	0	0	0	+	0
a. Using surface scouting	0	0	0	+	0	0	0	+	0	0	0	0	0	0	+	0
b. Using remote sensing scouting	0	0	0	+	0	0	0	+	0	0	0	0	0	0	+	0
IMPROVING PESTICIDE APPLICATION METHODS AND TIMING	+	0	0	+	0	0	0	+	0	0	+	+	0	0	+	0
a. Improving aerial application	0	0	0	+	0	0	0	0	0	0	0	0	0	0	+	0
b. Improving floater vehicle application	+	0	0	+	0	0	0	+	0	0	+	+	0	0	+	0
c. Developing fertilizer and pesticide dual application	+	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
d. Improving pesticide placement	0	0	0	+	0	0	0	+	0	0	0	0	0	0	+	0
DEVELOPING RESISTANT CROPS	+	0	0	+	0	0	0	+	0	0	+	+	0	0	+	0
a. Developing disease resistant crops	+	0	0	+	0	0	0	+	0	0	+	+	0	0	+	0
b. Developing insect and nematode resistant crops	+	0	0	+	0	0	0	+	0	0	+	+	0	0	+	0
c. Developing bird resistant crops	+	0	0	+	0	0	0	+	0	0	+	+	0	0	+	0
DEVELOPING NEW PESTICIDES	0	0	0	+	0	0	0	+	0	0	0	0	0	0	+	0
a. Developing micro-encapsulated pesticides	0	0	0	+	0	0	0	+	0	0	0	0	0	0	+	0
b. Developing systematic pesticides	0	0	0	+	0	0	0	+	0	0	0	0	0	0	+	0
c. Developing surfactants for herbicides	0	0	0	+	0	0	0	+	0	0	0	0	0	0	+	0
d. Developing bio-degradable pesticides	0	0	0	+	0	0	0	+	0	0	0	0	0	0	+	0
e. Developing alternative formulations	0	0	0	+	0	0	0	+	0	0	0	0	0	0	+	0

Table 13: (Continued)

TRENDS	Potential Contribution to Pollution--Major Pollutants: Surface Water						Ground Water			Air		Land				
	Sediment	Nitrogen	Phosphorus	Pesticides	Inorganic salt and minerals	Biodegradable organics	Nitrates	Pesticides	Inorganic salt and minerals	Gases	Particulates	Soil erosion	Salinity	Heavy metals	Pesticide residues	Biodegradable organics
DEVELOPING BIOLOGICAL CONTROLS	+	0	0	+	0	0	0	+	0	0	+	+	0	0	+	0
a. Developing juvenile hormones	+	0	0	+	0	0	0	+	0	0	+	+	0	0	+	0
b. Developing pheromones	+	0	0	+	0	0	0	+	0	0	+	+	0	0	+	0
c. Developing sterile males	+	0	0	+	0	0	0	+	0	0	+	+	0	0	+	0
d. Developing predators and parasites	+	0	0	+	0	0	0	+	0	0	+	+	0	0	+	0
DEVELOPING INTEGRATED CONTROLS (i.e., chemical-biological-mechanical)	0	0	0	+	0	0	0	+	0	0	0	0	0	0	+	0
RESOURCE USE TRENDS																
USING INCREASED RATES AND AMOUNTS OF CROP PRODUCTION INPUTS	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
a. Using commercial fertilizers	-	-	-	0	0	-	-	0	0	-	-	-	0	0	0	-
b. Using other nutrient sources: livestock wastes, municipal sludges	-	-	-	0	0	-	-	0	0	-	-	-	0	0	0	-
c. Using chemical pesticides: herbicides, insecticides, fungicides, rodenticides	-	0	0	-	0	0	0	-	0	0	-	-	0	0	-	0
d. Using energy: petroleum products, electricity, sunlight	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
e. Using new cropland (including set-aside lands)	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-

Table 1-16

Table 15: Environmental Ratings of Top Ten Trends and Associated Practices: Irrigated Production (Unger, 1977)

Panel Rank	Trend and Subtrend
1	Improving Water Application a. Furrow basin b. Large sprinklers c. Recycling & controlling tailwater d. Timing and amount with respect to crop and soil condition e. Irrigation scheduling
2	Runoff & Erosion Control a. Contour farming b. Terraces & grass waterways c. Winter cover crop d. Land grading
3	Methods of Nutrient Application a. Foliar application b. Multiple applications c. Fall application d. Aerial & floater application e. Improved nutrient placement f. Irrigation application
4	Developing Integrated Controls
5	Using Soil-Plant Analysis
6	Directly Monitoring Irrigation Needs a. Measuring soil moisture content b. Remote sensing of plant or soil water stress c. Field soil examination
7	Using Sprinkler Irrigation
8	Seed/Plant Improving a. Weather resistance b. Salt tolerance c. Production efficiency
9	Developing Nitrogen-Fixation Sources a. Legume sources b. Non-legume sources c. Non-symbiotic non-legume
10	Developing Improved Fertilizers a. Controlled release fertilizers b. High phosphate content fertilizers c. Liquid d. Nitrate inhibitors

Source: Canter 1986

Table 1-17

Table 16: Summary of Major Environmentally Related Trends in the Agriculture Sector by Subsector (Unger, 1979)

Subsector and Trend (P or I)[a]	Panel Ratings[b] Rank	Index
Nonirrigated Crop Production		
Runoff Control (P)	1	100
Improved Seeds (I)	2	90
Conservation Tillage (P)	3	80
Integrated Pest Control (P)	4	70
New Pesticides (I)	5	65
Irrigated Crop Production		
Water Application (P)	1	100
Runoff Control (P)	2	80
Nutrient Application (P)	3	70
Integrated Control (P)	4	60
Soil-Plant Analysis (P)	5	40

[a]P=practices (primarily); I=inputs (primarily changes in quality).
[b]Ratings established by subsector panels of agriculture professionals in an EPA sponsored evaluation workshop. The rank indicates the trend cluster's rank order of environmental importance; the index is a subjective measure of each trend's relative importance compared the top-ranked trend which has an index score of 100.

Source: Canter 1986

Table 1-18

Table 5. African agricultural systems and extent of sustainability.

Traditional and transitional systems		
1a. Shifting cultivation (Phase I)	L > 10	HS
b. Nomadic herding		SS
2. Bush fallowing or land rotation	L = 5-10	NS
3. Rudimentary sedentary agriculture	L = 2-4	NS
4a. Compound farming (shifting cultivation, Phase IV)	L < 2-4	S
b. Intensive subsistence agriculture		SU
5a. Terrace farming		SU
b. Floodland agriculture		HS
"Modern" farming systems and their local adaptations		
1. Livestock ranching		SU
2. Mixed farming		S
3. Intensive livestock production systems (poultry, pigs, and dairying)		SU
4a. Small-scale irrigated farms (lowland rice, vegetables, and arables)		S
b. Small-scale fish farming		S
5. Large-scale farms and plantations		
(a) Large-scale arable crop farms (unirrigated)		NS
(b) Irrigated crop production projects/systems		SU
(c) Tree crop plantations (oil palms, rubber)		S
6. Specialized horticulture		
(a) Market gardening		HS
(b) Truck gardening/fruit plantations		SU
(c) Commercial fruit/vegetable production for processing		SS

L = (C+F)/C where C = cropping period, F = fallow period, L = land use factor
HS = Highly sustainable
S = Sustainable
NS = Not sustainable
SS = Sometimes sustainable
SU = Sustainable only under specificied circumstances

Table 1-19

Table 1. Grain yields per hectare in four African countries with declining yields, from 1950 to 1952 and 1983 to 1985 (Brown and Wolf, 1986).

Country	Average Yields 1950-1952	Average Yields 1983-1985	Change
	Kg	Kg	%
Nigeria	760	714	−6
Mozambique	620	545	−12
Tanzania	1,271	1,091	−14
Sudan	780	479	−38

Source: Okigbe in: Edwards ed. 1990

Table 1-20

Table 2. World population growth by geographic region, 1986.

Region	Population	Population Growth Rate	Annual Increment
	—million—	—%—	— million —
Slow-growth regions			
Western Europe	381	0.2	0.8
North America	267	0.7	1.9
Eastern Europe and Soviet Union	392	0.8	3.1
Australia and New Zealand	19	0.8	0.1
East Asia*	1,263	1.0	12.6
Total	2,322	0.8	18.6
Rapid-growth regions			
Southeast Asia†	414	2.2	9.1
Latin America	419	2.3	9.6
Indian subcontinent	1,027	2.4	24.6
Middle East	178	2.8	5.0
Africa	583	2.8	16.3
Total‡	2,621	2.5	65.5

*Principally China and Japan.
†Principally Burma, Indonesia, the Philippines, Thailand, and Vietnam.
‡Numbers may not add up to totals due to rounding.

Table 1-21

Table 3. Projected population size at stabilization for selected countries.

Country	Population in 1986	Annual Rate of Population Growth	Size of Population at Stabilization	Change from 1986
	— million —	— % —	— million —	— % —
Slow-growth countries				
China	1,050	1.0	1,571	+50
Soviet Union	280	0.9	377	+35
United States	241	0.7	289	+20
Japan	121	0.7	128	+ 6
United Kingdom	56	0.2	59	+ 5
West Germany	61	−0.2	52	−15
Rapid-growth countries				
Kenya	20	4.2	111	+455
Nigeria	105	3.0	532	+406
Ethiopia	42	2.1	204	+386
Iran	47	2.9	166	+253
Pakistan	102	2.8	330	+223
Bangladesh	104	2.7	310	+198
Egypt	46	2.6	126	+174
Mexico	82	2.6	199	+143
Turkey	48	2.5	109	+127
Indonesia	168	2.1	368	+119
India	785	2.3	1,700	+116
Brazil	143	2.3	298	+108

Source: Brown et al. in Edwards ed. 1990

Table 1-22

Table 4. Measures of sustainability in seven African countries,* by ecological zone, 1980.

	Food			Fuelwood		
Zone	Agriculturally Sustainable Population	Actual Rural Population	Food Disparity	Fuelwood-Sustainable Population	Actual Total Population	Fuel Disparity
	million people					
Sahelo-Saharan	1.0	1.8	−0.8	0.1	1.8	−1.7
Sahelian	3.9	3.9	0.0	0.3	4.0	−3.7
Sahelo-Sudanian	8.7	11.1	−2.4	6.0	13.1	−7.1
Sudanian	8.9	6.6	2.3	7.4	8.1	−0.7
Sudano-Guinean	13.8	3.6	10.2	7.1	4.0	3.1
Total	36.3	27.0	9.3	20.9	31.0	−10.1

*Burkina Faso, Chad, Gambia, Mali, Mauritania, Niger, and Senegal. The five ecological zones are delineated by amounts of rainfall.

Source: Brown et al. in Edwards ed. 1990

Table 2-1

Table 2 LABORATORY DETERMINATIONS NEEDED TO EVALUATE COMMON IRRIGATION WATER QUALITY PROBLEMS

Water parameter	Symbol	Unit[1]	Usual range in irrigation water	
SALINITY				
Salt Content				
Electrical Conductivity	EC_w	dS/m	0 – 3	dS/m
(or)				
Total Dissolved Solids	TDS	mg/l	0 – 2000	mg/l
Cations and Anions				
Calcium	Ca^{++}	me/l	0 – 20	me/l
Magnesium	Mg^{++}	me/l	0 – 5	me/l
Sodium	Na^{+}	me/l	0 – 40	me/l
Carbonate	CO_3^{--}	me/l	0 – .1	me/l
Bicarbonate	HCO_3^{-}	me/l	0 – 10	me/l
Chloride	Cl^{-}	me/l	0 – 30	me/l
Sulphate	SO_4^{--}	me/l	0 – 20	me/l
NUTRIENTS[2]				
Nitrate-Nitrogen	NO_3-N	mg/l	0 – 10	mg/l
Ammonium-Nitrogen	NH_4-N	mg/l	0 – 5	mg/l
Phosphate-Phosphorus	PO_4-P	mg/l	0 – 2	mg/l
Potassium	K^{+}	mg/l	0 – 2	mg/l
MISCELLANEOUS				
Boron	B	mg/l	0 – 2	mg/l
Acid/Basicity	pH	1-14	6.0 – 8.5	
Sodium Adsorption Ratio[3]	SAR	$(me/l)^{1,2}$	0 – 15	

[1] dS/m = deciSiemen/metre in S.I. units (equivalent to 1 mmho/cm = 1 millimmho/centimetre)

mg/l = milligram per litre ≃ parts per million (ppm).

me/l = milliequivalent per litre (mg/l ÷ equivalent weight = me/l); in SI units, 1 me/l = 1 millimol/litre adjusted for electron charge.

[2] NO_3-N means the laboratory will analyse for NO_3 but will report the NO_3 in terms of chemically equivalent nitrogen. Similarly, for NH_4-N, the laboratory will analyse for NH_4 but report in terms of chemically equivalent elemental nitrogen. The total nitrogen available to the plant will be the sum of the equivalent elemental nitrogen. The same reporting method is used for phosphorus.

[3] SAR is calculated from the Na, Ca and Mg reported in me/l (see Figure 1).

Source: Ayers/Westcot (FAO) 1985

Table 2-2

TABLE 31. Selection of parameters for river water-quality surveys (after McDermott)

		Chemical parameters			Biological parameters	
Type of survey	Physical parameters	Inorganic	Organic	Nutrients	Microbiological	Hydrobiological
Proposed for inclusion in all surveys	Colour pH Specific conductance Suspended solids Total solids		Chemical Oxygen Demand (COD) Total Organic Carbon (TOC)		Coliforms, total and faecal	
Recommended for collection of baseline data	Odour	Acidity Alkalinity Calcium, Ca Chlorides, Cl Dissolved oxygen Hardness Iron, Fe Magnesium, Mg Manganese, Mn Potassium, K Selenium, Se Silver, Ag Sodium, Na	Biochemical Oxygen Demand (BOD); immediate, 5-day, ultimate	Nitrate nitrogen, NO_3	Total plate count	
Recommended additional parameters where municipal and/or industrial pollution are expected	Floating solids	Arsenic, As Barium, Ba Beryllium, Be Boron, B Cadmium, Cd Chromium, Cr Copper, Cu Dissolved Carbon Dioxide, CO_2 Fluorides, F Hydrogen sulphide, H_2S Lead, Pb Mercury, Hg Nickel, Ni Vanadium, V Zinc, Zn	Cyanide, CN Dissolved organic carbon Methylene Blue Active Substances (MBAS) Oil and grease Pesticides Phenolics	Ammonia nitrogen, NH_3 Nitrite nitrogen, NO_2 Organic nitrogen Soluble phosphorus Total phosphorus	Faecal streptococci Salmonella	Benthos Plankton counts
Optional parameters for surveys of special purpose	Bed load Light penetration Particle size Sediment concentration Settleable solids	Aluminium, Al Sulphates	Carbon Alcohol Extract (CAE) Carbon Chloroform Extract (CCE) Chlorine demand	Organic phosphorus Orthophosphates Polyphosphates Reactive silica	Shigella Viruses: —Coxsackie A &B —Polio —Adenoviruses —Echoviruses	Chlorophylls Fish Periphyton Taxanomic composition

UNESCO/WHO 1978

Table 2-3

TABLE 11. Suggested preservation techniques

Parameter	Preservation a —unnecessary b —possible c —not possible	Optimum storage time prior to analysis	Method of treatment (suggested analysis)
Acidity (pH)	c	Immediately Same day if cooled	Cap bottle, avoid bubbles and turbidity, keep cool (followed by titrimetric method to pH 4.5 and 8.3)
Alkalinity ($CaCO_3$)	c	Immediately Same day if cooled	Cap bottle, avoid bubbles and turbidity, keep cool (followed by potentiometric titration to pH 4.5 and 8.3; phenolphthalein and methyl orange indicators)

NOTES: Polyethylene bottles may be used unless otherwise mentioned.
* Bottles are rinsed with nitric acid (1 : 1 with distilled deionized water).

Parameter	Preservation a —unnecessary b —possible c —not possible	Optimum storage time prior to analysis	Method of treatment (suggested analysis)
Aluminium	b	No time limit	*Rinse sample bottle with acid; add 2 ml conc. HNO_3/l (followed by Atomic Absorption Spectroscopy (AAS) after complexation with 8-quinolinol, or by colourimetric Ferron Method)
Ammonia (ammonium ions)	b	Same day	Cool and store at 3–4°C; add 0.8 ml H_2SO_4/l sample to pH 2; add 2–4 ml $CHCl_3$/l sample (followed by specific ion electrode after distillation or nesslerization after distillation or o-tolidine method)
Arsenic	a	No time limit	*No special precautions (may use colourimetric method with silver diethyl dithio carbanate; or AAS)
Barium	b	No time limit	*Add 2 ml HNO_3/l sample (followed by AAS)
Beryllium	b	No time limit	*Rinse sample bottle with acid; add 2 ml HNO_3/l (followed by AAS or by 8-quinolinol $CHCl_3$ extraction and AAS)
Bicarbonates	c	Immediately Same day if cooled	*See alkalinity (determined by methyl orange and phenolphthalein titration)
Boron	a	No time limit	*Use polyethylene or boron free glass bottles (followed by colourimetric curcumin method)
Cadmium	b	No time limit	*Rinse bottle with acid; add 2 ml conc. HNO_3/l (May absorb on bottle walls). (followed by AAS)
Calcium	a	No time limit	(Use AAS or ethylenediamine-tetraacetic acid (EDTA) titration)
Carbon dioxide	c	Immediately Same day if cooled	*Polyethylene bottle filled to overflowing; tightly capped (May be determined from alkalinity by methyl orange titration and pH)

NOTES: Polyethylene bottles may be used unless otherwise mentioned.
* Bottles are rinsed with nitric acid (1 : 1 with distilled deionized water).

Parameter	Preservation a —unnecessary b —possible c —not possible	Optimum storage time prior to analysis	Method of treatment (suggested analysis)
Carbon, organic	b	Same day	*Add 1 ml H_2SO_4/l; or acidify with HCl. Cool (followed by Infra-Red (IR) analysis)
Carbonates	c	Immediately Same day if cooled	*See alkalinity
Chemical Oxygen Demand (COD)	a	Same day	*See Oxygen Demand, Chemical and also Oxidizability
Chloride	a	No time limit	(May be determined by automated colourimetric ferricyanide; mercuric nitrate, or silver nitrate method)
Chlorine	c	Immediately	Use brown glass bottles, protect from sunshine and shaking. Cooling not necessary. (followed by amperometric iodide titration)
Chlorine dioxide	c	Immediately	(May be determined by gas chromatographic method)
Chromium	b	No time limit	*See Cadmium
Cobalt	b	No time limit	*See Cadmium
Colour	c	Same day	Add 2 ml $CHCl_3$/l to suppress biochemical changes that may change colour (may be visual comparison)
Copper	b	No time limit	*See Cadmium. 5–10 ml 50% aq. HCl also suggested by some analysts. Must not be preserved in presence of cyanides
Cyanides	b	Same day	Do not add acid. Add NaOH pellets to pH 11 and cool to 3–4°C or freeze (followed by distillation—specific ion electrode; colourimetric pyrazolone or silver nitrate titration)
Dissolved gases	c	Immediately	Use gas-tight ampoules for transport to laboratory if immediate analyses is not feasible. See also: gases by name
Dissolved solids	a	Several days	Cool to 3–4°C

NOTES: Polyethylene bottles may be used unless otherwise mentioned.
* Bottles are rinsed with nitric acid (1 : 1 with distilled deionized water).

Source: UNESCO/WHO 1978

Table 2-3 cont.

Parameter	Preservation a —unnecessary b —possible c —not possible	Optimum storage time prior to analysis	Method of treatment (suggested analysis)
Extractible matters	b	Same day	Collect in wide mouth bottles; add 5 ml H_2SO_4 (50% solution)/l Do not use chloroform for conservation (followed by extraction with hexane or trichlorotrifluoro-ethane)
Fluoride	a	No time limit	Do not use bottles previously used for other halogens (may use specific ion electrode method)
Hardness	a	Immediately	Bottles should be tightly capped (may use AAS if > 0.5 ml/l heavy metals are present; or ethylenediaminetetraacetic acid (EDTA) titration)
Halogenated organics (pesticides)	a	Same day	Use glass bottles with Teflon caps. Never use plastic utensils. Cool (followed by Gas Chromatographic analysis)
Iron	b	No time limit	*See Cadmium (AAS or 2,4,6-tripyridyl-s-triazine colourimetric method)
Lead	b	No time limit	*See Cadmium
Magnesium	a	No time limit	(May be determined by AAS or by difference between total hardness and calcium)
Manganese	b	No time limit	*See Cadmium
Mercury	b	Several days	Do not use glass bottles. Filter. Acidify immediately; for dissolved mercury add 10 ml H_2SO_4/l, for suspended mercury add conc. H_2SO_4 to residue (followed by flameless AAS)
Nickel	b	No time limit	*See Cadmium. Must not be preserved in presence of cyanide
Nitrogen-Nitrate	b	Same day	Add 0.8 ml H_2SO_4/l sample or 2–4 ml $CHCl_3$/l; cool to 3–4°C (followed by cadmium reduction, brucine sulphate, automated cadmium, or hydrazine reduction method)

NOTES: Polyethylene bottles may be used unless otherwise mentioned.
* Bottles are rinsed with nitric acid (1 : 1 with distilled deionized water).

Parameter	Preservation a —unnecessary b —possible c —not possible	Optimum storage time prior to analysis	Method of treatment (suggested analysis)
Nitrogen—Nitrite	b	Same day	Preserve as Nitrate (followed by manual or automated colourimetric diazotization)
Nitrogen, organic	c	Same day Several days if frozen	(May use ultra-violet oxidation method; for higher concentrations use Kjeldahl method)
Nitrogen, total inorganic	b	Same day	(Sum of nitrogen from ammonia, nitrate and nitrite)
Odour	c	Immediately	(Description)
Oxidizability	b	Immediately Same day if cooled	Cool to 3–4°C, add 35% H_2SO_4 to sample (followed by Kubel Test: 2 ml H_2SO_4 to 100 ml sample Schulze Papp Test: 2ml H_2SO_4 to 100 ml sample then neutralize Dichromate Test: 1 ml H_2SO_4/l sample) See also Oxygen Demand Chemical (COD)
Oxygen dissolved	c	Immediately	Collect in oxygen bottle (BOD bottle) (followed by modified Winkler, Probe Method or azide modification of iodometric method)
Oxygen consumed	a	Same day	*(May use potassium permanganate ($KMnO_4$) oxidation and oxalate titration method)
Oxygen Demand Biochemical (BOD)	c	Immediately	Cap bottles, Cool. Start incubation within a few hours (followed by 5-day incubation method at 20°C, then compare dissolved oxygen content at beginning and at the end of the experiment)
Oxygen Demand Chemical (COD)	a	Same day	(May use H_2SO_4 potassium dichromate digestion method back titrated with ferrous ammonium sulphate)
Ozone	c	Immediately	Cool. Acidify slightly

NOTES: Polyethylene bottles may be used unless otherwise mentioned.
* Bottles are rinsed with nitric acid (1 : 1 with distilled deionized water).

Parameter	Preservation a —unnecessary b —possible c —not possible	Optimum storage time prior to analysis	Method of treatment (suggested analysis)
Vanadium	b	No time limit	*See Cadmium (may use AAS or AAS-solvent extraction with cupferron butyl acetate)
Zinc	b	No time limit	*See Cadmium

NOTES: Polyethylene bottles may be used unless otherwise mentioned.
b Bottles are rinsed with nitric acid (1 : 1 with distilled deionized water).

Parameter	Preservation a —unnecessary b —possible c —not possible	Optimum storage time prior to analysis	Method of treatment (suggested analysis)
pH	c	Immediately	May use tightly sealed plastic bottles. Analyse as soon as room temperature is reached (may use potentiometric method)
Petroleum hydrocarbon	c	Immediately	Cool (may use hexane extraction or trichlorotrifluoroethane extraction)
Pesticides	a	Same day	Cool sample to 3–4°C. Use all glass utensils with Teflon liners (followed by gas chromatographic method)
Phenols	b	Same day	Use glass bottle. Add 1 g $CuSO_4 . 5H_2O$/l to dry bottle; acidify to pH 4 with conc. H_3PO_4 (see text)
Phosphorous, Total (Orthophosphates and Polyphosphates)	b	Immediately Same day if cooled	Use glass Erlenmeyer for all phosphorous samples. Add 1 ml 30% H_2SO_4/100 ml sample. Cool to 3–4°C (followed by molybdenum blue colourimetric method)
Phosphorous (Orthophosphates)	b	Immediately Same day if cooled	Do not add acid. Cool to 3–4°C (followed by molybdenum blue colourimetric method)
Phosphorus Total	b	Same day	Add 1 ml 30% H_2SO_4/100 ml sample. Cool to 3–4°C (followed by persulphate digestion and molybdenum blue colourimetric metbod)
Polychlorinated Biphenyls (PCB's)	a	Same day	Cool sample to 3–4°C. Use all glass utensils with Teflon liners (followed by gas chromatographic method)
Potassium	a	No time limit	Sample into polyethylene bottles or in glass not releasing potassium (may use AAS—direct flame photometry)
Pyridine bases	b	Same day	Add 2 ml H_2SO_4 (25% by volume)
Residues	a	Immediately	(May use gravimetric method)

NOTES: Polyethylene bottles may be used unless otherwise mentioned.
b Bottles are rinsed with nitric acid (1 : 1 with distilled deionized water).

Parameter	Preservation a —unnecessary b —possible c —not possible	Optimum storage time prior to analysis	Method of treatment (suggested analysis)
Rhodanids	a	Same day if cooled	Cool
Salinity	c	Same day Several days cooled	Cool
Silica	a	Immediately Several days if frozen	Collect in polyethylene bottles. Freeze (followed by colourimetric molybdosilicate or heteropoly blue method)
Silver	b	About 10 days	Transfer sample to dry container with 4 g EDTA/100 ml samples added prior to collection (followed by AAS)
Sodium	a	No time limit	Use polyethylene bottle or glass not releasing sodium (may use AAS—direct flame photometry)
Specific Conductance	c	Several days	(May use conductivity meter)
Surface Active Agents (surfactants, MBAS)	b	Same day	Add 2–4 ml $CHCl_3$/l (followed by methylene blue colourimetric method)
Sugar	a	Same day	Cool 3–4°C (may use phenyl hydrazine sulphate method)
Sulphates	a	No time limit	Cool to 3–4°C (may use $BaCl_2$ titrimetric method)
Sulphides	b	Same day	Collect in special sample bottle with tube fitting. Add 10 ml of a 10% cadmium acetate or zinc acetate solution (followed by specific ion electrode or titrimetric iodine method)
Suspended solids	a	Within a few days	Cool to 3–4°C (may use filtration method)
Tannin	a	A few days	(May use colourimetric method)
Temperature	c	Immediately	(Thermometer)
Turbidity	b	Within a few days	Add 2–4 ml $CHCl_3$/l sample. Shake. Store in dark (may use turbidimeter)

NOTES: Polyethylene bottles may be used unless otherwise mentioned.
b Bottles are rinsed with nitric acid (1 : 1 with distilled deionized water).

Table 1 GUIDELINES FOR INTERPRETATIONS OF WATER QUALITY FOR IRRIGATION[1]

Potential Irrigation Problem	Units	Degree of Restriction on Use		
		None	Slight to Moderate	Severe
Salinity *(affects crop water availability)*[2]				
EC_w	dS/m	< 0.7	0.7 – 3.0	> 3.0
(or)				
TDS	mg/l	< 450	450 – 2000	> 2000
Infiltration *(affects infiltration rate of water into the soil. Evaluate using EC_w and SAR together)*[3]				
SAR = 0 – 3 and EC_w =		> 0.7	0.7 – 0.2	< 0.2
= 3 – 6 =		> 1.2	1.2 – 0.3	< 0.3
= 6 – 12 =		> 1.9	1.9 – 0.5	< 0.5
= 12 – 20 =		> 2.9	2.9 – 1.3	< 1.3
= 20 – 40 =		> 5.0	5.0 – 2.9	< 2.9
Specific Ion Toxicity *(affects sensitive crops)*				
Sodium (Na)[4]				
surface irrigation	SAR	< 3	3 – 9	> 9
sprinkler irrigation	me/l	< 3	> 3	
Chloride (Cl)[4]				
surface irrigation	me/l	< 4	4 – 10	> 10
sprinkler irrigation	me/l	< 3	> 3	
Boron (B)[5]	mg/l	< 0.7	0.7 – 3.0	> 3.0
Trace Elements (see Table 21)				
Miscellaneous Effects *(affects susceptible crops)*				
Nitrogen (NO_3 – N)[6]	mg/l	< 5	5 – 30	> 30
Bicarbonate (HCO_3) *(overhead sprinkling only)*	me/l	< 1.5	1.5 – 8.5	> 8.5
pH		Normal Range 6.5 – 8.4		

[1] Adapted from University of California Committee of Consultants 1974.

[2] ECw means electrical conductivity, a measure of the water salinity, reported in deciSiemens per metre at 25°C (dS/m) or in units millimhos per centimetre (mmho/cm). Both are equivalent. TDS means total dissolved solids, reported in milligrams per litre (mg/l).

[3] SAR means sodium adsorption ratio. SAR is sometimes reported by the symbol RNa. See Figure 1 for the SAR calculation procedure. At a given SAR, infiltration rate increases as water salinity increases. Evaluate the potential infiltration problem by SAR as modified by ECw. Adapted from Rhoades 1977, and Oster and Schroer 1979.

[4] For surface irrigation, most tree crops and woody plants are sensitive to sodium and chloride; use the values shown. Most annual crops are not sensitive; use the salinity tolerance tables (Tables 4 and 5). For chloride tolerance of selected fruit crops, see Table 14. With overhead sprinkler irrigation and low humidity (< 30 percent), sodium and chloride may be absorbed through the leaves of sensitive crops. For crop sensitivity to absorption, see Tables 18, 19 and 20.

[5] For boron tolerances, see Tables 16 and 17.

[6] NO_3-N means nitrate nitrogen reported in terms of elemental nitrogen (NH_4-N and Organic-N should be included when wastewater is being tested).

Table 1 (cont.)

Assumptions in the Guidelines

The water quality guidelines in Table 1 are intended to cover the wide range of conditions encountered in irrigated agriculture. Several basic assumptions have been used to define their range of usability. If the water is used under greatly different conditions, the guidelines may need to be adjusted. Wide deviations from the assumptions might result in wrong judgements on the usability of a particular water supply, especially if it is a borderline case. Where sufficient experience, field trials, research or observations are available, the guidelines may be modified to fit local conditions more closely.

The basic assumptions in the guidelines are:

Yield Potential: Full production capability of all crops, without the use of special practices, is assumed when the guidelines indicate no restrictions on use. A "restriction on use" indicates that there may be a limitation in choice of crop, or special management may be needed to maintain full production capability. A "restruction on use" does not indicate that the water is unsuitable for use.

Site Conditions: Soil texture ranges from sandy-loam to clay-loam with good internal drainage. The climate is semi-arid to arid and rainfall is low. Rainfall does not play a significant role in meeting crop water demand or leaching requirement. (In a monsoon climate or areas where precipitation is high for part or all of the year, the guideline restrictions are too severe. Under the higher rainfall situations, infiltrated water from rainfall is effective in meeting all or part of the leaching requirement.) Drainage is assumed to be good, with no uncontrolled shallow water table present within 2 metres of the surface.

Methods and Timing of Irrigations: Normal surface or sprinkler irrigation methods are used. Water is applied infrequently, as needed, and the crop utilizes a considerable portion of the available stored soil-water (50 percent or more) before the next irrigation. At least 15 percent of the applied water percolates below the root zone (leaching fraction [LF]≥15 percent). The guidelines are too retrictive for specialized irrigation methods, such as localized drip irrigation, which results in near daily or frequent irrigations, but are applicable for subsurface irrigation if surface applied leaching satisfies the leaching requirements.

Water Uptake by Crops: Different crops have different water uptake patterns, but all take water from wherever it is most readily available within the rooting depth. On average about 40 percent is assumed to be taken from the upper quarter of the rooting depth, 30 percent from the second quarter, 20 percent from the third quarter, and 10 percent from the lowest quarter. Each irrigation leaches the upper root zone and maintains it at a relatively low salinity. Salinity increases with depth and is greatest in the lower part of the root zone. The average salinity of the soil-water is three times that of the applied water and is representative of the average root zone salinity to which the crop responds. These conditions result from a leaching fraction of 15-20 percent and irrigations that are timed to keep the crop adequately watered at all times.

Salts leached from the upper root zone accumulate to some extent in the lower part but a salt balance is achieved as salts are moved below the root zone by sufficient leaching. The higher salinity in the lower root zone becomes less important if adequate moisture is maintained in the upper, "more active" part of the root zone and long-term leaching is accomplished.

Restriction on Use: The "Restriction on Use" shown in Table 1 is divided into three degrees of severity: none, slight to moderate, and severe. The divisions are somewhat arbitrary since change occurs gradually and there is no clearcut breaking point. A change of 10 to 20 percent above or below a guideline value has little significance if considered in proper perspective with other factors affecting yield. Field studies, research trials and observations have led to these divisions, but management skill of the water user can alter them. Values shown are applicable under normal field conditions prevailing in most irrigated areas in the arid and semi-arid regions of the world.

Source: Ayers/Westcot (FAO) 1985

USDA classification of irrigation water salinity (sulphate-free waters) — Table 8.7

Table 2-4/2

Salinity class and description	EC range (μS cm^{-1})	Equivalent salt concentration (approximate) TDS 1/ (g ℓ^{-1})	TDS 1/ (ppm)	Cl (ppm)
C1 Low salinity water can be used for irrigation with most crops on most soils, with little likelihood that a salinity problem will develop. Some leaching is required, but this occurs under normal irrigation practices, except in soils of extremely low permeability	< 250	< 0.2	< 200	< 60
C2 Medium salinity water can be used if a moderate amount of leaching occurs. Plants with moderate salt tolerance can be grown in most instances without special practices for salinity control	250 – 750	0.2 – 0.5	200 – 500	60–200
C3 High salinity water cannot be used on soil with restricted drainage. Even with adequate drainage, special management for salinity control may be required and plants with good salt tolerance should be selected	750 – 2 250	0.5 – 1.5	500 – 1 500	200–600
C4 Very high salinity water is not suitable for irrigation under ordinary conditions but may be used occasionally under very special circumstances. The soils must be permeable, drainage must be adequate, irrigation water must be applied in excess to provide considerable leaching, and very salt-tolerant crops should be selected	> 2 250	1.5 – 3.0	> 1 500	> 600

Note: 1/ TDS = total dissolved solids.

Source: Landon ed. 1984

Source: Adapted from Richards (1954, p 76); note that further divisions based on SAR are also made; see Figure 8.2 and Table 8.8.

Table 2-4/3

Table 9. Guidelines for interpretation of water quality for irrigation (Ayers and Tanji 1981)

SAR	EC (dS m^{-1}) No problem	Slight to moderate	Severe problem
0– 3	>0.9	0.9–0.2	<0.2
3– 6	>1.3	1.3–0.25	<0.25
6–12	>2.0	2.0–0.35	<0.35
12–20	>3.1	3.1–0.9	<0.9
> 20	>5.6	5.6–1.8	<1.8

Table 2-4/4

Table 1. Classification of irrigation water based on total salt concentration, according to five different reference sources

Salinity class	EC dAS m^{-1} USSL[a] (1954)	Thorn and Peterson (1954)	NTAC[b] (1968)	Carter (1969)	Ayers and Westcot (1976)
C1	0.1 –0.25	<0.25	<0.75	0.4	<0.75
C2	0.25–0.75	0.25–0.75	0.75–1.5	0.4 –1.2	0.75–1.5
C3	0.75–2.25	0.75–2.25	1.5 –3.0	1.2 –2.25	1.5 –3.0
C4	>2.25	2.25–4.0	3.0 –7.5	2.25–5.0	>3.0
C5		4.0 –6.0			

[a] US Salinity Laboratory
[b] National Technical Advisory Committee, USA

Source: in Bresler et al. ed. 1982

Table 2-4/

Table 2. Permissible upper limit for conductivity of irrigation water (dS m^{-1}) for three crop tolerance groups and five soil textures

	Crop tolerance group I	II	III			
	EC_e (dS m^{-1})					
	<4.0	4.0–10.0	>10.0			
Soil texture			Date palm	Horticultural crops	Forage crops	Field crops
Sandy	2.5	6.5	15.2	8.0	12.0	10.0
Loamy sand	1.6	4.0	6.1	4.5	7.0	6.0
Loamy	1.0	3.0	8.0	3.5	5.0	4.5
Loamy clay	0.8	2.0	6.0	2.4	3.5	3.0
Clay	0.4	1.0	3.0	1.8	1.8	1.6

Source: in Bresler et al. ed. 1982

Table 2-4/6

Table 44 GUIDELINES FOR INTERPRETATION OF WATER QUALITY FOR IRRIGATION UNDER INDIAN CONDITIONS (Bhumbla and Abrol, 1972)

Soil	Crops to be grown	Upper permissible limit of EC of water for safe use for irrigation, dS/m
Deep black soils and alluvial soils having a clay content of more than 30 percent. Soils that are fairly to moderately well drained.	Semi-tolerant Tolerant	1.5 2
Heavy textured soils having a clay content of 20-30%. Soils that are well drained internally and have a good surface drainage system.	Semi-tolerant Tolerant	2 4
Medium textured soils having a clay content of 10-20%. Soils that are very well drained internally and have a good surface drainage system.	Semi-tolerant Tolerant	4 6
Light textured soils having a clay content of less than 10%. Soils that have excellent internal and surface drainage.	Semi-tolerant Tolerant	6 8

Qualifying remarks:

1. A monsoon rainfall of 300 to 400 mm is common for most areas having a groundwater quality problem. This rainfall periodically leaches out salts accumulated in the root zone during the previous season.
2. In the above proposed limits of water quality it is presumed that the groundwater table at no time of the year is within 1.5 metres from the surface. If the water table does come up within the root zone the above limits need to be reduced to half the above values.
3. If the soils have impeded internal drainage either on account of presence of hard pans, unusually high amounts of clay or other morphologic reasons, for advisory purposes, the limit of water quality should again be reduced to half.
4. If the waters contain soluble sodium percentage more than 70, gypsum should be added to soil occasionally.
5. If supplemental canal irrigation is available, water of higher electrical conductivity could be used in periods of water shortage.

Source: Kandiah ed. (FAO) 1990

Table 1. Soil and water salinity criteria based on plant salt tolerance groupings (Maas and Hoffman 1977, at 10% yield reduction), for soils of about 60% clay content, Shaw (1988).

Table 2-5 a

Plant salt tolerance grouping [a]	Soil/ water salinity rating	Soil salinity			Irrigation water quality
		$EC_{1:5}$ [c] dS/m	EC_{se} [b] dS/m	Chloride [d] %	EC [e] dS/m
sensitive crops	very low	<0.15	<0.95	<0.025	<0.65
moderately sensitive crops	low	0.15-0.30	0.95-1.19	0.025-0.05	0.65-1.30
moderately tolerant crops	medium	0.30-0.70	1.9-4.5	0.05-0.10	1.30-2.90
tolerant crops	high	0.70-1.20	4.5-7.7	0.10-0.18	2.90-5.20
very tolerant crops	very high	1.20-1.90	7.7-12.2	0.18-0.29	5.20-8.10
generally too saline	extreme	>1.90	12.2	>0.29	>8.10

a Groupings are statistically derived divisions based on families of linear curves representing the salt tolerance ratings of the majority of crops reported by Maas and Hoffman (1977). Terminology have been varied and extra group of sensitive crops incorporated.

b EC_{se} is the boundary EC_{se} at which 10% yield reduction occurs for these plant tolerance groups.

c $EC_{1:5}$ derived from EC_{se} divided by 6.4, that is, applicable to soils with clay content of about 60%.

d Cl% derived from $EC_{1:5}$ assuming all salts present are as chloride, EC = 6.64 x Cl%. EC of salt solution based on Marion and Babcock (1976), McNeal *et al.* (1970) and USSL (1954).

e Derived from EC_{se} on the basis that saturation extract is 2 x field capacity and a leaching fraction (LF) of 0.15 at the bottom of the root zone occurs (Ayers 1977), that is, ECwater = 2/3 EC_{se}. Conversion to other LF values can be made.

Actual plant response depends on soil, rainfall, management and the soil salinity profile shape. The boundaries should be considered as approximate divisions between groups.

Table 2-5 b

Water salinity capability rating

water salinity category	EC range dS/m	relative rating
very low	< 0.65 [1]	100%
low	0.65 - 1.3	85%
medium	1.3 - 2.9	55%
high	2.9 - 5.2	25%
very high	5.2 - 8.1	10%
extreme	> 8.1	5%

waters with a salinity below around 0.25 dS/m are more difficult to manage because of the low salt content can give reduced infiltration rates. There problems can be overcome much more easily with management practices than can the use of higher salinity waters and thus should be rated at 100%

Source: Shaw 1992

Table 2-6 a

Table 28 WATER QUALITY GUIDE FOR LIVESTOCK AND POULTRY USES [1]

Water Salinity (EC_w) (dS/m)	Rating	Remarks
< 1.5	Excellent	Usable for all classes of livestock and poultry.
1.5 - 5.0	Very Satisfactory	Usable for all classes of livestock and poultry. May cause temporary diarrhoea in livestock not accustomed to such water; watery droppings in poultry.
5.0 - 8.0	Satisfactory for Livestock	May cause temporary diarrhoea or be refused at first by animals not accustomed to such water.
	Unfit for Poultry	Often causes watery faeces, increased mortality and decreased growth, especially in turkeys.
8.0 - 11.0	Limited Use for Livestock	Usable with reasonable safety for dairy and beef cattle, sheep, swine and horses. Avoid use for pregnant or lactating animals.
	Unfit for Poultry	Not acceptable for poultry.
11.0 - 16.0	Very Limited Use	Unfit for poultry and probably unfit for swine. Considerable risk in using for pregnant or lactating cows, horses or sheep, or for the young of these species. In general, use should be avoided although older ruminants, horses, poultry and swine may subsist on waters such as these under certain conditions.
> 16.0	Not Recommended	Risks with such highly saline water are so great that it cannot be recommended for use under any conditions.

[1] Adapted from National Academy of Sciences (1972; 1974).

Table 2-6 b

Table 30 GUIDELINES FOR LEVELS OF TOXIC SUBSTANCES IN LIVESTOCK DRINKING WATER [1]

Constituent (Symbol)	Upper Limit (mg/l)
Aluminium (Al)	5.0
Arsenic (As)	0.2
Beryllium (Be) [2]	0.1
Boron (B)	5.0
Cadmium (Cd)	0.05
Chromium (Cr)	1.0
Cobalt (Co)	1.0
Copper (Cu)	0.5
Fluoride (F)	2.0
Iron (Fe)	not needed
Lead (Pb) [3]	0.1
Manganese (Mn) [4]	0.05
Mercury (Hg)	0.01
Nitrate + Nitrite (NO_3-N + NO_2-N)	100.0
Nitrite (NO_2-N)	10.0
Selenium (Se)	0.05
Vanadium (V)	0.10
Zinc (Zn)	24.0

[1] Adapted from National Academy of Sciences (1972).

[2] Insufficient data for livestock. Value for marine aquatic life is used here.

[3] Lead is accumulative and problems may begin at a threshold value of 0.05 mg/l.

[4] Insufficient data for livestock. Value for human drinking water used.

Source: FAO (SB 39) 1988

Table 2-7 a

Table 11 CALCIUM CONCENTRATION (Ca_x) EXPECTED TO REMAIN IN NEAR-SURFACE SOIL-WATER FOLLOWING IRRIGATION WITH WATER OF GIVEN HCO_3/Ca RATIO AND EC_w [1,2,3]

		Salinity of applied water (EC_w) (dS/m)											
		0.1	0.2	0.3	0.5	0.7	1.0	1.5	2.0	3.0	4.0	6.0	8.0
Ratio of HCO_3/Ca	.05	13.20	13.61	13.92	14.40	14.79	15.26	15.91	16.43	17.28	17.97	19.07	19.94
	.10	8.31	8.57	8.77	9.07	9.31	9.62	10.02	10.35	10.89	11.32	12.01	12.56
	.15	6.34	6.54	6.69	6.92	7.11	7.34	7.65	7.90	8.31	8.64	9.17	9.58
	.20	5.24	5.40	5.52	5.71	5.87	6.06	6.31	6.52	6.86	7.13	7.57	7.91
	.25	4.51	4.65	4.76	4.92	5.06	5.22	5.44	5.62	5.91	6.15	6.52	6.82
	.30	4.00	4.12	4.21	4.36	4.48	4.62	4.82	4.98	5.24	5.44	5.77	6.04
	.35	3.61	3.72	3.80	3.94	4.04	4.17	4.35	4.49	4.72	4.91	5.21	5.45
	.40	3.30	3.40	3.48	3.60	3.70	3.82	3.98	4.11	4.32	4.49	4.77	4.98
	.45	3.05	3.14	3.22	3.33	3.42	3.53	3.68	3.80	4.00	4.15	4.41	4.61
	.50	2.84	2.93	3.00	3.10	3.19	3.29	3.43	3.54	3.72	3.87	4.11	4.30
	.75	2.17	2.24	2.29	2.37	2.43	2.51	2.62	2.70	2.84	2.95	3.14	3.28
	1.00	1.79	1.85	1.89	1.96	2.01	2.09	2.16	2.23	2.35	2.44	2.59	2.71
	1.25	1.54	1.59	1.63	1.68	1.73	1.78	1.86	1.92	2.02	2.10	2.23	2.33
	1.50	1.37	1.41	1.44	1.49	1.53	1.58	1.65	1.70	1.79	1.86	1.97	2.07
	1.75	1.23	1.27	1.30	1.35	1.38	1.43	1.49	1.54	1.62	1.68	1.78	1.86
	2.00	1.13	1.16	1.19	1.23	1.26	1.31	1.36	1.40	1.48	1.54	1.63	1.70
	2.25	1.04	1.08	1.10	1.14	1.17	1.21	1.26	1.30	1.37	1.42	1.51	1.58
	2.50	0.97	1.00	1.02	1.06	1.09	1.12	1.17	1.21	1.27	1.32	1.40	1.47
	3.00	0.85	0.89	0.91	0.94	0.96	1.00	1.04	1.07	1.13	1.17	1.24	1.30
	3.50	0.78	0.80	0.82	0.85	0.87	0.90	0.94	0.97	1.02	1.06	1.12	1.17
	4.00	0.71	0.73	0.75	0.78	0.80	0.82	0.86	0.88	0.93	0.97	1.03	1.07
	4.50	0.66	0.68	0.69	0.72	0.74	0.76	0.79	0.82	0.86	0.90	0.95	0.99
	5.00	0.61	0.63	0.65	0.67	0.69	0.71	0.74	0.76	0.80	0.83	0.88	0.93
	7.00	0.49	0.50	0.52	0.53	0.55	0.57	0.59	0.61	0.64	0.67	0.71	0.74
	10.00	0.39	0.40	0.41	0.42	0.43	0.45	0.47	0.48	0.51	0.53	0.56	0.58
	20.00	0.24	0.25	0.26	0.26	0.27	0.28	0.29	0.30	0.32	0.33	0.35	0.37
	30.00	0.18	0.19	0.20	0.20	0.21	0.21	0.22	0.23	0.24	0.25	0.27	0.28

[1] Adapted from Suarez (1981).

[2] Assumes a soil source of calcium from lime ($CaCO_3$) or silicates; no precipitation of magnesium, and partial pressure of CO_2 near the soil surface (P_{CO_2}) is .0007 atmospheres.

[3] Ca_x, HCO_3, Ca are reported in me/l; EC_w is in dS/m.

EXAMPLE 6 - COMPARISON OF METHODS TO CALCULATE THE SODIUM HAZARD OF A WATER

Given: The water analysis is:

Ca = 2.32 me/l
Mg = 1.44 me/l
Na = 7.73 me/l

Sum = 11.49 me/l

CO_3 = 0.42 me/l
HCO_3 = 3.66 me/l

Sum = 4.08 me/l

EC_w = 1.15 dS/m

Explanation:

1. The Sodium Adsorption Ratio (SAR) can be calculated from equation (1):

$$SAR = \frac{Na}{\sqrt{\frac{Ca + Mg}{2}}} \qquad (1)$$

$$SAR = \frac{7.73}{\sqrt{\frac{2.32 + 1.44}{2}}} = 5.64$$

2. The adjusted Sodium Adsorption Ratio (adj SAR) can be calculated from the procedure given in Ayers and Westcot (1976):

$$adj\ SAR = SAR\ [1 + (8.4 - pHc)] \qquad (15)$$

where $pHc = (pk_2 - pk_c) + p\ (Ca + Mg) + p\ (Alk)$

$(pk_2 - pk_c) = 2.3$
$p\ (Ca + Mg) = 2.7$
$p\ (Alk) = 2.4$

$pHc = 7.4$

$$adj\ SAR = 5.64\ [1 + (8.4 - 7.40)] = 11.3$$

3. The adjusted Sodium Adsorption Ratio (adj RNa) can be calculated from equation (14) and Table 11):

$$adj\ R_{Na} = \frac{Na}{\sqrt{\frac{Ca_x + Mg}{2}}} \qquad (14)$$

EC_w = 1.15 dS/m

HCO_3/Ca = 1.76

From Table 11, Ca_x = 1.43 me/l

$$adj\ R_{Na} = \frac{7.73}{\sqrt{\frac{1.43 + 1.44}{2}}} = 6.45$$

Source: Ayers/Westcot (FAO) 1985

Table 2-7 b

Table 2-8

Table 13 AVERAGE COMPOSITION AND EQUIVALENT ACIDITY OR BASICITY OF FERTILIZER MATERIALS[1]

Fertilizer materials	Chemical Formula	Total Nitrogen (N)	Available Phosphoric Acid (P_2O_5)	Water Soluble Potash (K_2O)	Combined Calcium (Ca)	Combined Sulphur (S)	Equivalent[2] Acid or Base in kg $CaCO_3$: Acid	Base
		---- Percent ----						
Nitrogen materials								
Ammonium nitrate	NH_4NO_3	33.5-34					62	
Ammonium nitrate-sulphate	$NH_4NO_3.(NH_4)_2SO_4$	30				6.5	68	
Monoammonium phosphate	$NH_4H_2PO_4$	11	48				58	
Ammonium phosphate-sulphate	$NH_4H_2PO_4.(NH_4)_2SO_4$	13	39			7	69	
Ammonium phosphate-sulphate	$NH_4H_2PO_4.(NH_4)_2SO_4$	16	20			15	88	
Ammonium phosphate-nitrate	$NH_4H_2PO_4.NH_4NO_3$	27	12			4.5	75	
Diammonium phosphate	$(NH_4)_2HPO_4$	16-18	46-48				70	
Ammonium sulphate	$(NH_4)_2SO_4$	21				24	110	
Anhydrous ammonia	NH_3	82					147	
Aqua ammonia	NH_4OH	20					36	
Calcium ammonium nitrate solution	$Ca(NO_3)_2.NH_4NO_3$	17			8.8		9	
Calcium nitrate	$Ca(NO_3)_2$	15.5			21			20
Calcium cyanamide	$CaCN_2$	20-22			37			63
Sodium nitrate	$NaNO_3$	16						29
Urea	$CO(NH_2)_2$	45-46					71	
Urea formaldehyde[3]		38					60	
Urea ammonium nitrate solution	$NH_4NO_3.CO(NH_2)_2$	32					57	
Phosphate materials								
Single superphosphate	$Ca(H_2PO_4)_2$		18-20		18-21	12		neutral
Triple superphosphate	$Ca(H_2PO_4)_2$		45-46		12-14	1		neutral
Phosphoric acid	H_3PO_4		52-54				110	
Superphosphoric acid[4]			76-83				160	
Potash materials								
Potassium chloride	KCl			60-62				neutral
Potassium nitrate	KNO_3	13		44			23	
Potassium sulphate	K_2SO_4			50-53		18		neutral
Sulphate of potash-magnesia	$K_2SO_4.2MgSO_4$			26	1	15		neutral

[1] From Soil Improvement Committee (1975).

[2] Equivalent per 100 kg of each material.

[3] Also known as ureaform, reaction product of urea and formaldehyde.

[4] H_3PO_4, $H_4P_2O_7$, $H_5P_3O_{10}$, $H_6P_4O_{13}$ and other higher forms.

Source: Ayers/Westcot (FAO) 1985

Table 36-6. Chloride tolerance limits of some fruit-crop cultivars and rootstocks. After Maas (1986).

Crop	Rootstock or cultivar	Maximum permissible Cl^- in soil water without leaf injury
	Rootstocks	
Avocado	West Indian	15
	Guatemalan	12
	Mexican	10
Citrus (*Citrus* spp.)	Sunki mandarin, grapefruit, Cleopatra mandarin, Rangpur lime	50
	Sampson tangelo, rough lemon,‡ sour orange, Ponkan mandarin	30
	Citrumelo 4475, trifolate orange, Cuban shaddock, Calamondin, sweet orange, Savage citrange, Rusk citrange, Troyer citrange	20
Grape (*Vitis* spp.)	Salt Creek, 1613-3	80
	Dog ridge	60
Stone fruit (*Prunus* spp.)	Marianna	50
	Lovell, Shalil	20
	Yunnan	15
	Cultivars	
Berries§ (*Rubus* spp.)	Boysenberry	20
	Olallie blackberry	20
	Indian summer raspberry	10
Grape (*Vitis* spp.)	Thompson seedless, Perlette	40
	Cardinal, Black rose	20
Strawberry (*Fragaria* spp.)	Lassen	15
	Shasta	10

† For some crops these concentrations may exceed the osmotic threshold and cause some yield reductions.
‡ Data from Australia indicate that rough lemon is more sensitive to Cl^- than sweet orange.
§ Data available for one variety of each species only.

Source: Stewart ed. 1990

Table 2-9a

Table 14 CHLORIDE TOLERANCE OF SOME FRUIT CROP CULTIVARS AND ROOTSTOCKS [1]

Table 2-9b

Crop	Rootstock or Cultivar	Maximum Permissible Cl^- without Leaf Injury [2]: Root Zone (Cl_e) (me/l)	Irrigation Water (Cl_w) [3,4] (me/l)
	Rootstocks		
Avocado	West Indian	7.5	5.0
(*Persea americana*)	Guatemalan	6.0	4.0
	Mexican	5.0	3.3
Citrus (*Citrus spp.*)	Sunki Mandarin Grapefruit Cleopatra mandarin Rangpur lime	25.0	16.6
	Sampson tangelo Rough lemon Sour orange Ponkan mandarin	15.0	10.0
	Citrumelo 4475 Trifoliate orange Cuban shaddock Calamondin Sweet orange Savage citrange Rusk citrange Troyer citrange	10.0	6.7
Grape	Salt Creek, 1613-3	40.0	27.0
(*Vitis spp.*)	Dog Ridge	30.0	20.0
Stone Fruits	Marianna	25.0	17.0
(*Prunus spp.*)	Lovell, Shalil	10.0	6.7
	Yunnan	7.5	5.0
	Cultivars		
Berries	Boysenberry	10.0	6.7
(*Rubus spp.*)	Olallie blackberry	10.0	6.7
	Indian Summer Raspberry	5.0	3.3
Grape	Thompson seedless	20.0	13.3
(*Vitis spp.*)	Perlette	20.0	13.3
	Cardinal	10.0	6.7
	Black Rose	10.0	6.7
Strawberry	Lassen	7.5	5.0
(*Fragaria spp.*)	Shasta	5.0	3.3

[1] Adapted from Maas (1984).

Source: Ayers/Westcot (FAO) 1985

[2] For some crops, the concentration given may exceed the overall salinity tolerance of that crop and cause some reduction in yield in addition to that caused by chloride ion toxicities.

[3] Values given are for the maximum concentration in the irrigation water. The values were derived from saturation extract data (EC_e) assuming a 15-20 percent leaching fraction and $EC_e = 1.5\ EC_w$.

[4] The maximum permissible values apply only to surface irrigated crops. Sprinkler irrigation may cause excessive leaf burn at values far below these (see Section 4.3).

Table 4 GUIDELINE TO IDENTIFY POTENTIAL INFILTRATION PROBLEM DUE TO SODIUM IN IRRIGATION WATER [1]

Table 2-10 a

Salinity levels of irrigation water	Degree of reduction in infiltration rate: No reduction	Slight reduction	Medium reduction	Severe reduction
	SAR of irrigation water			
Non-saline water EC_w (dS/m) = 0.7	< 1	1 to 5	5 to 11	> 11
Slightly saline water EC_w (dS/m) = 0.7 to 3.0	< 10	10 to 15	15 to 23	> 23
Medium saline water EC_w (dS/m) = 3.0 to 6.0	< 25	> 25	No effect on infiltration	No effect on infiltration
Highly saline water EC_w (dS/m) = 6.0 to 14.0	< 35	> 35	No effect	No effect
Very highly saline water EC_w (dS/m) = > 14.0	No effect by sodium on infiltration rate			

[1] Based on the results of Rhoades (1977) and Oster and Schroer (1979).

Source: Ayers/Westcot (FAO) 1985

Table 15 RELATIVE TOLERANCE OF SELECTED CROPS TO EXCHANGEABLE SODIUM [1]

Table 2-10 b

Sensitive [2]	Semi-tolerant [2]	Tolerant [2]
Avocado (*Persea americana*)	Carrot (*Daucus carota*)	Alfalfa (*Medicago sativa*)
Deciduous Fruits	Clover, Ladino (*Trifolium repens*)	Barley (*Hordeum vulgare*)
Nuts	Dallisgrass (*Paspalum dilatatum*)	Beet, garden (*Beta vulgaris*)
Bean, green (*Phaseolus vulgaris*)	Fescue, tall (*Festuca arundinacea*)	Beet, sugar (*Beta vulgaris*)
Cotton (at germination) (*Gossypium hirsutum*)	Lettuce (*Lactuca sativa*)	Bermuda grass (*Cynodon dactylon*)
Maize (*Zea mays*)	Bajara (*Pennisetum typhoides*)	Cotton (*Gossypium hirsutum*)
Peas (*Pisum sativum*)	Sugarcane (*Saccharum officinarum*)	Paragrass (*Brachiaria mutica*)
Grapefruit (*Citrus paradisi*)	Berseem (*Trifolium alexandrinum*)	Rhodes grass (*Chloris gayana*)
Orange (*Citrus sinensis*)	Benji (*Melilotus parviflora*)	Wheatgrass, crested (*Agropyron cristatum*)
Peach (*Prunus persica*)	Raya (*Brassica juncea*)	Wheatgrass, fairway (*Agropyron cristatum*)
Tangerine (*Citrus reticulata*)	Oat (*Avena sativa*)	Wheatgrass, tall (*Agropyron elongatum*)
Mung (*Phaseolus aurus*)	Onion (*Allium cepa*)	Karnal grass (*Diplachna fusca*)
Mash (*Phaseolus mungo*)	Radish (*Raphanus sativus*)	
Lentil (*Lens culinaris*)	Rice (*Oryza sativus*)	
Groundnut (peanut) (*Arachis hypogaea*)	Rye (*Secale cereale*)	
Gram (*Cicer arietinum*)	Ryegrass, Italian (*Lolium multiflorum*)	
Cowpeas (*Vigna sinensis*)	Sorghum (*Sorghum vulgare*)	
	Spinach (*Spinacia oleracea*)	
	Tomato (*Lycopersicon esculentum*)	
	Vetch (*Vicia sativa*)	
	Wheat (*Triticum vulgare*)	

Adapted from data of FAO-Unesco (1973); Pearson (1960); and Abrol (1982).

The approximate levels of exchangeable sodium percentage (ESP) corresponding to the three categories of tolerance are: sensitive less than 15 ESP; semi-tolerant 15-40 ESP; tolerant more than 40 ESP. Tolerance decreases in each column from top to bottom. The tolerances listed are relative because, usually, nutritional factors and adverse soil conditions stunt growth before reaching these levels. Soil with an ESP above 30 will usually have too poor physical structure for good crop production. Tolerances in most instances were established by first stabilizing soil structure.

Source: Ayers/Westcot (FAO) 1985

Table 2-11 a

Table 36-5. Boron tolerance limits for agricultural crops. After Maas (1986).

Common name (Botanical name not included in text)	Threshold†
	mg/L
Very sensitive	
Lemon‡	<0.5
Blackberry‡	<0.5
Sensitive	
Avocado‡	0.5–0.75
Grapefruit‡	0.5–0.75
Orange‡	0.5–0.75
Apricot‡	0.5–0.75
Peach‡	0.5–0.75
Cherry‡	0.5–0.75
Plum‡	0.5–0.75
Persimmon, Japanese (*Diospyros kaki* L.f.)	0.5–0.75
Fig, kadota‡	0.5–0.75
Grapa‡ (*Vitis vinifera*)	0.5–0.75
Walnut‡ (*Juglans regia* L.)	0.5–0.75
Pecan‡ [*Carya illinoensis* (Wangenh.) K. Koch]	0.5–0.75
Cowpea‡	0.5–0.75
Onion	0.5–0.75
Garlic (*Allium sativum* L.)	0.75–1.0
Sweet potato	0.75–1.0
Wheat	0.75–1.0
Sunflower	0.75–1.0
Bean, mung‡ [*Vigna radiata* (L.) R. Wilcz.]	0.75–1.0
Sesame‡	0.75–1.0
Lupine‡ (*Lupinus hartwegii* Lindl.)	0.75–1.0
Strawberry‡ (*Fragaria* sp. L.)	0.75–1.0
Artichoke, Jerusalem‡	0.75–1.0
Bean, kidney‡ (*Phaseolus vulgaris*)	0.75–1.0
Bean, lima‡ (*Phaseolus lunatus*)	0.75–1.0
Peanut (*Arachis hypogaea*)	0.75–1.0
Moderately sensitive	
Broccoli	1.0–2.0
Pepper, red	1.0–2.0
Pea‡	1.0–2.0
Carrot	1.0–2.0
Radish	1.0–2.0
Potato	1.0–2.0
Cucumber	1.0–2.0
Moderately tolerant	
Lettuce‡	2.0–4.0
Cabbage‡	2.0–4.0
Celery‡	2.0–4.0
Turnip	2.0–4.0
Bluegrass, Kentucky‡ (*Poa pratensis* L.)	2.0–4.0
Barley	2.0–4.0
Oat	2.0–4.0
Corn	2.0–4.0
Artichoke, globe‡ (*Cynara scolymus* L.)	2.0–4.0
Tobacco‡ (*Nicotiana tabacum* L.)	2.0–4.0
Mustard, Indian‡ [*Brassica juncea* (L.) Czerni.]	2.0–4.0
Clover, sweet‡	2.0–4.0
Squash	2.0–4.0
Muskmelon‡	2.0–4.0
Cauliflower	2.0–4.0
Tolerant	
Tomato	4.0–6.0
Alfalfa‡	4.0–6.0
Vetch, purple‡ (*Vicia benghalensis*)	4.0–6.0
Parsley‡ (*Petroselinum crispum*)	4.0–6.0
Beet, red	4.0–6.0
Sugarbeet	4.0–6.0
Very tolerant	
Sorghum	6.0–10.0
Cotton	6.0–10.0
Asparagus‡	10.0–15.0

† Maximum permissible concentration in soil water without yield reduction. Boron tolerances may vary depending upon climate, soil conditions, and crop varieties.
‡ Tolerance based on reductions in vegetative growth.

Table 2-11 b

Table 16 RELATIVE BORON TOLERANCE OF AGRICULTURAL CROPS[1,2]

Common name	Botanical name
Very Sensitive (<0.5 mg/l)	
Lemon	*Citrus limon*
Blackberry	*Rubus spp.*
Sensitive (0.5 - 0.75 mg/l)	
Avocado	*Persea americana*
Grapefruit	*Citrus X paradisi*
Orange	*Citrus sinensis*
Apricot	*Prunus armeniaca*
Peach	*Prunus persica*
Cherry	*Prunus avium*
Plum	*Prunus domestica*
Persimmon	*Diospyros kaki*
Fig, kadota	*Ficus carica*
Grape	*Vitis vinifera*
Walnut	*Juglans regia*
Pecan	*Carya illinoiensis*
Cowpea	*Vigna unguiculata*
Onion	*Allium cepa*
Sensitive (0.75 - 1.0 mg/l)	
Garlic	*Allium sativum*
Sweet potato	*Ipomoea batatas*
Wheat	*Triticum eastivum*
Barley	*Hordeum vulgare*
Sunflower	*Helianthus annuus*
Bean, mung	*Vigna radiata*
Sesame	*Sesamum indicum*
Lupine	*Lupinus hartwegii*
Strawberry	*Fragaria spp.*
Artichoke, Jerusalem	*Helianthus tuberosus*
Bean, kidney	*Phaseolus vulgaris*
Bean, lima	*Phaseolus lunatus*
Groundnut/Peanut	*Arachis hypogaea*
Moderately Sensitive (1.0 - 2.0 mg/l)	
Pepper, red	*Capsicum annuum*
Pea	*Pisum sativa*
Carrot	*Daucus carota*
Radish	*Raphanus sativus*
Potato	*Solanum tuberosum*
Cucumber	*Cucumis sativus*
Moderately Tolerant (2.0 - 4.0 mg/l)	
Lettuce	*Lactuca sativa*
Cabbage	*Brassica oleracea capitata*
Celery	*Apium graveolens*
Turnip	*Brassica rapa*
Bluegrass, Kentucky	*Poa pratensis*
Oats	*Avena sativa*
Maize	*Zea mays*
Artichoke	*Cynara scolymus*
Tobacco	*Nicotiana tabacum*
Mustard	*Brassica juncea*
Clover, sweet	*Melilotus indica*
Squash	*Cucurbita pepo*
Muskmelon	*Cucumis melo*
Tolerant (4.0 - 6.0 mg/l)	
Sorghum	*Sorghum bicolor*
Tomato	*Lycopersicon lycopersicum*
Alfalfa	*Medicago sativa*
Vetch, purple	*Vicia benghalensis*
Parsley	*Petroselinum crispum*
Beet, red	*Beta vulgaris*
Sugarbeet	*Beta vulgaris*
Very Tolerant (6.0 - 15.0 mg/l)	
Cotton	*Gossypium hirsutum*
Asparagus	*Asparagus officinalis*

Source: Ayers/Westcot (FAO) 1985

[1] Data taken from Maas (1984).

[2] Maximum concentrations tolerated in soil-water without yield or vegetative growth reductions. Boron tolerances vary depending upon climate, soil conditions and crop varieties. Maximum concentrations in the irrigation water are approximately equal to these values or slightly less.

Table 2-12 a

Table II.2 Recommended maximum concentrations of trace elements in irrigation water[1]

Elements	For waters used continuously on all soil (mg/liter)	For use up to 20 yrs. on fine-textured soils at pH 6.0 to 8.5 (mg/liter)
Aluminum	5.0	20.0
Arsenic	0.10	2.0
Beryllium	0.10	0.50
Boron	0.75	2.0 – 10.0
Cadmium	0.010	0.050
Chromium	0.10	1.0
Cobalt	0.050	5.0
Copper	0.20	5.00
Fluorine	1.0	15.0
Iron	5.0	20.0
Lead	5.0	10.0
Lithium	2.5	2.5[2]
Manganese	0.20	10.0
Molybdenum	0.010	0.050[3]
Nickel	0.20	2.0
Selenium	0.020	0.020
Vanadium	0.10	1.0
Zinc	2.0	10.0

[1] These levels will not normally have an adverse effect on plants or soils. No data available for mercury, silver, tin, titanium, tungsten.
[2] Recommended maximum concentration for citrus is 0.75 mg/liter.
[3] Only for fine-textured acid soils, or acid soils with relatively high content of iron oxide.

10

Source: Shainberg/Oster 1978

Table 2-12 b

Table 21 RECOMMENDED MAXIMUM CONCENTRATIONS OF TRACE ELEMENTS IN IRRIGATION WATER[1]

Element		Recommended Maximum Concentration[2] (mg/l)	Remarks
Al	(aluminium)	5.0	Can cause non-productivity in acid soils (pH < 5.5), but more alkaline soils at pH > 7.0 will precipitate the ion and eliminate any toxicity.
As	(arsenic)	0.10	Toxicity to plants varies widely, ranging from 12 mg/l for Sudan grass to less than 0.05 mg/l for rice.
Be	(beryllium)	0.10	Toxicity to plants varies widely, ranging from 5 mg/l for kale to 0.5 mg/l for bush beans.
Cd	(cadmium)	0.01	Toxic to beans, beets and turnips at concentrations as low as 0.1 mg/l in nutrient solutions. Conservative limits recommended due to its potential for accumulation in plants and soils to concentrations that may be harmful to humans.
Co	(cobalt)	0.05	Toxic to tomato plants at 0.1 mg/l in nutrient solution. Tends to be inactivated by neutral and alkaline soils.
Cr	(chromium)	0.10	Not generally recognized as an essential growth element. Conservative limits recommended due to lack of knowledge on its toxicity to plants.
Cu	(copper)	0.20	Toxic to a number of plants at 0.1 to 1.0 mg/l in nutrient solutions.
F	(fluoride)	1.0	Inactivated by neutral and alkaline soils.
Fe	(iron)	5.0	Not toxic to plants in aerated soils, but can contribute to soil acidification and loss of availability of essential phosphorus and molybdenum. Overhead sprinkling may result in unsightly deposits on plants, equipment and buildings.
Li	(lithium)	2.5	Tolerated by most crops up to 5 mg/l; mobile in soil. Toxic to citrus at low concentrations (<0.075 mg/l). Acts similarly to boron.
Mn	(mangaoese)	0.20	Toxic to a number of crops at a few-tenths to a few mg/l, but usually only in acid soils.
Mo	(molybdenum)	0.01	Not toxic to plants at normal concentrations in soil and water. Can be toxic to livestock if forage is grown in soils with high concentrations of available molybdenum.
Ni	(nickel)	0.20	Toxic to a number of plants at 0.5 mg/l to 1.0 mg/l; reduced toxicity at neutral or alkaline pH.
Pd	(lead)	5.0	Can inhibit plant cell growth at very high concentrations.
Se	(selenium)	0.02	Toxic to plants at concentrations as low as 0.025 mg/l and toxic to livestock if forage is grown in soils with relatively high levels of added selenium. An essential element to animals but in very low concentrations.
Sn Ti W	(tin) (titanium) (tungsten)	----	Effectively excluded by plants; specific tolerance unknown.
V	(vanadium)	0.10	Toxic to many plants at relatively low concentrations.
Zn	(zinc)	2.0	Toxic to many plants at widely varying concentrations; reduced toxicity at pH > 6.0 and in fine textured or organic soils.

[1] Adapted from National Academy of Sciences (1972) and Pratt (1972).

[2] The maximum concentration is based on a water application rate which is consistent with good irrigation practices (10 000 m^3 per hectare per year). If the water application rate greatly exceeds this, the maximum concentrations should be adjusted downward accordingly. No adjnstment should be made for application rates less than 10 000 m^3 per hectare per year. The values given are for water used on a continuous basis at one site.

Source: Ayers/Westcot (FAO) 1985

Table 2-13

Table 22 PHYSICAL, CHEMICAL AND BIOLOGICAL CONTRIBUTORS TO CLOGGING OF LOCALIZED (DRIP) IRRIGATION SYSTEMS AS RELATED TO IRRIGATION WATER QUALITY[1]

PHYSICAL (Suspended Solids)	CHEMICAL (Precipitation)	BIOLOGICAL (Bacteria and algae)
1. Sand	1. Calcium or magnesium carbonate	1. Filaments
2. Silt	2. Calcium sulphate	2. Slimes
3. Clay	3. Heavy metal hydroxides, oxides, carbonates, silicates and sulphides	3. Microbial depositions: (a) Iron (b) Sulphur (c) Manganese
4. Organic matter	4. Fertilizers (a) Phosphate (b) Aqueous ammonia (c) Iron, zinc, copper, manganese	4. Bacteria
		5. Small aquatic organisms: (a) Snail eggs (b) Larva

[1] Adapted from Bucks et al. (1979).

Source: Ayers/Westcot (FAO) 1985

Table 2-14

Table 23 STANDARD WATER QUALITY TESTS NEEDED FOR DESIGN AND OPERATION OF LOCALIZED (DRIP) IRRIGATION SYSTEMS

1. Major Inorganic Salts (see Table 2)	8. Micro-organisms
2. Hardness[1]	9. Iron
3. Suspended Solids	10. Dissolved Oxygen
4. Total Dissolved Solids (TDS)[1]	11. Hydrogen Sulphide
5. BOD (Biological Oxygen Demand)	12. Iron Bacteria
6. COD (Chemical Oxygen Demand)	13. Sulphate Reducing Bacteria
7. Organics and Organic Matter	

[1] A calculated value from analyses

Source: Ayers/Westcot (FAO) 1985

Table 2-15

Table 2.10 Clogging potential of irrigation water used in drip irrigation systems (After Nakayama 1982)

Type of hazard	Extent of hazard: Slight	Moderate	Severe
Physical			
Suspended soids (mg/l)	< 50	50–100	> 100
Chemical			
pH	< 7.0	7.0–8.0	> 8.0
Dissolved solids (mg/l)	< 500	500–2000	> 2000
Manganese (mg/l)	< 0.1	0.1–1.5	1.5
Iron (mg/l)	< 0.1	0.1–1.5	> 1.5
Hydrogen sulfide (mg/l)	< 0.5	0.5–2.0	> 2.0
Biological			
Bacterial populations (maximum number/ml)	< 10 000	10 000–50 000	> 50 000

Source: Feigin et al. 1991

Table 2-16

Table 24 INFLUENCE OF WATER QUALITY ON THE POTENTIAL FOR CLOGGING PROBLEMS IN LOCALIZED (DRIP) IRRIGATION SYSTEMS[1]

Potential Problem	Units	Degree of Restriction on Use: None	Slight to Moderate	Severe
Physical				
Suspended Solids	mg/l	< 50	50 – 100	> 100
Chemical				
pH		< 7.0	7.0 – 8.0	> 8.0
Dissolved Solids	mg/l	< 500	500 – 2000	> 2000
Manganese[2]	mg/l	< 0.1	0.1 – 1.5	> 1.5
Iron[3]	mg/l	< 0.1	0.1 – 1.5	> 1.5
Hydrogen Sulphide	mg/l	< 0.5	0.5 – 2.0	> 2.0
Biological				
Bacterial populations	maximum number/ml	<10 000	10 000 – 50 000	>50 000

[1] Adapted from Nakayama (1982).

[2] While restrictions in use of localized (drip) irrigation systems may not occur at these manganese concentrations, plant toxicities may occur at lower concentrations (see Table 21).

[3] Iron concentrations > 5.0 mg/l may cause nutritional imbalances in certain crops (see Table 21).

Source: Ayers/Westcot (FAO) 1985

Table 2-17

Table 25 PROCEDURE FOR CALCULATION OF pHc[1,2]

$$pHc = (pK_2 - pKc) + pCa + p(Alk)$$

$pK_2 - pKc$ is obtained from the concentration of Ca + Mg + Na in me/l
pCa is obtained from the Ca in me/l
p(Alk) is obtained from the concentration of CO_3 + HCO_3 in me/l
} Obtained from the water analysis

Concentration (me/l)	$pK_2 - pKc$	pCa	p(Alk)
0.05	2.0	4.6	4.3
0.10	2.0	4.3	4.0
0.15	2.0	4.1	3.8
0.20	2.0	4.0	3.7
0.25	2.0	3.9	3.6
0.30	2.0	3.8	3.5
0.40	2.0	3.7	3.4
0.50	2.1	3.6	3.3
0.75	2.1	3.4	3.1
1.00	2.1	3.3	3.0
1.25	2.1	3.2	2.9
1.50	2.1	3.1	2.8
2.00	2.2	3.0	2.7
2.50	2.2	2.9	2.6
3.00	2.2	2.8	2.5
4.00	2.2	2.7	2.4
5.00	2.2	2.6	2.3
6.00	2.2	2.5	2.2
8.00	2.3	2.4	2.1
10.00	2.3	2.3	2.0
12.50	2.3	2.2	1.9
15.00	2.3	2.1	1.8
20.00	2.4	2.0	1.7
30.00	2.4	1.8	1.5
50.00	2.5	1.6	1.3
80.00	2.5	1.4	1.1

[1] Procedure from Nakayama (1982).

[2] pHc is a theoretical, calculated pH of the irrigation water.

Source: Ayers/Westcot (FAO) 1985

Table 2-18

Table 27 LIMIT VALUES FOR EVALUATING THE AGGRESSIVITY OF WATER AND SOIL TO CONCRETE[1]

Test	Intensity of attack: None to slight	Mild	Strong	Very Strong
Water				
pH	> 6.5	6.5–5.5	5.5–4.5	< 4.5
Lime-dissolving carbonic acid (CO_2), mg/l	< 15	15–30	30–60	> 60
Ammonium (NH_4), mg/l	< 15	15–30	30–60	> 60
Magnesium (Mg), mg/l	< 100	100–300	300–1500	> 1500
Sulphate in water (SO_4), mg/l	< 200	200–600	600–3000	> 3000
Soil				
Sulphate in soil (air-dry) (SO_4), mg/kg	< 2000	2000–5000	> 5000	

[1] Data taken from Biczok (1972).

Source: Ayers/Westcot (FAO) 1985

Table 2-19

Table 3.6 Relative susceptibility of crops to foliar injury from saline sprinkling water[a] (After Maas 1986)

Sodium or chloride concentrations (mol/m^3) causing foliar injury[b]: < 5	5–10	10–20	> 20
Almond	Grape	Alfalfa	Cauliflower
Apricot	Pepper	Barley	Cotton
Citrus	Potato	Corn	Sugar beet
Plum	Tomato	Cucumber	Sunflower
		Safflower	
		Sesame	
		Sorghum	

[a] Susceptibility based on direct accumulation of salts through the leaves.
[b] Foliar injury is influenced by cultural and environmental conditions. These data are presented only as general guidelines for daytime sprinkling.

Source: Feigin et al. 1991

Table 2-20 a

EXAMPLE 8 – BLENDING IRRIGATION WATER TO REDUCE THE SAR OF A POOR QUALITY SUPPLY

A canal water supply is available but will not meet the total crop water demand. The canal supply could ba blended with a poorer quality well water to the extent of 75% canal water and 25% well water. What is the SAR of the blended water?

Given: The water analysis is:

	ECw (dS/m)	Ca (me/l)	Mg (me/l)	Na (me/l)	HCO_3 (me/l)	SAR
Canal water	0.23	1.41	0.54	0.48	1.8	0.5
Wall water	3.60	2.52	4.00	32.0	4.5	18.0

Explanation: The resulting blend quality can be found by using equation (13):

(me/l of (a) x proportion of (a) used) +
(me/l of (b) x proportion of (b) used) =
resulting blend in me/l

Ca = (1.41x0.75) + (2.52x0.25) = 1.69 me/l (blend)
Mg = (0.54x0.75) + (4.00x0.25) = 1.41 me/l (blend)
Na = (0.48x0.75) + (32.0x0.25) = 8.36 me/l (blend)
HCO_3 = (1.8 x0.75) + (4.5 x0.25) = 2.48 me/l (blend)
EC_w = (0.23x0.75) + (3.6 x0.25) = 1.07 dS/m (blend)

$$SAR = \frac{8.36}{\sqrt{\frac{1.69 + 1.41}{2}}} = 6.7$$

Table 2-20 b

EXAMPLE 5 – BLENDING IRRIGATION WATER FOR MAIZE

A farmer is irrigating a maize crop with canal water (ECw = 0.23 dS/m) and is able to achieve a leaching fraction (LF) of 0.15 by using efficient irrigation practices. The irrigated area could be expanded but no additional canal water is available. A well is available but the water quality is marginal for maize production (ECw = 3.6 dS/m). Could these two water sources be safely blended and thus expand the irrigated area?

Given:

Canal water	EC_w	= 0.23 dS/m
Well water	EC_w	= 3.6 dS/m
Water demand (ET) for maize	ET	= 800 mm/year
Leaching fraction achieved	LF	= 0.15

Explanation:

The leaching needed for a 90% yield potential of maize is estimated using equation (9):

$$LR = \frac{EC_w}{5(EC_e) - EC_w} \quad (9)$$

$$LR_{(canal\ water)} = \frac{0.23}{5(2.5) - 0.23} = 0.02$$

$$LR_{(well\ water)} = \frac{3.6}{5(2.5) - 3.6} = 0.40$$

The calculated leaching requirement (LR) for the canal water is less than the actual leaching achieved by the farmer. Water is being lost by over leaching but a LF leaa than 0.15 is not often achievable. The calculated leaching requirement of well water alone when added to ET would greatly increase the amount of water needed for production. For example, with the caoal water and a LF of 0.15, the applied water needed (Aw) is found from equation (7):

$$Aw = \frac{ET}{1 - LF} \quad (7)$$

$$Aw_{(canal\ water)} = \frac{800}{1 - 0.15} = 941 \text{ mm/year}$$

For the well water:

$$Aw_{(well\ water)} = \frac{800}{1 - 0.40} = 1333 \text{ mm/year}$$

The use of well water alone would result in a 40 percent increase in water use per hectare to achieve the same maize production as could be obtained using the canal water.

From Table 4, the maximum ECw of the blended water that will allow a 90% yield potential with a leaching fraction of 0.15 is 1.7 dS/m. The optimum blend of water can then be found by modifying equation (13):

$$EC_{w\ (canal\ water)} \cdot a) + (EC_{w\ (well\ water)} \cdot b) = \text{Maximum } EC_{w\ (blend\ water)} \quad (13)$$

where:
- $EC_{w\ (canal\ water)}$ = electrical conductivity of the canal water in dS/m
- $EC_{w\ (well\ water)}$ = electrical conductivity of the well water in dS/m
- a = proportion of canal water used
- b = proportion of well warer used
- Maximum $EC_{w\ (blend\ water)}$ = Maximum electrical conductivity of the blended water in dS/m

if a = 1 – b, then the above equation is:

0.23 (1 – b) + 3.6 (b) = 1.7
3.37b = 1.47
b = 0.44 or 44 percent well water
a = 1 – b = 0.56 or 56 percent canal water

The above shows that the area presently irrigated with canal water at Aw = 941 mm/ha/year could be expanded with no increase in Aw/ha/year if the canal water were blended with up to 44% well water. Yield potential would be maintained at about 90% and the planted area could be expanded by 44%.

Source: Ayers/Westcot (FAO) 1985

Table 2-21

Table 2.3 Inorganic constituents added to effluents through domestic use[a]

Constituent	Range of increment mg/l
Total dissolved solids	150–400
Sodium	40–70
Potassium	7–15
Calcium	15–40
Magnesium	15–40
Chloride	20–50
Carbonate	0–10
Bicarbonate	50–100
Sulfate	15–30
Silica	2–10
Alkalinity (as calcium carbonate)	100–150
Boron	0.1–0.4
Phosphate	5–15
Ammonium	15–40

[a] Metcalf & Eddy Inc. (1979); Asano et al. (1985).

Source: Feigin et al. 1991

Table 2-22a

Table 4.1 Physical and chemical characteristics of domestic wastewater

Major constituents	*Concentration* (in mg/l)		
	Strong	*Medium*	*Weak*
Total solids	1200	700	350
Dissolved solids	850	500	250
Suspended solids	350	200	100
Nitrogen (as N)	85	40	20
Phosphorus (as P)	20	10	6
Chlorides*	100	50	30
Alkalinity (as $CaCo_3$)	200	100	50
Grease	150	100	50
BOD_5†	300	200	100

Source: These data are adapted from Metcalf and Eddy Inc. (1972), p. 231.

* This amount should be increased by the concentration of these constituents in the carriage water: the table shows major constituents only.

† BOD_5 is the 5-day biochemical oxygen demand at 20°C. It is a measure of the biodegradable organic content of wastewater.

Source: in Pescod/Arar ed. 1988

Table 2-22 b

Table 2.1 Typical composition of raw municipal sewage (Pound and Crites 1973[a]; Bond and Straub 1974; Thomas and Law 1977; Idelovitch 1978; Asano et al. 1985)[a]

Constituent	Concentration, mg/l[b]		
	High	Medium	Low
Solids			
Total	1300	700	200
Dissolved	1000	500	260
Suspended	350	220	100
BOD_5	350	200	100
COD	1000	500	250
TOC	290	160	80
Nitrogen			
Total	85	40	20
Ammonium	50	25	10
Organic	35	15	5
Nitrate	1.5	0.2	0
Phosphorus	36	10	4
Chlorides	650	150	10
Calcium + magnesium	150	80	25
Sodium	460	120	10
Potassium	25	10	5
Alkalinity (as calcium carbonate)	400	200	50
Grease	150	100	35
pH	8.0	7.2	7.0

[a] Tables 2.1 to 2.5 give typical data on the chemical quality of raw sewage. However, due to the great variations in quality of the original water and other factors affecting the chemical properties of sewage water, a wide range of data is found in the literature. For example, the Cl^- levels commonly reported range between 10–750 mg/l, which stresses the need for adequate local information concerning the quality of wastewater used.
[b] Except for pH.

Source: Feigin et al. 1991

Table 2-22 c

TABLE 5-1

Typical characteristics of sewage from Indian cities

Sample number	Characteristics		Ahemedabad	Bombay Dadar	Calcutta	Delhi	Hyderabad	Kanpur	Madras	Madurai	Nagpur
1.	pH		7.7	6.9	7.1	7.4	7.3	7.0	7.3	7.5	7.2
2.	Total solids	mg/l	1732	-	-	1100	1708	1500	1700	1740	1200
3.	Suspended solids	mg/l	290	220	420	470	985	600	500	420	200
4.	Dissolved solids	mg/l	1442	1375*	-	630	723	900	1200	1320	1000
5.	BOD	mg/l	196	320	-	223	339	250	350	480	350
6.	Total N	mg/l	-	47.7	40.0	28.5	37.0	73.0	60	-	60
7.	Phosphate as PO^4	mg/l	-	-	5.5	13.7	14.7	15.0	22.0	-	20.0
8.	Potassium	mg/l	-	-	15.9	15.0	26.0	40.0	55.0	-	41.6

Source: Shende et al. (1982).

Source: Shuval et al. 1986

Table 2-23

TABLE 1-1

California State Department of Health standards for the safe and direct use of reclaimed wastewater for irrigation and recreational impoundments

	Description of minimum required wastewater characteristics			
Use of reclaimed wastewater	Primary[a]	Secondary and disinfected	Secondary coagulated filtered[b] and disinfected	Coliform MPN/100 ml median (daily sampling)
Irrigation				
Fodder crops	x			No requirement
Fiber crops	x			No requirement
Seed crops	x			No requirement
Produce eaten raw, surface irrigated		x		2.2
Produce eaten raw, spray irrigated			x	2.2
Processed produce, surface irrigated	x			No requirement
Processed produce, spray irrigated		x		23
Landscapes, parks, etc.		x		23
Creation of impoundments				
Lakes (aesthetic enjoyment only)		x		23
Restricted recreational lakes		x		2.2
Nonrestricted recreational lakes			x	2.2

a. Effluent not containing more than 1.0 ml/liter/hr settlable solids.
b. Effluent not containing more than 10 turbidity units.

Source: After Ongerth and Jopling in Shuval (1977), p. 230.

Source: Shuval et al. 1986

Table 2-24 a

Table 4.4 Suggested treatment processes to meet the given health criteria for wastewater reuse

	Irrigation			*Recreation*		*Industrial reuse*	*Municipal reuse*	
	Crops not for direct human consumption	*Crops eaten cooked; fish culture*	*Crops eaten raw*	*No contact*	*Contact*		*Non-potable*	*Potable*
Health criteria (see below for explanation of symbols)	A + F	B + F or D + F	D + F	B	D + G	C or D	C	E
Primary treatment	●●●	●●●	●●●	●●●	●●●	●●●	●●●	●●●
Secondary treatment		●●●	●●●	●●●	●●●	●●●	●●●	●●●
Sand filtration or equivalent polishing methods		●	●		●●●	●	●●●	●●
Nitrification						●		●●●
Denitrification								●●
Chemical clarification						●		●●
Carbon adsorption								●●
Ion exchange or other means of removing ions						●		●●
Disinfection		●	●●●	●	●●●	●	●●●	●●●*

Health criteria:

A Freedom from gross solids; significant removal of parasite eggs.
B As A, plus a significant removal of bacteria.
C As A, plus more effective removal of bacteria, plus some removal of viruses.
D Not more than 100 coliform organisms/100 ml in 80% of samples.
E No faecal coliform organisms in 100 ml, plus no virus particles in 1000 ml, plus no toxic effects on man, and other drinking-water criteria.
F No chemicals that lead to undesirable residues in crops or fish.
G No chemicals that lead to irritation of mucous membranes and skin.

In order to meet the given health criteria, processes marked ●●● will be essential. In addition, one or more processes marked ●● will also be essential, and further processes marked ● may sometimes be required.

* Free chlorine after 1 h.

Source: WHO (1973)

Source: in Pescod/Arar ed. 1988

Table 4.5 Tentative microbiological quality guidelines for treated wastewater reuse in agricultural irrigation

Note: In specific cases, the guidelines should be modified according to local epidemiological, sociocultural, and hydrogeological factors.

Reuse process	Intestinal nematodes[a] (arithmetic mean no. of viable eggs per litre)	Faecal coliforms (geometric mean no. per 100 ml)
Restricted irrigation[b] Irrigation of trees, industrial crops, fodder crops, fruit trees[c] and pasture[d]	≤1	not applicable
Unrestricted irrigation Irrigation of edible crops, sports fields, and public parks[e]	≤1	≤1000[f]

[a] *Ascaris, Trichuris* and hookworms.
[b] A minimum degree of treatment equivalent to at least a 1-day anaerobic pond followed by a 5-day facultative pond or its equivalent is required in all cases.
[c] Irrigation should cease two weeks before fruit is picked, and no fruit should be picked off the ground.
[d] Irrigation should cease two weeks before animals are allowed to graze.
[e] Local epidemiological factors may require a more stringent standard for public lawns, especially hotel lawns in tourist areas.
[f] When edible crops are always consumed well cooked, this recommendation may be less stringent.

Source: International Reference Centre for Waste Disposal (1985)

Table 2-24 b

Source: Mara/Cairncross 1989

Table 2-24 c

Table 4.4 Examples of current microbiological standards for wastewater used for crop irrigation

Country	Restricted irrigation	Unrestricted irrigation
Oman	Maximum 23 TC/100 ml[a] Average < 2.2 TC/100 ml Greenbelt irrigation only	Crop irrigation not permitted
Kuwait	< 10 000 TC/100 ml	< 100 TC/100 ml Not salad crops or strawberries
Saudi Arabia	Use of secondary effluent permitted for forage crops, field crops and vegetables which are processed and also for landscape irrigation	< 2.2 TC/100 ml < 50 FC/100 ml[b]
Tunisia	Fruit trees, forage crops and vegetables eaten cooked: — secondary treatment (including chlorination) — absence of *Vibrio cholerae* and salmonellae	No irrigation of vegetables eaten raw
Mexico	For recreational areas: < 10 000 TC/100 ml < 2 000 FC/100 ml	For vegetables eaten raw and fruits with possible soil contact: < 1000 TC/100 ml
Peru	Treatment specified depending on reuse option	No irrigation of low-growing and root crops that may be eaten raw

[a] TC: total coliforms
[b] FC: faecal coliforms

Reproduced by permission from Strauss (1987).

Table 2-24 d

Table 4.6 Existing standards governing the use of renovated water in agriculture

	California	*Israel*	*South Africa*	*Federal Republic of Germany*
Orchards and vineyards	Primary effluent; no spray irrigation; no use of dropped fruit	Secondary effluent	Tertiary effluent, heavily chlorinated where possible; no spray irrigation	No spray irrigation in the vicinity
Fodder, fibre crops, and seed crops	Primary effluent; surface or spray irrigation	Secondary effluent, but irrigation of seed crops for producing edible vegetables not permitted	Tertiary effluent	Pretreatment with screening and setting tanks; for spray irrigation, biological treatment and chlorination
Crops for human consumption that will be processed to kill pathogens	For surface irrigation, primary effluent. For spray irrigation, disinfected secondary effluent (no more than 23 coliform organisms/ 100 ml)	Vegetables for human consumption not to be irrigated with renovated wastewater unless it has been properly disinfected (<1000 coliform organisms/100 ml in 80% of samples)	Tertiary effluent	Irrigation up to 4 weeks before harvesting only
Crops for human consumption in a raw state	For surface irrigation, no more than 2.2 coliform organisms/100 ml. For spray irrigation, disinfected, filtered wastewater with turbidity of 10 units permitted, providing it has been treated by coagulation	Not to be irrigated with renovated wastewater unless they consist of fruits that are peeled before eating		Potatoes and cereals – irrigation through flowering stage only

Source: California State Department of Public Health (1968); Indian Standards Institution (1965); Israel, Ministry of Agriculture, Water Commission (1969); Müller (1969); Peru, Ministry of Health, Department of Environmental Sanitation (1970); Shuval (1976).

Source: in Pescod/Arar ed. 1988

Table 2-25

Table 4.6 Geometric mean bacterial and viral numbers[a] and percentage removals in raw wastewater (RW) and the effluents of five waste stabilization ponds in series (P1–P5)[b] in northeast Brazil at a mean mid-depth pond temperature of 26 °C

Organism	RW	P1	P2	P3	P4	P5	Percentage removal
Faecal coliforms	2×10^7	4×10^6	8×10^5	2×10^5	3×10^4	7×10^3	99.97
Faecal streptococci	3×10^6	9×10^5	1×10^5	1×10^4	2×10^3	300	99.99
Clostridium perfringens	5×10^4	2×10^4	6×10^3	2×10^3	1×10^3	300	99.40
Total bifidobacteria	1×10^7	3×10^6	5×10^4	100	0	0	100.00
Sorbitol-positive bifids	2×10^6	5×10^5	2×10^3	40	0	0	100.00
Campylobacters	70	20	0.2	0	0	0	100.00
Salmonellae	20	8	0.1	0.02	0.01	0	100.00
Enteroviruses	1×10^4	6×10^3	1×10^3	400	50	9	99.91
Rotaviruses	800	200	70	30	10	3	99.63

[a] Bacterial numbers per 100 ml, viral numbers per 10 litres.
[b] P1 was an anaerobic pond with a mean hydraulic retention time of 1 day; P2 and P3–P5 were secondary facultative and maturation ponds respectively, each with a retention time of 5 days. Pond depths were 3.4–2.8 m.

Source: Oragui et al. (1987)

Source: Mara/Cairncross 1989

Table 2-26

3 Indicators

In particular, the subjects studied and the indicators use were the following:

(a) Physical studies

Morphology
- Erosion and growth of the coastline
- Bathymetric sections of rivers and mouths of lagoons
- Composition of sedimentary beds

Hydrology
- Flow and distribution of river branches
- Speed direction of currents
- Salinity and temperature
- Movement of solids in suspension
- Salt-wedge intrusion
- Water and solid content of the lagoon

Oceanography
- Residual and tidal currents
- Thermocline trends
- Dispersion of the fluvial plume in the sea
- Wave intensity

Underground waters
- Ground water levels
- Salinity
- Quality of underground waters

(b) Chemical studies of the waters

General quality of water
- pH
- Alcalinity
- Inorganic ions

Pollution by toxic substances
- Ammonia
- Nitrates
- Copper
- Nickle
- Zinc
- Chrome
- Lead
- Cadmium
- Aluminum
- Arsenic
- Phenols
- Detergents

Organic substances and eutrophication
- Ammonia
- Nitrates
- Nitrites
- Silicates
- Phosphates
- Total phosphorus
- Organic nitrogen
- T.O.C.
- B.O.D.
- Dissolved oxygen

Sediments
- Bacterial dehydrogenases
- Heavy metals
- Total phosphorus
- T.O.C.

(c) Microbiology

Contamination of fecal origin
- Total bacterial counts
- Total and fecal coliforms
- Fecal streptococci
- Clostridia

Pathogenic micro-organisms
- Salmonellae
- Viruses

Contamination of sediments
- Bacterial counts
- Salmonellae
- Viruses

d) Hydrobiological studies

Phytoplankton
- Cell density
- Composition
- Chlorophyll

Zooplankton
- Density
- Composition

Macrobenthos
- Density
- Composition

Fouling
- Accumulation
- Density
- Composition
- Periods of settlement

Fish fauna
- Composition
- Feeding
- Migratory patterns along the river branches

(e) Studies of the soil and vegetation

Phyto-sociology
- Floristic catalogue
- Natural vegetation series
- Anthropic and pest vegetation series

Pedology
- Characterization and classification of soils
- Density of micro fauna
- Microbial density

Phyto-pathology
- Plant disease occurence

(f) Studies on agriculture and fishing

Land use
- Land use mapping

Production of main agriculture crops
- Record of existing farms
- Classification of crops
- Unit and total annual production
- Characterization and quantification of fertilizers and pesticides

Fish production
- Quantity of fish per catch effort
- Number of catch effort
- Estimate of production using direct methods
- Estimate of production through market research

4 Indices

The indices (indicators related to quantified limits) were used to formulate an assessment on the quality of the waters, based on scientific recommendations and existing legal regulations on the subject (Fig.G2).

Health indices	Ecological indices
Fecal coliforms	Oxygen
Salmonellae	B.O.D.
Viruses	Total phosphorus
	Ammonia
	Phenols
	Detergents
	Nickel
	Lead
	Copper
	Zinc

It was more difficult to define indices for other categories studied; the biological indices have not yet any general applicability, and the special nature of the environment limits their use. As regards hydrological quantities, it is not logical to contemplate any standardization, while, with regard to fish and agricultural production, there was no

Source: UNESCO/UNEP 1984

Table 2-27

Box 2: Individual and Group Strategies for Groundwater Management

	Individual Strategies	Group Strategies
1. increase r, the rate of recharge;	farm pond as recharge source; exploit deeper aquifer by more bores; dig larger diameter well below the recharge zone;	more check dams and percolation tanks; reduce pumping from the Dadhichi tank;
2. reduce x, the pumping rate;	reduce summer cropping; use piped conveyance and sprinklers;	group decision on extent and mix of summer cropping; cooperative exploitation of groundwater;
3. better crop and water use planning;	better understanding of one's well and its interaction with the aquifer;	better understanding of the interaction between wells; efficient water markets;

Source: Shah 1990

Table 2-28

6

Table 1: Average Yields per Hectare for Four Water Supply Situations in Pakistan (1978)*

Water Supply Situations	Average Yield per hectare (kg) Wheat No. farms	Wheat kg/ha	Paddy Rice No. farms	Paddy Rice kg/ha
1. No control (no tubewell)	170	1681	75	1308
2. Fair control (public tubewell supplies)	33	1868	13	1775
3. Good control (purchase from private tubewell)	133	1962	35	1962
4. Very good control (tubewell owners)	42	2242	9	2148
TOTAL:	378		132	

*From Lowdermilk, M. K., A.C. Early and D.M. Freeman. Farm Irrigation Constraints and Farmers' Responses: Comprehensive Field Survey in Pakistan. Water Management Research Project Technical Report 48. Fort Collins, Colorado State University, Sept. 1978.

Table 2-29

8

Table 2: Policy options for groundwater management*

Policy options	Water-logged area	Good ground-water area	Poor ground-water area	Risk of saline intrusion area
Likely impact of sustained withdrawal	++	+	-	—
Power pricing a) flat component b) pro rata component	 nil nil	 high low	 high low	 high high
Power supply regulations	very liberal	liberal	limited	very stringent
Siting regulations	very liberal	liberal	stringent	very stringent
Capital cost subsidy (+)/ tax (-) on wems	++	+ to resource poor	-	—
Surface water irrigation	Strongly discourage	discourage	strongly support	strongly support

* Table presented by Shah at Common Property Resource Workshop on Groundwater, WRDTC, University of Roorkee, February 1987.

Source: Shah 1990

Table 2-30

Table 16-1. Key features and cost estimates for several irrigation systems.

Category	Relative required water	Required labor	Initial cost	Pumping cost	Soil adapta-bility†	Terrain adapta-bility‡	Special features§	Field adapta-bility¶	Chemigation applica-ble#
		h/ha	$/ha	$/(ha yr)		%			
				Surface					
Wild flooding	1.4	30	700	35	L,C	<10	–	NL	N
Border dike	1.2	12	1150††	25	L,C	<2	SFC	NL	N
Graded furrow	1.2	35	1000	25	L,C	<3	SFC	NL	N
Corrugation	1.2		900	25	L,C	<3	SFC*	NL	N
Level basin	1.0	3	1400	15	L,C	<1	SFC*	NL	Y
				Sprinkler					
Movable set									
Hand lines	1.0	30	1000	50	All	15	--	R	N
Wheel lines	1.0	15	1200	50	Ali	10	--	R	N
Tow lines	1.0	15	1200	50	All	10	--	R	N
Stationary set									
PVC solid set	1.0	5	2650	50	All	NL	FC,C	NL	Y
Aluminum solid set	1.0	7	2550	50	All	NL	FC,C	NL	Y
Mobile									
Center pivot	1.0	3	1050	45	S,L	15	--	C‡‡	Y
Lateral	1.0	3	1150	45	S,L	15	--	R	Y
Labor assisted									
Wheel lines	1.0	15	1200	50	All	10	--	R	N
Tow lines	1.0	15	1200	50	All	10	--	R	N
Traveler	1.1	20	1000	60	S,L	10	--	N	N
				Micro					
Drip/trickle	0.9	10	1850	35	All	NL	--	NL	Y
Subsurface	0.8	10	1950	35	All	NL	–	NL	Y
Bubbler/spray	1.0	7	2300	40	All	30	SFC	NL	Y

† S: Sand, L: Loam, C: Clay.
‡ Maximum % slope (NL: No limit).
§ FC: Frost control, C: Cooling, SFC: Some frost protection is possible.
¶ C: Limited to circular shapes, R: Limited to rectangular shapes, NL: No limit.
# Y: Yes, N: No or limited adaptability to chemigation.
†† Includes $700/ha for moving 1500 m^3/ha soil.
‡‡ Some center pivots are available with adaptations to accommodate noncircular field shapes.

Source: in Stewart ed. 1990

Table 2-31

Table 2. Factors affecting the selection of different types of modern irrigation systems for use in developing countries (Facteurs affectant la sélection des divers systèmes modernes d'irrigation destinés aux pays en voie de développement)

Method and Type	Divis-ibility	Maintain by	Risk	Mgt and O&M Skill	Mgt and O&M Effort	Rugged-ness
Surface						
Canal-Feed						
Basin	Total*	Grower	Low	Master	5	Lasting
Border	Total*	Farmer	Low	Master	6	Lasting
Furrow	Total*	Farmer	Low	Medium	10	Lasting
Pump/Pipe-Feed						
Basin (level)	Partial*	Shop	Med	Master	3	Robust
Border	Partial	Shop	Med	Master	3	Robust
Furrow	Partial*	Shop	Med	Master	6	Robust
Sprinkle						
Lateral						
Hand-Move	Total	Shop	Med	Simple	9	Durable
End-Tow	Partial	Shop	Med	Medium	5	Durable
Side-Roll	Partial	Shop	High	Medium	6	Durable
Side-Move	No	Agency	High	Master	5	Fragile
Hose-Fed	Total*	Farmer	Med	Simple	10	Durable
Traveling Gun	Partial	Agency	High	Master	4	Sturdy
Center-Pivot	No	Agency	High	Complex	1	Sturdy
Linear-Moving	No	Agency	High	Complex	2	Sturdy
Solid-Set						
Portable	Total*	Shop	Med	Medium	5	Durable
Permanent	Total*	Farmer	Med	Medium	1	Durable
Localized						
Orchard						
Drip/Spray	Total*	Grower	High	Complex	2	Fragile
Bubbler	Total*	Grower	Low	Complex	4	Robust
Hose-Pull	Total*	Farmer	Med	Simple	9	Durable
Hose-Basin	Total*	Farmer	Low	Simple	10	Robust
Row-crop						
Reusable	Total*	Grower	High	Complex	5	Fragile
Disposable	Total*	Grower	High	Complex	3	Fragile

* well adapted for irregular shaped fields

Source: Keller in IICID 1991

Table 2-32

Table 1 . Irrigation scheduling techniques and their effectiveness for coping with droughts and water stress

Irrigation scheduling techniques	Equipment/procedure	Measured properties	Effectiveness	References
Soil water indicators				
Appearance and feel	Hand probe	Appearance and touch	Poor	Stegman et al, 1981.
Electrical resistance	Porous blocks	Electrical conductance	Limited	Stegman et al, 1981.
	Electrode probes	Electrical conductivity	High	Rhoades et al, 1981.
Soil matric potential	Tensiometers	Soil water pression	High	Peyremorte, 1985.
	Potential sensors	Idem, by temperature transducer	Promising	Phene et al, 1981
	Thermocouple psychrometers	Wet bulb or dew-point temperature	Variable	Savage & Cass, 1984.
Soil moisture	Soil sampler	Gravimetric measurement	Limited	
	Neutron probe	Reflection of neutrons	High	Hodnett, 1986.
	Time-domain reflectometry	Dielectric constant	Promising	Topp & Davis, 1985.
Water content and potential	Neutron probe/ tensiometers	Water motion parameters	High	Fernando et al, 1988.
Remote sensed soil moisture	Thermal infrared scanner	Soil surface temperature and emissivity	Limited	Jackson et al, 1981; Lo, 1986.
	Passive microwave sensors	Brightness temperature and emissivity	Limited	Newton et al, 1983.
Crop indicators				
Appearance and feel	Observation	Leaf rolling, orientation, colour	Variable	Stegman et al, 1981.
Water content	Sampling	Gravimetric measurement	Limited	Reginato & Howe, 1985.
Water potential	Pressure chamber	Tissues water pression	High	Kramer, 1983.
	Thermocouple psychrometer	Wet bulb or dew-point temperature	Promising	Savage & Cass, 1984.
Stomatal resistance	Porometer	Resistance to vapour diffusion	Limited	Kramer, 1983.
Canopy temperature	Infrared thermometer	Surface-air temperature difference	High	Jackson, 1982; Everest, 1986.
Changes in diameter of stems or other organs	Micrometric sensor	Changes in tissue water content	Limited	Huguet, 1985; Gensler, 1986.
Combinatory indicators	Combinatory procedures	Water content and temperature	High	Reginato & Howe, 1985.
		Water potential and temperature	High	Ziska et al, 1985.
		Leaf and stem responses	Promising	Schoch et al, 1987.
Vapour flux, evapotranspiration (ET)				
Evaporation	Evaporation pans	Daily rate of evaporation	High	Cardon, 1985.
	Evaporimeters	Idem	Limited	
ET estimation	Meteorologic instruments and crop coefficients	Estimated crop vapour losses from atmospheric demand	High	Doorenbos & Pruitt, 1977; Wright, 1982; 1985; Burman et al, 1983; Snyder et al, 1985.
ET measurements	Lysimeters	Rate of crop evapotranspiration	Important	Pruitt et al, 1985.
	Energy balance	Latent heat flux	Important	Rosenberg et al, 1983; Itier et al, 1985.
	Eddy correlation	Vapour flux above canopy	Important	Rosenberg et al, 1983.
Remote sensed local and regional ET	Thermal infrared and multi-spectral scanners	Surface and air temperature differences, rate of crop ET	Promising	Jackson, 1985; Nieuwenhuis, 1986; Jackson et al, 1987.
Soil - plant - atmosphere water fluxes				
Crop water stress index	Canopy temperature, vapour deficit, net radiation	Canopy responses and atmospheric demand	High	Jackson, 1982.
Plant responses and vapour fluxes	Energy balance, leaf and canopy measures	Combined explanation of vapour fluxes and crop responses	Important	Katerjiet al, 1987.
Remote sensed crop water stress	Reflective wavelengths and thermal infrared wavelengths	Canopy reflectance and surface temperature	Promising	Hatfield, 1983; Wiegand et al, 1983; Lo,1986.

Source: Pereira 1989

Table 2-33

Table 2 . Irrigation management for coping with droughts and water stress

Support for irrigation scheduling decisions	Managerial information or target	References
Appearance and feel; delaying first irrigation, increasing irrigation intervals, but avoiding stress at critical growth stages	Crop sensitivity	Stegman et al, 1981.
Observation of soil water status: irrigations according allowed soil water depletion, depending on the growth stages	Soil-crop stress parameters	Stegman et al, 1981; Peyremorte, 1985.
Observation of plant stress indicators: irrigations according the allowable stress at the different growth stages	Crop stress parameters	Hiler & Howell, 1983; Stegman, 1983.
Meteorological information and simulation of water balance with allowable stress	Crop coefficients	Doorenbos & Pruitt, 1977; Wright, 1982; 1985 Smith, 1988.
Meteorological information, water balance and relative yield simulation model	Yield response factor	Doorenbos & Kassam, 1979; Stegman, 1983; Hulsman, 1986; Teixeira & Pereira, 1988.
Monitoring of soil moisture and soil water balance model for targeted depletion levels	Acceptable yield reduction	Stegman, 1983; Jones & Bauder, 1987.
Monitoring of soil moisture and water potential, simulation of soil water balance (including water table contributions)	Acceptable yield reduction	Cambell & Campbell, 1982; Feyen, 1987.
Combined meteorological and soil water information, simulation of the soil water balance, crop growth (LAI, dry matter accumulation) and havestable yield	Targeted yield (economic decision)	Stockle & Campbell, 1985; Raju et al, 1982; Feyen, 1987; De Jong & Zeutner, 1985.
Combined meteorological, soil water and crop indicators parameters for soil water and crop modelling	Targeted yield	Feddes, 1987; Hansen, 1987.
Combining evapotranspiration, soil water, crop growth, yield modelling with economical optimization	Irrigation costs and benefits	English & Nuss, 1982; Raju et al, 1983.

Source: Pereira 1989

Table 2-34

Table 4 . Management of irrigation systems for coping with droughts and water stress conditions

Management techniques	Benefits	Effectiveness	References
Supply systems			
New sources of surface water; water transfers	Increase local water availability	High	Cunha et al, 1983a.
Increased groundwater utilization	Idem	High	Cunha et al, 1983a.
Subsurface groundwater dams	Avoidance of subsurface losses	High	Uwatoko at Tomita, 1987.
Use/reuse of low quality water	Alternative sources of water	High	See Table 9.
Conjunctive use	Maximized use of available water resources	High	Rossi et al, 1983; Morel-Seytoux, 1987.
Improved operation/management :			
. hydrological forecasting	Improved assessment of supplies	High	Yevjevich, 1983.
. application of optimization/risk/decision analysis to water systems	Optimized rules; hierarchical allocation of water resources	Promising	Duckstein, 1980; 1983a; Salas et al, 1983.
. application of optimization/decision theories to reservoirs	Idem	Promising	Duckstein, 1983b; Harboe, 1983.
. automation of reservoir releases	Real time response to downstream demand	High	Tardieu, 1988.
Control of evaporation in surface reservoirs	Water savings	Limited	Reviewed by Cooley, 1983.
Precipitation augmentation	Increased regional water availability	Controversial	Summers et al, 1983.
Regional water data-banks	Information for optimized operation and management	Promising	Francalanza et al, 1988.
Conveyance and distribution systems			
Canal lining	Avoidance of seepage losses	High	
Increased flexibility on the operation of conveyance and distribution systems	Improved responses to farm demands, decrease on operational water losses	High	Burt & Lord, 1981; Replogle & Merriam, 1981; Rijo & Pereira, 1987.
Intermediate storage (in canal, reservoirs, farm ponds)	Increase flexibility of the system, with lower water losses	Important	Replogle et al, 1981.

Management techniques	Benefits	Effectiveness	References
Avoid night irrigation : intermediate storage or improvement of conditions of night irrigation including on-farm automation	Avoidance of low efficient irrigation and improvement of social conditions	Important	Chambers, 1986.
Adapt irrigation delivery to irrigation scheduling	Improved responses to farm demands, increased overall irrigation efficiency	High	Brower & Buchheim, 1984; Clemens, 1986; El-Kady & Molden, 1987.
Application of optimization methods to schedule deliveries	Increased efficiencies, reliability and equity in responses to farm demands	Promising	Yoo, 1985; Suryaranshi & Reddy, 1986.
Develop intelligent control :			
. automation, surface systems	Adjusted response to downstream demand	Variable	Replogle & Clemens, 1987.
. remote control, surface and pressurized systems	Higher irrigation efficiencies; higher flexibility, deliveries matching demands	High	Jean, 1981; Verdier, 1986; Bolognino, & Giorgi, 1988; De Vito & De Vito, 1988; Di Nardo, 1988.
Hydraulic modelling :			
. open channels	Basic tool for improved control	Important	Hamilton & DeVries, 1986; Corriga et al, 1988; Rijo et al,1988.
. transients in pressure pipes	Idem	Important	Messina & Poggi, 1988
Operation and maintenance (O&M):			
. monitoring and evaluation, use of indicators	Improved O&M systems, identification of critical areas and solutions	Important	Reviewed by Pereira & Lamaddalena, 1988.
. vegetation and sediments control	Avoidance of delivery interruptions and water losses	High	
. water measurement	Improved O&M, water savings	High	Peri & Karmeli, 1977; Bos et al, 1984.

Source: Pereira 1989

Table 2-38

Crops	Steady state formulas		Transient flow methods	
Primary crops	Fine textured permeable soil	Light texture soil	Fine textured permeable soil	Light texture soil
Field crops	1.2	1.0	0.9	0.9
Vegetable	1.1	1.0	0.9	0.9
Tree crops	1.6	1.2	1.4	1.1

Table 1 - Suggested irrigation season watertable depths for drain spacing design (Watertable depth below ground surface in meters)

Source: in Lesaffre 1990

Table 2-50

Table 3.22 Suggested treatment processes to meet the given health criteria for wastewater reuse[a]

Wastewater use	Irrigation			Recreation		Industrial reuse	Municipal reuse	
Health criteria[b]	Crops not for direct human consumption (A + F)	Crops eaten cooked: fish culture (B + F or D + F)	Crops eaten raw (D + F)	No contact (B)	Contact (D + G)	(C or D)	Non-potable (C)	Potable (E)
Primary treatment	3	3	3	3	3	3	3	3
Secondary treatment		3	3	3	3	3	3	3
Sand filtration or equivalent polishing methods		1	1		3	1	3	2
Nitrification						1		3
Denitrification								2
Chemical clarification						1		2
Carbon adsorption								2
Ion exchange or other means of removing ions						1		2
Disinfection[c]		1	3	1	3	1	3	3[c]

[a]After WHO (1973).
[b]Health criteria: A, freedom from gross solids, plus significant removal of parasite eggs; B as A, plus significant removal of bacteria; C as A, plus more effective removal of bacteria, plus some removal of viruses; D, not more than 100 coliform organisms per 100 ml in 80% of samples; E, no fecal coliform ortanisms in 100 ml, plus no virus particles in 1000 ml, plus no toxic effects on man, and other drinking-water criteria; F, no chemicals that lead to undesirable residues in crops or fish; G, no chemicals that lead to irritation of mucous membranes and skin. In order to meet the given health criteria, processes marked 3 will be essential. In addition, one or more processes marked 2 will also be essential, and further processes marked 1 may sometimes be required.
[c]Free chlorine after 1 h.

Source: Feigin et al. 1991

Table 2-51

TABLE 2.4. Advantages and disadvantages of various sewage treatment systems

	Criteria	*Package plant*	*Activated sludge plant*	*Extended aeration activated sludge*	*Trickling filter*	*Oxidation ditch*	*Aerated lagoon*	*Waste stabilization pond system*
Plant performance	BOD removal	F	F	F	F	G	G	G
	FC removal	P	P	F	P	F	G	G
	SS removal	F	G	G	G	G	F	F
	Helminth removal	P	F	P	P	F	F	G
	Virus removal	P	F	F	P	F	G	G
Economic factors	Simple and cheap construction	P	P	P	P	F	F	G
	Simple operation	P	P	P	F	F	P	G
	Land requirement	G	G	G	G	G	F	P
	Maintenance costs	P	P	P	F	P	P	G
	Energy demand	P	P	P	F	P	P	G
	Sludge removal costs	P	F	F	F	P	F	G

FC = Faecal coliforms
SS = Suspended solids
G = Good
F = Fair
P = Poor
Source: Arthur (1983).

Source: in Biswas/Arar ed. 1988

Table 2-52

Table 3.2 Suggested treatment processes to meet the given health criteria for wastewater reuse in agriculture

Unit treatment process	*Type of agricultural reuse*		
	Crops not for direct human consumption	*Crops eaten cooked*	*Crops eaten raw*
Primary treatment	+++	+++	+++
Secondary treatment		+++	+++
Sand filtration		+	+
Disinfection		+	+++
Health criteria	A + F	D + F	

Key: +++ = Essential
+ = May sometimes be required
A = Freedom from gross solids; significant removal of parasite eggs
D = Not more than 100 coliforms per 100 ml in 80% of samples
F = No chemicals that lead to undesirable residues in crops

Source: WHO (1973)

Source: in Pescod/Arar ed. 1988

Tavle 2-53a

Table 7.1 Expected removal of excreted bacteria and helminths in various wastewater treatment processes

Treatment process	Removal (log_{10} units)			
	Bacteria	Helminths	Viruses	Cysts
Primary sedimentation				
Plain	0–1	0–2	0–1	0–1
Chemically assisted[a]	1–2	1–3 (E)	0–1	0–1
Activated sludge[a]	0–2	0–2	0–1	0–1
Biofiltration[b]	0–2	0–2	0–1	0–1
Aerated lagoon[c]	1–2	1–3 (E)	1–2	0–1
Oxidation ditch[b]	1–2	0–2	1–2	0–1
Disinfection[d]	2–6 (E)	0–1	0–4	0–3
Waste stabilization ponds[e]	1–6 (E)	1–3 (E)	1–4	1–4
Effluent storage reservoirs[f]	1–6 (E)	1–3 (E)	1–4	1–4

E—With good design and proper operation the Engelberg guidelines are achievable.
[a] Further research is needed to confirm performance
[b] Including secondary sedimentation
[c] Including settling pond
[d] Chlorination, ozonation
[e] Performance depends on number of ponds in series
[f] Performance depends on retention time, which varies with demand

Source: Feachem et al. (1983).

Source: Mara/Cairncross 1989

Table 2-53b

TABLE 2.3. Microorganism removal in wastewater treatment

Type of microorganism	*Percentage removal*	
	Primary	*Biological**
Salmonella	15	96–99.9
Mycobacterium	48–57	Slight–99.9
Amoebic cyst	Limited removal	0–99.9
Helminth ova	72–98	0–76
Viruses	3–extensive	0–84

* Biological includes trickling filter, activated sludge and waste stabilization ponds.
Source: Feachem *et al.* (1983).

Source: in Biswas/Arar ed. 1988

Table 2-53c

TABLE 2-10

Enteric pathogen removal efficiencies of wastewater treatment processes (in log_{10} units)
(i.e., $4 = 10^{-4} = 99.99$ percent removal)

Treatment process	Viruses	Bacteria	Protozoa	Helminths
Primary sedimentation	0-1	0-1	0-1	0-1
Septic tanks	0-1	1-2	1-2	1-2
Trickling filters	0-1	0-2	0-1	0-1
Activated sludge	1-2	2-3	1-2	1-2
Stabilization ponds (20 day--4 cells)	2-4	4-6	4-6	4-6

Source: This table was developed for this study and is based on a review of numerous published laboratory and field studies.

Source: Shuval et al. 1986

Table 2-54 a

TABLE 5-7

Expected values of properly designed stabilization ponds in Southern Africa

Parameter (mg/l except where otherwise stated)		Effluent Composition	
		Stabilization ponds: for raw and settled wastewater, septic tank, and aqua privy effluent	Maturation ponds: for well-nitrified secondary effluent
Color, taste, and odor		Not objectionable	Not objectionable
pH	(range)	7.0-10.5	7.0-10.5
Temperature, °C	maximum	30	30
Dissolved oxygen, % sat.	minimum	75	75
Fecal coliform bacteria	maximum	100/100 ml (97.5% probability)	1,000/100 ml (97.5% probability)
BOD_5 (total)	maximum	16	12
BOD_5 (filtrate)	maximum	12	8
COD (total)	maximum	150	120
COD (soluble)	maximum	120	100
OA*/ (total)	maximum	20	15
OA*/ (soluble)	maximum	15	10
Ammonia nitrogen	maximum	10	10

Note: Aimed at small communities of up to 5,000 people, 800 m^3/day flow. Detention times 18-25 days, depending on temperature and plant configuration.

*/ Oxygen adsorbed from N/80 $KMNO_4$ in 4 hours.

Source: Drews (1983).

Source: Shuval et al. 1986

Table 2-54b

Table 7.2 Performance of a series of five waste stabilization ponds in north-east Brazil (mean pond temperature: 26 °C)

Sample	Retention time (days)	BOD_5 (mg/l)	Suspended solids (mg/l)	Faecal coliforms	Intestinal nematode eggs (per litre)
Raw wastewater	–	240	305	4.6×10^7	804
Effluent from:					
Anaerobic pond	6.8	63	56	2.9×10^6	29
Facultative pond	5.5	45	74	3.2×10^5	1
Maturation pond 1	5.5	25	61	2.4×10^4	0
Maturation pond 2	5.5	19	43	450	0
Maturation pond 3	5.8	17	45	30	0

Source: Mara et al. (1983), Mara & Silva (1986).

Source: Mara/Cairncross 1989

Table 2-54 c

Table 7.3 Reported effluent quality for several series of waste stabilization ponds, each with a retention time > 25 days

Pond system	No. of ponds in series	Effluent quality (FC/100 ml)[a]
Australia, Melbourne	8–11	100
Brazil, Campina Grande[b]	5	30
France, Porquerolles	3	100
Jordan, Amman	9	30
Peru, Lima	5	100
Tunisia, Tunis	4	200

[a] FC = Faecal coliforms
[b] Experimental Centre for Biological Treatment of Westewater (Extrabes).

Source: Bartone & Arlosoroff (1987).

Source: Mara/Cairncross 1989

Table 2-55

Table 3.15 Relative sensitivity of crops to sludge-applied heavy metals[a] (Logan and Chaney 1983)

Very sensitive[b]	Sensitive[c]	Tolerant[d]	Very tolerant[e]
Chard	Mustard	Cauliflower	Corn
Lettuce	Kale	Cucumber	Sudan grass
Red beet	Spinach	Zucchini squash	Smooth bromegrass
Carrot	Broccoli		'Merlin' red fescue
Turnip	Radish	Flat pea	
Peanut	Tomato		
	Marigold	Oat	
Ladino clover		Orchard grass	
Alsike clover	Zigzag, red, Kura and crimson clover	Japanese bromegrass	
Crown vetch	Alfalfa	Switchgrass	
'Arc' alfalfa	Korean lespedeza	Red top	
White sweet clover	Sericea lespedeza	Buffel grass	
Yellow sweet clover	Blue lupin	Tall fescue	
	Birdsfoot trefoil	Red fescue	
Weeping love grass	Hairy vetch	Kentucky bluegrass	
Lehman love grass	Soybean		
Deer tongue	Snapbean		
	Timothy		
	Colonial bent grass		
	Perennial ryegrass		
	Creeping bent grass		

[a]Sassafras sandy loam amended with a highly stabilized and leached digested sludge containing 5300 mg Zn; 2400 mg Cu; 320 mg Ni; 390 mg Mn; and 23 mg Cd/kg dry sludge. At 5% sludge, maximum cumulative recommended applications of Zn and Cu are made.
[b]Injured at 10% of a high metal sludge at pH 6.5 and at pH 5.5.
[c]Injured at 10% of a high metal sludge at pH 5.5, but not at pH 6.5.
[d]Injured at 25% high metal sludge at pH 5.5, but not at pH 6.5, and not at 10% sludge at pH 5.5 or 6.5.
[e]Not injured even at 25% sludge, pH 5.5.

Source: Feigin et al. 1991

Table 2-56

Category A — Protection needed only for field workers

1. Crops not for human consumption (for example cotton, sisal)
2. Crops normally processed by heat or drying before human consumption (grains, oilseeds, sugar-beet)
3. Vegetables and fruit grown exclusively for canning or other processing that effectively destroys pathogens
4. Fodder crops sun-dried and harvested before consumption by animals
5. Landscape irrigation in fenced areas without public access (nurseries, forests, green belts).

Category B — Further measures may be needed

1. Pasture, green fodder crops
2. Crops for human consumption that do not come into direct contact with wastewater, on condition that none must be picked off the ground and that spray irrigation must not be used (tree crops, vineyards, etc.)
3. Crops for human consumption normally eaten only after cooking (potatoes, eggplant, beetroot).
4. Crops for human consumption, the peel of which is not eaten (melons, citrus fruits, bananas, nuts, groundnuts)
5. Any crop if sprinkler irrigation is used (see Section 7.4.1).

Category C — Treatment to Engelberg "unrestricted" guidelines is essential

1. Any crops often eaten uncooked and grown in close contact with wastewater effluent (fresh vegetables such as lettuce or carrots, or spray-irrigated fruit)
2. Landscape irrigation with public access (parks, lawns, golf courses)

Source: Mara/Cairncross 1989

Table 2-57

Table 3.21 Wastewater treatment and quality criteria for irrigation (California) (Crook 1985)

Treatment level	Coliform limits	Type of use
Primary		Surface irrigation of orchards and vineyards, fodder, fiber and seed crops
Oxidation and disinfection	≤ 23/100 ml	Pasture for milking animals Landscape impoundments Landscape irrigation (golf courses, cemeteries, etc.)
	≤ 2.2/100 ml	Surface irrigation of food crops (no contact between water and edible portion of crop)
Oxidation, coagulation, clarification, filtration[a], and disinfection	≤ 2.2/100 ml max. = 23/100 ml	Spray irrigation of food crops
		Landscape irrigation (parks, playgrounds, etc.)

[a]The turbidity of filtered effluent cannot exceed an average of 2 turbidity units during any 24-h period.

Source: Feigin et al. 1991

Table 2-58

Table 3.24 Recommended microbiological quality guidelines for wastewater use in agriculture[a] (WHO Scientific Group 1989)

Category	Reuse conditions	Exposed group	Intestinal nematodes[b] (arithmatic mean No. of eggs/l[c])	Faecal coliforms (geometric mean No. per 100 ml[c])	Wastewater treatment expected to achieve the required microbiological quality
A	Irrigation of crops likely to be eaten uncooked, sports fields, public parks[d]	Workers, consumers, public	≤ 1	≤ 1000[d]	A series of stabilization ponds designed to achieve the microbiological quality indicated or, equivalent treatment
B	Irrigation of cereal crops, industrial crops, fodder crops, pasture and trees[e]	Workers	≤ 1	No standard recommended	Retention in stabilization ponds for 8–10 days or equivalent helminth and faecal coliform removal
C	Localized irrigation of crops in category B if exposure of workers and the public does not occur	None	Not applicable	Not applicable	Pretreatment as required by the irrigation technology, but not less than primary sedimentation

[a]In specific cases, local epidemiological, sociocultural and environmental factors should be taken into account, and the guidelines modified accordingly.
[b]*Ascaris* and *Trichuris* species and hookworms.
[c]During the irrigation period.
[d]A more stringent guideline (≤ 200 faecal coliforms per 100 ml) is appropriate for public lawns, such as hotel lawns, with which the public may come into direct contact.
[e]In the case of fruit trees, irrigation should cease 2 weeks before fruit is picked, and no fruit should be picked off the ground. Sprinkler irrigation should not be used.

Source: Feigin et al. 1991

Table 2-59

Table 7.4 Factors affecting choice of irrigation method, and special measures required when wastewater is used

Irrigation method	Factors affecting choice	Special measures for wastewater
Border (flooding) irrigation	Lowest cost, exact levelling not required	Thorough protection for field workers, crop-handlers and consumers
Furrow irrigation	Low cost, levelling may be needed	Protection for field workers, possibly for crop-handlers and consumers
Sprinkler irrigation	Medium water use efficiency, levelling not required	Some Category B crops, especially tree fruit, should not be grown. Minimum distance 50–100 m from houses and roads. Anaerobic wastes should not be used because of odour nuisance
Subsurface and localized irrigation	High cost, high water use efficiency, higher yields	Filtration to prevent clogging of emitters.

Source: Mara/Cairncross 1989

Table 2-60

TABLE 1.3. Framework for use of wastewater for irrigation and/or groundwater recharge

(1) **Nature of the problem**
a) How much wastewater will be produced and what will be the seasonal distribution?
b) At what places will wastewater be produced?
c) What will be the characteristics of wastewater that will be produced?
d) What are feasible alternative disposal possibilities?

(2) **Legal feasibility**
a) What uses of wastewater are possible under national and/or state regulations, if they exist?
b) If no regulations exist, what uses seem feasible under WHO and FAO guidelines for irrigation?
c) What are the prevailing water rights and how will these be affected by wastewater use?

(3) **Technical feasibility**
a) Is the quality of treated wastewater produced acceptable for restricted or unrestricted irrigation?
b) How much land is available or required for wastewater irrigation?
c) What are the soil characteristics of land to be irrigated?
d) What are the present land use practices? Can these be changed?
e) What types of crops can be grown?
f) How do crop-water requirements match with seasonal availability of wastewater?
g) What types of irrigation techniques can be used?
h) If groundwater recharge is a consideration, are the hydrogeological characteristics of the study area suitable?
i) What will be the impact of such recharge on groundwater quality?
j) Are there additional health and environmental hazards that should be considered?

(4) **Political and social feasibility**
a) What have been the political reactions to past health and environmental hazards which may have been associated with wastewater reuse?
b) What is the public perception of wastewater reuse?
c) What are the attitudes of influential people in areas where wastewater will be reused?
d) What are the potential benefits of reuse to the community?
e) What are the potential risks?

(5) **Economic feasibility**
a) What are the capital costs?
b) What are the operation and maintenance costs?
c) What is the economic rate of return?
d) What are the costs of development effluent-irrigated agriculture, e.g. cost of conveyance of wastewater to the irrigation site, land-levelling, installation of irrigation system, agricultural inputs, etc.?
e) What are the benefits from the effluent-irrigated agriculture system?
f) What is the benefit-cost ratio for the irrigation project?

(6) **Manpower feasibility**
a) Is adequate local manpower available for adequate operation and maintenance of:
wastewater treatment
irrigation and groundwater recharge works
agricultural facilities
health and environmental control aspects?
b) If not, what types of training programmes should be instituted?

Source: in Biswas/Arar ed. 1988

Table 2-61

TABLE 1.4. Comparison of factors relating to water and land for irrigation and groundwater recharge

Factors	*Irrigation*	*Groundwater recharge*	*Overland flow*
Treatment	Primary to secondary	Untreated to primary	Untreated to primary
Consistently good operation of treatment plants	Critical	Not critical	Not critical
Water quality	High	Medium to low	Medium to low
Land area required	High	Low	Medium
Land slope	Up to 6% for surface irrigation; up to 30% for sprinkler and drip irrigation	Not important, but difficult on steep slopes	1–12%
Soil permeability	Moderate	Rapid to very rapid	Low
Soil quality	Medium to good	Not important	Not important
Utilization of water and nutrients	High	None	Medium to low
Monitoring requirements	Extensive	Limited	Limited

Source: in Biswas/Arar ed. 1988

Table 2-62

Box 7.1 Wastewater treatment costs

A recent World Bank report gives a detailed economic comparison of waste stabilization ponds, aerated lagoons, oxidation ditches and biological filters. The data for this cost comparison were taken from the city of San'a in the Yemen Arab Republic. Certain assumptions were made, for example the use of maturation ponds to follow the aerated lagoon, and the chlorination of the oxidation ditch and biological filter effluents, in order that the four processes would have a similar bacteriological quality so that fish farming and effluent reuse for irrigation were feasible. The design is based on a population of 250 000; a per capita flow and BOD_5 (biochemical oxygen demand measured on day 5 of treatment) contribution of 120 litres/day and 40 g/day respectively; influent and required effluent faecal coliform concentrations of 2×10^7 and 1×10^4 per 100 ml, respectively; and a required effluent BOD_5 of 25 mg/litre. The calculated land area requirements and total net present worth of each system (assuming an opportunity cost of capital of 12% and land values of US$ 5/m²) are shown in the table below. The waste stabilization pond is the cheapest option. Clearly the preferred solution is very sensitive to the price of land, and the above cost of US$ 5 per m² represents a reasonable value for low-cost housing estates in developing countries.

The cost of chlorination accounts for US$ 0.22 million per year of the operational costs of the last two options.

	Waste stabilization pond system	Aerated lagoon system	Oxidation ditch system	Conventional treatment (biofilters)
Costs (million US$)				
Capital	5.68	6.98	4.80	7.77
Operational	0.21	1.28	1.49	0.86
Benefits (million US$)				
Irrigation income	0.43	0.43	0.43	0.43
Pisciculture income	0.30	0.30	–	–
Net present worth (million US$)	5.16	7.53	5.86	8.20
Land area (ha)	46	50	20	25

Source: Arthur (1983).

Source: Mara/Caircross 1989

Table 2-63

There are four types of water to be analysed:

- drinking water (A_2);
- raw wastewater influent to the wastewater treatment plant (A_0);
- effluent from the primary settling tank (A_1);
- effluent from the final settling tank (A_3).

Table 26.7 Parameters analysed in A_2

Organoleptic	Aspect Colour Odour	
Physical	pH pH 25°C Conductivity Turbidity	
Chemical	Alkalinity Alkalinity to $CaCO_3$ saturation equilibrium Total hardness Carbonate hardness Non-carbonate hardness Oxidizability	
	Anions	*Cations*
	HCO_3^-	Ca^{2+}
	$SO_4^=$	Mg^{2+}
	Cl^-	Na^+
		K^+

Table 26.8 Parameters analysed in A_1 and A_3

Parameters analysed — *Routine* — *During irrigation*		*After irrigation*		*Occasional*	
BOD_5				As	(1)
COD				Hg	(1)
SS				Se	(1)
DS	(3)			CN	(1)
T					
N: NO_3	(2)				
N: NH_4	(2)				
N: org.	(2)				
pH	(3)	Cd	(1)		
Hardness	(3)	Cr	(1)		
Carbonates	(3)	Cu	(1)		
Bicarbonate	(3)	Fe	(1)		
Phosphorus		Ni	(1)		
Orthophosphate		Pb	(1)		
Chloride	(3)	Mn	(1)		
Sulphate	(3)	Zn	(1)		
Conductivity		Mo	(1)		
Calcium	(1)				
Magnesium	(1)				
Sodium	(1)				
Potassium	(1)				
Boron	(1)				

(1) Analyses to be carried out at the end of the irrigation period, on a sample composed of subsamples collected during each irrigation, suitably preserved with HNO_3 at pH = 2, kept in boron-silicate glass flasks with the stopper lined with teflon.
(2) The samples for determining the different nitrogen species will be kept in glass flasks with the stopper lined with teflon. These samples will be acidified to pH = 2 with sulphuric acid and kept at 4°C.
(3) Samples for the determination of the different ionic species cannot be chemically conserved; they have to be kept in plastic bottles at 4°C and analysed as soon as possible.

Table 26.9 Parameters analysed in A_0

pH
BOD_5
COD
TSS
FSS
VSS

Table 26.10 Microorganisms analysed

Analytical laboratory	*Microorganism*
Regional Health Administration	Faecal coliforms
Regional Health Administration	Faecal streptococci
Leeds University	*Campylobacter*
Leeds University	*Salmonella*
Leeds University	*Shigella*

Table 26.11 Surface soil parameters analysed

Parameters analysed before sowing and after harvesting	
Physical	Texture Structure Porosity Apparent specific density
Hydraulic	Permeability Rate of infiltration Field capacity Fading coefficient
Chemical	pH Cation exchange capacity Calcium Magnesium Potassium Sodium Carbonates Sulphates TOC Hydrogencarbonates Conductivity Chlorides N: total N: organic P: total K: assimilable Boron

Table 26.12 Parameters analysed in soil at 50 cm depth

Parameters analysed before sowing and after irrigation		
Sulphates	N: total	Copper
Carbonates	N: NO_3	Cadmium
Hydrogencarbonates	N: organic	Nickel
Chlorides	P: total	Chromium
Cation exchange capacity	P: P_2O_5	Mercury
Calcium	Conductivity	Lead
Magnesium	Boron	Cobalt
Potassium	Iron	
Sodium	Zinc	

Table 26.13 Surface soil parameters analysed

Iron	Manganese	Lead
Molybdenum	Cadmium	Cobalt
Zinc	Nickel	Mercury
Copper	Chromium	

Table 26.14 Chemical parameters determined in crop material

Part of plant for consumption	*Part of plant not to be consumed*
Boron	
N: total (N: Kjeldahl)	
Potassium	
Iron	
Nickel	
Zinc	Zinc
Chromium	
Copper	
Mercury	
Cadmium	Cadmium
Lead	
Cobalt	

Source: in Pescod/Arar ed. 1988

Table 3-1

Table 12 CHECKLIST OF INFORMATION NEEDS, METHODS and output at Steps 3 and 4

Information from first consultation with users	Planning goals and constraints Spatial, temporal, quantitative data:	
	- Social	sociology, demography, land tenure
	- Economic	demand, consumption patterns, income and investments, land use and production
	- Land	topography, climate, soils, water, ecology
	- Infra-structure	transport, communications, services, administration and legal structure
Planner's methods	Overview existing data, identify gaps: - summarise maps, reports, agency files Rapid appraisal: - remote sensing, field survey, questionnaires, local reports Modelling land use systems	
Information output for second consultation with users	Summary maps and statistical analysis of the existing situation Projections for the planning period Identification of land use problems and opportunities Specifications for improved land use systems	

Table 3-2

What will the Land Use Plan contain?

Terms of reference

- area involved, goals, time horizon

Analysis of land use opportunities and problems

Environmental/conservation standards

- for example no cultivation on slopes greater than 15°, protection of water supplies for people and stock

What to do and where to do it

- including maps of present and planned land use and infrastructure, details of land use practices needed, performance targets

Who will do it and how

- responsibilities for action, staff, timing, budget

Procedure for assessing the performance of the plan and revising it in the light of experience

Supporting information

- so that people can understand the plan and the basis for decisions. This may include information on land resources, land use options, land suitability, economic analysis, social and other considerations.

Source: FAO 1989

Table 3-3

Headings for description of land use types

1. Items common to most major kinds of land use:

Name and summary of land use type – main crops and management level, for example 'rainfed rice cultivation by smallholders, traditional management with low inputs'

Main products and markets

Associated land use types

Tenure and size of management units

Capital intensity: investment required, recurrent costs

Labour and management skills needed

Power and transport requirements

Storage and processing requirements

2. For rainfed agriculture:

Cultivation practices:

- recommended varieties
- growing period
- land preparation
- planting
- fertilizer
- weed control, pests and diseases
- harvesting
- soil and water conservation

Yield, production trends

Local farming problems

3. Additional items for irrigated agriculture:

Source of water, water rights

Water management system

4. For livestock:

Pasture management and grazing practices – fencing, rotational grazing, seasonal factors, irrigation, topdressing

Supplementing forage production and conservation practices

Water sources and distribution

Soil and water conservation practices

Livestock husbandry practices:

- stock management
- pests and diseases

Forage production and trends

Livestock kind and numbers

Production and production trends

Local problems

5. For forestry:

Cultivation practices, where applicable:

- recommended species and provenance
- nursery practices
- land preparation
- planting
- fertilizing
- weed control, pests and diseases
- harvesting
- soil and water conservation

Yield, production trends

Local management problems

6. For water supply:

Catchment management practices:

- standards for forestry, grazing and agricultural use
- soil conservation
- engineering standards – road construction, drainage, flood control
- siting of settlement
- control of pollution

7. For fisheries and fish farming:

Water supply and water rights

Water management practices:

- control of water quality
- maintenance of ponds and waterways
- flood control

Pisicultural practices:

- nursery practices
- fertilizers, feeding
- pests and diseases
- harvesting

Yields and production trends

Local management problems

8. For recreation and reserves:

Facilities and services for visitors

Land management practices to maintain unique character:

- standards for parallel land uses
- policing

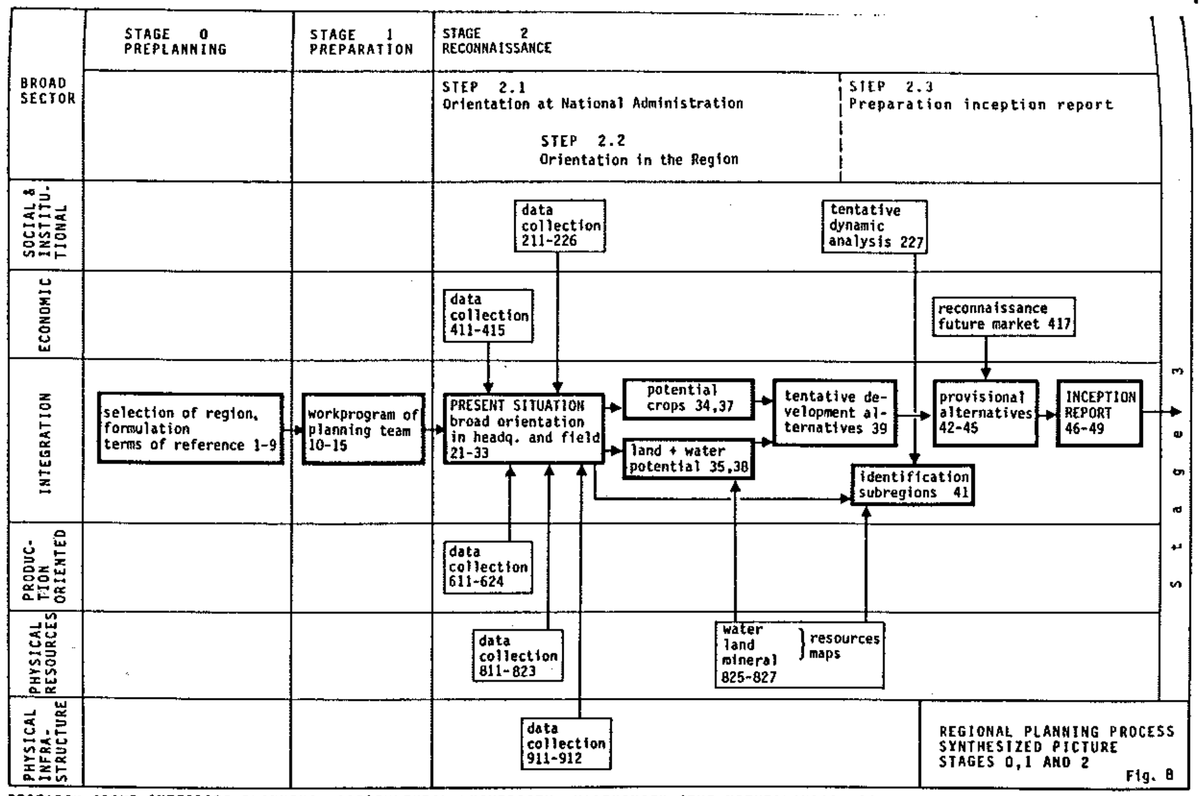
Source: FAO 1989

Table 3-4

Table I. Possible future structures

Structure	Main elements
Economic structure	The output and employment in each sector; income distribution
Socio-economic structure	Type of production units: large factories, plantations, small-scale family-owned industries or farms, production cooperatives, or a certain combination of these units. An indication of the number of people involved in the various production units and their output.
Social structure	The various groups, based either on consanguinal or territorial criteria, and their interrelations, leadership, and power structure. Rough indication of the number of persons in the various groups.
Administrative and participation structure	Structure of the governmental organizations, their interrelations, number of people involved and their output. Organization of participation, village councils, district councils; their major tasks and functions.
Structure of the health sector	Types of service units, their interrelations, people employed in the various units and their output.
Structure of the educational sector	Types of school, their interrelations, teachers employed, the school population in the various school types and their output.
Land use pattern	What areas are used for what types of agriculture, for forestry, fishing, animal husbandry, recreation, conservation, mining, industry, housing, etc. This information should be compiled in a map, scale 1:100,000 up to 250,000.
Pattern of service centres (incl.urban)	The types of service centres (central places) and their interrelations. The services provided by the centres: schools, clinics, hospitals, shops, banks, offices of the administration, extension services, markets, industrial sites, etc. Rough indication of population living in, and served by, the centres. The information should be compiled in a map, scale 1:100,000 up to 250,000.
Infrastructure	Network of roads, canals, railroads, ports, airports, power supplies, water supplies, telecommunications, etc. The information to be compiled in a map, scale 1:100,000 up to 250,000.

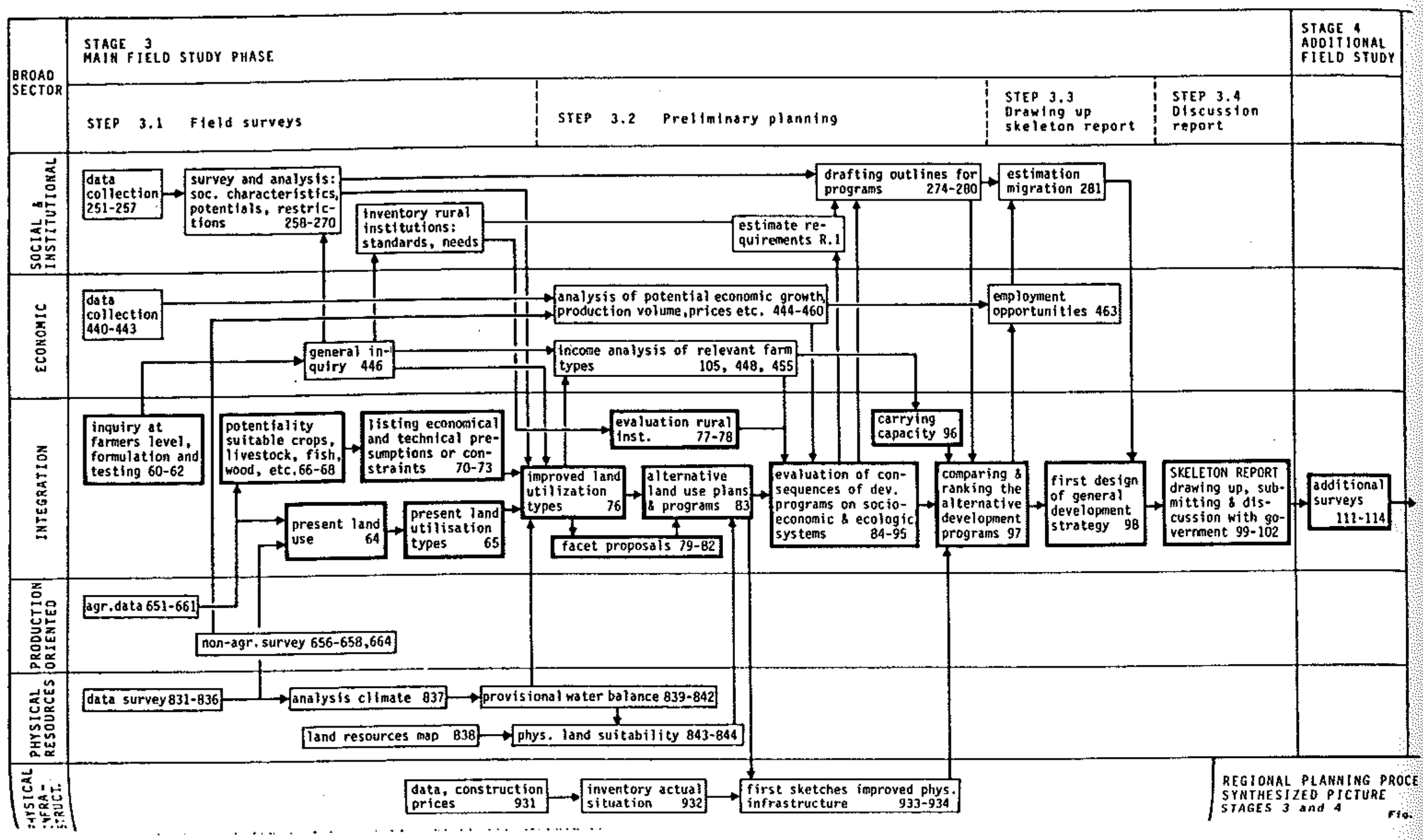
Table 3-5

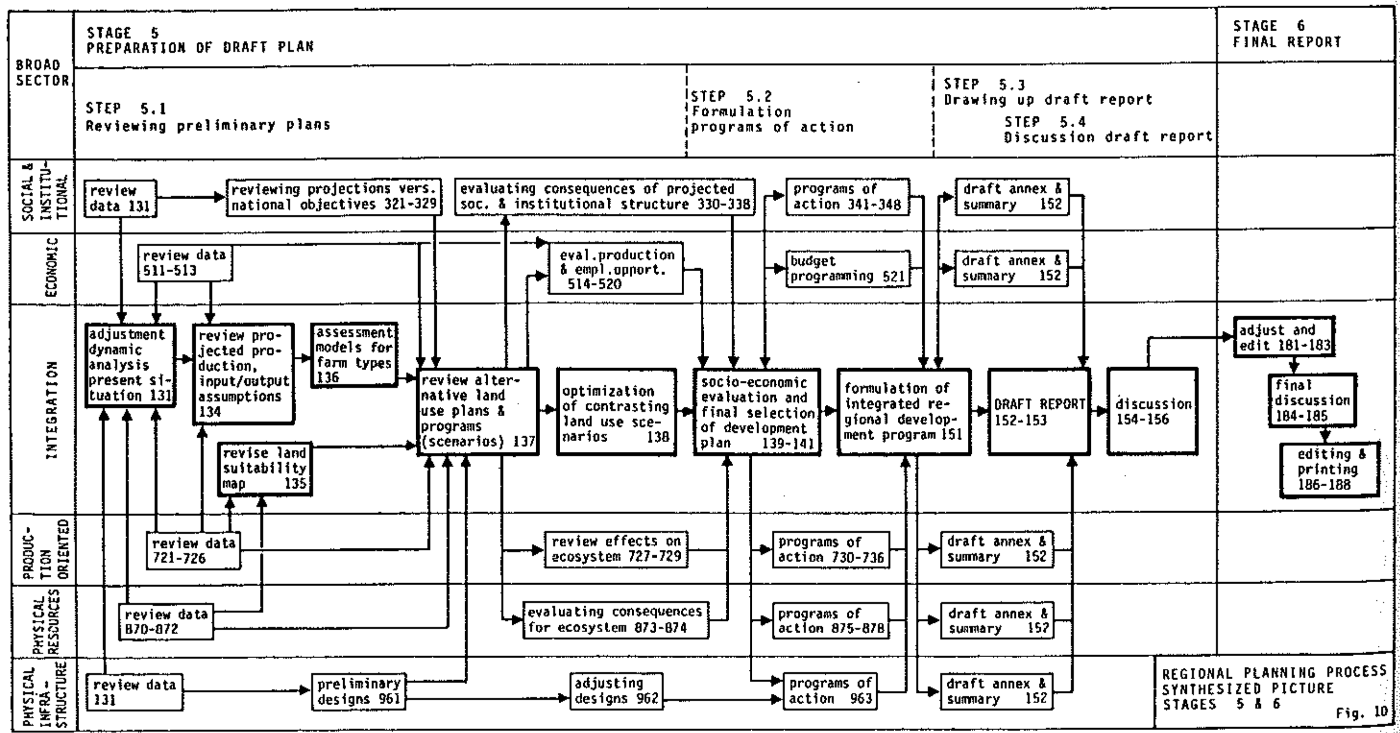


RESEARCH GROUP INTERDISC.PLANNING, AGRICULTURAL UNIVERSITY, WAGENINGEN,(THE NETHERLANDS), 1979

Source: van Staveren/Dusseldorp ed. 1993

Table 3-5 cont.





RESEARCH GROUP INTERDISC. PLANNING, AGRICULTURAL UNIVERSITY, WAGENINGEN, (THE NETHERLANDS), 1979

Source: van Staveren/Dusseldorp ed. 1993

ANNEX I. LIST OF IDENTIFIED ACTIVITIES

Table 3-6

ABBREVIATION USED

Clim	Climate
Geol	Geology
Hydr	Hydrology
Land	Land and Soils
Ecol	Ecology
Crop	Crop Production
AnPr	Animal Production
For	Forestry
Fish	Fisheries and Aquaculture
Min	Mining
Ind	Secondary & Tertiary Production Sectors (industries, etc.)
Dem	Demography
Soc	Sociology
Edu	Education
Ext	Rural Extension
Hea	Health
PubA	Public Administration
Coop	Agricultural Cooperatives
Cred	Agricultural Credit
LT	Land Tenure
MaEc	Macro Economy
AgrEc	Agricultural Economy
IndEc	Economy of non-agricultural production sectors
Infr (Civ/Infr)	Physical Infrastructure (incl. civil engineering)

NOTE. Each participant's degree of responsibility is indicated as follows:

(a) mainly responsible
(b) obligatorily assisting
(c) optionally assisting

Source: van Staveren/Dusseldorp ed. 1993

Table 3-7

Table 15 CHECKLIST OF SOIL QUALITIES, FIELD CHARACTERISTICS AND SPECIAL FIELD AND LABORATORY DETERMINATIONS

Quality	Field characteristic	Special determinations
Sufficiency of energy	-	Soil temperature regime
Sufficiency of water	Soil texture, depth, stoniness, salinity	Soil water release characteristics and infiltration capacity
	Rooting pattern	
Sufficiency of oxygen	Soil drainage class, colour	Eh, saturated hydraulic conductivity
	Depth to water table	
Sufficiency of nutrients	Soil texture, depth, stoniness, organic matter, pH	Cation exchange capacity
	Weatherable minerals,	Determination of individual nutrients, eg N, P, K, Mg
	Foliar examination	
Ease of water management	Landform, slope angle, microtopography	Infiltration rate and saturated hydraulic conductivity
	Soil texture, depth	
	Depth to groundwater	
Tilth	Soil structure, consistence	Exchangeable sodium
Strength/bearing capacity	Soil texture	Atterburg limits, shear strength
Erosion hazard/ slope stability	Landform, slope angle, slope length	Shear strength, angle of friction
	Soil texture, drainage, structure	Particle size distribution
Toxicity	Foliar examination, pH	Determination of individual ions, e.g. HBO3-, Al3+, Se
Disease	Foliar examination	Microbiological and entomological examination
	Soil drainage	

Table 13 CLIMATIC DATA FOR LAND USE PLANNING

Land qualities	Climatic characteristics
Sufficiency of energy	Temperature regime, sunshine hours, day length
Frost hazard	Probability of frost (local occurrence and not adequately recorded in standard data)
Sufficiency of water	Reference evaporation Eo
	Crop water requirement = Eo x Kc (crop coefficient)
	Rainfall probability, effective rainfall
Irrigation need/ Drought hazard	Rainfall probability - crop water requirement
Length of growing season	Period of energy and water sufficiency
Hazard of high winds, high temperature, hail; low humidity	Probability of occurrence in the growing season
Erosion hazard	Rainfall intensity

References: ILACO (1985), FAO (1977), FAO (1979)

Table 14 WATER RESOURCE DATA FOR LAND USE PLANNING

Present water use - river abstraction, tanks, groundwater
- location of abstraction points, sluices, dams, wells and boreholes, with yields.

Present storage capacity of tanks and reservoirs.

Reliable yield of water for each river catchment - 75% and 90% probability low flow, from hydrograph records, or 75% and 90% probability rainfall - Eo over 7/10 day periods x area of catchment.

Safe yield of groundwater, from test pump data or well records.

Depth below surface of useful groundwater

Location of aquifers

Water quality

Location of irrigable land

Legal and customary rights

Source: FAO 1989

Table 3-8b

Summary of types of land resource surveys — Table 2.1

Type of survey 1/	Nearest FAO equivalent nomenclature and final map scale 2/	Aim and level	Site intensity and survey method	Approximate proportion of time input (%)			Preferred scales	
				API	Literature	Field work and sampling	Aerial photos	Final maps 3/
Exploratory	Exploratory to low intensity < 1:1 000 000 to 1:100 000	Resource inventory Project location Prefeasibility	Free survey of variable intensity usually much < 1 per 100 ha	60	20	20	< 1:60 000 < 1:100 000	Variable
				(Probable averages, very variable)				
Reconnaissance	Medium intensity 1:100 000 to 1:25 000	Prefeasibility Regional planning Project location	Free survey of variable intensity usually < 1 per 100 ha	50	25	25	1:40 000 to 1:20 000	< 1:50 000
Semi-detailed	High intensity 1:25 000 to 1:10 000	Feasibility Development planning	Flexible or rigid grid. Intensity 1 per 15 to 50 ha	20	20	60	1:25 000 to 1:10 000	1:25 000 to 1:10 000
Detailed	Very high intensity > 1:10 000	Development Management Special purpose	Rigid grid. 1 per 1 to 25 ha	5	20	75	1:10 000 to 1:5 000	1:10 000 to 1:5 000

Notes: 1/ These terms are loosely used for a wide variety of intensities and final map scales: see Young (1973), Stobbs (1970) and Western (1978, Chapter 3).
2/ See FAO (1979a, p 88).
3/ For many integrated projects the final map scale may be chosen to conform to civil engineering or project development requirements, rather than to the most appropriate scale for the survey intensity and complexity of the soil pattern (see Subsection 9.5.1).

Table 3-8a

Summary of mapping units used in land resource surveys — Table 2.2

Types of survey	Final mapping unit	Landscape components 1/			
		Geomorphology	Soil	Vegetation	Land use
Exploratory	1. Physiographic units/ land systems 2. Potential development areas	Major relief units	Orders 2/ to associations	Soil/climate-related types	Agro-ecological groups
Reconnaissance	1. Physiographic units/ land systems 2. Soil associations 3. Land capability units 4. Potential development areas	Relief units, major landforms	Associations	Soil/climate-related types, plant associations	Land use systems, cultivation density
Semi-detailed	1. Geomorphic units 2. Soil series/ associations 3. Land suitability/ management classes 4. Major constraints or development parameters	Detailed landforms and elements, slope units	Series, complexes or associations; soil phases and selected parameters	Plant associations and distribution	Land use and farming systems, specific parameters, cropping patterns
Detailed	1. Soil phases and/or land parameters 2. Land management units	Slope units	Soil phases and selected parameters	Specific crop or natural vegetation variables related to soil parameters - eg drainage or salinity effects	

Notes: 1/ After Baulkwill (1972).
2/ ie the highest level of soil classification (see Annex C); not to be confused with the USDA term 'order of soil survey' which refers to the kind of survey (see Orvedal, 1977).

Source: Landon ed. 1984

Table 3-9

Table 14 INVENTORY OF SOILS DATA

	DATA ITEM	PURPOSES FOR WHICH MAY BE REQUIRED
A.	PHYSICAL	
1.	Effective soil depth	Root room, water and nutrient retention; land levelling; drainage; aligning and design of irrigation and drainage channels.
2.	Presence of organic or histic horizons	Special problems or opportunities.
3.	Grain size distribution (texture)	For establishing homogeneity of land units and for deriving many characteristics.
4.	Soil structure and porosity Bulk density. Pore space volume and distribution. Air-filled pore space at field capacity. Structure stability.	Root environment, nutrient, water and soil management. Drainage and permeability especially of sodic soils. Leaching of excess salts. Tilth and workability for seedbed and land preparation. Ability to puddle riceland. Erodibility.
5.	Infiltration rate	Rainfall and irrigation intake or run-off. Selection of irrigation method. Furrow lengths or basin size. Sprinkler nozzle selection. Erodibility.
6.	Hydraulic conductivity or permeability	Soil drainage, removal of excess water and salts.
7.	Available water capacity (field capacity and permanent wilting point)	Soil water balance, residual water between and following irrigations. Choice of irrigation method and schedules.
8.	Plastic and liquid limits	Indicative of mineralogy and physical behaviour.
9.	Soil strength, linear extensibility	Mechanical strength for construction works; swelling and shrinking; root penetration.
B.	CHEMICAL	
1.	Soil reaction (pH)	To identify very alkaline, sodic and acid sulphate soils; nutrient deficiencies and toxicities.
2.	Carbon and nitrogen	Organic matter content and management.
3.	Gypsum and calcium carbonate	Hardpans, gypsiferous layers liable to subside, gypsum requirements for sodic soils.
4.	Electrical conductivity of saturation extract (ECe)	Salinity hazard.
5.	Soluble salts (Na, K, Ca, Mg, Cl, SO_4, CO_3 and HCO_3)	Interpretation of salinity hazard.

Table 14 (contd.) INVENTORY OF SOILS DATA

	DATA ITEM	PURPOSES FOR WHICH MAY BE REQUIRED
6.	Cation exchange capacity (CEC), total exchangeable bases (TEB) and base saturation %	Nutrient retention and chemical fertility status.
7.	Exchangeable sodium percentage (ESP) or adjusted sodium adsorbtion ratio of saturation extract(adj.SAR)	Sodicity or alkalinity problems.
8.	Exchangeable cations (Na, K, Ca, Mg)	Base saturation, ESP, potassium status.
9.	Available phosphorus	See Table 35, Part Two.
10.	Total contents of P, K, Mg, Na, Cu, Mn, Zn, B, Fe, Al, As, Ni, Cr	Macro and micronutrient content. Toxic elements.
C.	MINERALOGICAL	
1.	Sand and silt fraction	Indicates parent material and degree of weathering.
2.	Clay fraction and iron and aluminium oxides	1:1 clay minerals less sticky, swell and shrink less and have a smaller surface area (and less CEC) than 1:2 clay minerals. 1:1 clay minerals with Fe and Al oxides predominating may prove excessively well-drained for wetland rice, and often physically favourable but chemically less fertile for non-rice crops.
3.	Calcium and magnesium carbonates	Hardpans restricting rooting depths. Large amounts decrease nutrient retention and fertility; but soils with 60% $CaCO_3$ can be successfully irrigated but with a restricted choice of crops. Deposition under saline conditions of fine grained material blocks pores and reduces permeability. Surface crusting interferes with seedling emergence and infiltration. Lime-induced nutrient deficiencies. Magnesium carbonate soils often very fertile. High exchangeable Mg leads to sodic-like impermeable profile.
4.	Gypsum	Gypsiferous hardpans restrict rooting and make installation of drains and channels difficult. Dissolution may lead to land subsidence after irrigation. Gypsum crystals in soil may offset sodicity tendency. If too high, causes nutrient problems due to unfavourable K/Ca, Mg/Ca ratios and extra costs in fertilizers and soil management.

Note: The characteristics in Table 14 should be evaluated in the context of morphological and geographical considerations.

Source: Landon ed. 1984

Table 3-10a

Summary of routine soil physical measurements and their interpretation — Table 6.2

Measurement	Recommended method(s)	Preferred units	Range of values and comments	
Infiltration rate	Basin, furrow or ring at site	cm h^{-1}		Rating for surface irrigation:
			< 0.1	Unsuitable (too slow) except for rice
			0.1–0.3	Unsuitable (too slow); marginal for rice
			0.3–6.5	Main suitable range (> 0.3 unsuitable for rice)
			6.5–12.5	Marginal (too rapid)
			12.5–25.0	Only suitable in special conditions (small basins)
			> 25.0	Only suitable for overhead irrigation Note: Values from ring infiltration may be high because of lateral seepage
Hydraulic conductivity	Auger hole or inverse auger hole	m day^{-1}	< 0.2	Very slow
			0.2–1.4	Slow to moderate
			1.4–3.0	Moderately rapid to rapid
			> 3.0	Very rapid Note: both horizontal and vertical components should be considered
Bulk density	Replacement at site and/or undisturbed core in laboratory	g cm^{-3}	0.9–1.2	Recently cultivated soil
			1.1–1.4	Main range uncultivated, uncompact soil
			1.6–1.8	Sands and loams) Ranges that
			1.4–1.6	Silts) restrict
			Very variable	Clays) roots
Porosity	From bulk density tests	% by vol	30–70	Usual range in soils
			10	Limiting value for air-filled pores
Field capacity (FC)	In situ tests	mm m^{-1} (% by vol)	100–450	High values for clays; low values for sandy soils
Permanent wilting point (PWP)	Pressure membrane method at 15 bar	mm m^{-1} (% by vol)	50–250	High values for clays; low values for sandy soils
Available water capacity (AWC)	FC – PWP	mm m^{-1} (% by vol)	50–230 but mostly 70–190	Approximate range for stone-free tropical soils. High values (> 180 mm m^{-1}) for soils with very fine sandy and silty textures; moderate values (120–180 mm m^{-1}) for clayey soils; low values (< 120 mm m^{-1}) for sandy soils
Water content	Gravimetric	% by vol or by mass	See ranges above	Tensiometers and neutron probe methods need careful calibration; former unsatisfactory on gravel soils
Structure	Water immersion	-	Class 1–8	Class 1 (least stable) to Class 8 (most stable); may be great variation within classes. Limited use in routine surveys
Strength	Penetrometer	kg cm^{-2}	Highly variable	Careful calibration and operation needed; highly dependent on water content; limited use in routine surveys
Stone content, and particle size distribution	Wet and dry sieving; sedimentation	Stones: % by vol Fines: % by wt	) See) Section 6.9	Note variation due to different pretreatments

Source: Landon ed. 1984

Table 3-10b

Brief summary of recommended routine soil chemical analyses and their interpretation

Table 7.4

Analysis	Recommended method(s)	Units	Rating	Range	General interpretation	Section reference
pH	1:2.5 soil:water suspension	-	Very high	> 8.5	Alkaline soils: Ca and Mg liable to be unavailable; may be high Na; possible B toxicity; otherwise as below:	7.5
			High	7.0-8.5	Decreasing availability of P and B to deficiencies at higher values. Above 7.0 increasing liability of deficiency of Co, Cu, Fe, Mn, Zn	Interpreta-ation 7.5.3
			Medium	5.5-7.0	Preferred range for most crops; lower end of range too acidic for some	
			Low	< 5.5	Acid soils: possibly Al toxicity and excess Co, Cu, Fe, Mn, Zn; deficient Ca, K, N, Mg, Mo, P, S (and B below pH 5)	
CEC	a) Unbuffered 1 M KCl at pH of soil b) Na or NH_4 acetate at pH 8.2, 7.0	me/100 g soil	Very high High	> 40 25-40	Normally good agricultural soils - only small quantities of lime and K fertilisers required	7.6
			Medium	15-25	Normally satisfactory for agri-culture, given fertilisers	Interpreta-tion 7.6.3
			Low	5-15	Marginal for irrigation (FAO (1979a) quoted low is 8-10 me/100 g soil)	
			Very low	< 5	Few nutrient reserves. Usually un-suitable for irrigation, except rice	
BSP	Calculation: total exchange-able bases/CEC	%	High Medium Low Eutric Dystric	> 60 20-60 < 20 > 50 < 50	Generally fertile soils Generally less fertile soils	7.6.4 Table 5.7
Exchangeable cations						7.7
Ca	As CEC	me/100 g soil	High Low	> 10 < 4	Response to Ca fertiliser expected at levels < 0.2 me/100 g soil. If high Na levels, response occurs with higher Ca levels	7.7.3
Mg	As CEC	me/100 g soil	High Low	> 4.0 < 0.5	Mg deficiency more likely on coarse, acidic soils. With high Ca, Mg is less plant available	7.7.4
K	As CEC	me/100 g soil	High	> 0.6	Response to K fertiliser unlikely. High K effects often similar to high Na, but depends on soil type - especially texture	7.7.5
			Low	< 0.2	Response to K fertiliser likely	
EPP	Calculation: K^+/CEC	%	High	> 25%	Very approximate upper limit (cf ESP > 15%)) 1/	
			Low	< 2%	Very approximate lower limit) 1/	
Na	As CEC	me/100 g soil	High	> 1)	Alkali or sodic soils 1/	7.7.6
ESP	Calculation: Na^+/CEC	%	High	> 15%)		
		%	High	> 15%	50% yield reduction for sensitive crops 1/	
				15-25%	50% yield reduction for semi-tolerant crops 1/	
				35%	50% yield reduction for tolerant crops 1/	
Al:CEC	1 M KCl unbuffered	%	High Medium Low	< 85 30-85 > 30	Tolerated only by few crops Generally toxic Sensitive crops affected	7.7.8

cont

Notes: See page 114.

Source: Landon ed. 1984

Table 3-11

Table 44 GROWTH LIMITING CONDITIONS FOR RICE ON SUBMERGED SOILS OF VARIOUS TYPES

KIND OF SOIL AND MAIN LIMITATIONS	OTHER GROWTH LIMITING CONDITIONS
Saline soils	
Arid saline soils	Alkalinity, Zn deficiency, N & P deficiencies
Acid coastal saline soils	Iron toxicity, P deficiency, deep water
Neutral and alkaline coastal and saline soils	Zn deficiency, deep water
Deltaic and estuarine acid sulphate soils	Iron toxicity, P deficiency, deep water
Coastal histosols	Nutrient deficiencies, H_2S toxicity, toxicity of organic substances, deep water, Fe toxicity
Acid sulphate soils	
Coastal soils	Salinity, Fe toxicity, N & P deficiencies, deep water
Old inland soils	N & P deficiencies
Histosols	Fe toxicity, H_2S toxicity, nutrient deficiencies, deep water, salinity
Iron-toxic soils	
Acid sulphate soils	Salinity, N & P deficiencies, deep water
Acid oxisols and ultisols	P deficiency, low base status, low Si content
Histosols	H_2S toxicity, toxicity of organic substances, macro-nutrient deficiencies, Zn and Cu deficiencies, deep water
Phosphorus deficiency in wetland rice	
Acid sulphate soils	Strong acidity, iron toxicity, low nutrient status, base deficiency, salinity
Acid oxisols and ultisols	Iron toxicity, base deficiency
Vertisols	Zinc deficiency, iron deficiency, salinity, alkalinity
Zinc deficient soils	
Saline-sodic and sodic soils	Salinity, N & P and Fe deficiencies
Vertisols	P and Fe deficiencies, salinity, alkalinity
Calcareous soils	K deficiency
Wet soils	Cu deficiency
Histosols	N, P, K, Si, Cu, deficiencies; H_2S toxicity, deep water

Source: after Ponnamperuma 1976.

Source: Landon ed. 1984

Table 3-12a

LANDEVALUIERUNG FÜR DEN BEWÄSSERUNGSFELDBAU IM FEZZAN

Anhand der "Grenzwert- Methode" für einen kleinbäuerlichen Familienbetrieb mit kombinierten Oberflächen- und Beregnungsmethoden;

FACTOR OF LAND AND SOIL QUALITY OR CHARACTERISTICS	CLASS 1	CLASS 2	CLASS 3	CLASS 4	CLASS 5+6
Effective soil depth	>150 cm	150-75 cm	75-50 cm	30-50 cm	<30 cm
Topography/Slope	<0.5%	<1%	<2%	2-4%	>4%
Microrelief	level uniform	slighly homogeneous	moderately homogeneous	homogen.	undulating homogeneous
Permeability	40-100cm/d	>20cm/d	>10cm/d	<1cm/d	any
Drainage class	3 + 4	2 - 5	1 - 6	all	all
Infiltration class	12-48 cm/d	12-144 cm/d	1-300 cm/d	any	any
Topsoil texture 0-30 cm	sL,scL,L	lS to sC/cL/siC	clay<65% sand <90%	all	all
Subsoil texture 30-100 cm	ls to sC/cL/siC	clay <65% sand <90%	all	all	all
Available water capacity	>140 mm	>90 mm	>50 mm	all	all
Potential fertility	high	moderate	low	low	any
Actual fertility status	high	moderate	low	low	any
$CaCO_3$-content	2-20%	<35%	<65%	any	thick petrocalcic
$CaSO_4$-content	0.5 - 5%	<25%	<40%	any	thick petrogypsic
Soil toxicity (B etc.)	low	moderate	mod. high	high	any
Salinity of top-soil 0-50 cm	<4m S/cm	4-15 mS/cm	15-50 mS/cm (< 1% salts)	any	any
Salinity of sub-soil 50-150 cm	<8 mS/cm	<30 mS/cm (< 1% salts)	any	any	any
Alkalkinity of topsoil	pH < 8.0	pH <9.0	pH <10.0	any	any
Alkalinity of subsoil	pH < 8.5	pH <9.5	pH <10.0	any	any
Wind ersoion hazard	low	moderate	high	high	extremely high shifting sands

Land Class specifications according to USDI (1953) (in:Klingebiel & Montgomery 1961)
C 1: soils/land with few or no limitations ; C 2:soils/land requiring moderately intensive treatment;
C 3: severe limitations that require special practices; C 4: severe limitations that restrict choice of land use and require very careful management; C 5+6: severe limitations requiring further studies or problems which are consideres to be non-correctable at an economic rate.
Classes C1-C3: *Irrigable* ; Class C4: *Restricted Irrigable;* Classes 5+6: *Provisionally Non-Irrigable.*

Table 3-12b

LANDEVALUIERUNG FÜR DEN BEWÄSSERUNGSFELDBAU IM FEZZAN

Anhand der "Grenzwert- Methode" für ein großflächiges Center-Pivot-Projekt

FACTOR OF LAND AND SOIL QUALITY OR CHARACTERISTICS	CLASS 1	CLASS 2	CLASS 3	CLASS 4	CLASS 5+6
Effective soil depth	>100 cm	>75cm	>50cm		<50cm
Topography/Slope	<0.5%	<2%	<4%		>4%
Microrelief	level uniform	slightly homogeneous	moderat. homogeneous		homogeneous
Permeability	40-100cm/d	<10cm/d	>2cm/d	>0.5cm/d	<0.5cm/d
Drainage class	3 + 4	2 to 6	1 to 6	all	all
Infiltration	12-144cm/d	12-300cm/d	>1cm/d	any	any
Topsoil texture 0-30 cm	sL,scL,L	clay<40% sand<90%	clay <65%* sand >90%	any	any
Subsoil texture 30-100 cm	clay<40% sand<85	clay <65%	any		
Available water capacity	>140 mm	>50 mm	any		
Potential fertility	high	moderate	low		
Actual fertility status	high	moderate to low	any		
$CaCO_3$-content	2-20%	<40	any		
$CaSO_4$-content	0.5-10%	<25%	<45%	any	
Soil toxicity (B etc.)	low	moderate	mod. high	any	
Salinity of top-soil 0-50 cm	<4mS/cm	<15mS/cm	>15mS/cm <2% salts	any	
Salinity of sub-soil 50-150 cm	<8mS/cm	<15mS/cm	>15mS/cm	any	
Alkalkinity of topsoil	pH <8.0	pH <9.0	pH <10.0	any	
Alkalinity of subsoil	pH <8.5	pH <9.5	pH <10.0	any	
Wind ersoion hazard	low	moderate to mod. high	high	high	extremely high; shifting sands

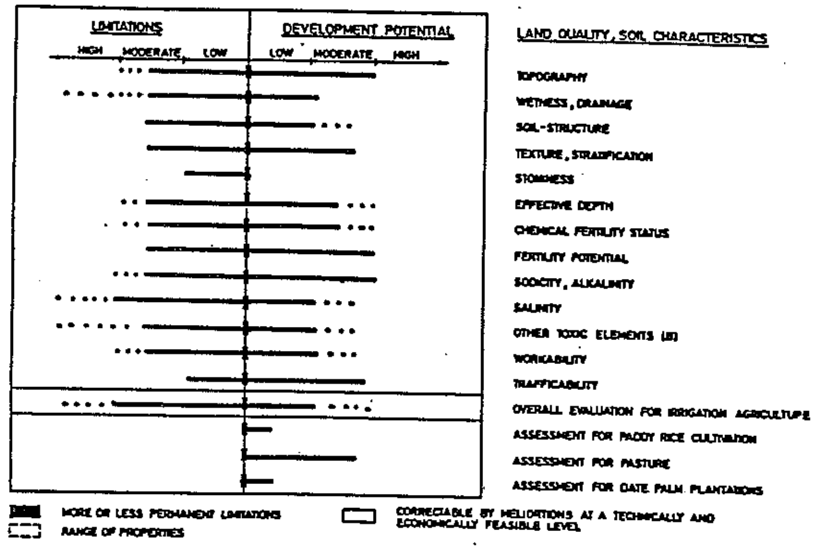
* Bei gutem Management können auch tonreiche Substrate in die Class C2 eingestuft werden.

DIRECTIVES DE GROUPEMENT DE SOLS EN CLASSES D'APTITUDE POUR LA CULTURE DU RIZ IRRIGUE (NIVEAU D'EXPLOITATION MOYEN)

Guideline for grouping soils in current suitability classes for paddy rice (medium level of management)

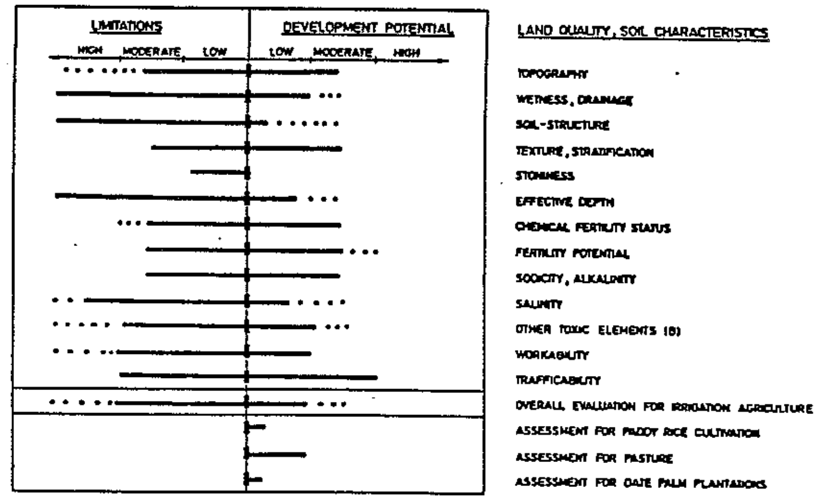
Land and Soil Quality	P1	P2	P3	P4	N
Topography	< 0.5%	< 1%	< 3%	≤ 5%	-
Microrelief	smooth plan	smooth	levelling required	levelling required	-
Drainage (class*)	8, 9	6, 7, 10	5, 10	4 to 10	4
Water table	shallow < 20 cm	mod. deep 20-50 cm	deep (>50 cm)	deep (>50 cm)	deep
Risk of damage by flodding	Seldom <1 in 10 years	occasional	moderate damage	damage may be frequent	-
Texture	very fine	v. fine to fine	v. fine to medium	v. fine to coarse	v. coarse
Hydraulic cond. of subsoil	1-10 cm/d	10-40 cm/d < 1 cm/d	40-100 cm/d	100-600 cm/d	> 600 cm/d
Sulphuric horizon	no	no	no or deeper than 50 cm	—	-
Effective soil depth	> 100 cm	> 75 cm	> 50 cm	> 25 cm	< 25 cm
Exchange Capacity	> 24 me %	12-24 me %	7-12 me %	< 7 me %	< 4 me %
Base saturation	> 50%	35-50%	15-35%	< 15%	-
Nutrient status	high to mod.	high to mod. low	high to low	high to low	-
Organic matter	> 2%	1-2 %	< 1%	< 1%	-
Salinity groundw. / Soil extr.	< 0.3 mS/cm / < 1.0 mS/cm	0.3 - 1.0 / 1 - 3	1.0 - 3.0 / 3.0 - 5.0	> 3.0 / 5 - 8	- / > 8
Alkalinity/Acidity	pH 5.5-6.5	pH 5.0-8.0	pH 4.5-8.5	pH 4.0-9.0	< 4
Presence of toxic elements x1	slight	moderate	moderate	severe	-
Calcium carbonate %	< 15%	< 15%	15-25%	> 25%	-
Absence of specific deficiencies x2	slight	moderate	moderate	severe	-
Exchangeable sodium	< 20%	< 40%	< 60%	≥ 60%	-
Infiltration rate	< 3 mm/d	3-30 mm/d	30-60 mm/d	60-100 mm/d	> 100 mm/d

ASSESSMENT OF GENERAL SOIL SUITABILITY
(ALL CROPS, WITHOUT PADDY RICE)



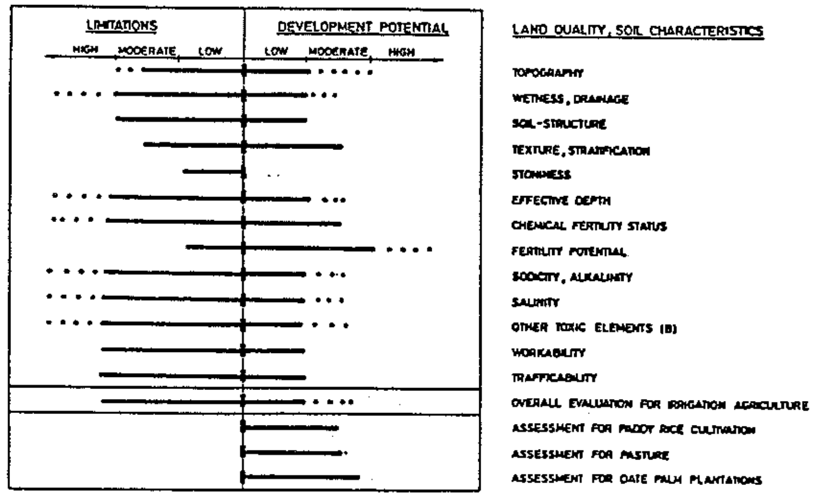
Graphik 7.7

ARIDIC (HAPLIC-) CALCIC SOLONCHAKS



Graphik 7.8

ARIDIC (PETRO-) CALCIC SOLONCHAKS



Graphik 7.9

ARIDIC (TAKYRIC-) SODIC SOLONCHAKS

Table 11 LAND UTILIZATION TYPES IN BALI (IRRIGATED) 1/

1.	IRRIGATED LANDS
1.1	Irrigated rice only
	1.1.1 Two crops of local 140-160 day varieties per year 2/
	1.1.2 Five crops of short duration 120 day varieties per two years
	1.1.3 One crop of 140-160 day local variety followed by one crop of 120 day local or new variety per year (where dry season water is limited)
	1.1.4 One irrigated rice crop (wet season) and land fallow in dry season (where soil is unsuitable for palawija crops and there is insufficient water for second rice crop)
1.2	Irrigated rice (wet season), irrigated or rainfed palawija (dry season) 3/
	1.2.1 Rice, rice, palawija per year 4/
	Irrigation of palawija dependent on water availability; often grown on residual moisture, e.g. rice, rice, soybeans (relay planted)
	1.2.2 Rice, palawija, palawija per year
	The palawija is usually irrigated. Many combinations of crop are planted, e.g. rice, maize, groundnuts
	Rice, groundnuts, red onion Rice, soybean, soybean Rice, soybean, green gram Rice, groundnut, groundnut Rice, tobacco, red onion Rice, soybean, cucumber
	1.2.3 Rice followed by one relay-planted soybean crop per year
	The irrigation of the soybean crop depends on rainfall and availability of stream water. Land is only recultivated once each year
	1.2.4 Rice followed by one palawija crop other than soybeans.
	Rice, melons Rice, cucumbers
1.3	Irrigated rice under coconuts
	1.3.1 Rice (wet season), palawija or fallow (dry season)
	1.3.2 Rice, rice per year
1.4	Irrigated palawija crops only
	Palawija crops rarely irrigated because of serious weed problems
1.5	1.5.1 Pure stand citrus
	1.5.2 Citrus under-planted with maize, groundnuts and red onions

1/ Eavis and Walker 1976.

2/ Rice is usually transplanted under groups 1.1, 1.2 and 1.3 but direct seeding is a possible future variant. Days refer to time from transplanting to harvest.

3/ Palawija is an Indonesian term that collectively refers to crops grown in rotation with rice, e.g. maize, groundnuts, green gram (mung), tobacco, red onion, soybeans, sweet potato, melon, cucumber etc.

4/ Generally relay-planted, i.e. sown in rice stubble or before rice is harvested, without any cultivation.

Source: FAO (SB 55) 1985

Table 4 FORMAT 1: SPECIFICATIONS OF LAND USE REQUIREMENTS AND LIMITATIONS

LUT Name:	LUT Description							
CLASS-DETERMINING REQUIREMENTS OR LIMITATIONS (Delete factors that are not selected as class-determining)	REVELANT LAND QUALITY OR LAND CHARACTERISTIC	INPUTS AND LAND IMPROVEMENTS REQUIRED	UNIT OF MEASURE-MENT	CRITICAL LIMITS OR RANGES				
				s1	s2	s3	n1	n2
A. Crop (agronomic) requirements or limitations								
1. Growing period requirement								
2. Radiation requirement								
3. Temperature requirement								
4. Rooting requirement								
5. Aeration requirement								
6. Water requirement								
7. Nutritional requirements (NPK)								
8. Water quality limitation								
9. Salinity limitation								
10. Sodicity limitation								
11. pH, micronutrients and toxicities								
12. Pest, disease, weed limitations								
13. Flood, storm, wind, frost, hail limitations								
B. Management requirements and limitations								
14. Location								
15. Water application management requirements								
16. Pre-harvest farm management requirements								
17. Harvest and post-harvest requirements								
18. Requirements for mechanization								
C. Land development or improvement requirements or limitations								
19. Land clearing requirements								
20. Flood protection requirements								
21. Drainage requirements								
22. Land grading requirements								
23. Physical, chemical, organic aids and amendments								
24. Leaching requirements								
25. Reclamation period								
26. Irrigation engineering needs								
D. Conservation and environmental requirements and limitations								
27. Long-term salinity, sodicity hazard								
28. Ground or surface water hazard								
29. Long-term erosion hazard								
30. Environmental hazard								
E. Socio-economic requirements or limitations								
31. Farmers' attitudes to irrigation								
32. Others that are class-determining								

Note: s1, s2, s3, n1 and n2 denote decreasing suitability levels for single factors or their interactions. See Table 12 and Section 6.5 Example 2.

Table 5 FORMAT 2: LAND QUALITIES AND LAND CHARACTERISTICS DESCRIBING A LAND UNIT WITH AN ASSESSMENT OF INPUTS AND LAND IMPROVEMENTS REQUIRED

CLASS DETERMINING FACTORS: - land quality or characteristic - inputs or improvements	UNIT OF MEASUREMENT	LAND CHARACTERISTIC OR QUALITY VALUE		INPUTS AND IMPROVEMENTS ASSUMED FOR LUT A, B, C etc.
		PRESENT	FUTURE UNDER IRRIGATION	
e.g.				
7. NUTRITION (NPK)				
- Total N depth 0-25 cm	%	0.05	0.5	
- Available P (Olsen)	mg/l	10		
- Exchangeable K	me/100 g	0.6		
Fertilizer requirement	kg/ha			
N				200 kg/ha
P				nil
K				nil

Source: FAO (SB 55) 1985

Table 3-16

Table 12 LIST OF CLASS-DETERMINING FACTORS (i.e. AS LAND USE REQUIREMENTS OR LIMITATIONS OR AS LAND QUALITIES) WITH SOME LAND CHARACTERISTICS, INPUTS AND LAND IMPROVEMENTS FOR CONSIDERATION IN SETTING CRITICAL LIMITS

	CLASS-DETERMINING FACTORS: 1/ - land use requirements or limitations - land qualities (where applicable)	REPRESENTATIVE LAND CHARACTERISTICS, INPUTS, LAND IMPROVEMENTS AND OTHER RELEVANT CONSIDERATIONS (see Part Two for full explanations)
A.	AGRONOMIC: - crop requirements or limitations - the crop environment	
1.	GROWING PERIODS: - growing period requirement - growing periods	Growing cycle of crops. Dates and duration (days).
2.	RADIATION: - radiation requirements - radiation regime	Day length, extra-terrestrial radiation; solar radiation (Rs); photosynthetically active radiation (PAR); actual sunshine hours (n); possible number of sunshine hours (N); net shortwave radiation Rns; total net radiation (Rn); mm of evaporation ($Rn = 1\ cal/cm^2/min$ approximate equivalent to 1 mm water/hr).
3.	TEMPERATURE: - temperature requirement - temperature regime	Temperature data. Heat units. Frost free periods.
4.	ROOTING: - rooting requirement - rooting conditions	Effective soil depth for roots. Root room. Volume percent of stones. Penetration resistance or soil strength.
5.	AERATION: - oxygen & aeration requirement - oxygen supply and soil aeration	Periods with or without adequate aeration during the growing period. (Depth and fluctuation of groundwater)
6.	WATER QUANTITY: - water requirement - water supply	Water balance, water storage. Yield vs. evapotranspiration relationships; deficient periods. Run-off, run-on, seepage and percolation, groundwater contribution, effective precipitation. Stream flows, diversions, storage releases, aquifer safe yields.

1/ Evaluate only selected factors i.e. those that are class-determining in a given evaluation.

Source: FAO (SB 55) 1985

Table 12 (contd.)

	CLASS-DETERMINING FACTORS: - land use requirements or limitations - land qualities (where applicable)	REPRESENTATIVE LAND CHARACTERISTICS, INPUTS, LAND IMPROVEMENTS AND OTHER RELEVANT CONSIDERATIONS (see Part Two)
7.	NUTRIENTS (NPK) - nutritional requirement - fertilizer requirement, etc. - nutrient supply - fertilizer supply	NPK uptake by crops and responses to NPK. Losses of NPK (leaching, volatilization, fixation, etc.). Nitrogen fixation. Soil nutrients and their retention, cation exchange capacity, etc. Fertilizer requirements and availability including manures, etc.
8.	WATER QUALITY: - crop tolerance to water quality - water quality	Total salt concentration. Ionic composition. Electrical conductivity dS/m at 25°C. Sodium adsorption ratio (SAR). pH, carbonates and bicarbonates. Suspended solids, BOD, COD, etc.
9.	SALINITY: - crop tolerance to salinity - salinity regime (salt balance)	Plant salt tolerances, present and future soil salinity, inputs of salt through water supply, losses of salt by leaching, salt balance. Seasonal salt movement in profile, salt from groundwater.
10.	SODICITY: - crop tolerance to sodicity - sodicity regime	Predicted pH, ESP and or SAR of soil solution, predicted effects on soil structure, infiltration and permeabilities. Sodium toxicity.
11.	pH, MICRONUTRIENTS AND TOXICITIES: - crop tolerances, susceptibilities - toxicity or micronutrient regimes	On non-rice cropland, pH effects and crop tolerances and susceptibilities to excesses or deficiencies of Ca, Mg, Zn, Fe, S, B, Cu, Mn, Mo, Al. On submerged soil effects of pH, salts, Fe, Si, Mo, Zn, Cu, H_2S. Soil and plant composition, relevant inputs.
12.	PEST, DISEASE, WEEDS: - crop tolerances, susceptibilities - pest, disease, weed hazard.	Crop tolerances and susceptibilities. Wild animals, birds, arthropods etc. Fungal, bacterial, viral pathogens. Weeds. Pesticides, fencing, inputs.
13.	FLOOD, STORM, WIND, FROST: - crop tolerances, susceptibilities - flood, storm, wind, frost, hail hazard	Adaptations of rice to flooded conditions. Frequency and severity of flood, storm, wind, frost and hail.

Table 12 (contd.)

	CLASS-DETERMINING FACTORS: - land use requirements or limitations - land qualities (where applicable)	REPRESENTATIVE LAND CHARACTERISTICS, INPUTS, LAND IMPROVEMENTS AND OTHER RELEVANT CONSIDERATIONS (see Part Two)
B.	MANAGEMENT: - management requirements and limitations - conditions affecting management	
14.	LOCATION: - location requirements - location	Closeness to markets, processing units. Access to inputs and services. Access to water (gravity, pumped). Travel & transport problems & cost. Day-to-day management problems. Accessibility of machinery.
15.	WATER APPLICATION MANAGEMENT: - limitations of irrigation method - conditions affecting water application management	Size, shape of management units. Labour requirement availability. Conditions affecting uniformity of water application, rate, frequency and duration of application.
16.	PRE-HARVEST FARM MANAGEMENT: - pre-harvest farm management requirements and limitations - conditions affecting pre-harvest farm management	Effects on timing of pre-harvest operations (e.g. of soil workability) including land preparation, nurseries, seeding, transplanting, fertilizer application, irrigation, weeding, spraying, etc.
17.	HARVEST AND POST HARVEST MANAGEMENT: - requirements or limitations - conditions affecting	Atmospheric wetness, dryness, wind. Soil wetness, dryness. Effects of soil or humidity on the quality of the crop produce.
18.	MECHANIZATION: - requirements for mechanization - conditions affecting potential for mechanization and on-farm transportation	Slope angle, rock hindrances, stoniness, soil depth, soil texture, shape and size of fields. Effects of soil compaction. On-farm transportation.

Table 12 (contd.)

	CLASS-DETERMINING FACTORS: - land use requirements or limitations - land qualities (where applicable)	REPRESENTATIVE LAND CHARACTERISTICS, INPUTS, LAND IMPROVEMENTS AND OTHER RELEVANT CONSIDERATIONS (see Part Two)
C.	LAND DEVELOPMENT AND IMPROVEMENTS - land development requirements - factors affecting cost of land development and improvement	
19.	LAND CLEARING: - land clearing requirements - conditions affecting cost of land clearing	Forest: underbrushing, felling, burning, stacking; costs, value of timber, charcoal; time period to development. Persistent weeds: mechanical cultivation, flooding, chemical control; costs, time period to development. Rocks and stones: removal costs.
20.	FLOOD PROTECTION: - flood protection requirements - conditions affecting cost of flood protection	Earthmoving costs for embankments, costs of structures.
21.	DRAINAGE: - drainage requirements - conditions affecting cost of drainage	Watertable depth, depth to barrier of low permeability, vertical resistance to flow through soil and barrier, slope angle, need for salt removal; size, spacing, depth of surface or pipe-drainage and cost of drainage.
22.	LAND GRADING AND LEVELLING: - grading and levelling requirements - conditions affecting land grading and levelling costs	Slope, microrelief, macrorelief, cover. Field size and shape, cut and fill, earthmoving costs.
23.	PHYSICAL, CHEMICAL AND ORGANIC AIDS AND AMENDMENTS: - requirements - conditions affecting costs	Need for deep ploughing, subsoiling, profile inversion, sanding, marling; gypsum, lime, organic matter, costs.
24.	RECLAMATION LEACHING: - leaching requirement - conditions affecting leaching	Primary or one-time reclamation leaching requirements mm of water; continuous or intermittent, costs.

Table 3-16 cont.

Table 3-16 cont.

Table 12 (contd.)

	CLASS-DETERMINING FACTORS: - land use requirements or limitations - land qualities (where applicable)	REPRESENTATIVE LAND CHARACTERISTICS, INPUTS, LAND IMPROVEMENTS AND OTHER RELEVANT CONSIDERATIONS (see Part Two)
25.	DURATION OF RECLAMATION PERIOD: - period required to reclaim by drainage and leaching, etc. - conditions affecting leaching periods	Number of project years to full production, project year in which field drainage is installed, rate of rise in watertable.
26.	IRRIGATION ENGINEERING: - irrigation engineering requirements - conditions affecting engineering works and costs	Earthwork and other structures for diversion, storage, conveyance, and regulation of water. Topography, substratum conditions, permeability of channels, access to construction sites, costs of engineering works.
D.	CONSERVATION AND ENVIRONMENTAL: - conservation and environmental requirements and limitations - conditions affecting conservation and the environment	
27.	LONG-TERM PREVENTION OF SALINITY AND SODICITY: - requirements and limitations - conditions affecting long-term salinity and sodicity hazards	Long-term inputs and outputs of salts, (see Fig. 18), water quality, groundwater depth, permeability, drainage, tidal swamp conditions, intrusion of saline water into an aquifer, control measures and their cost.
28.	LONG-TERM CONTROL OF GROUNDWATER AND SURFACE WATER: - requirements and limitations - conditions affecting long-term control	Protection of catchment areas, degradation of catchment, sedimentation of reservoirs, control of groundwater, and their costs.
29.	EROSION HAZARD: - requirements and limitations - conditions affecting erosion	Erosion control. Maximum acceptable soil loss and effects of climate, soil, topography, land use factor, costs.
30.	ENVIRONMENTAL HAZARDS: - environmental control requirement and limitations - conditions affecting long-term environmental risks	Wildlife, water-borne human diseases, need for environmental control of vectors.
E.	SOCIO-ECONOMIC: - socio-economic requirements and limitations - socio-economic conditions	
31.	FARMERS' ATTITUDES TO IRRIGATION	Will the farmers utilize the irrigation facilities?
32.	OTHER SOCIO-ECONOMIC LIMITATIONS THAT MAY BE CLASS-DETERMINING	Water rights, tenurial and land-ownership complications, disincentives of taxation, fragmentation, etc.

Source: FAO SB 55 1985

Table 3-17a

Table 13 RATINGS OF CLASS-DETERMINING FACTORS (FACTOR RATINGS)

FACTOR RATINGS	GUIDELINES FOR SETTING CRITICAL LIMITS
s1	The critical limits indicate that in terms of the given factor, the land is highly suitable for the specified land use.
s2	The critical limits indicate that in terms of the given factor, the land conditions are slightly adverse for the specified land use.
s3	The critical limits indicate that in terms of the given factor, the land is marginally suitable for the specified land use.
n1	The critical limits indicate that in terms of the given factor, the land is marginally not suitable for the specified land use (usually for adverse benefit/cost reasons).
n2	The critical limits indicate that in terms of the given factor, the land is permanently unsuitable for the specified land use.

Note: Critical limits to define factor ratings should reflect benefit/cost or other economic indices that indicate the influence of the factor on the value of production, costs of production, land development costs, etc.

Table 3-17b

Table 29 FACTORS THAT MAY DETERMINE LAND SUITABILITY CLASS FOR LOWLAND RICE IN INDONESIA 1/

DESCRIPTION OF THE LAND USE TYPE:
Crop: Lowland rice

Land Characteristic or Land Quality	Units	CRITICAL LIMITS s1	s2	s3	n
Length of growing period	days	120	105-120	95-105	95
Average temperature over the growing period	°C	24-26	26-28 22-24	28-30 20-22	30 20
Water requirements (rainfall and irrigation)	mm/yr	>1 600	1 300-1 600	1 000-1 300	<1 000
Soil drainage class 2/		1, 2	3, 4	5	
Soil texture 3/		8, 9 10, 11	6, 7 12, 13 14, 15	5 16, 17	1,2,3,4 18
Rooting depth	cm	25	25	25	25
Soil pH		5.5-6.5	6.5-7.5 5.0-5.4	7.6-8.2 4.5-4.9	8.2 4.5
Soil salinity	dS/m	3	3-5	5.1-6.5	6.6-8
Nutrient uptake/ N (nutrient removal P in brackets) K	kg/ha	160 32 250	110 24 170	75 18 110	48 (30) 14 (9) 60 (10)

Adapted from Bunting 1981.

1/ Note that not all the above land characteristics would be class-determining. Land suitability class is based on those that are, taking into account their 'Interactions' (Section 6.2) and 'Significance' (see Section 6.3).

2/ Key to drainage classes: 1 = very poorly drained, 2 = poorly drained, 3 = imperfectly drained, 4 = moderately well drained, 5 = well drained, 6 = somewhat excessively drained, 7 = excessively drained.

3/ Key to texture classes: 1 = gravel, 2 = coarse sand, 3 = medium sand, 4 = fine sand, 5 = loamy sand, 6 = sandy clay loam, 7 = loam, 8 = sandy clay loam, 9 = silt loam, 10 = silt, 11 = clay loam, 12 = silty clay loam, 13 = sandy clay, 14 = kaolinitic clay, 15 = silty clay, 16 = mixed clays, 17 = structured montmorillonitic clay, 18 = massive montmorillonitic clay.

Sources: FAO SB 55 1985

Soil requirements and limitations for selected tropical and subtropical crops 1/

Table 3-18a

Crop	TEXTURE: Fine	TEXTURE: Medium	TEXTURE: Coarse	TEXTURE: Very coarse tolerated	DRAINAGE: Free essential or desirable	DRAINAGE: Imperfect well tolerated	DRAINAGE: Poor tolerated or needed	DRAINAGE: Tolerance to short periods of waterlogging 2/	DRAINAGE: Minimum groundwater depth (cm) 3/	MINIMUM ROOTING DEPTH CLASS 4/	MOISTURE: Drought resistance 2/	MOISTURE: High AWC important	MOISTURE: Low AWC well tolerated	EROSION HAZARD 2/5/	REACTION: Optimum pH	REACTION: Range of pH tolerance for satisfactory yield 5/	NUTRIENT NEEDS: General level of requirements 2/	NUTRIENT NEEDS: Specific requirements	SALINITY TOLERANCE 2/
Cereals																			
Barley		+	+					M	60	M							H		G
Maize		+			+			L	75	M	L	+		H	5.5-7.0	5.0-8.0	H	High N	L
Millet (bulrush)		+	+	+	+						H		+	H					
Millet (finger)		+	+		+			M	60	S	M		+	M		5.0-6.0	M		L
Millet (panicum)		+	+								H		+	M					
Rice (paddy)	+						+				L	+		L	5.0-6.5	4.0-8.0	M	High N	
Rice (upland)	+	+						H		S	L			M		4.5-7.5	M		M
Rice (hungry)	+	+									M		+	H		4.5-7.5	L		
Sorghum	+	+	+			+		M/H	50	M	M		+	H	5.5-6.5	5.0-8.5	M	High N	L
Wheat	+	+						M	60	M					6.0-7.0		H		M
Fibre crops																			
Cotton	+	+			+			M/L	100	M	M				5.2-6.0	4.8-7.5	H		H
Hemp	+	+						M/L	75	D						6.0-7.0	H		L
Jute	+	+						H/M	10-75	M						6.0-7.0	M		L
Kenaf		+	+					M/L	75	M						6.0-7.5	M		L
Rosella		+	+					M	60	M						6.0-7.5	H		L
Sisal			+	+				L	150	D						6.5-8.0	M		L
Fruit crops																			
Banana		+	+		+			M	100	D	L	+		H	6.0-7.5	4.0-8.0	M/H	High N, K	L
Cashew			+					M	100	D						5.5-7.0	M		M
Citrus		+	(+)		+			L	130	D	M			L	5.5-6.5	5.0-8.0	M	High N, K	L
Date palm		+	+			+		H	100	D	H			H		6.5-8.0	M		H
Grape	+	+								D						6.0-7.0	M		L
Mango		+						M	60	D						5.5-7.5	H		L
Olive			+	+						D	H		+		7.0		M		M
Papaya		+								D					6.0-6.5		H		L
Pineapple		+	+		+			L	60	S	M			H		5.0-6.5	M		L
Oil crops																			
Coconut		+	+	+		+		H	50	D	L		+	L	6.0-7.5	5.0-8.0	L		M
Groundnut		+	+	+	+			L	50	M	M		+	M	5.3-6.6	5.0-7.0	M		L
Oil palm		+	+		+			H	100	D	L	+		M	5.5-6.0	4.0-8.0	H	Very high K	L
Safflower		+	+		+			M/L	75	M						5.5-6.5	H		L
Sesame		+	+		+			M/L	100	M						5.5-7.0	H		L
Soyabean		+	+			+		M	50	M				M	6.0-7.0	4.5-7.5	M		M
Sunflower		+	+		+			M	75	M	M		+	M		6.0-7.5	M		M
Pulses																			
Bean		+	+		+			M/L	30-50	M	L	+		M	6.0-7.0		M		L
Cowpea		+	+					M/L	40	M						5.5-7.5			L
Gram	+	+						M/L	30-50	M									M
Root crops																			
Cassava		+	+	+	+			L	50	D	H		+	M		5.5-6.5	M	(Low tolerated)	L
Cocoyam	+	+					+	H			L			L			H	High K	
Potato		+	+		+			L	30	M	L			M	5.0-5.8	4.5-7.0	M	High K	M
Sweet potato		+	+		+									M	5.8-6.0		H	High K	
Yams		+	+		+			L	50	D	M	+		M		5.5-6.5	H	High K, Mg	L
Sugar																			
Sugarbeet	+	+						M/H	45	M							H		H
Sugarcane	+	+				+		M/H	40	D	L	+		H	6.0-7.5	4.5-8.5	H	High N	M/L
Tree and shrub perennials																			
Cocoa		+	+		+			L	150	(D)	L	+		M	6.0-7.0	4.5-8.0	M/H		L
Coffee (arabica)		+	+		+			L	100	D	L	+		M	5.0-6.0	4.5-7.0	M/H		L
Rubber		+	+			+		H	75	D	L			H	4.0-6.5	3.5-8.0	L	N when young	L
Tea		+	+		+			L	100	D	L	+		H	4.0-5.5	4.0-6.5	M	High N	L
Coconut	see under oil crops above																		
Oil palm	see under oil crops above																		
Banana	see under fruit crops above																		
Citrus	see under fruit crops above																		
Vegetables																			
Cabbage		+			+			L	50	S						6.0-7.5	H		M
Cucumber		+			+			L	50	M						6.5-7.5	H		L
Onion		+			+			L	50	S						6.0-7.5	H		L
Tomato		+			+			L	50	M						5.0-7.0	H		L
Others																			
Alfalfa		+	+			+		L	50	D	M	+		L	6.5-7.5	6.0-8.0	M/H	Low N, high Ca,S	M
Tobacco																			
air-cured			+		+													High N, K	
fire-cured	+				+			L	100	M	L			M	5.5-6.0	5.0-7.5	M	High N, K	L
flue-cured			+		+													Low N, high K	

+ = Desirable condition or attribute.

<u>Notes</u>: 1/ See also Table F.5. Note that CEC and OM criteria omitted because of lack of data; in general the higher the better - the latter up to at least 5%.
2/ L = low; M = medium or moderate; H = high.
3/ Minimum depth during growing period; this level produces about 25% reduction in optimum yield.
4/ D = deep (> 90 cm); M = medium (60 to 90 cm); S = shallow (30 to 60 cm).
5/ For conditions before full canopy development and/or without cover crop; note that at maturity sugarcane, tea and rubber have low erosion hazards.

<u>Sources</u>: ILACO (1981, p 569); Young (1976, p 308), including figures from Jacob and Uexküll (1963) and Richards (1954). Sugarcane figures from R A Yates (personal communication).

Source: Landon ed. 1984

Table 3-18b

Indicative soil requirements and tolerances of selected crops

Table F.5

Crop	Requirement for: Water	Requirement for: Clayey texture	Requirement for: Good structure	Requirement for: Calcium	Requirement for: Acid conditions	Tolerance of: Water-logging	Tolerance of: Drought	Tolerance of: Clayey texture	Tolerance of: Acid conditions	Tolerance of: Salinity
Apple	M/H	M	H	M	L	L	L/M	L	L	L
Barley	L/M	L	L	L	L	L	M/H	M	M	H
Beans	M	M*	M*	M*	L	L/M*	L*	M/H	L	L*
Cherry	M/L	L	M	L	L	L	M	L/M	M	L
Citrus	M	M	H	H	L	L	M	M*	M	L/M*
Cocoa	M	M	H	M	L	L	M	L	L	L
Coffee	M	L	H	M	L	L	M	L	L	L
Date palm	M	L	H	H	L	L	M	L	L	H
Flax	M	M	H	M	L	L	L	L	L	L
Maize	L/M	L	M	L	L	L	M/H	L	L	L/M
Mangolds	H	L	M	L	L	H	L	H	H	M
Oats	M	L	L	L	L	H	L	H	H	L
Oil palm	H	M	H	L	M	L	L	H	M	L
Pear	H	L/M	H	M	L	M	L	M	L	L
Peas	M	M	H	M	L	L	M	M	L	L*
Potatoes	M/H	L	H	L	H	M/H	L	L	H	L
Rice	H	M	L	L	L	H	L	H	H	L/M
Rubber	H	H	L	L	M	H	L	H	M	L
Rye	L	L	L	L	L	L	L/M	H	H	M
Sisal	M	M	L*	M	L	M*	M	H*	M	M
Sugarbeet	H	M	H	M	L	M	L	H	M	M/H
Tapioca	M	M	M	M	L	L	M	M	M	L
Tea	H	L	H	L	H	M	L	L	H	L
Tobacco	M	L	H	M	L	L	M	L	L	L
Wheat	L/M	H	H	H	L	L	M	M/H	L	M

<u>Notes</u>: 1. L = low, M = medium, H = high, * = depending on variety.
2. See also Table F.4.

<u>Sources</u>: McRae and Burnham (1981) after Vink (1975); see also ILACO (1981, p 569).

Source: Landon ed. 1984

Indicative climatic and soil requirements for selected crops

Table 3-18c

Crop	Total growing period (days)	Mean daily temperature for growth (°C) optimum (and range)	Day length requirements for flowering	Specific climatic constraints/requirements 1/	Soil requirements 2/	Sensitivity to salinity 3/
Alfalfa (Medicago sativa)	100-365	24-26 (10-30)	Day neutral	Sensitive to frost; cutting interval related to temperature; requires low RH in warm climates	Deep, medium-textured, well drained: pH 6.5-7.5	Moderately sensitive
Banana (Musa spp)	300-365	25-30 (15-35)	Day neutral	Sensitive to frost; temperature < 8°C for longer periods causes serious damage; requires high RH, wind < 4 m s^{-1}	Deep, well-drained loam without stagnant water: pH 5-7	Sensitive
Bean (Phaseolus vulgaris)	Fresh: 60-90 Dry: 90-120	15-20 (10-27)	Short day/ day neutral	Sensitive to frost, excessive rain, hot weather	Deep, friable soil, well drained and aerated: optimum pH 5.5-6	Sensitive
Cabbage (Brassica oleracea)	100-150+	15-20 (10-24)	Long day	Short periods of sharp frost (-10°C) are not harmful: optimum RH 60-90%	Well drained: optimum pH 6-6.5	Moderately sensitive
Citrus (Citrus spp)	240-365	23-30 (13-35)	Day neutral	Sensitive to frost (dormant trees less), strong wind, high humidity; cool winter or short dry period preferred	Deep, well aerated, light- to medium-textured soils, free from stagnant water: pH 5-8	Sensitive
Cotton (Gossypium hirsutum)	150-180	20-30 (16-35)	Short day/ day neutral	Sensitive to frost, strong or cold winds; temperature required for boll development: 27-32°C (20-38°C range); dry ripening period required	Deep, medium- to heavy-textured soils: pH 5.5-8 with optimum pH 7-8	Tolerant
Grape (Vitis vinifera)	180-270	20-25 (15-30)		Resistant to frost during dormancy (down to -18°C) but sensitive during growth: long, warm to hot, dry summer and cool winter preferred/required	Well-drained, light soils are preferred	Moderately sensitive
Groundnut (Arachis hypogaea)	90-140	22-28 (18-33)	Day neutral	Sensitive to frost; for germination temperature > 20°C	Well-drained, friable, medium-textured soil with loose topsoil: pH 5.5-7	Moderately sensitive
Maize (Zea mays)	100-140+	24-30 (15-35)	Day neutral/ short day	Sensitive to frost; for germination temperature > 10°C; cool temperature causes problem for ripening	Well-drained and aerated soils with deep water-table and without waterlogging: optimum pH 5-7	Moderately sensitive
Oil palm (Elaeis guineensis)	365	27 (24-30)		Sensitive to frost; requires high RH, > 1 500 mm well-distributed rainfall and > 1 300 h sunshine	Well-drained, aerated soils with good water-holding capacity and unrestricted rooting medium	Moderately sensitive
Olive (Olea europaea)	210-300	20-25 (15-35)		Sensitive to frost (dormant trees less); low winter temperature required (< 10°C) for flower bud initiation	Deep, well-drained soils free from waterlogging	Moderately tolerant
Onion (Allium cepa)	100-140 (+30-35 in nursery)	15-20 (10-25)	Long day/ day neutral	Tolerant to frost; low temperature (< 14-16°C) required for flower initiation; no extreme temperature or excessive rain	Medium-textured soil: pH 6-7	Sensitive
Pea (Pisum sativum)	Fresh: 65-100 Dry: 85-120	15-18 (10-23)	Day neutral	Slight frost tolerance when young	Well-drained and aerated soils: pH 5.5-6.5	Sensitive
Pepper (Capsicum spp)	120-150	18-23 (15-27)	Short day/ day neutral	Sensitive to frost	Light- to medium-textured soils: pH 5.5-7	Moderately sensitive
Pineapple (Ananas comosus)	365	22-26 (18-30)	Short day	Sensitive to frost; requires high RH; quality affected by temperature	Sandy loam with low lime content: pH 4.5-6.5	Sensitive
Potato (Solanum tuberosum)	100-150	15-20 (10-25)	Long day/ day neutral	Sensitive to frost; night temperature < 15°C required for good tuber initiation	Well-drained, aerated and porous soils: pH 4.5-6	Moderately sensitive
Rice (paddy) (Oryza sativa)	90-150	22-30 (18-35)	Short day/ day neutral	Sensitive to frost; cool temperature causes head sterility; small difference in day and night temperature is preferred	Heavy soils preferred for percolation losses, high tolerance to O_2 deficit: pH 5.5-6	Moderately sensitive
Rubber (Hevea brasiliensis)	365	28 (26-30)		Sensitive to frost; wide range in temperature unfavourable, strong winds harmful. Pronounced dry season reduces yield	Deep, well aerated, permeable, acid soils. Shallow and peaty soils to be avoided	Very sensitive
Safflower (Carthamus tinctorius)	Spring: 120-160 Autumn: 200-230	Early growth: 15-20 Later growth: 20-30 (10-35)		Tolerance to frost; cool temperature required for good establishment and early growth	Fairly deep, well-drained soils, preferably medium textured: pH 6-8	Moderately tolerant
Sorghum (Sorghum bicolor)	100-140+	24-30 (15-35)	Short day/ day neutral	Sensitive to frost; for germination, temperature > 10°C; cool temperature causes head sterility	Light to medium/heavy soils relatively tolerant to periodic waterlogging: pH 6-8	Moderately tolerant

Source: Landon ed. 1984

Table 3-18c cont.

Crop	Total growing period (days)	Mean daily temperature for growth (°C) optimum (and range)	Day length requirements for flowering	Specific climatic constraints/requirements 1/	Soil requirements 2/	Sensitivity to salinity 3/
Soyabean (Glycine max)	100-130	20-25 (18-30)	Short day/ day neutral	Sensitive to frost; for some varieties temperature > 24°C required for flowering	Wide range of soil except drought susceptible and poorly drained: pH 6-6.5	Moderately tolerant
Sugarbeet (Beta vulgaris)	160-200	18-22 (10-30)	Long day	Tolerant to night frost; towards harvest mean daily temperature < 10°C for high sugar yield	Medium- to slightly heavy-textured soils, friable and well drained: pH 6-7	Tolerant
Sugarcane (Saccharum officinarum)	270-1 200	22-30 (15-35)	Short day	Tolerant of only very light frost; during the harvest period cool (10-20°C), dry, sunny weather is beneficial	Deep, well aerated with ground water deeper than 1.5-2 m but relatively tolerant to periodic high water-tables and/or flooding and O_2 deficit: pH 4.5-8.5; optimum pH 6.5	Moderately sensitive
Sunflower (Helianthus annuus)	90-130	18-25 (15-30)	Short day/ day neutral	Sensitive to frost	Fairly deep soils: pH 6-7.5	Moderately tolerant
Tobacco (Nicotiana tabacum)	90-120 (+40-60 in nursery)	20-30 (15-35)	Short day/ day neutral	Sensitive to frost	Quality of leaf depends on soil texture: pH 5-6.5	Moderately sensitive
Tomato (Lycopersicon esculentum)	90-120 (> 25-35 in nursery)	18-25 (15-28)	Day neutral	Sensitive to frost, high RH and strong wind; optimum night temperature 10-20°C	Light loam, well drained without waterlogging: pH 5-7	Sensitive
Watermelon (Citrullus vulgaris)	80-110	22-30 (18-35)	Day neutral	Sensitive to frost	Sandy loam is preferred: pH 5.8-7.2	Moderately sensitive
Wheat (Triticum spp)	Spring: 100-130 Winter: 180-250	15-20 (10-25)	Day neutral/ long day	Spring wheat: sensitive to frost; winter wheat; resistant to frost during dormancy (> 15°C), sensitive during post-dormancy period; requires a cold period for flowering during early growth. For both, dry period required for ripening	Medium texture is preferred; relatively tolerant to high water-table: pH 6-7	Moderately sensitive

Notes:
1/ Temperatures quoted are optimal, with ranges in parentheses.
2/ Indicative rooting depths and soil-water tension are given in Table F.8.
3/ See also Tables 7.12, 7.13 and 8.2 to 8.4.

Sources: Adapted from Doorenbos and Kassam (1979); see also ILACO (1981, pp 562ff) and Tables 7.12 and 13, 8.2 to 4. Sugarcane figures amended according to R A Yates (personal communication).

Table 3-18d

Indicative nutrient and water requirements for selected crops

Table F.7

Crop	Nutrient requirements 1/ N : P : K (kg ha^{-1}/growing period)	Ideal water requirements 2/ (mm/growing period)	Sensitivity to water supply (and ky value) 3/	Water utilisation efficiency for harvested yield (Ey) 4/ kg m^{-3} (and % moisture of product)
Alfalfa (Medicago sativa)	0-40: 55-65: 75-100	800-1 600	Low to medium-high (0.7-1.1)	1.5-2.0 Hay (10-15%)
Banana (Musa spp)	200-400: 45-60: 240-480	1 200-2 200	High (1.2-1.35)	Plant crop: 2.5-4 Ratoon: 3.5-5.6 Fruit (70%)
Bean (Phaseolus vulgaris)	20-40: 40-60: 50-120	300-500	Medium-high (1.15)	Fresh: 1.5-2.0 (80-90%) Dry: 0.3-0.6 (10%)
Cabbage (Brassica oleracea)	100-150: 50-65: 100-130	380-500	Medium-low (0.95)	12-20 Head (90-95%)
Citrus (Citrus spp)	100-200: 35-45: 50-160	900-1 200	Low to medium-high (0.8-1.1)	2-5 Fruit (85%, lime: 70%)
Cotton (Gossypium hirsutum)	100-180: 20-60: 50-80	700-1 300	Medium-low (0.85)	0.4-0.6 Seed cotton (10%)
Grape (Vitis vinifera)	100-160: 40-60: 160-230	500-1 200	Medium-low (0.85)	2-4 Fresh fruit (80%)
Groundnut (Arachis hypogaea)	10-20: 15-40: 25-40	500-700	Low (0.7)	0.6-0.8 Unshelled dry nut (15%)
Maize (Zea mays)	100-200: 50-80: 60-100	500-800	High (1.25)	0.8-1.6 Grain (10-13%)
Olive (Olea europaea)	200-250: 55-70: 160-210	600-800 (per year)	Low	1.5-2.0 Fresh fruit (30%)
Onion (Allium cepa)	60-100: 25-45: 45-80	350-550	Medium-high (1.1)	8-10 Bulb (85-90%)
Pea (Pisum sativum)	20-40: 40-60: 80-160	350-500	Medium-high (1.15)	Fresh: 0.5-0.7 Shelled (70-80%) Dry: 0.15-0.2 (12%)
Pepper (Capsicum spp)	100-170: 25-50: 50-100	600-900	Medium-high (1.1)	1.5-3.0 Fresh fruit (90%)
Pineapple (Ananas comosus)	230-300: 45-65: 110-220	700-100	Low	Plant crop: 5-10 Ratoon: 8-12 Fruit (85%)
Potato (Solanum tuberosum)	80-120: 50-80: 125-160	500-700	Medium-high (1.1)	4-7 Fresh tuber (70-75%)

Notes: See page 288.

cont

Source: Landon ed. 1984

Table 3-18d cont.

Crop	Nutrient requirements 1/ N : P : K (kg ha^{-1}/growing period)	Ideal water requirements 2/ (mm/growing period)	Sensitivity to water supply (and ky value) 3/	Water utilisation efficiency for harvested yield (Ey) 4/ kg m^{-3} (and % moisture of product)
Rice (paddy) (Oryza sativa)	100-150: 20-40: 80-120	350-700	High	0.7-1.1 Paddy (15-20%)
Safflower (Carthamus tinctorius)	60-110: 15-30: 25-40	600-1 200	Low (0.8)	0.2-0.5 Seed (8-10%)
Sorghum (Sorghum bicolor)	100-180: 20-45: 35-80	450-650	Medium-low (0.9)	0.6-1.0 Grain (12-15%)
Soyabean (Glycine max)	10-20: 15-30: 25-60	450-700	Medium-low (0.85)	0.4-0.7 Grain (6-10%)
Sugarbeet (Beta vulgaris)	150: 50-70: 100-160	550-750	Low to medium-low (0.7-1.1)	Beet: 6-9 (80-85%) Sugar: 0.9-1.4 (0%)
Sugarcane (Saccharum officinarum)	100-200: 20-90: 125-160	1 500-2 500 (per year)	High (1.2)	Cane: 5-10 (80%) Sugar: 0.6-1.2 (0%)
Sunflower (Helianthus annuus)	50-100: 20-45: 60-125	600-1 000	Medium-low (0.95)	0.3-0.5 Seed (6-10%)
Tobacco (Nicotiana tabacum)	40-80: 30-90: 50-110	400-600	Medium-low (0.9)	0.4-0.6 Cured leaves (5-10%)
Tomato (Lycopersicon esculentum)	100-150: 65-110: 160-240	400-600	Medium-high (1.05)	10-12 Fresh fruit (80-90%)
Watermelon (Citrullus vulgaris)	80-100: 25-60: 35-80	400-600	Medium-high (1.1)	5-8 Fruit (90%)
Wheat (Triticum spp)	100-150: 35-45: 25-50	450-650	Medium-high (Spring: 1.15 winter: 1.0)	0.8-1.0 Grain (12-15%)

Notes:

1/ Rough figures under irrigation; actual values will obviously depend on soil, climate, cultivar etc; also note that:
1 kg P = 2.4 kg P_2O_5
and 1 kg K = 1.2 kg K_2O

2/ Indicative rooting depths and soil-water tensions are given in Table F.8.

3/ ky = yield response factor = ratio of relative yield decrease (1 - actual yield/maximum yield) to relative evapotranspiration deficit (1 - actual ET/maximum ET)
ie ky = (1 - Ya/Ym):(1 - ETa/ETm)
ky of the total growing period:
low: ky < 0.85
medium: ky 0.85-1.0
medium-high: ky 1.0-1.15
high: ky > 1.15

4/ Ey = water utilisation efficiency = kg of produce m^{-3} of water supplied.

Source: Adapted from Doorenbos and Kassam (1979); sugarcane figures amended according to R A Yates (personal communication).

Table 3. Major criteria used in assessing the soil suitability for crops.

Crop Group / Crop	Slope	Effective Soil Depth	Soil Texture / Structure	Drainage	Water Release	Salinity mmhos/cm at 25°C	pH	Depth to Acid Sulphate	Thickness of Peat (drained)	Workability
					Soil Criteria					
A. Rubber										
Rubber	0–20°	>125 cm	Exclude LS or coarser	Exclude poorly drained	All Year	<2 mmhos in top 150 cm	4.0–6.0	>150 cm	<50 cm	N.I.*
B. Oil Palm										
Oil Palm	0–16°	>125 cm	Exclude SL or coarser	Some temporarily poorly drained	All year	<2 mmhos in top 150 cm	4.0–6.5	>100 cm	<100 cm	N.I.
C. Sago Palm										
Sago Palm	0–2°	>100 cm	Exclude SL or coarser	Very poorly to poorly only	–	<2 mmhos in top 150 cm	4.0–6.0	>125 cm	<50 cm	N.I.
D. Tapioca										
Tapioca	0–6°	>50 cm	Exclude clays and poor structures	Exclude poorly drained	All year	<2 mmhos in top 100 cm	4.3–7.3	>50 cm	No restriction	No restrictions allowed
Sweet Potatoes	0–6°	>50 cm	Exclude clays and poor structures	Exclude poorly drained	All year	<2 mmhos in top 100 cm	4.3–6.0	>50 cm	No restriction	No restrictions allowed
Soyabeans	0–6°	>25 cm	Exclude clays and poor structures	Well to imperfectly only	Growing season	<4 mmhos in top 50 cm	5.5–6.5	>50 cm	<25 cm	No restrictions allowed
Chilies	0–6°	>25 cm	Exclude clays and poor structures	Well to imperfectly	Growing season	<4 mmhos in top 50 cm	5.0–6.8	>50 cm	<25 cm	No restrictions allowed
Vegetables	0–6°	>25 cm	Exclude clays and poor structures	Well to imperfectly	Growing season	<4 mmhos in top 50 cm	4.5–6.5	>50 cm	No restriction	No restrictions allowed
E. Tea										
Lowland Tea	0–20°	>100 cm	Exclude sands, clays	Well to imperfectly	All Year	<2 mmhos in top 150 cm	4.0–6.0	>25 cm	No peat	N.I.
F. Grass										
Grasses (Cut)	0–12°	>25 cm	Exclude LS and coarser	Well to poorly	All year	<4 mmhos in top 50 cm	4.3–7.0	>50 cm	No restriction	No restrictions allowed
Stylo	0–12°	>25 cm	Exclude sands	Well to poorly	All year	<4 mmhos in top 50 cm	4.3–7.0	>50 cm	Not known	No restrictions allowed
G. Citrus										
Citrus	0–20°	>125 cm	Exclude sands and heavy clays	Well, some imperfectly	All year	<2 mmhos in top 150 cm	5.0–7.0	>150 cm	<50 cm	No stones
Chiku	0–20°	>125 cm	Exclude sands and heavy clays	Well to imperfectly	All year	<2 mmhos in top 150 cm	Not known	>150 cm	<50 cm	No stones
Mangosteen	0–20°	>125 cm	Exclude sands and heavy clays	Well to imperfectly	All year	<2 mmhos in top 150 cm	Not known	>150 cm	<50 cm	No stones
H. Papaya										
Papaya	0–12°	>50 cm	Exclude LS or coarser	Well to imperfectly	All year	>2 mmhos in top 100 cm	5.0–6.5	<100 cm	No peat	No stones
Pineapple	0–6°	>25 cm	All textures	Well to imperfectly	All year	<2 mmhos in top 100 cm	4.5–5.5	>50 cm	No restriction	No stones
Passion fruit	0–12°	>50 cm	Exclude sands and heavy clays	Well to imperfectly	All year	<2 mmhos in top 100 cm	4.5–6.5	>100 cm	<50 cm	No stones
Guava	0–12°	>50 cm	Exclude LS or coarser	Well to imperfectly	All year	<2 mmhos in top 100 cm	4.5–6.5	>100 cm	<100 cm	No stones
Salak	0–12°	>50 cm	Exclude LS or coarser	Well drained	All year	<2 mmhos in top 100 cm	Not known	>100 cm	No peat	No stones
I. Bananas										
Bananas	0–12°	>125 cm	Exclude LS or coarser	Well to imperfectly	All year	<2 mmhos in top 100 cm	5.0–7.0	>125 cm	<25 cm	No stones
Durian	0–12°	>100 cm	Exclude LS or coarser; firm soils; oxisolic soils	Well to imperfectly	All year	<2 mmhos in top 100 cm	4.5–6.5	>100 cm	No peat	N.I.
Rambutan	0–12°	>100 cm	Exclude LS or coarser	Well to imperfectly	All year	<2 mmhos in top 100 cm	4.5–6.5	>100 cm	<100 cm	No stones
Langast	0–12°	>100 cm	Exclude clays and sands	Well drained	All year	<2 mmhos in top 100 cm	Not known	>100 cm	No peat	N.I.
Duku	0–12°	>100 cm	Exclude clays and sands	Well drained	All year	<2 mmhos in top 100 cm	Not known	>100 cm	No peat	N.I.
Avocado	0–12°	>100 cm	Exclude LS or coarser	Well to imperfectly	All year	<2 mmhos in top 150 cm	5.5–8.5	>125 cm	No peat	N.I.
Kundangan	0–12°	>100 cm	Exclude clays	Well drained	All year	<2 mmhos in top 150 cm	Not known	>125 cm	No peat	N.I.
J. Cashew										
Cashew	0–20°	>100 cm	Exclude clays	Well to imperfectly	9 months	<2 mmhos in top 150 cm	4.0–7.3	>150 cm	<100 cm	N.I.
K. Cocoa										
Cocoa	0–12°	>150 cm	Exclude LS or coarser	Well to imperfectly	High all year	<2 mmhos in top 150 cm	5.0–7.5	>150 cm	<50 cm	N.I.
Coffee	0–12°	>125 cm	Exclude sands	Well to imperfectly	All year	<2 mmhos in top 150 cm	4.5–6.5	>100 cm	<125 cm	N.I.
L. Coconut										
Coconut	0–6°	>100 cm	Exclude LS or coarser	Well to imperfectly	All year	<2 mmhos in top 150 cm	4.5–7.5	>100 cm	<100 cm	N.I.
M. Maize										
Maize	0–6°	>50 cm	Exclude sands and clays	Well to imperfectly	Good in growing season	<2 mmhos in top 50 cm	>5.0	>125 cm	No restriction	No restrictions allowed
Sorghum	0–6°	>50 cm	Exclude sands	Well to imperfectly	Good in growing season	<4 mmhos in top 50 cm	>5.0	>125 cm	No restriction	No restrictions allowed
Groundnut	0–6°	>25 cm	Exclude sands and clays	Well to moderately well	Good in growing season	<4 mmhos in top 50 cm	5.5–7.0	>50 cm	No peat	No restrictions allowed
N. Rice										
Lowland Rice	0–2°	>25 cm	SCL or finer	Drainage control necessary	Dry during harvest	<4 mmhos in top 25 cm	>4.0	>25 cm	No peat	No restrictions allowed

*N.I.—Not important.

Source: USDA-SMSS 1981

Table 8 SOIL REQUIREMENTS OF RAINFED CROPS

CROPS	SLOPE (PERCENT) High Inputs		SLOPE (PERCENT) Low & Int. Inputs		DRAINAGE All Inputs		FLOODING All Inputs		TEXTURE High & Int. Inputs		TEXTURE Low Inputs		DEPTH (cm) All Inputs	
	Optimum	Marginal	Optimum	Marginal	Optimum	Range	Optimum	Marginal	Optimum	Range	Optimum	Range	Optimum	Marginal
Wheat	0 – 8	8 – 16	0 – 8	8 – 24	MW–W	I–SE	F_o	F_1	L–MCs	SL–MCs	L–SC	SL–KC	>50	25 – 50
Barley	0 – 8	8 – 16	0 – 8	8 – 24	MW–W	I–SE	F_o	F_1	L–MCs	SL–MCs	L–Sc	Sl–KC	>50	25 – 50
Pearl millet	0 – 8	8 – 16	0 – 8	8 – 24	MW–SE	I–E	F_o	F_1	L–CL	LS–KC	L–CL	LS–KC	>50	25 – 50
Sorghum	0 – 8	8 – 16	0 – 8	8 – 20	MW–W	I–SE	F_o	F_1	L–C	LS–MCs	L–SC	LS–KC	>50	25 – 50
Maize	0 – 8	8 – 16	0 – 8	8 – 20	MW–W	I–SE	F_o	F_1	L–C	SL–MCs	L–SC	LS–KC	>50	25 – 50
Upland rice	0 – 8	8 – 16	0 – 8	8 – 24	MW–W	I–SE	F_o	F_1	L–C	LS–KC	L–SC	LS–KC	>50	25 – 50
Bunded rice (paddy)	0 – 4	4 – 8	0 – 4	4 – 8	I–MW	VP–W	F_o–F_1–F_2	F_3	L–SiCL	SL–MCs	L–SiCL	SL–KC	>100	50 – 100
Cassava	0 – 8	8 – 16	0 – 4	4 – 16	W	MW–SE	F_o	F_1	L–SiCL	SL–KC	L–SiCL	LS–KC	>100	75 – 100
Sweet potato	0 – 8	8 – 16	0 – 8	8 – 20	MW–W	I–SE	F_o	F_1	L–SiCL	SL–C	L–SiCL	LS–KC	>75	50 – 75
White potato	0 – 8	8 – 16	0 – 8	8 – 20	W	MW–SE	F_o	F_1	L–SiCL	LS–MCs	L–SiCL	FS–KC	>75	50 – 75
Yam/cocoyam	0 – 8	8 – 16	0 – 4	4 – 16	W	MW–SE	F_o	F_1	L–SiL	SL–KC	L–SiL	LS–KC	>75	50 – 75
Chickpea	0 – 8	8 – 16	0 – 8	8 – 20	MW–W	I–SE	F_o	F_1	L–SC	SL–MCs	L–SC	MS–KC	>75	50 – 75
Phaseolus bean	0 – 8	8 – 16	0 – 8	8 – 20	MW–W	I–SE	F_o	F_1	L–CL	SL–KC	L–CL	LS–KC	>75	50 – 75
Soybean	0 – 8	8 – 16	0 – 8	8 – 20	MW–W	I–SE	F_o	F_1	L–SC	SL–KC	L–SC	LS–KC	>75	50 – 75
Groundnut	0 – 8	8 – 16	0 – 8	8 – 20	W–SE	MW–E	F_o	F_1	SL–SCL	LS–KC	SL–SCL	MS–KC	>50	20 – 50
Cotton	0 – 8	8 – 16	0 – 8	8 – 20	W	MW–SE	F_o	F_1	L–MCs	SL–MCs	L–SC	SL–KC	>100	75 – 100
Sugar cane	0 – 8	8 – 16	0 – 8	8 – 24	MW–W	P/I–SE	F_o	F_1	L–C	SL–MCs	L–KC	SL–SiC	>75	50 – 75
Banana	0 – 16	16 – 30	0 – 16	16 – 50	MW–W	I–SE	F_o	F_1–F_2	L–C	SL–MCs	L–KC	SL–SiC	>100	50 – 100
Oil palm	0 – 16	16 – 30	0 – 16	16 – 50	MW–W	I–SE	F_o	F_1–F_2	SCL–KC	L–C	L–KC	SL–SiC	>100	50 – 100
Cocoa	0 – 16	16 – 30	0 – 16	16 – 50	W	MW–SE	F_o	F_1	SCL–SC	L–C	L–KC	SL–SiC	>150	75 – 150
Coffee	0 – 8	8 – 16	0 – 8	8 – 30	W	MW–SE	F_o	F_1	L–SC	SL–KC	L–KC	SL–SiC	>150	75 – 150
Rubber	0 – 16	16 – 30	0 – 16	16 – 50	W	MW–SE	F_o	F_1	L–KC	SL–C	L–KC	SL–SiC	>150	75 – 150
Tea	0 – 16	16 – 30	0 – 16	15 – 50	W	MW–SE	F_o	F_1	L–CL	SL–SiC	L–KC	SL–SiC	>150	75 – 150
Citrus	0 – 8	8 – 16	0 – 8	8 – 30	W	MW–SE	F_o	F_1	LS–L	MS–SiCL	L–KC	SL–SiC	>150	75 – 150
Pasture	–	–	0 – 16	16 – 30	W–MW 1/	SE–I 1/	F_o – F_1 1/	F_2			SL–C	FS–MCm	>50	10 – 50

Source: Sys/Riquier 1979

Table 3-20 cont.

Table 8 (Cont.) SOIL REQUIREMENTS OF RAINFED CROPS

$CaCO_3$ (PERCENT)		GYPSUM (PERCENT)		pH		FERTILITY REQUIREMENT	SALINITY (mmhos)		ALKALINITY	
All Inputs		All Inputs		All Inputs		All Inputs	All Inputs		All Inputs	
Optimum	Marginal	Optimum	Marginal	Optimum	Range		Optimum	Marginal	Optimum	Marginal
0 – 30	30 – 60	0 – 5	5 – 20	6.0–8.2	5.2–8.5	moderate/high	0 – 5	5 – 10	0 – 30	30 – 45
0 – 30	30 – 60	0 – 5	5 – 20	6.0–7.5	5.2–8.5	moderate	0 – 8	8 – 12	0 – 35	35 – 50
0 – 25	25 – 50	0 – 3	3 – 15	5.5–7.5	5.2–8.2	low	0 – 4	4 – 6	0 – 30	30 – 45
0 – 30	30 – 75	0 – 5	5 – 20	5.5–8.2	5.2–8.5	low/moderate	0 – 5	5 – 10	0 – 20	20 – 35
0 – 15	15 – 30	0 – 3	3 – 15	5.5–8.2	5.2–8.2	moderate	0 – 4	4 – 6	0 – 15	15 – 25
0 – 15	15 – 30	0 – 3	3 – 15	5.5–7.5	5.2–8.2	low	0 – 2	2 – 4	0 – 20	20 – 40
0 – 15	15 – 30	0 – 3	3 – 15	5.5–7.5	5.2–8.2	low	0 – 2	2 – 4	0 – 20	20 – 40
0 – 1	1 – 10	0 – 0.5	0.5– 3	5.2–7.0	4.5–8.2	low	0 – 2	2 – 4		
0 – 15	15 – 30	0 – 3	3 – 15	5.2–8.2	4.5–8.5	moderate	0 – 3	3 – 6		
0 – 10	10 – 25	0 – 1	1 – 5	5.5–7.0	5.2–8.2	moderate	0 – 3	3 – 6		
0 – 1	1 – 10	0 – 0.5	0.5– 3	5.5–7.5	5.2–8.2	moderate	0 – 2	2 – 4		
0 – 25	25 – 50	0 – 3	3 – 15	6.0–7.5	5.5–8.2	low/moderate	0 – 3	3 – 6	0 – 8	8 – 15
0 – 20	20 – 35	0 – 0.5	0.5– 3	5.5–7.5	5.2–8.2	moderate	0 – 1	1 – 2	0 – 5	8 – 12
0 – 20	20 – 35	0 – 3	3 – 15	5.5–7.5	5.2–8.2	moderate	0 – 3	3 – 6	0 – 8	8 – 15
0 – 25	25 – 50	0 – 3	3 – 15	6.0–7.5	5.5–8.2	moderate	0 – 3	3 – 6		
0 – 25	25 – 40	0 – 3	3 – 15	6.0–7.5	5.5–8.2	moderate/high	0 – 8	8 – 12	0 – 20	20 – 35
0 – 25	25 – 50	0 – 5	5 – 20	5.5–8.2	4.5–8.5	moderate	0 – 5	5 – 8	0 – 8	8 – 15
0 – 5	5 – 15	0 – 1	1 – 5	5.5–7.5	5.2–8.2	moderate/high	0 – 2	2 – 4	0 – 4	4 – 10
0 – 1	1 – 10	0 – 0.5	0.5– 3	5.0–6.5	3.5–7.5	low/moderate	0 – 2	2 – 4		
0 – 1	1 – 10	0 – 0.5	0.5– 3	6.0–7.0	5.2–8.2	high	0 – 1	1 – 2		
0 – 1	1 – 10	0 – 0.5	0.5– 3	5.3–6.0	4.5–6.5	moderate/high	0 – 1	1 – 2		
0	0 – 1	0	0 – 0.2	5.0–6.0	4.0–6.5	low	0 – 1	1 – 2		
0	0 – 1	0	0 – 0.2	4.5–5.5	3.0–6.0	low	0 – 1	1 – 2		
0 – 10	10 – 25	0 – 1	1 – 5	5.5–7.0	5.2–8.2	moderate/high	0 – 4	4 – 8	0 – 4	4 – 10
0 – 30	30 – 50	0 – 5	5 – 25	5.5–8.5	4.5–9.5	moderate/low	0 – 16	16 – 25	0 – 35	35 – 50

Drainage classes

VP = very poor
P = poorly drained
I = imperfectly drained
MW = moderately well drained
W = well drained
SE = somewhat excessively drained
E = excessively drained

Textural sequence

MCm = montmorillonitic clay, massive
MCs = montmorrillonitic clay, structured
C = clay (mixed unspecified)
SiC = silty clay
KC = kaolinitic clay
SC = sandy clay
SiCL = silty clay loam
CL = clay loam
SiL = silt loam
SCL = sandy clay loam
L = loam
SL = sandy loam
LS = loamy sand
FS = fine sand
MS = medium sand
CS = coarse sand

Grassland

1/ Grazing in dry season

Table 3-21

Table 44 GROWTH LIMITING CONDITIONS FOR RICE ON SUBMERGED SOILS OF VARIOUS TYPES

KIND OF SOIL AND MAIN LIMITATIONS	OTHER GROWTH LIMITING CONDITIONS
Saline soils	
Arid saline soils	Alkalinity, Zn deficiency, N & P deficiencies
Acid coastal saline soils	Iron toxicity, P deficiency, deep water
Neutral and alkaline coastal and saline soils	Zn deficiency, deep water
Deltaic and estuarine acid sulphate soils	Iron toxicity, P deficiency, deep water
Coastal histosols	Nutrient deficiencies, H_2S toxicity, toxicity of organic substances, deep water, Fe toxicity
Acid sulphate soils	
Coastal soils	Salinity, Fe toxicity, N & P deficiencies, deep water
Old inland soils	N & P deficiencies
Histosols	Fe toxicity, H_2S toxicity, nutrient deficiencies, deep water, salinity
Iron-toxic soils	
Acid sulphate soils	Salinity, N & P deficiencies, deep water
Acid oxisols and ultisols	P deficiency, low base status, low Si content
Histosols	H_2S toxicity, toxicity of organic substances, macronutrient deficiencies, Zn and Cu deficiencies, deep water
Phosphorus deficiency in wetland rice	
Acid sulphate soils	Strong acidity, iron toxicity, low nutrient status, base deficiency, salinity
Acid oxisols and ultisols	Iron toxicity, base deficiency
Vertisols	Zinc deficiency, iron deficiency, salinity, alkalinity
Zinc deficient soils	
Saline-sodic and sodic soils	Salinity, N & P and Fe deficiencies
Vertisols	P and Fe deficiencies, salinity, alkalinity
Calcareous soils	K deficiency
Wet soils	Cu deficiency
Histosols	N, P, K, Si, Cu, deficiencies; H_2S toxicity, deep water

Source: after Ponnamperuma 1976.

Source: FAO SB 55 1985

Table 3-22a

Table 48 FEATURES OF IRRIGATION APPLICATION TECHNIQUES FOR EVALUATING CHOICE OF SYSTEM AND SUITABILITY OF LAND
A. SURFACE APPLICATION TECHNIQUES (page 1)

FEATURE	SMALL BASINS (MEDIUM) 1/	LARGE BASINS	BORDER STRIPS	SHORT FURROWS (MEDIUM) 1/	LONG FURROWS
1. Land development costs	Low	Often high, precision grading required	Low to medium depending on topography	Low	Often high, precision grading required
2. Capital intensity (field equipment)	Low	Low	Low	Low	Low
3. Labour intensity	High	Low	Medium	High	Low
4. Energy intensity	Low (gravity) High (pumped)	Low (gravity) High (pumped)	Low (gravity) High (pumped)	Low (gravity) High (pumped)	Low (gravity) High (pumped)
5. Size and shape of fields	Very flexible, often small and irregular	Large and regular shaped fields required	Long, rectangular, can be narrow	Very flexible, often small and irregular	Medium to large, regular shape
6. Topography	Important but generally not critical	Often critical if graded or level basin	Suitable slope and absence of cross slopes	Important but generally not critical	Often critical both for graded and dead level furrows
7. Soils	Intake rates often critical for efficient use of water and uniformity of application; influences size of basins, lengths of furrows or border strips in relation to the rate of water delivery, slope and uniformity of microrelief.				
8. Management skills	Suitable for small farmers in LDCs	Sophisticated management required	Suitable for middle level management	Suitable for small farmers in LDCs	Sophisticated management required
9. Cropping limitations and mechanization	Wide range of crops, but not mechanized	Suitable field crops planted on the flat or ridges and mechanized	Suitable field crops planted on the flat and mechanized	Wide range of crops, but not mechanized	Row crops, not those planted on the flat; mechanized
10. Scheduling by frequency, rate and duration of the water supply	Continuous (rice); Intermittent, generally fixed by water agency; often 10-30 l/s, limited, fixed duration	Usually intermittent, by arrangement or fixed by water agency; high delivery rates, short duration possible	Intermittent, by arrangement or fixed by water agency; rate must be matched by labour, cutbacks to flow important	Intermittent, by arrangement or fixed by water agency; often 10-30 l/s, limited, fixed duration	Intermittent, by arrangement or fixed by water agency; delivery rate must match labour, cutbacks to flow important
11. Factors affecting uniformity of application	Topography, soils management, size and shape of fields, water supply, labour skills	Levelling and grading of land, soils, management, size and slope of basin, in-field variability	Uniformity of grade, absence of cross slope, rate and duration, cut-back stream size, labour skills	Topography, soils, management, size and shape of fields, water supply, labour skills	Uniformity of grade or level, rate and duration, cutbacks to stream flow, or use of return flows, variability
12. Mechanical problems	None	None	None	None	None
13. Security problems	None	None	None	None	None
14. Leaching and salts problems	Salty patches on underwatered high spots	No special problems	No special problems	Salt accumulation on ridges, salty patches on high spots	Salt accumulation on ridges, otherwise no special problems
15. Location	If water in short supply distance from source is important	Usually adequately serviced	No special problems	If water in short supply distance from source is important	No special problems
16. Field water use efficiencies	Inherently low on permeable soil; minimum application is 50 mm per irrigation	Can be very high in very accurately levelled basins	Very dependent on the water control, cross slope, can be high and low	Inherently low on parmeable soil; minimum application is 50 mm per irrigation	Very dependent on the water control, rate, duration, slope, high or low
17. Main problems generally encountered	Poor uniformity of application, overwatering, land wasted in bunds and channels	Very high land levelling costs. Exposure of subsoils	Poor uniformity of application, erosion, crop damage	Poor uniformity of application, overwatering, land wasted in channels	Poor uniformity of application, excessive run-off, erosion
18. General remarks	Easily administered water schedules, at expense of efficient water use. Good for third world farmers	Suitable for large mechanized units where labour is costly and energy/water use efficiency is important	Suitable for medium sized farms not growing row crops, especially for forage	Easily administered water schedules at expense of efficient water use Good for third world farmers	Suitable for large mechanized units where labour is skilled

1/ This indicates that there are intermediate conditions to be considered.

Source: FAO SB 55 1985

Table 3-22b

Table 48 FEATURES OF IRRIGATION APPLICATION TECHNIQUES FOR EVALUATING CHOICE OF SYSTEM AND SUITABILITY OF LAND
B. SPRINKLER AND LOCALIZED IRRIGATION TECHNIQUES (page 1)

	SPRINKLERS				
	LOW OUTPUT MEDIUM 1/	HIGH OUTPUT	MINI-SPRINKLERS	ORIFICE AND LONG PATHWAY EMITTERS (ON-LINE OR IN-LINE)	BIWALL TUBING
1. Land development costs	Low or nil	Low or nil	Low or nil	Low or nil	Low or nil
2. Capital intensity (field equipment)	High	High	High	High	High
3. Labour intensity	Hand move systems, high labour need, mechanized and mobile systems low.		High need for labour in laying and removing tubing, low labour need during period of irrigation and/or automatic control of water supply		High labour for installation, low for operating, often ploughed in
4. Energy intensity	Medium-high water pressures required	Medium to very high pressures	Low pressures (losses on filtration)	Low pressures (no advantage if pressure for filtration is high)	Low pressures but losses over filters
5. Size and shape of fields	Not suitable for very small fields. Hand move systems are flexible; and mobile, mechanized systems inflexible requiring large, regular shaped fields.		Very adaptable; limited length of laterals	Very adaptable; limited length of laterals	Very adaptable; Limited length of laterals
6. Topography	Not suitable for very steep land. Some limitations for mobile and mechanized systems but less so than for surface irrigation systems		Very adaptable	Very adaptable	Very adaptable
7. Soils	Suitable for soils with high intake rates. Sometimes problems with low intake soils. Problems with high rate of application, mobile systems and rainguns		No intake problems. Some lateral water spreading	No intake problems. Lateral spread is limited especially on sandy soils	No intake problems. Lateral spread is limited especially on sandy soils
8. Management skills	Not suitable for farmers in the third world who cannot get spares or manage the operation effectively		Intermediate level of management but fairly simple	Sophisticated management to prevent malfunction	Sophisticated management to prevent malfunction
9. Cropping limitations and mechanization	Apart from some tall crops and rice no problems. Highly mechanized wheel mounted laterals, centre pivots, cable systems, or permanent systems reduce labour requirements		Better for tree crops and widely spaced row crops; automated control possible	Intensive high value crops; unsuited for seedbed irrigation, reel-in systems, automation	Wide row crops, can be subsurface (e.g. sugarcané), mechanized laying
10. Scheduling by frequency, rate or duration of the water supply	Usually on demand. Intervals are days or weeks, medium to high rates, 3-15 mm per hour	Usually on demand. Intervals are days or weeks, medium to high rates, 3-15 mm per hour	Usually on demand. 1-3 day intervals. Low-medium rate, medium-long duration	Usually on demand. 1-3 day intervals or continuous. Low rate, long duration	Usually on demand. 1-3 day intervals or continuous. Low rate, long duration
11. Factors affecting uniformity of application	Wind is the major problem of hand-mover sprinkler systems. Drop in pressures along lines, distances of throw and spacing between sprinklers		Not uniform when used as localized irrigaation; pressure regulators can be used to improve uniformity	Not uniform when used as localized irrigation, variation along laterals is a design factor	Not uniform when used as localized irrigation, variation along laterals is a design factor
12. Mechanical problems	Moving parts wear, nozzles may block, some filtration and servicing needs		Nozzle blockages	Filtration critical aspect to stop clogging; a major limitation	
13. Security problems	Not vandal proof; pipe and metal fittinge must be removed from field at night in some countries		Not very vulnerable to damage or theft. Needs attention	Not particularly vulnerable and equipment can be left operating in field for long periods unattended	
14. Leaching and salt problems	Under-watering can be a problem on very impermeable soils; uniformity problems; scorch on wetted leaves especially important e.g. citrus		No special problem. Low level avoids leaf scorch in tree crops	The major advantage is better yields with salty water due to the soil never drying out, frequent irrigations. Salt encrustations on soil surface	
15. Location	Distance and elevation major cost factors in pressure head losses and requirements		Intermediate costs for pressurizing	Long duration irrigation results in smaller head losses but note pressure head loss across filters	
16. Field water use efficiency	Much affected by wind and distribution uniformity, can be high or low		Very high	Very high	Very high
17. Main problems generally encountered	Costly equipment, high pumping costs, operational difficulties, hand move problems on wetted land, application rates too high with moving systems, wind drift and uneven application		Excessive lengths of piping, especially for closely spaced crops. High labour for unblocking nozzles	Clogging, installation and removing long lengths of tubing. Weeding. High cost. No use for seedbeds	Clogging, installation, no use for seedbed irrigation and therefore may need sprinklers as well
18. General remarks	Suitable for high intake soils and uneven topography for a wide range of crops and extensive farming or intensive systems		Low pressure requirements suitable for small to medium-scale farmers	Better yields and water use efficiency justifies high capital costs on unintensive farms	Better yields and water use efficiency can justify high capital costs

Source: FAO SB 55 1985

Table 3-22 c1

TABLE 16. Qualification of the grades in land use types qualities

Characteristics	Grade		
	High	Fair	Low
1. Soil nutrients availability	1	2	3
2. Soil water availability	1	2	3
3. Soil oxygen availability	1	2	3
4. Salts and/or sodium presence in soil	3	2	1
5. Soil salinization and/or sodization risk	3	2	1
6. Soil surface crusting risk	3	2	1

Table 15. Qualification of the grades of irrigation management qualities

Characteristics	Grade			
	High	Fair	Low	Very Low
1. Availability and water qualities for irrigation	1	2	3	4
2. Soil topography	1	2	3	4
3. Soil compaction risks	4	3	2	1
4. Drainage possibilities	1	2	3	4
5. Salts and/or sodium management in soil	4	3	2	1
6. In depth water losses risk	4	3	2	1
7. Flooding and/or puddling risk	4	3	2	1
8. Possibility of applying mechanization practices	1	2	3	4

Source: in ICID 1989

Table 3-22 c2

TABLE 9. Characteristics which define "Soil nutrients availability"

Characteristics	Grade		
	High	Fair	Low
1. Fertility	Very high to high	Moderate	Low to very low
2. (Ca+Mg)/K	< 40	40 - 150	>150
3. Ca/Mg	2 - 4	1 - 2 or	< 1 or
Relation		4 - 10	> 10

TABLE 10. Characteristics which define "Soil water availability"

Characteristics	Grade		
	High	Fair	Low
1. Availability water (cm/m of soil)	> 15.1	15 - 5.1	< 5
2. Infiltration Family	Fair	High	Low
Basic Infiltration (mm/h)	37.5 - 12.5	> 37.5	< 12.5
3. Hydraulic conductivity (cm/h)	< 1.5	7.6 - 2.5	> 7.6
4. Water table level in the irrigation time (cm)			
If:			
- Moderate texture soils	80 - 120	120 - 150	> 150
- Coarse and clayey texture soils	100 - 60	100 - 120	> 120
- Sodium or salts soils	40 - 60	80 - 100	> 100

TABLE 11. Characteristics which define "Soil Oxygen availability"

Characteristics	Grade		
	High	Fair	Low
1. Natural drainage	Excessively to well	Well to moderately	Somewhat poorly or less
2. Color soil	Reds, yellows, fort yellow whites	Values more than 1	Gray, values less than 1 or mottles
3. Air porosity in 30cm first in depth	> 120	10 - 20	< 10
4. Water table level (cm)	More depth than 120 all year	60 - 120 some time in year	Less than 60 some time in year
5. Unpermeability layer position (cm)	> 300	300 - 150	< 150
6. Flooding or puddling risk	< 1 in 5 years	1 in 3 years	1 in a year

TABLE 12. Characteristics which define "Soil salinization and/or sodization risk"

Characteristics	Depth (cm) in which there are salts and/or sodium			
	Suitability Grade			
	High	Fair	Low	Very Low
1. Salts (dS/m)				
> 16	< 25	25 - 50	50 - 100	> 100
16 - 8		< 25	25 - 50	> 50
8 - 4			< 25	> 25
4 - 2				< 25
< 2	There isn't limitation			
2. Sodium E.S.P. (%)				
> 50	< 25	25 - 50	50 -100	> 100
50 - 15		< 25	25 - 50	> 50
15 - 7			< 25	> 25
< 7	There isn't limitation			

TABLE 13. Characteristics which define "Soil salinization and/or sodization risk"

Characteristics	Grade		
	High	Fair	Low
1. Soil			
a) Basic Infiltration (cm/h)	< 5	5 - 12.5	> 12.5
b) Hydraulic conductivity (m/day)	< 0.5	0.5 - 3	> 3
2. Water Table depth (cm)			
a) If normal water:			
- Fine or coarse textures	< 60	60 - 90	> 90
- Medial textures	< 100	100 - 150	> 150
b) If water quality isn't normal:			
- Fine or coarse textures	< 120	120 - 150	> 150
- Medial textures	< 150	150 - 200	> 200
3. Drenability			
Layer between 50 - 100 cm			
a) CE (ds/m)	> 4	4 - 2	< 2
b) ESP (%)	> 15	15 - 8	< 8
4. Water irrigation quality (USDA System)			
Salinization risk	C_4 and C_3	C_2	C_1
Sodization risk	S_4 and S_3	S_2	S_1
6. Effective precipitation > Evapotranspiration (month/year)	< 2	2 - 6	> 6

TABLE 14. Characteristics which define "Soil surface crusting risk"

Characteristics	Grade		
	High	Fair	Low
IF: % Organic Matter is more than 3% and surface layer have:			
(1) Texture*	CL.SC.SL.S	SCL. C	Sa.LS.SaL.L
(2) Silt % IF pH>7	> 30		
(3) Clays kind	Montmorillonite	Kaolinate	Mice
(4) % Carbonate as $CaCO_3$	> 18		
(5) ESP %	> 40	40 - 15	< 15
IF: % Organic Matter is less than 3% and surface layer is:			
(1) Texture*	SCL.SC.CL.SL	SaL.L.C	Sa.Ls
(2) Silt %	> 30		
(3) Clays kind	Montmorillonite	Kaolinate	Mice
(4) % Carbonate as $CaCO_3$	> 25	25 - 18	< 18
(5) ESP %	> 15	15 - 8	< 8

* CL = Clay loam, SC = Silty clay, SL = Silt loam, S = Silt, SCL = Silty clay loam, C = clayly, Sa = Sand, Ls = Loamy sand, SaL = Sand loamy, L = Loam

TABLE 17. Irrigation System Requirements in Quality Terms

Irrigation System	Availability and water qualities for irrigation				Soil Topography				Soil Compaction risk				Drainage Possibilities				Salts and/or sodium management in soil				In-depth water losses risk				Flooding and/or puddling risk				Possibility of applying mechanization			
Suitability grade	A_1	A_2	A_3	A_4	A_1	A_2	A_3	A_4	A_1	A_2	A_3	A_4	A_1	A_2	A_3	A_4	A_1	A_2	A_3	A_4	A_1	A_2	A_3	A_4	A_1	A_2	A_3	A_4	A_1	A_2	A_3	A_4
1. Basin listing	1	2	2	3	3	4	4	4	2	3	4	4	1	2	3	4	1	2	2	3	2	2	3	4	2	3	3	4	2	3	3	4
2. Basin Irrigation	1	1	2	3	2	3	3	4	2	2	3	3	2	3	4	4	2	3	3	4	1	1	2	3	2	3	3	4	1	2	3	4
3. Border	1	1	2	3	1	1	2	3	1	1	2	3	1	2	3	4	1	2	2	3	1	2	3	4	2	2	3	4	1	1	2	3
4. Contour border																																
- wide interval dikes	1	1	2	3	2	2	3	4	1	1	2	3	1	2	3	4	1	2	2	3	1	1	2	3	2	2	3	4	1	1	2	3
- short interval dikes	1	2	3	4	1	2	3	4	1	2	3	3	1	2	3	4	1	2	2	3	1	1	2	3	2	2	3	4	1	1	2	3
5. Pool	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	2	2	3	4	1	2	3	4	1	1	2	3
6. Corrugation	1	2	3	4	2	2	3	3	1	1	2	3	1	2	3	4	1	2	2	3	1	2	3	4	1	2	3	4	1	1	2	3
7. Furrows	1	2	3	4	2	2	3	3	1	2	3	4	1	2	3	4	1	1	2	3	1	2	3	4	1	2	3	4	1	1	2	3
8. Contour furrows	2	2	3	3	2	2	3	4	2	3	4	5	1	2	3	4	1	1	2	3	2	2	3	4	1	2	3	4	2	3	4	4
9. Sprinkler Irrigation	2	3	3	4	3	4	5	5	2	3	3	4	2	3	4	5	3	3	4	4	2	3	3	4	1	1	2	3	2	3	4	5
10. Drip Irrigation	3	4	4	4	5	5	5	5	5	5	5	4	3	4	5	5	4	5	5	5	4	5	5	5	1	2	3	4	5	5	5	5

Source: in ICID 1989:321

Table 3-23

Table 1

LAND EVALUATION CRITERIA FOR TECHNICAL SELECTION OF SPRINKLER IRRIGATION SYSTEMS

LAND CONDITIONS	Type of aspersion 1/			Type of sprinkler (and pressure)			Type of system				Type of cooperative distribution system	
	High rain intensity	Medium rain intensity	Low rain intensity	Long range 2/	Medium range	Short range	Fixed	Stationary	Semifixed mobile	Mechanized	By "shifts"	Without shifts
SOIL												
- sticky, clayey	-	-	xx	-	-	xxx	x	x	x	-	-	xx
- gravelly, sandy	x	x	-	x	x	-	xx	x	-	-	xx	-
- medium texture	x	xx	-	x	x	-	x	x	x	x	x	x
TOPOGRAPHY												
- sloping terrain	-	x	xx	x	xx	x	x	x	x	-	x	x
- flat terrain	x	x	-	x	x	x	x	x	x	xxx	x	x
CROPS												
- corn	xx	x	-	xx	x	-	-	xx	x	x	-	xx
- alfalfa	x	x	-	x	xx	-	-	7	xx	x	-	xx
- orchards or vineyards	-	x	xx	-	x	xx	xx	x	x	-	-	xx
- citrus grove	xx	xx	x	-	-	xxx	xx	x	-	-	x	x
- vegetables	-	x	xx	-	x	xx	x	xx	-	-	x	xx
PROPERTY HOLDINGS												
- small farms (and small fields)	x	x	x	-	x	x	x	xx	xx	-	-	xxx
- medium size farms	x	x	x	x	x	x	x	xx	x	xx	x	xx
- large farms (and large fields)	x	x	x	xx	x	-	x	x	xx	xxx	xx	x
CLIMATE												
- windy	xx	x	-	-	-	xxx	xx	xx	-	x	x	x
- humid or subhumid	x	x	x	x	x	-	-	x	xx	xx	-	xxx
- arid	xx	x	-	-	x	xx	xx	xx	-	x	xx	x

NOTES: 1/ high intensity 12 mm/hr; medium intensity 6-12 mm/h; low intensity 6 mm/h.
2/ jet length: long range 40 m (4-10 atm); medium range 25-40 m (2,5-4 atm); short range 25 m (2.5 atm).

Source: FAO. WSSR 50. 1979

Table 3-24

Table 1: Natural metal contents of important parent materials of soil*) (X = order of magnitude)

	Cd	Mn	Ni	Co	Zn	Cu	Cr	Pb	Hg	Fe	Al
	mg/kg									mg/g	
Ultrabasic rocks	0.X	1600	2000	150	50	10	1600	1	0.0X	90	20
Basalt	0.2	1500	130	50	100	90	170	6	0.09	90	80
Granite, rich in Ca	0.1	500	15	7	60	30	20	15	0.08	30	80
Granite, poor in Ca	0.1	400	5	1	40	10	4	20	0.08	15	70
Syenite	0.1	900	5	1	130	5	2	10	0.0X	40	90
Shale	0.3	900	70	20	100	50	90	20	0.4	50	80
Sandstone	0.0X	X0	2	0.3	15	X	30	7	0.03	10	25
Limestone	0.04	1000	20	0.1	20	4	10	10	0.04	4	4
Loess			10	10	40	10		30		20	50
Marl	0.2	400			50	20		30		20	30
Flurvoglacial sand	0.1							10		1—2	6

*) TUREKIAN, K.K. and WEDEPOHL, K.H., 1961: Distribution of the elements in some major units of the earth's crust: The Geological Society of America, Bulletin vol. 72, 175—192: with supplements by BLUME and FLEIGE

Table 3: Relative binding strength1) for metal ions depending on soil constituents for a given pH limit

Metal	pH limit	sustrate-dependent binding strength below threshold pH2) through: humus	clay	sesquioxides3)
Cd	6	4	2	3
Mn	5.5	2	3	3
Ni	5.5	3—4	2	3
Co	5.5	3	2	3
Zn	5.5	2	3	3
Al	5.5	5	4	4
Cu	4.5	5	3	4
Cr(III)	4.5	5	4	5
Pb	4	5	4	5
Hg	4	5	4	5
Fe(III)	3.5	5	5	

1) rating: 1 = very weak, 2 = weak, 3 = medium, 4 = strong, 5 = very strong
2) Above threshold pH considerable accumulation through formation of oxides (Al, Fe, Mn) and binding of hydrocomplexes (others)
3) Sesquioxides = Fe-, Al- and Mn-oxides

Table 2: Metal contents frequently occurring in soils as well as legal threshold values for sewage sludge application (after German sewage sludge decree)

Metal		total content in air-dry soil (mg/kg): normal values	threshold values1)
Cd	cadmium	0.01 — 0.7	3
Mn	manganese	20 — 3000	
Ni	nickel	2 — 50	50
Co	cobalt	1 — 10	25 1)
Zn	zinc	3 — 100	300
Al	aluminium	5000 — 10^5	
Cu	copper	1 — 40	100
Pb	lead	0.1 — 20	100
Cr	chrome	2 — 50	100
Hg	mercury	0.01 — 0.5	2
Fe	iron	10^3 — $5 \cdot 10^4$	

1) Swiss sewage sludge decree

Table 4: Influence of soil acidity on the relative binding strength for metals (FSM) in sandy soils (texture class S, Su2) with low humus content (<2%)

Metal	Relative binding strength FSM for pH ($CaCl_2$) values of: 2.5	3	3.5	4	4.5	5	5.5	6	6.5	7—8
Cd	0	0—1	1	1—2	2	3	3—4	4	4—5	5
Mn	0	1	1—2	2	3	3—4	4	4—5	5	5
Ni	0	1	1—2	2	3	3—4	4	4—5	5	5
Co	0	1	1—2	2	3	3—4	4	4—5	5	5
Zn	0	1	1—2	2	3	3—4	4	4—5	5	5
Al	1	1—2	2	3	4	4—5	5	5	5	5
Cu	1	1—2	2	3	4	4—5	5	5	5	5
Cr (III)	1	1—2	2	3	4	4—5	5	5	5	5
Pb	1	2	3	4	5	5	5	5	5	5
Hg	1	2	3	4	5	5	5	5	5	5
Fe (III)	1—2	2—3	3—4	5	5	5	5	5	5	5

Evaluation of FSM: 0 = none, 1 = very weak, 2 = weak, 3 = medium, 4 = strong, 5 = very strong

Table 5: Additions to take the ratings of Table 4 for metal binding in relation to differences in humus content (mean of the upper 30 cm)

Humus-range h1)	Humus-content %	binding strength of humus acc. Table 3: 2	3	3—4	4	5
1—2	< 2	0	0	0	0	0
3—4	2— 8	0	0—1	0—1	0—1	1
5	8—15	0—1	0—1	1	1	1—2
6	> 15	0—1	1	1	1—2	2

1) according to Water Management Standards No. 115

Table 6: Additions to the ratings of Table 4 for metal binding (FMSo) in relation to differences in the clay content or texture (mean of upper 30 cm)1)

Clay content %	German texture class	US-Soil Taxonomy2)	binding strength of clay according to Table 3: 2	3	4	5
<5(8)	S, Su2	sand	0	0	0	0
5—15(17)	St2, Sl2, Sl3, Su, Us, U	loamy s., s. loam1), silt loam1), s. clay loam, loam	0	0	0—1	0—1
17—25	Sl4, Ul, Uls, Ls, Lu, St3, Ts4	s. loam2), silt loam2)	0	0—1	0—1	1
25—45	T1, Ts2, 3, Tu, Lts, Lt	s. clay, clay loam, silty clay (loam)	0	0—1	1	1—2
>45	T	clay	0	1	1—2	2

1) For 25 weight % gravel or stones, each addition is to be reduced by 0.5
2) s. = sandly, 1 = 10% clay, 2 = >10% clay

Source: Blume ed. 1992

Table 7: Additions to the ratings of Table 4 for metal binding (FMSo) in relation to elevated iron oxides

Sesquioxide influence acc. Table 3	Influence of higher iron-oxide content on FSM at Hue ≦7.5 YR and Chroman: value 0—1	1—1.5	>1.5
3	0	0—1	1
4	0	1	1—2
5	0	1—2	2

Table 8: Additions to the ratings of Table 4 for metal binding in order to take into account the humus content and texture of the subsoil (at least 30 cm thick) layer

Subsoil property	addition
h 3—6 or > 2 % humus	up to 1
> 17 % clay	up to 1

Table 9: Influence of the climatic water balance (infiltration rate) and metal binding on metal retention in soils (FSMt)1)

Climatic water balance2): ~~Symbol~~ class	mm/year	Binding strength FSMt according to Tables 4—8: 0	1	2	3	4	5
1	0—100	0—1	2	3—4	4—5	5	5
2	100—200	0	1—2	3	4	4—5	5
3—4	200—400	0	1—2	2—3	3—4	4—5	5
5—6	>400	0	1	2	3	4	5

1) FSMt scale:
0 = none, 3 = medium,
1 = very weak, 4 = high,
2 = low, 5 = very high
2) Climatic water balance as the difference of annual precipitation and evaporation (DVWK Water Management Standards No. 116)

Table 10: Influence of metal retention in the groundwater free soil (FSMt) after Table 9, and of the mean groundwater table (groundwater scale in line with DVWK Water Management Standards No. 115, Table 6) on the risk of groundwater pollution FSMw1)

FSMt	groundwater ~~scales~~ class: 1 <0.2	2 −0.4	3 −0.8	4 −1.3	5 −1.6	6 −2	>2 2)
0—1	5	5	5	5	5	5	5—4
2	5	5	4	4	4	4	3
3	5	5	4	3	3	3	2
4	5	5	4	3	3	2	1
5	5	5	3	2	2	1	1

1) FSMw scale:
1 = very low, 4 = high,
2 = low, 5 = very high
3 = medium,
2) mean groundwater table in m below surface

5.2 Soil unit : Gleysol from debris marl under a meadow near Ravensbruck (Upper Swabia), climatic water balance 4 (+ 350 mm/a)

Ah (0—30 cm): Lt, very dark brown (7.5 YR 2.5/4), strongly humus (h4), pH 5.1

Go (30—50 cm): Ls, reddish brown (5 YR 4/6), poor in humus (h1), ph 5.1

Gr (below 100cm): Ls, green-grey (5 BG 6/1)

Groundwater scale Gw 3 (mean groundwater level 38 cm)

Diagnosis of immobilization of heavy metals in topsoil:

	Cd	Zn	Cu
Influence of pH (Table 4)	3	4	5
Influence of humus (Tables 3 and 5)	+1	0	+1
Influence of texture (Tables 3 and 6)	0	+1	+1
Fe-oxide influence (Tables 3 and 7)	+1	+1	+1
Deduction for temporary waterlogging	−1	−1	−1
Binding strength FSMo	4	5	5
Evaluation	high	- very high -	

Diagnosis of groundwater pollution risk:

	Cd	Zn	Cu
Influence of pH (Table 4)	3	4	5
Influence of humus (Tables 3, 5 and 8)	+1	0	+1
Influence of texture (Tables 3, 6 and 8)	0	+1	+1
Fe-oxide influence (Tables 3 and 7)	+1	+1	+1
Deduction for temporary water logging	−1	−1	−1
Binding strength in total soil FSMt	4	5	5
Influence of the climate 350 mm and the binding strength (Table 9)	4	5	5
Groundwater pollution risk (Table 10)	4	3	3
Evaluation	high	- medium -	

Table 11: Recommended measures depending on the binding strength FSMo and groundwater risk scale FSMw of a soil with regard to heavy metals

Binding strength FSMo	Risk to ground water FSMw	Recommended measures	heavy metal measures scale
1 very weak	5 very high	Discharge of any type of waste products is prohibited. Where the presence of former contaminated sites is suspected, immediate investigation of the heavy metal load is requested. For former contamination, the binding strength of the soil is to be increaaed and the pH value in the aoil and displacement of the heavy metals is to be controlled annually.	5
2 weak	4 high	Discharge of wastes is prohibited if there is suspicion even of low heavy metal load. Where the presence of former contamination or potential contamination from the environment is suspected, the heavy metal contamination must be investigated immediately. Provided there is a heavy metal contamination the binding capacity of the soil must be increased and the pH values in the soil controlled annually. Control is required also in case of heavy metal displacements in the soil profile if pH values decrease, otherwise at least every three years.	4
3 medium	3 medium	Avoid, if possible, the discharge of waste products even if occasionally with low heavy metal content. At any rate investigation of previous pollution. In the case of discharge or where former contamination is present, control of the pH values in the soil every 3 years. Control of heavy metal displacement in the profile where pH values decrease, otherwise at least every 6 years.	3
4 strong	2 low	Discharge of waste pursuant to valid legal provisions possible after investigation of other previous load. In the case of discharge or the presence of former contaminated sites, control of pH values in soil every five years, control of heavy metal displacement in the case of falling pH values, otherwise every 10 years.	2
5 very strong	1 very low	In case of discharge measures must be taken as under 2. In case of discharge or former contaminations, control of pH values in the soil every 7 years, control of heavy metal displacement in soil profile in the case of falling pH values otherwise every 10 years.	1

Source: DVWK 1991

Tab. 2.7.5/2: Eigenschaften organischer Biozide und Verhalten in Böden bei praxisüblicher Dosis und günstigen Abbaubedingungen bei 11 – 16 °C in lockeren, lehmigen Ackerböden (pH 5.5 – 6.5, 2 – 4 % Humus) (n. HELLING u.a. 1971, HAMAKER 1972, PESTEMER 1975/77, KENAGA 1980, Anonym 1982 u. 1990, OTTOW 1982, BAIER u.a. 1985; K. DOMSCH u. H. NORDMEYER, freundl.mündl.Mittlg.)

Bewertungsstufen: 0 praktisch nicht; 1 sehr gering, sehr schwach; 2 gering, schwach; 3 mittel bis erhöht; 4 hoch, stark; 5 sehr hoch, sehr stark; ( ) Unsichere Angaben

Löslichkeitsstufen (mg/l H_2O bei 20 °C): 1 < 1; 2 1 – 50; 3 50 – 500; 4 > 500

Bindungsstufen: Sorptionskoeffizient nach FREUNDLICH von Humus bzw. Ton:
k_{oc}: 1 1 – 100; 2 100 – 300; 3 300 – 1 000; 4 1 000 – 10 000; 5 > 10 000
k_{Ton}: 1 0.5 – 50; 2 50 – 150; 3 150 – 500; 4 500 – 5 000; 5 > 5 000
pH-Einfluß: Bindung steigt mit zu- (+) oder abnehmendem (–) pH; 0 ohne Einfluß

Abbaustufe (> 75 %): 1 > 3 Jahre; 2 1 – 3 Jahre; 3 18 Wochen bis 1 Jahr; 4 < 18 Wochen; 5 < 6 Wochen

Flüchtigkeitsstufen (Dampfdruck in hPa bei 20 – 25 °C): 1 < 10^{-3}; 2 10^{-3} – 100; 3 100 – 5 x 10^3; 4 > 5 x 10^3 (orientierende Daten für die reine Substanz)

Mobilitätsstufen (Jährl. Verlagerungstiefe durch 1 500 mm N bei 25 °C in Lehmbod..m. ca. 2 % Humus u. pH 6 im A_p): 1 < 10; 2 5 – 20; 3 15 – 40; 4 > 35 cm

Alphabetische Ordnung der Pflanzenschutzmittel:

Aldicarb 60, Aldrin 32, Amitrol 11, Anilazin 9, Atrazin 6, Benomyl 77, Bentazon 4, Bromacil 91, Bromoxynil 85, Butylat 52, Captafol 82, Captan 81, Carbaryl 44, Carbenazin 79, Carbofuran 45, Carboxin 62, Chloramben 23, Chlordan 35, Chloridazon 3, Chlormequat 90, Chlortoluron 72, Chloropropham 49, DDT 37, 2.4-D 16, D(e)iquat 1, Dicamba 22, Diallat 50, Diazinon 43, Dichlobenyl 83, Dichlorprop 21, Dichlorpropen 38, Dieldrin 33, Dinoseb 26, DNOC 27, Diuron 67, Endosulfan 31, EPTC 53, Ethofumesat 92, Fenpropimorph 89, Fenuron 65, Fluazifop-butyl 20, Glyphosat 86, Heptachlor 34, Hexachlorbenzol 30, Ioxynil 84, Isoproturon 71, Lindan 36, Linuron 7, Malathion 40, Mancozeb 54, Maneb 59, MCPA 17, Mecoprop 18, Metaldehyd 88, Metam 55, Metamitron 15, Metazachlor 64, Metalachlor 63, Methabenzthiazuron 69, Metalaxyl 87, Metoxuron 70, Methylbromid 39, Metribuzin 14, Monolinuron 68, Monuron 66, Nitralin 74, Paraquat 2, Parathion 41, Pendimethalin 76, Pentachlorphenol 28, Phenmedipham 47, Phorat 42, Picloram 25, Propazin 8, Propanil 58, Prochloraz 80, Prometryn 5, Propachlor 61, Propham 48, Propiconazol 12, Propoxur 46, Quintozen 29, Simazin 7, Terbutylazin 10, 2.4.5-T 19, 2.3.6-TBA 24, Thiophonatmethyl 78, Thiram 57, Triadimenol 13, Triallat 51, Trifluralin 75, Zineb 56.

Nr.	Name (Wirkung)[1]	Chemische Bezeichnung	BRD[2]) verb. zug.	Lös-lich-keit	Flüch-tig-keit	Bindung durch Hu-mus	Ton Fe-Ox	pH Einfl.	Abbau ae-rob	an-aerob	Mobili-tät
1. Kation-aktiv											
Bipyridylderivate											
1	Deiquat (H)	1,1'-Ethylen-2,2'-bipyridylium	+	4	1	5	4 – 5	+	3		1 – 2
2	Paraquat (H)	1,1'-Dimethyl-4,4'-bipyridylium	+	4	1	5	4 – 5	+	1		1
2. Basisch (schwach)											
Diazine											
3	Chloridazon (H)	5-Amino-4-chlor-2-phenyl-(2H)-pyridazinon	+	3	1	3	2	(–)	4 – 5		2
4	Bentazon (H)	3-Isopropyl-2,1,3-benzothiadiazin-4-on-2,2-dioxid	(+)	4	1				4 – 5		

[1]) (A) Akarizid, (F) Fungizid, (H) Herbizid, (I) Insektizid, (N) Nematizid, (R) Rodentizid, (M) Molluskizid
[2]) Seit 19.. in der BRD verbotene, + zugelassene, ( ) aber in Wasserschutzgebieten seit 1. 9. 88 verbotene Präparate (n. Pflanzenschutzanwendungsverordnung)

Source: Blume ed. 1992

Table 3-25

Forts. Tab. 2.7.5/2

Nr.	Name (Wirkung)[1]	Chemische Bezeichnung	BRD[2]) verb. zug.	Lös-lich-keit	Flüch-tig-keit	Bindung durch Hu-mus	Ton Fe-Ox	pH Einfl.	Abbau ae-rob	an-aerob	Mobili-tät
S-Triazine											
5	Prometryn (H)	4,6-Diisopropylamino-2-methylthio-s-triazin		4	1	3	2	(–)	4		2
6	Atrazin (H)	4-Ethylamino-2-chlor-6-isopropylamino-s-triazin	(+)	2 – 3	1	2	1	–	3 – 4	3 – 4	3
7	Simazin (H)	4,6-Diethylamino-2-chlor-s-triazin	(+)	2	1	2	2	(–)	3 – 4		3
8	Propazin (H)	2-Chlor-4,6-diisopropylamino-s-triazin	(+)	2	1	2		(–)	3 – 4		3
9	Anilazin (F)	2,4-Dichlor-N-(6-chlor-phenyl)-1,3,5-triazin-2-amin	+	2	1			(–)	5		
10	Terbuthylazin (H)	4-Ethylamino-6-ter.-butylamino-2-chlor-s-triazin	+	2	1	2 – 3	2	(–)	3 – 4		
S-Triazole											
11	Amitrol (H)	3-Amino-1,2,4-triazol	(+)	4	1	2	2	(–)	4		4
12	Propiconazol (F)	1-[2-(2,4-Dichlorphenyl)-4-propyl-1,3-dioxolan-2-y [methyl]-1 H-1,2,4-Triazol	+	3	1			(–)			
13	Triadimenol (F)	1-(4-Chlorphenoxy)-3,3-dimethyl-(1H-1,2,3-triazol-2-yl)-butan-2-ol	+	3	1	(1)		(–)	(1)		
Triazinone											
14	Metribuzin (H)	4-Amino-6-tert.-butyl-3-methylthio-1,2,4-triazin	(+)	4	1	2	(2)	(–)	4		
15	Metamitron (H)	4-Amino-3-methyl-6-phenyl-1,2,4-triazin	+	4	1			(–)	5		
3. Sauer											
Phenoxyfettsäuren											
16	2,4-D (H)	2,4-Dichlorphenoxyessigsäure	+	4	1	1 – 2	1	–	4		4
17	MCPA (H)	4-Chlor-2-methylphenoxyessigsäure	+	3	1	2	1	–	4		4
18	Mecoprop (H) CMPP	2-(4-Chlor-2-methyl-phenoxy)-propionsäure	+	4	1	2	1	–	4		3
19	2,4,5-T (H)	2,4,5-Trichlorphenoxyessigsäure	+	3	1	2 – 3	1	–	4	3	3
20	Fluazifop-butyl (H)	Butyl-2-[4(5-trifluormethyl-2-pyridyloxy)phenoxy] propionat	(+)	1 – 2	1	2		(–)	5		
21	Dichlorprop (H)	2-(2,4-Dichlorphenoxy)-propions.	(+)	3 – 4	1			(–)	4 – 5		
Benzoesäuren											
22	Dicamba (H)	3,6-Dichlor-2-methoxybenzoesäure	(+)	4	1	2	1	–	5		4
23	Chloramben (H)	3-Amino-2,5-dichlorbenzoesäure	(+)	4	2			(–)	2		4
24	2,3,6-TBA (H)	2,3,6-Trichlorbenzoesäure		4	2	2	1	–	3		4

Forts. Tab. 2.7.5/2

Nr.	Name (Wirkung)[1]	Chemische Bezeichnung	BRD[2]) verb. zug.	Lös-lich-keit	Flüch-tig-keit	Bindung durch Hu-mus	Ton Fe-Ox	pH Einfl.	Abbau ae-rob	an-aerob	Mobili-tät
Picolinsäureabkömmling											
25	Picloram (H)	3-Amino-3,5,6-tri-chlor-picolinsäure	(+)	3 – 4	1	2	1	–	2 – 3		3
Phenole, Benzole											
26	Dinoseb (H)	2-(1-Methylpropyl)-4,6-dinitrophenylacetat	(+)	4	2	2		(–)	5		4
27	DNOC (H)	2-Methyl-4,6-dinitrophenol	(+)	3	1	2 – 3		–	4		3
28	PCP (I)	Pentachlorphenol	86	2	1	4	2	–	3 – 4	4	1
29	Quintozen (F)	Pentachlornitrobenzol (PCNB)	+	1	2			0	2 – 3	4	1
30	Hexachlorbenzol (F)	Hexachlorbenzol	77	1	1	4	2	0	2	1	1
4. Nicht Ion-Aktiv (apolar)											
Halogenierte Kohlenwasserstoffe											
31	Endosulfan (I)	6,7,8,9,10-Hexachlor-1,5,5a,6,9,9a-hexahydro-6,9-methano-2,4,3-benzodioxathiepin-3-oxid	+	1	2	4		0	3	(2)	1
32	Aldrin	1,2,3,4,10,10-Hexachlor-1,4,4a,5,8,8a hexahydro-1,4-endo, exo-5,8-dimethannaphthalen	81	1	1	(5)	(3)	0	3	(2)	1
33	Dieldrin (I)	1,2,3,4,10,10-Hexachlor-6,7-epoxy-1,4,4a,5,6,7,8,8a-octahydro-1,4-endo, exo-5,8-dimethannaphthalen	71	1	1	5	3	0	1 – 2	1 – 2	1
34	Heptachlor (I)	1,4,5,6,7,8-Heptachlor-3a,4,7,7a-tetrahydro-4,7-methanoinden	86	1	2	5	3	0	2 – 3	2 – 3	1
35	Chlordan (I)	1,2,4,5,6,7,8,8-Heptachlor-3a,4,7,7a-tetrahydro-4,7-methanoinden	71	1	2	5		0	3		1
36	Lindan (γ-HCH) (I)	γ-1,2,3,4,5,6-Hexachlorocyclohexan	(+)	2	1	3 – 4	3	0	2 – 3	5	1
37	DDT (I)	1,1,1-Trichlor-2,2-bis (p-chlorphenyl) ethan	77	1	1	5	4	0	1 – 2	3	1
38	Dichlorpropen (N)	1,3-Dichlorpropen	(+)	2	2	2	2	0	5	4	4
39	Methylbromid (I,N)	H_3C-Br	(+)	4	3			0			

[1]) (A) Akarizid, (F) Fungizid, (H) Herbizid, (I) Insektizid, (N) Nematizid, (R) Rodentizid, (M) Molluskizid
[2]) Seit 19.. in der BRD verbotene, + zugelassene, ( ) aber in Wasserschutzgebieten seit 1. 9. 88 verbotene Präparate (n. Pflanzenschutzanwendungsverordnung)

Forts. Tab. 2.7.5/2

Nr.	Name (Wirkung)[1]	Chemische Bezeichnung	BRD[2]) verb. zug.	Lös-lich-keit	Flüch-tig-keit	Bindung durch Hu-mus	Ton Fe-Ox	pH Einfl.	Abbau ae-rob	an-aerob	Mobili-tät
Organische P-Ester											
40	Malathion (I)	0,0-Dimethyl-dithiophosphat-diethylmercaptosuccinat	+	3	2	2 – 3		0	3	3 – 4	2
41	Parathion (I,A)	0,0-Diethyl 0-4-nitrophenyl-thiophosphat	+	2	2	4 – 5	2 – 3	0	4 – 5	4	2
42	Phorat (I,A)	0,0-Diethyl-S-((ethylthio)-methyl) phosphodithioat		2 – 3	2	4	2	0	4		2
43	Diazinon (I)	0,0-Diethyl-0-(2-isopropyl-6-methylpyrimidin-4-yl)-thiophosphat		2	2	3	2	0	4	4	2 – 3
Carbamate											
a) Methylcarbamate											
44	Carbaryl (I)	N-Methyl-1-naphthylcarbamat	86	2 – 3	2	2 – 3		0	3 – 4	4	2 – 3
45	Carbofuran (I,A,N)	2,3-Dihydro-2,2-dimethyl-7-benzofuranylmethylcarbamat	(+)	3	1	3		0	4	3 – 4	2 – 3
46	Propoxur (I)	2-Isopropoxyphenyl-N-methylcarbamat	(+)	4	2	2		0	(4)		
47	Phenmedipham (H)	Methyl-3-m-tolycarbamoyloxy-phenylcarbamat	+	2	1	3 – 4		0	4		–
b) Phenylcarbamate											
48	Propham (H)	Isopropyl-N-phenylcarbamat	+	2	1	2	1 – 2	0	4 – 5		3
49	Chlorpropham (H)	Isopropyl-N-(3-chlorphenyl)-carbamat	+	3	1	3	1 – 2	0	4		2
c) Thiocarbamate											
50	Diallat (H)	S-2,3-Dichlorallyl-N,N-diisopropylthiocarbamat		2	1	4		0	4 – 5		2
51	Triallat (H)	2,3,3-Trichlorallyl-diisopropylthiocarbamat	+	2	1	4	2	0	3 – 4		2
52	Butylat (H)	S-Ethyl-N,N-diisobutylthiocarbamat	+	2	2	3		0	4		2
53	EPTC (H)	S-Ethyl-N,N-dipropylthiocarbamat	+	3	2	2		0	4		2
d) Dithiocarbamate											
54	Maneb (F)	Mangan(II)-1,1-ethylen-bis-dithiocarbamat	+	1	1			0	5	5	
55	Metam-Na (F,N,H)	N-Methyldithiocarbamat	(+)	4	1	1 – 2		0	4		3
56	Zineb (F)	Zink-ethylen-bis-dithiocarbamat	+	2	1	3 – 4		0	4 – 5		2
57	Thiram (F)	Tetramethylthiuramdisulfid	+	3	1	3		0	4 – 5		
58	Propanil (H)	N-(3,4-dichlorphenyl)-propionamid		3	1 – 2	2	1 – 2	0	4		
59	Mancozeb (F)	Ethylen-bis-dithiocarbamat	+	1	1			0	4 – 5		

Table 3-25 cont.

Forts. Tab. 2.7.5/2

Nr.	Name (Wirkung)[1]	Chemische Bezeichnung	BRD[2]) verb. zug.	Löslichkeit	Flüchtigkeit	Bindung durch Humus	Bindung durch Ton Fe-Ox	Bindung durch pH Einfl.	Abbau aerob	Abbau anaerob	Mobilität
	e) Oxicarbamate										
60	Aldicarb (I,N)	2-Methyl-2-(methylthio)propion-aldehyd-0-methylcarbamoyl-oxim	(+)	4	1	2	1	0	3–4	4	4
	Acetanilide										
61	Propachlor (H)	2-Chlor-N-isopropyl-N-phenyl-acetamid	(+)	4	1	2	1–2	0	4		3
62	Carboxin (F)	5,6-Dihydro-2-methyl-1,4-oxathiin-3-carb-oxanilid	+	3	1	5	3	0	4–5		2
63	Metalachlor (H)	Chloracetanilid	+	4	1	2–3		0	4		
64	Metazachlor (H)	Chlorazetanilid	(+)	3	1	2–3		0	4–5		
	Harnstoffderivate										
65	Fenuron (H)	1,1-Diemethyl-3-phenylharnstoff		4	1	2–3	2	0	3		3
66	Monuron (H)	3-(4-Chlorphenyl)-1,1-dimethylharnstoff	+	3	1	3	2	0	4		3
67	Diuron (H)	3-(3,4-Dichlorphenyl)-1,1-dimethylharnstoff	+	4	1	3	2	0	3		2
68	Monolinuron (H)	3-(4-Chlorphenyl)-1-methoxy-1-methyl-harnstoff	+	3–4	1	3	2	0	4		2
69	Methabenz-thiazuron (H)	1-(Benzthiazol-2-yl)-1,3-dimethylharnstoff	+	3	1	3	2	0	3		2
70	Metoxuron (H)	3-(3-Chlor-4-methoxy-phenyl)-1,1-dimethyl-harnstoff	+	4	1	2	(2)	0	4–5		2
71	Linuron (H)	3-(3,4-Dichlorphenyl) 1-methoxy-1-methyl-harnstoff		3	1	3–4	2	0	4		2
72	Chlor-toluron (H)	3-(3 Chlor-4 methyl-phenyl)-1,1-dimethyl-harnstoff	+	3–4	1	2–3		0	4–5		
73	Isoproturon (H)	N-(4-isopropyl-phenyl)-N',N'-dimethylharnstoff	+	3	1	2		0	5		
	Dinitroaniline										
74	Nitralin (H)	4-(Methylsulfonyl)-2,6-dinitro-N,N-dipropylanilin	+	1	1	3–4	(3)	0	3–4		1
75	Trifluralin (H)	2,6-Dinitro-N,N-dipropyl-4-trifluor-methylanilin	+	1	1	4–5	(3)	0	3–4		1

[1]) (A) Akarizid, (F) Fungizid, (H) Herbizid, (I) Insektizid, (N) Nematizid, (R) Rodentizid, (M) Molluskizid

[2]) Seit 19.. in der BRD verbotene, + zugelassene, ( ) aber in Wasserschutzgebieten seit 1. 9. 88 verbotene Präparate (n. Pflanzenschutzanwendungsverordnung)

Forts. Tab. 2.7.5/2

Nr.	Name (Wirkung)[1]	Chemische Bezeichnung	BRD[2]) verb. zug.	Löslichkeit	Flüchtigkeit	Bindung durch Humus	Bindung durch Ton Fe-Ox	Bindung durch pH Einfl.	Abbau aerob	Abbau anaerob	Mobilität
76	Pendimethalin (H)	N-(3-phenyl)-3,4-dimethyl-2,6-dinitroanilin	+	1	1			0	4		
	Benzimidazole										
77	Benomyl (F)	Methyl-1-(butylcarbamoyl)-2-benzimidazolcarbamat	+	2	1	5	3	0	4		1
78	Thiophanat-methyl (F)	1,2-bis-((3-Methoxy-carbonyl)-2-thioureido)-benzol	+	2	1			0	4–5		1
79	Carbendazim (F)	Methyl-2-benzimidazolcarbamat	+	2	1	4		–	3–4		1
80	Prochloraz (F)	N-Propyl-N-2,4,6-trichlorphenoxy-ethyl-imidazol-carboxamid	+	2	1						
	Phthalimid-Derivate										
81	Captao (F)	N-Trichlormethylthio-4-cyclohexen-1,2-dicarboximid	+	1	1	1–2		0	4–5		2
82	Captafol (F)	N-(1,1,2,2,2-Tetrachlorethylthio)-3,6,7,8-tetrahydrophthalimid	+	1–2	1	1–2		0	4–5		
	Aromatische Cyanide										
83	Dichlobenil (H)	2,6-Dichlorbenzocyanid	+	2	2	2		0	3		2
84	Ioxynil (H)	3,5-Dijod-4-hydroxybenzonitril	+	2	1	2		0	5		
85	Bromoxynil (H)	3,5-Dibrom-4-hydroxybenzonitril	+	3	1	2		0	4–5		
	Aminosäurederivate										
86	Glyphosat (H)	Aminomethylphosphorsäure	+	4	1	3			3–4		
87	Metalaxyl (F)	D,L-N-2,6-Dimethyl-phenyl-N-(2'-methoxy-acetyl-alanin-methyl-ester	(+)	4	1	3			4		
	Aldehydoligomere										
88	Metaldehyd (M)	2,4,6,8-Tetramethyl-1,2,3,5,7-tetraoxacyclooctan	+	3	2	2					
	Morpholinderivate										
89	Fenpropimorph (F)	cis-4-[3-(4-tert-Butyl-phenyl)-2-methylpropyl]-2,6-dimethyl-morpholin	(+)	2	1						
	Quartäre Ammoniumverbindung										
90	Chlormequat (H)	2-Chlorethyl-trimethyl-NH_4Cl	+	4	1						

[1]) (A) Akarizid, (F) Fungizid, (H) Herbizid, (I) Insektizid, (N) Nematizid, (R) Rodentizid, (M) Molluskizid

[2]) Seit 19.. in der BRD verbotene, + zugelassene, ( ) aber in Wasserschutzgebieten seit 1. 9. 88 verbotene Präparate (n. Pflanzenschutzanwendungsverordnung)

Nr.	Name (Wirkung)[1]	Chemische Bezeichnung	BRD[2]) verb. zug.	Löslichkeit	Flüchtigkeit	Bindung durch Humus	Bindung durch Ton Fe-Ox	Bindung durch pH Einfl.	Abbau aerob	Abbau anaerob	Mobilität
	Uracilderivate										
91	Bromacil (H)	5 Br-3-sec-butyl-6-methyl-uracil	+	4	1				3		
	Benzofuranderivate										
92	Ethofumesat (H)	2-Ethoxy-2,3-dihydro-3,3-dimethyl-benzofuran-5-yl-methansulfonat	+	3	1	2			3–4		

[1]) (A) Akarizid, (F) Fungizid, (H) Herbizid, (I) Insektizid, (N) Nematizid, (R) Rodentizid, (M) Molluskizid

[2]) Seit 19.. in der BRD verbotene, + zugelassene, ( ) aber in Wasserschutzgebieten seit 1. 9. 88 verbotene Präparate (n. Pflanzenschutzanwendungsverordnung)

11

Tab. 2.7.5/10: Einfluß von Humus, Bodenart und pH-Wert auf die relative Bindungsstärke[3]) von Wirkstoffen in Böden (0 (fast) nicht bis 5 sehr stark)

% Humus[1]) (Mittel 0–3 cm)	Bodenart[2])	Bindung nach Tab. 2.7.5/2: 1	2	3	4	5
0.5–1	S, Su2	0	0.5	1	1.5	2
1 –2	Sl, St, Su, Us, U	0.5	1	1.5	2	3
2 –8	Uls, Ul, Lu, Ls, Lt, Ts4, Ut2,3	0.5	1	2	3	4
8 –15	Ts2, Tl, Tu, Lts, Ltu, Ut4	1	1.5	2.5	3.5	4.5
> 15	T	1	2	3	4	5

Zu-/Abschlag (+ od. –, n. Tab. 2.7.5/2): ± 0.5 0 ∓ 0.5 ∓ 1
bei pH ($CaCl_2$) > 6.5 – 5.5 – 4 >

[1]) Nach Blume und Helsper (1987) [2]) Nach AG BODENKUNDE (1982)
[3]) Stufe der bodenbezogenen Sorptionskonstanten (k_f) n. Freundlich

12

Tab. 2.7.5/11: Beurteilung einer Eliminierung von Wirkstoffen in Böden, 0 (*fast*) *nicht* bis 5 *sehr stark*

(a) Einfluß der Temperatur auf den Abbau

Abbau n. Tab. 2.7.5/2	a) Mitteltemp. d. Sommerhalbj. 21 – 16	– 11	– 6 °	b) Jahresmitteltemperatur 12 – 9	– 6	– 3 °C
1	1.5	1	0.5	0.5	0.5	0
2	2.5	2	1.5	1.5	1	0.5
3	3.5	3	2.5	2.5	2	1.5
4	4.5	4	3.5	3.5	3	2.5
4.5, 5	5	4.5	4	4	3.5	3

(b) Einfluß der Wasser-, Luft- und Nährstoffverhältnisse auf den Abbau

Abschlag:	1	0–1	0
bei Standortkundl. Feuchtestufe SF[1])	01.11	°02 12 21 31 41	übrige
Effektiver Durchlüftung (DL[1])	1	2–3	4–5
S-Wert in mval/100 ccm[2])	< 4	4–12	> 12

[1]) Nach AG BODENKUNDE (1982) [2]) Nach Tabelle 4 in Blume u. Brümmer 1987

(c) Einfluß starker Bindung auf den Abbau

Abschlag bei:	Bindungsstufe (n. Tab. 2.7.5/10) 1 u. 2	3	4 u. 5
Seemarsch, Tschernosem	0	0	–0.5
Übrige	0	–0.5	–1

(d) Einfluß möglicher Verflüchtigung auf Eliminierung

Zuschlag bei:	Verflüchtigung n. Tab. 2.7.5/2: 1	2	3	4
Temperatur > 10 °C oder langes Verweilen an Bodenoberfläche	0	1	1.5	2
Temperatur < 10 °C oder kurzes Verweilen an der Oberfläche	0	0	1	1.5

13

Tab. 2.7.5/12: Einfluß von Bindung, Eliminierung und klimatischer Wasserbilanz auf die Bewegung eines Wirkstoffs im grundwasserfreien Bodenraum

KWBa[1])	Sickerung[2]) mm/Jahr	Bindung[3]) + Eliminierung[4]):2: 5	4	3	2	1	0
1	0–100	0	1	2	3	4	5
2	100–200	0	1.5	2.5	3.5	4.5	5
3–4	200–400	0	2	3	4	4.5	5
5–6	> 400	0.5	2	3.5	4.5	5	5

[1]) Klimat. Wasserbilanz als Differenz von Jahresniederschlag und Verdunstung n. Tab. 3 in AG Bodenkunde 1982
[2]) Bei Acker mit Winterung 50 mm Zuschlag
Bei Acker mit Sommerung 100 mm Zuschlag
Bei Forst 50 mm Abschlag
[3]) n. Tab. 2.7.5/10
[4]) n. Tab. 2.7.5/11

14

Tab. 2.7.5/13: Einfluß von Grundwasserstand (mittl. Hochstand) und Bewegung (n. Tab. 2.7.5/12) org. Chemikalien im grundwasserfreiem Bodenraum auf die Grundwassergefährdung (1 sehr gering, 5 sehr hoch)

Bewegung	Grundwasserstufen[1]) 1	2	3	4	5	6	7[2])
0–1	5	5	3	2	2	1	1
2	5	5	4	3	3	2	1
3	5	5	4	3	3	3	2
4	5	5	4	4	4	4	3
5	5	5	5	2	5	5	4.5

[1]) n. Tab. 53 in AG BODENKUNDE 1982
[2]) mittl. Grundwasserhochstand tiefer 2 m

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Tab. 2.7.5/14: Bewertung des Verhaltens eines Wirkstoffs im Boden

Bei Bindung n. Tab. 2.7.5/10 von: Anreicherung im Boden:	1 sehr gering	2 gering	3 mittel	4 stark	5 sehr stark
Bei Bindung (Tab. 2.7.5/10) + Eliminierung (Tab. 2.7.5/11) geteilt durch 2 von: Aufnahme durch Pflanzen, Schädigung von Bodenorganismen:	1 sehr wahrschein.	2 wahrscheinlich	3 wahrschein.	4 weniger wahrschein.	5 unwahrschein.
Bei Grundwassergefährdung n. Tab. 2.7.5/13 von: Mitteleinsatz:	1 sehr gering	2 gering	3 mittel	4 stark	5 sehr stark
	möglich		begrenzt mögl.	nicht möglich	

Das Verfahren soll im folgenden kurz erläutert werden (DVWK 1989).

Eine negative Nebenwirkung auf Bodenorganismen und eine Pflanzenaufnahme sind dann zu erwarten, wenn der Wirkstoff im Hauptwurzelraum wenig gebunden und langsam abgebaut wird und sich gleichzeitig kaum verflüchtigt.

Die zu erwartende Bindungsstärke des nach Tab. 2.7.5/2 klassierten Stoffes ergibt sich nach Tab. 2.7.5/10 für Humus aus dem mittleren Humusgehalt und für Ton aus der mittleren Bodenart (der oberen 3 dm). Bei verminderter (oder verstärkter) Bindung infolge niedrigen (oder hohen) pH-Wertes nach Tab. 2.7.5/2 ist bei der Bindungsstärke durch Humus und der durch Ton ein Abzug (oder Zuschlag) nach Tab. 2.7.5/10 vorzunehmen. Die Gesamtbindung wird dann durch die Summe der humus- und der tonbezogenen Bindungsstärke charakterisiert, wobei höchstens die Stufe 5 anzusetzen ist.

Der während der Vegetationsperiode (April bis September) zu erwartende Abbau des nach Tab. 2.7.5/2 klassierten Stoffes wird nach Tab. 2.7.5/11 a aus der Mitteltemperatur des Sommerhalbjahres abgeleitet. Bei einer Kontamination zwischen Oktober und März wird die Jahresmitteltemperatur herangezogen, weil sich dann der Abbau meist bis in das nächste Frühjahr verlängert. Bei Wasser-, Luft- und/oder Nährstoffmangel sind Abschläge um maximal 1 nach Tab. 2.7.5/11 b vorzunehmen. Bei Wirkstoffen, die unter anaeroben Bedingungen besser als unter aeroben abgebaut werden, erfolgt bei Luftarmut (DL 1–3) nach Tab. 2.7.5/11 b kein Abschlag sondern ein entsprechender Zuschlag. Wurde eine hohe, den Abbau hemmende Bindungsstärke nach Tab. 2.7.5/2 und 2.7.5/10 prognostiziert, erfolgt ein Abschlag nach Tab. 2.7.5/11 c. Der Einfluß der Flüchtigkeit nach Tab. 2.7.5/2 auf die Gesamteliminierung wird durch einen Zuschlag nach Tab. 2.7.5/11 d berücksichtigt. Die erreichbare Höchststufe beträgt 5.

Bei einer Abschätzung der Grundwassergefährdung sind neben Bindung und Eliminierung im (aus dem) Oberboden auch die Vorgänge im Unterboden zu berücksichtigen, außerdem die Sickerungsraten und der Grundwasserstand. Die Bewegung des Wirkstoffs im grundwasserfreien Bodenraum wird nach Tab. 2.7.5/12 aus dem Mittel von Bindung (Tab. 2.7.5/10) und Eliminierung (Tab. 2.7.5/11) sowie der klimatischen Wasserbilanz (KWBa) abgeleitet. Dabei ist die Bindung nach Tab. 2.7.5/10 um bis zu 1 Stufe zu erhöhen, wenn auch der Unterboden bis zum Grundwasserspiegel eine mindestens 4 dm mächtige, humose (> 2 % org. S.) Lage aufweist und/oder eine mittlere Bodenart von Sl4 oder toniger besitzt. Die klimatische Wasserbilanz gilt für Grünland in ebener Lage; bei Acker ist sie um 50–100 mm zu erhöhen, bei Wald um 50 mm zu erniedrigen. Senken- und Unterhanglagen weisen eine stärkere, Kuppen- und Oberhanglagen eine geingere Sickerung auf, was entsprechend zu berücksichtigen ist. In Böden mit hoher Wasserdurchlässigkeit (kf durchgehend > 40 cm/d: Schätzung n. AG Bodenkunde 1982) kann die Sickerung um bis zu 100 mm höher liegen. Die Grundwassergefährdung ergibt sich dann nach Tab. 2.7.5/13 aus der nach Tab. 2.7.5/12 prognostizierten Bewegung und dem mittleren Grundwasserhochstand; 1 bedeutet sehr geringe, 5 sehr starke Gefährdung. Ist zu erwarten, daß lateral abziehendes Stauwasser (gilt bei geringer Wasserdurchlässigkeit, d.h. bei kf < 10 cm/d des Unterbodens) einen benachbarten Vorfluter kontaminiert, ist Tab. 2.7.5/13 entsprechend anzuwenden.

Eine Bewertung der Befunde erfolgt nach Tab. 2.7.5/14.

Ein ähnliches Verfahren zur Prognose einer möglichen Grundwasserkontamination, das auf dem Abbau- und Perkolationsverhalten eines Pestizids unter Laborbedingungen fußt, wurde von Herzel (1987) entwickelt.

Source: Blume ed. 1992

Table 3-27

Table 6

RELATIVE MOBILITY OF PESTICIDES IN SOILS[1] (CAST 1985)

Very Mobile	Moderately Mobile	Slightly Mobile	Nearly Immobile	Immobile
TCA	Picloram	Propachlor[3]	Siduron	Neburon
Dalapon	Fenac	Fenuron	Bensulide	Chloroxuron
2,3,6 TBA[2]	Pyrichlor	Prometone	Prometryn	DCPA
Tricamba	MCPA	Naptalam	Terbutryn	Lindane
Dicamba	Amitrole	2,4,5-T	Propanil	Phorate
Chloramben	2,4-D	Terbacil	Diuron	Parathion
	Dinoseb	Propham	Linuron	Disulfoton
	Bromacil	Fluometuron	Pyrazon	Diquat
		Norea	Molinate	Chlordimeform
		Diphenamid	EPTC	Dichlormate[3]
		Thionazin[3]	Chlorthiamid	Ethion
		Endothall	Dichlobenil	Zineb
		Monuron	Vernolate	Nitralin
		Atratone	Pebulate	Fluorodifen
		Cyanazine	Chloropropham	ACNQ[3]
		Atrazine	Azinphosmethyl	Morestan
		Simazine	Diazinon	Isodrin[2]
		Ipazine		Benomyl
		Alachlor		Dieldrin[2]
		Ametryn		Chloroneb
		Propazine		Paraquat
		Trietazine		Trifluralinh
				Benefin
				Heptachlor[2]
				Endrin[2]
				Aldrin[2]
				Chlordane
				Toxaphene[2]
				DDT[2]

[1] Ranked according to estimated order of decreasing mobility within each class
[2] Most or all uses cancelled by the Environmental Protection Agency as of November 1984
[3] Not used at present in the United States

Source: Kandiah FAO 1990

Table 3-28

TABLE 6. The various salts influencing the formation of salt-affected soils

Group of salts	Occurrence	Origin	Solubility	pH in solution	Toxicity to plants	Effect on soil
Carbonates	All regions. In: soil, subsoil, ground water, surface water, marine deposits.	Predominantly weathering products.	Varies.	Alkaline.	Varies, depending on solubility.	Varies, depending on mobility and solubility.
$CaCO_3$	In: fresh river water, ground water, soils (5–80 per cent). Mostly in steppe and desert soils.	Predominantly weathering products in sedimentary rocks and from ground water.	Low, depending on: CO_3 conceutration, CO_2 concentration, pH values in solution $L = 9{\cdot}3 \times 10^{-9}$ $9{\cdot}8 \times 10^{-3}$ g/l.	Alkaline.	No toxicity.	Different form of $CaCO_3$ medium concretions hardpan.
$MgCO_3$	As $CaCO_3$.	Predominantly weathering products.	Low, but higher than $CaCO_3$. $L_{MgCO_3} = 2{\cdot}10^{-4}$ 1·2 g/l. Dolomite dissolution is poor.	Alkaline.	Toxicity due to alkaline hydrolysis.	Rare in free form, mainly dolomite or dolomitized $CaCO_3$ concretions.
Na_2CO_3	In: surface and ground waters at mineralization 0·5–3 g/l, soils (mainly in absence of gypsum), deposits.	Weathering products (in CO_2-containiug water), Hilgard, Gedroitz, sulphate reduction, from plants.	Highly soluble $CO_3 \leftrightarrows HCO_3$ reaction.	Alkaline, up to pH 12.	Very toxic, due to high solubility and alkaline hydrolysis.	Peptization of soil, low water permeability, poor water-physical properties, non-leachable.
K_2CO_3	Similar to Na_2CO_3. Its occurrence in soils is very rare.					
Sulphates	In: deserts and steppes, deposits, soils, ground waters.	Sometimes weathering products, sometimes magmatic origin.	Varies, but higher than carbonates.	Neutral or slightly acidic.	Different, depending on solubility and concretions.	Effect on soils varies, depending on compounds.
$CaSO_4$	In: deserts and semi-desert regions, ground water, deposits soils.	Sometimes weathering products, partly formed secondarily from SO_4 having magmatic origin in sediment due to reaction $Na_2SO_4 + CaCl_2$ $CaSO_4 + 2NaCl$.	$L_{CaSO_4 \cdot 2H_2O} = 1{\cdot}3 \times 10^{-4}$ $C = 2$ g/l $L_{CaSO_4} = 6{\cdot}1 \times 10^{-5}$ $C = 1$ g/l.	Slightly acidic.	No toxicity.	Forms transparent mottles; compact layer used for soil amelioration.
$MgSO_4$	In: desert and semi-desert regions, saline soils, saline ground water.	As $CaSO_4$.	High: $C = 262$ g l.	Slightly acidic.	Very toxic.	Accumulates always in combination with other soluble salts. Reclamation by leaching.
Na_2SO_4	In: desert and semi-desert regions, saline ground water, saline lakes, saline soils.	Partly weathering products, partly magmatic origin.	High solubility, 280 g/l (25° C). Depends very much on temperature.	Nearly neutral.	Two or three times less than $MgSO_4$.	Accumulates together with other easily soluble salts. In warm periods dehydration. Reclamation by leaching in dry season.
Chlorides	In: desert and semi-desert regions, saline ground water, saline lakes, saline soils, sea water, seashores, marine deposits.	Partly magmatic origin, partly weathering products.	High solubility.	Nearly ueutral or slightly acidic.	High toxicity.	Saline soil. Physiological effect.
$CaCl_2$	Waters of saline lakes (at salinity 400–500 g/l), deep-lying ground water.	Partly magmatic origin, partly weathering products.	High solubility.	Slightly acidic.	Toxic in high concentration.	Seldom present in soil (form $CaCO_3$ or $CaSO_4$) only at very high salinity.
$MgCl_2$	Common in saline ground waters, lakes, soils. Only at very high salinity.	Partly magmatic origin, partly weathering products.	High solubility, 353 g/l.	Nearly neutral.	Very toxic.	Together with $CaCl_2$ very hygroscopic. Saline soils with $CaCl_2$ and $MgCl_2$ remain humid for a long time after rain. Reclamation: intensive leaching.
NaCl	Sea water, marine sediments, coastal area, saline surface waters, saline ground waters, saline soil, desert and semi-desert regions.	Magmatic. Only partly weathering product.	High solubility, 264 g/l.		Very toxic from 1 g/l.	In saline soil together with Na_2SO_4 and $MgSO_4$. Amelioration: leaching of soil containing gypsum. In absence of gypsum, alkalization.

Source: Darab and Ferencz (1969).

Source: Szabolcs 1979

Table 3-29

TABLE 19. Classification of saline soils by degree and type of salinity in relation to field crops

Condition of agricultural crops with medium salt resistance	Degree of soil salinity	Type of salts dominating in soils: Soda	Chloridic soda and soda chloridic	Sulphatic soda and soda sulphatic	Chloridic	Sulphatic-chloridic	Chloridic-sulphatic	Sulphatic
Good growth and development (no bare patches, crop normal)	Practically non-saline (or only very slightly saline)	0.10	0.15	0.15	0.15	0.20	0.25	0.30
Slight withering (bare patches and decrease of crop by 10–20 per cent	Slightly saline	0.10–0.20	0.15–0.25	0.15–0.30	0.15–0.30	0.20–0.30	0.25–0.40	0.30–0.60
Medium withering (bare patches and decrease of crop by 20–50 per cent	Medium saline	0.20–0.30	0.25–0.40	0.30–0.50	0.30–0.50	0.30–0.60	0.40–0.70	0.60–1.0
Marked withering (bare patches and decrease of crop by 50–80 per cent	Strongly saline	0.30–0.50	0.40–0.60	0.50–0.70	0.50–0.80	0.60–1.0	0.70–1.20	1.0 –2.0
A few scattered plants survive (virtually no crop)	Solonchaks	>0.50	>0.60	>0.70	>0.80	>1.0	>1.20	>2

Source: Kovda, Hagan and van den Berg (eds.) (1973, p. 70).

Source: Szabolcs 1979

Table 3-30

A) STUDY AND PLANNING

Environmental issues:

- sources and current processes of salinization
- the geochemical characteristics of the area
- salinization and/or alkalization of soils resulted by primer (natural) and secondary (man-made) effects
- environmental possibilities of removal of excess salts (place of disposal, drainage systems, etc.)
- environmental changes to be expected by reclamation (short and long term)

Socio-economical issues:

- cost and possibilities of reclamation project (purpose, area, time limit, etc.)
- possibilities of agri-, sylvi-, horticultural as well as other productions of the area before and after the reclamation. Cost and benefit analysis.
- combination of meliorative measures with application of by-products of industry, mining as well as of sludge
- public projects, colonization, employment and production on reclaimed territories

Feasibility studies, reports and plans for action

↓

B) REALIZATION

1) Strategy for restauration
2) Alternatives, scenaries, preferences
3) Decision making
4) Implementation
5) Maintaining the rehabilited ecosystems
6) Protection of the rehabilited ecosystems from new degradation and deterioration

Tab. 1: *Scheme of amelioration of salinized areas.*

Source: Shaw 1992

Table 3-31

(A) Before construction of irrigation system	Preliminary survey	
	Landscape	Planned irrigation
	climate	available irrigation water quality and quantity
	hydrology	groundwater depth and quality
	hydrogeology	technology of irrigation
	geomorphology	cropping pattern tolerance
(B) During irrigation	Monitoring	
	salinity and alkalinity of soil and groundwater table	
	chemical composition of groundwater	
	chemical composition of irrigation	
	water filtration	
	physical soil properties toxic elements, if any, in soil and water	

Tab. 5: *Scheme of methods recommended for the control of salinity and alkalinity in irrigated areas.*

Source: Shaw 1992

Table 3-32

TABLE 2

Engineering measures for salinity control in the Shapur and Dalaki basin (Yekom, 1980).

	Engineering measures	Applicability	Proposed salt-disposal projects (Ref. Fig. 4)
Salt disposal	Collecting, diverting and evaporation in natural or artificial ponds	Applicable	Shur river project Shekastian river project
	Collecting and desalting	Not applicable	-
	Sealing of springs through grouting with cement, etc.	Not applicable	-
	Recharge through wells into deep aquifers	Not applicable	-
	Evaporation of salty tributaries by use of sequence of dykes and mining the salt	Not applicable (too costly)	-
	Disconnect the recharge (limestone) from the polluting source (salt plugs) by pumping	Applicable	Cerezak spring project
	Diverting the polluting source to a point downstream	Applicable	Tol-Kharaki drain project
	Use of salt water in the chemical industry	Not applicable (too costly)	-
Salinity mitigation	Construction and management of storage reservoirs	Applicable	Jarreh storage res. project
	Desalination	Not applicable (too costly)	-
	Partial storage of saline or fresh water	Not applicable	-
	Blending or cyclic use	Applicable (costly)	Shapur and Zohreh river water blending project

Source: Shiati 1991

Table 3-33

Table 2. Provisional listing of suitable situations and desirable management practices for each of the major salinity management options.

	Manage existing situation	Minimise recharge	Intercept water	Increase water use in discharge area
Situations most suitable to the proposed control option	. affected land not of high value or productivity . control of recharge area too costly or recharge area of much higher productivity . current vegetation is surviving on most of the affected area . vegetation can be enhanced and/or area fenced for grazing control . seepage of fair quality water represents a majority of the affected area . erosion not a problem or can be stabilised with vegetation . downstream water quality not significantly affected by salting . only moderate salt load in discharge area	. Identifiable recharge area for treatment . agroforestry is an option . winter rainfall regime . shallow rooted pastures main vegetative cover . cropping practices could be more water use efficient . rainfall periods not aligned with crop high water use . high recharge rates . value of discharge area greater than recharge area . sodicity of water in discharge area low and soil structure not severely affected	. transmission zone is relatively well defined . recharge area is large and not well defined . groundwater quality acceptable . can identify good aquifers in transmission zone . aquifers can be pumped or are accessible by tree roots . pumped water can be discharged into stream, evaporated or used for irrigation . discharge area under upward hydraulic pressure through clay confining layer . recharge areas and discharge areas are high value lands . large quantities of water are involved . major salt loads &/or high sodicity in discharge area	. diffuse and extensive recharge area . recharge areas distant from discharge area . discharge area extensive in area . economic value of recharge areas is high . economic value of discharge area lands are high or low . diffuse transmission zone . finite salt loads in discharge area . generally acceptable groundwater quality or saline water and evaporation basins are cost effective . drainage, pumping or use of high water use trees are options . waterlogging is an important component
Desirable management practices	. enhance salt tolerant vegetation in worst areas . fence and manage grazing pressures . maintain adequate vegetative cover at all costs . stabilise against erosion but do not prevent seasonal flooding of area where it would normally occur . improve surface drainage . plant trees or other perennial deep rooted vegetation	. avoid summer fallow in summer rainfall areas and use double or opportunity cropping . revegetate stock routes, fencelines etc . mix pasture species with deeper rooted ones or more perennial species . agroforestry . reduce ponded areas where possible if leakage is significant	. pumping with pumps or windmills from single or linked tubewells. Need a minimum of flow of at least 3 L/sec . plant dense vegetation belts in groundwater accessible areas with high water use vegetation . subsurface drainage . irrigation on adjacent areas	. pumping with pumps or windmills from single or linked tubewells. Need a minimum flow of at least 3 L/sec . revegetate area with perennial high water use and salt tolerant vegetation . subsurface &/or surface drainage . use of pumped water for irrigation on adjacent areas . plant halophytes which take up salts

Source: Shaw 1992b

Table 3-34 a

Table 36-1. Salt tolerance of herbaceous crops.†

Crop		Electrical conductivity of saturated soil extract		
Common name	Botanical name‡	Threshold§	Slope	Rating¶
		dS/m	% per dS/m	
	Fiber, grain, and special crops			
Barley#	*Hordeum vulgare* L.	8.0	5.0	T
Bean	*Phaseolus vulgaris* L.	1.0	19.	S
Broadbean	*Vicia faba* L.	1.6	9.6	MS
Corn	*Zea mays* L.	1.7	12.	MS
Cotton	*Gossypium hirsutum* L.	7.7	5.2	T
Cowpea	*Vigna unguiculata* (L.) Walp	4.9	12.	MT
Flax	*Linum usitatissimum* L.	1.7	12.	MS
Guar	*Cyamopsis tetragonolaba* (L.) Taub			MT
Millet, foxtail	*Setaria italica* (L.) Beauvois	–	–	MS
Oat	*Avena sativa* L.			MT*
Peanut	*Arochis hypogaea* L.	3.2	29.	MS
Rice, paddy††		3.0‡‡	12.‡‡	S
Rye	*Secale cereale* L.	–	–	MT*
Safflower	*Carthamus tinctorius* L.	–	–	MT
Sesame	*Sesamum indicum* L.	–	–	S
Sorghum	*Sorghum bicolor* (L.) Moench	6.8	16.	MT
Soybean	*Glycine max* (L.) Merrill	5.0	20.	MT
Sugarbeet§§	*Beta vulgaris* L.	7.0	5.9	T
Sugarcane	*Saccharum officinarum* L.	1.7	5.9	MS
Sunflower	*Helianthus annuus* L.	–	–	MS*
Triticale	*X Triticosecale*			T
Wheat#	*Triticum aestivum* L.	6.0	7.1	MT
Wheat (semidwarf)¶¶	*T. aestivum* L.	8.6	3.0	T
Wheat, durum	*T. durum* Desf.	5.9	3.8	T
	Grasses and forage crops			
Alfalfa		2.0	7.3	MS
Alkaligrass, Nuttall	*Puccinellia airoides* (Nutt.)	–	–	T*
Alkali sacaton	*Sporobolus airoides*	–	–	T*
Barley (forage)#		6.0	7.1	MT
Bentgrass	*Agrostis stolonifera* L., *palustris*	–	–	MS
Bermudagrass##	*Cynodon dactylon* L.	6.9	6.4	T
Bluestem, Angleton	*Dichanthium aristatum* (Poir) C.E. Hubb.	–	–	MS*
Brome, mountain	*Bromus marginatus* Nees ex Steud.	–	–	MT*
Brome, smooth	*B. inermis* Leyss	–	–	MS
Buffelgrass	*Cenchrus ciliaris* L.	–	–	MS*
Burnet	*Poterium sanguisorba*	–	–	MS*
Canarygrass, reed	*Phalaris arundinacea* L.	–	–	MT
Clover, alsike	*Trifolium hybridum* L.	1.5	12.	MS
Clover, berseem	*T. alexandrinum* L.	1.5	5.7	MS
Clover, hubam	*Melilotus alba*	–	–	MT*
Clover, ladino	*Trifolium repens* L.	1.5	12.	MS
Clover, red	*T. pratense* L.	1.5	12.	MS
Clover, strawberry	*T. fragiferum* L.	1.5	12.	MS
Clover, sweet	*Melilotus* Mill.	–	–	MT*
Clover, white Dutch	*Trifolium repens* L.	–	–	MS*
Corn (forage)		1.8	7.4	MS
Cowpea (forage)		2.5	11.	MS
Dallisgrass	*Paspalum dilotatum* Poir.	–	–	MS*
Fescue, meadow	*F. pratensis* Huds.	–	–	MT*
Fescue, tall	*Festuca arundinacea* Schreb.	3.9	5.3	MT
Foxtail, meadow	*Alopecurus pratensis* L.	1.5	9.6	MS
Grama, blue	*Bouteloua gracilis* (HBK) Leg.	–	–	MS*
Harding grass	*Phalaris stenoptera* L.	4.6	7.6	MT
Kallargrass	*Diplachne fusca*	–	–	T*
Lovegrass†††	*Eragrostis* sp. n.m. Wolf	2.0	8.4	MS
Milkvetch, cicer	*Astragalus cicer* L.	–	–	MS*
Oatgrass, tall	*Arrhenatherum elatius* Beauvois, Danthonia	–	–	MS*
Oats (forage)		–	–	MS*
Orchardgrass	*Dactylis glomerata* L.	1.5	6.2	MS
Panicgrass, blue	*Panicum antidatale* Retz.	–	–	MT*
Rape	*Brassica napus* L.	–	–	MT*
Rescuegrass	*Bromus unioloides* HBK	–	–	MT*
Rhodesgrass	*Chloris gayana* Kunth	–	–	MT
Rye (forage)	*Secale cereale* L.	–	–	MS*
Ryegrass, Italian	*Lolium italicum* L. *multiflorum*	–	–	MT*
Ryegrass, perennial	*L. perenne* L.	5.6	7.6	MT
Saltgrass, desert	*Distichlis stricta*	–	–	T*
Sesbania††	*Sesbania exaltata* (Raf.) V.L.Cory	2.3	7.0	MS
Siratro	*Macroptilium atropurpureum* (DC.)	–	–	MS
Sphaerophysa	*Sphaerophysa salsula*	2.2	7.0	MS
Sudangrass	*Sorghum sudanense* (Pipee) Stapf	2.8	4.3	MT
Timothy	*Phleum pratense* L.	–	–	MS*
Trefoil, big	*Lotus uliginosus* L.	2.3	19.	MS
Trefoil, narrowleaf birdsfoot	*L. corniculatus* L., *tenuifolium*	5.0	10.	MT
Trefoil, broadleaf birdsfoot‡‡‡	*L. corniculatus* L., *arvenis*	–	–	MT
Vetch, common	*Vicia sativa* L.	3.0	11.	MS
Wheat (forage)¶¶		4.5	2.6	MT
Wheat, durum (forage)	*T. durum*	2.1	2.5	MT
Wheatgrass, standard crested	*Agropyron desertorum* A.	3.5	4.0	MT
Wheatgrass, fairway crested	*A. cristatum* (L.) Gaertn.	7.5	6.9	T
Wheatgrass, intermediate	*A. intermedium* (Host) Beauv.	–	–	MT*
Wheatgrass, slender	*A. trachycaulum* (Link) Malte	–	–	MT
Wheatgrass, tall	*A. elongatum* (Hort) Beauv.	7.5	4.2	T
Wheatgrass, western	*A. smithii* Rydb.	–	–	MT*
Wildrye, Altai	*Elymus angustus* Trin.	–	–	T
Wildrye, beardless	*E. triticoides* Buckl.	2.7	6.0	MT
Wildrye, Canadian	*E. canadensis* L.	–	–	MT*
Wildrye, Russian	*Psathyrostachys juncea* (Fisch.)	–	–	T
	Vegetable and fruit crops			
Artichoke, Jerusalem	*Helianthus tuberosus* L.	–	–	MT*
Asparagus	*Asparagus officinalis* L.	–	–	T
Bean	*Phaseolus vulgaris* L.	1.0	19.	S
Beet, red§§	*Beta vulgaris* L.	4.0	9.0	MT
Broccoli	*Brassica oleracea* B., *Botrytis*	2.8	9.2	MS
Brussels sprouts	*B. oleracea gemmifera* B.	–	–	MS*
Cabbage	*B. oleracea capitata* B.	1.8	9.7	MS
Carrot		1.0	14.	S
Cauliflower	*Brassica oleracea* B., *botrytis*	–	–	MS*
Celery	*Apium graveolens* L.	1.8	6.2	MS
Corn, sweet		1.7	12.	MS
Cucumber	*Cucumis sativus* L.	2.5	13.	MS
Eggplant	*Solanum melongena* L.	–	–	MS*
Kale	*Brassica oleracea* B., *acephala*	–	–	MS*
Kohlrabi	*B. oleracea gongylode*	–	–	MS*
Lettuce	*Lactuca sativa* L.	1.3	13.	MS
Muskmelon	*Cucumis melo* L.	–	–	MS
Okra	*Abelmoschus esculentus* (L.) Moench	–	–	S
Onion	*Allium cepa* L.	1.2	16.	S
Parsnip	*Pastinaca sativa* L.	–	–	S*
Pea	*Pisum sativum* L.	–	–	S*
Pepper	*Capsicum annuum* L.	1.5	14.	MS
Potato	*Solanum tuberosum* L.	1.7	12.	MS
Pumpkin	*Cucurbita pepo pepo* L.	–	–	MS*
Radish	*Raphanus sativus* L.	1.2	13.	MS
Spinach	*Spinacia oleracea* L.	2.0	7.6	MS
Squash, scallop	*Cucurbita pepo melopepo*	3.2	16.	MS
Squash, zucchini		4.7	9.4	MT
Strawberry	*Fragaria* sp. L.	1.0	33.	S
Sweet potato	*Ipomoea batatas* (L.) Lom.	1.5	11.	MS
Tomato		2.5	9.9	MS
Turnip	*Brassica rapa* L.	0.9	9.0	MS
Watermelon	*Citrullus lanatus* (Thunb.)	–	–	MS*

Source: in Stewart ed. 1990

Table 3-34b

† These data serve only as a guideline to relative tolerances among crops. Absolute tolerances vary depending upon climate, soil conditions, and cultural practices.
‡ Botanical and common names follow the convention of *Hortus Third* where possible.
§ In gypsiferous soils, plants will tolerate EC_e's about 2 dS/m higher than indicated.
¶ Ratings are defined by the boundaries in Fig. 36-1. Ratings with an * are estimates. For references consult the indexed bibliography by Francois and Maas (1985).
# Less tolerant during emergence and seedling stage. EC_e at this stage should not exceed 4 or 5 dS/m.
†† Less tolerant during emergence and seedling stage.
‡‡ Because paddy rice is grown under flooded conditions, values refer to the electrical conductivity of the soil water while the plants are submerged.
§§ Sensitive during germination. EC_e should not exceed 3 dS/m.

Table 36-2. Salt tolerance of woody crops.†

Crop		Electrical conductivity of saturated soil extract		
Common name	Botanical name‡	Threshold§	Slope	Rating¶
		dS/m	% per dS/m	
Almond#	*Prunus dulcis* (Mill.)	1.5	19	S
Apple	*Malus sylvestris* Mill.	–	–	S
Apricot#	*Prunus armeniaca* L.	1.6	24	S
Avocado#		–	–	S
Blackberry	*Rubus* spp.	1.5	22	S
Boysenberry	*Rubus ursinus* Cham. and Schlechtend	1.5	22	S
Castorbean	*Ricinus communis* L.	–	–	MS*
Cherimoya	*Annona cherimola* Mill.	–	–	S*
Cherry, sweet	*Prunus avium* L.	–	–	S*
Cherry, sand	*P. besseyi* L.	–	–	S*
Currant	*Ribes* sp.	–	–	S*
Date palm	*Phoenix doctylifera* L.	4.0	3.6	T
Fig	*Ficus carica* L.	–	–	MT*
Gooseberry	*Ribes* sp.	–	–	S*
Grape#	*Vitis* sp.	1.5	9.6	MS
Grapefruit	*Citrus paradisi* Macfad.	1.8	16	S
Guayule		–	–	T
Jojoba#	*Simmondsia chinensis* (Link) C. Schneid.	–	–	T
Jujube	*Ziziphus jujuba* Mill.	–	–	MT*
Lemon#	*Citrus limon* (L.) Burm. f.	–	–	S
Lime	*C. aurantiifolia* (Christm.) Swingle	–	–	S*
Loquat	*Eriobotrya japonica*	–	–	S*
Mango	*Mangifera indica* L.	–	–	S*
Olive	*Olea europaea* L.	–	–	MT
Orange	*Citrus sinensis* (L.) Oab.	1.7	16	S
Papaya#	*Carica papaya* L.	–	–	MT
Passion-fruit	*Passiflora mollissima* (HBK) L.H. Bailey	–	–	S*
Peach	*Prunus persica* (L.) Batsch	1.7	21	S
Pear	*Pyrus communis* L.	–	–	S*
Persimmon	*Diospyros virginiana* L.	–	–	S*
Pineapple	*Ananas comosus* (L.) Merr.	–	–	MT*
Plum; Prune#	*Prunus domestica* L.	1.5	18	S
Pomegranate	*Punica granatum* L.	–	–	MT*
Pummelo	*Citrus grandis* C.	–	–	S*
Raspberry	*Rubus idaeus* L.	–	–	S
Rose apple	*Syzygium jambos* (L.) Alston	–	–	S*
Sapote, white	*Casimiroa edulis* Llave	–	–	S*
Tangerine	*Citrus reticulata* Blanco	–	–	S*

† These data are applicable when rootstocks are used that do not accumulate Na or Cl rapidly or when these ions do not predominate in the soil.
‡ Botanical and common names follow the convention of *Hortus Third* where possible.
§ In gypsiferous soils plants will tolerate EC_e's about 2 dS/m higher than indicated.
¶ Ratings are defined by the boundaries in Fig. 36-1. Ratings with an * are estimates. For references consult the indexed bibliography by Francois and Maas (1985).
# Tolerance is based on growth rather than yield.

Table 3-35a

Table 1. Salinity Threshold Values and Yield Decreases

Crop	Threshold Value EC_{ex} in mmhos/cm	Yield Decrease per mmhos/cm in kg/feddan
Cotton	6.5	150
Wheat	4.5	200
Barley	5.0-5.0	180
Clover	2.5-3.0	650
Rice	3.5	250

Table 3-35b

Table 2. Expected Yield Decrease for Certain Crops due to Salinity of Irrigation Water

Crop	Salinity of Irrigation Water (ppm)	Yield Decrease
Cotton	2 000	0
	4 000	18%
	6 000	25%
	8 000	50%
	10 000	75%
Wheat	3 000	20%
	4 000	35%
	6 000	70%
	8 000	100%
Barley	3 000	10%
	5 000	40%
	7 000	50%
	12 000	75%
Clover	1 000	6%
	2 000	20%
	4 000	60%
Rice	1 500	15%
	2 000	45%
	4 000	60%

Source: El-Guindi/Abu Bakr in ICID (STS-C16) 1991

Table 3-36

Table 36-4. Relative salt tolerance of various crops at emergence and during growth to maturity. After Maas (1986).

Common name†	Electrical conductivity of saturated soil extract: 50% Yield‡ (dS/m)	50% Emergence‡ (dS/m)
Barley	18	16-24
Cotton	17	15
Sugarbeet	15	6-12
Sorghum	15	13
Safflower	14	12
Wheat	13	14-16
Beet, red	9.6	13.8
Cowpea	9.1	16
Alfalfa	8.9	8-13
Tomato	7.6	7.6
Cabbage	7.0	13
Corn	5.9	21-24
Lettuce	5.2	11
Onion	4.3	5.6-7.5
Rice	3.6	18
Bean	3.6	6.0

† Common names follow the convention of *Hortus Third* where possible.
‡ Emergence percentage of saline treatments determined when nonsaline control treatments attained maximum emergence.

Source: in Stewart ed. 1990

Table 3-37

Table 2 RELATIVE TOLERANCE OF SPRINKLER CROPS TO SALINITY IMPINGING ON THE LEAVES OR ROOTS. SALINITY LEVELS ARE EXPRESSED AS THE ELECTRICAL CONDUCTIVITY OF THE IRRIGATION WATER (EC_i) (from Maas 1985)

Crop	Salinity threshold: Max. EC_i without injury from foliarly-absorbed salts[1] (dS/m)	Max. EC_i without detrimental soil salinity effects[2] (dS/m)
Almond	< 0.5	1.0
Apricot	< 0.5	1.1
Citrus	< 0.5	1.1
Plum	< 0.5	1.0
Grape	0.5-1.0	1.0
Pepper	0.5-1.0	1.0
Potato	0.5-1.0	1.1
Tomato	0.5-1.0	1.7
Alfalfa	1.0-2.0	1.3
Barley	1.0-2.0	5.3
Maize	1.0-2.0	1.1
Cucumber	1.0-2.0	1.7
Safflower	1.0-2.0	
Sesame	1.0-2.0	
Sorghum	1.0-2.0	4.5
Strawberry	2.0-4.0	0.7
Cauliflower	3.0-6.0	
Cotton	3.0-6.0	5.1
Sugarbeet	3.0-6.0	4.7
Sunflower	3.0-6.0	

[1] Saline water (primarily NaCl) with EC_i values higher than the threshold is expected to cause foliar injurt on crops sprinkled 5 hours or more each week during the irrigation season. The degree of injury is influenced by the cultural and environmental conditions.

Source: Kandiah ed. 1990

Table 3-38

3.5. Management Practices to Control Soil Salinity and Water Quality

i. On-farm management

Management measures should not be considered in isolation but should be developed in an integrated manner to optimize water use, minimize drainage and increase crop yields within the limits of the physical and social environment.

Three general management strategies seem practical: (i) control salinity within permissible levels, (ii) change conditions to improve crop response, (iii) change management to maintain yield at the field level when salinity causes damage at the plant level. All three can be used together. The first is the most commonly used.

Crop management

1. In the near future, crop management with respect to salt tolerance should concentrate on the choice of appropriate crop species rather than on major conventional breeding efforts within species. In the longer term, wide crosses and genetic engineering methods might give more promising results in terms of improved cultivar tolerance within a species.
2. Appropriate seed placement in respect to irrigation methods can minimize salt accumulation around the seed and improve germination and seedling establishment.
3. Increasing seeding rates can compensate for reduced crop establishment resulting from salt stress or surface crusting.
4. Increased crop density can compensate for the effect of reduced plant size on the field level yield.
5. The crop response function can be changed through reducing the stress level in the plant under a given salinity by growing the crop in a region of milder climate, using protected environments, changing irrigation method or enhancing CO_2 enrichment, etc.

Water management

1. Issues of irrigation water application and of leaching should be considered as distinct.
2. Irrigating with water of different qualities separately offers more benefit compared with traditional blending. Higher efficiency can be achieved by using non-saline water at sensitive growth stages or for sensitive crops in alternation with saline water during the remainder of the growing period or tolerant crops in a rotation.
3. For each kind of saline irrigation water, coupled with the availability of fresh water, appropriate crop rotations need to be worked out in order to: (a) make optimal use of both fresh and saline water; (b) periodically, restore the soil to its original state; (c) minimize the volume of unusable drainage effluent that must be disposed of; and (d) optimize crop yields under the given situation.
4. The temporal and spatial average salinity in the actual root zone may be considered as a first approximation of effective salinity at each stage of plant growth. When starting with a low salt profile, management of the saline water should concentrate on minimizing drainage volumes by delaying leaching, allowing salinity to build up to permissible values (physical or economic) before it is removed from the soil by seasonal or annual leaching.
5. Seasonal leaching should control salinity to the desired depth. It is more effective with respect to salt removal, and it can be applied at optimal timing with respect to crop requirements, physical conditions for leaching and water value.
6. When seasonal rainfall can leach the soil profile, a no-leaching irrigation strategy within the season may be optimal.
7. The benefit of increased irrigation frequency for saline water is still controversial; it was found effective in sands but not on medium textured soils. Further research is required on this aspect of water management.
8. Where irrigation systems such as drip or furrow accumulate salts in upper layers, rainfall or changing irrigation position may result in significant damage by washing salt into the root zone.
9. Even with high-efficiency irrigation, a certain leaching fraction is essential over the long term. Wherever there is shallow groundwater or a perched water table, this will require on-farm drainage. Effluent from on-farm drainage, whether by surface or subsurface drains, without or with mole drains, can be reused on appropriately tolerant crops. This would reduce the effective net drainage volume to be dealt with at system level.

Source: Kandiah ed. 1990

Table 3-38 cont.

Fertility management

1. Normal soil analysis guidelines also apply to land irrigated with saline water. For soils affected by sodium bicarbonate water, pH is of particular importance. Salinity tends to lower fertilizer efficiencies, increase rates of fertilizer loss and decrease the efficiency of rhizobium nodulation. Appropriate timing and placement of fertilizers, adjusting the timing of leaching treatments, as well as choice of slow-release fertilizers can improve efficiency of fertilizer use.

2. Organic manures, where it is practical to use them, are beneficial through increasing structural stability and infiltration rates, slow release of nutrient elements and some lowering of pH and calcium release from $CaCO_3$. However, they do not appear to counteract sodication in all cases; further research is required in this regard.

3. There is no clear evidence that damage through salinity can be overcome by the addition of K or NO_3. The salinizing effect of heavy applications of soluble fertilizers should be recognized.

Soil management

1. Precision levelling in basin or furrow systems is essential for uniform water application, leaching and efficient salinity control.

2. Appropriate tillage is needed to prepare for seeding, to improve soil permeability, to break up surface crusts and to improve water infiltration. Sub-soiling may be beneficial on soils having an impermeable layer, hard pan or compacted layer in the root zone. Deep ploughing may be harmful where saline or sodic soil is brought up to the surface.

3. Where there is a rainy season or where non-saline water is used following irrigation with saline water, special management is needed to prevent problems from slaking, crusting, slow infiltration and poor seedling emergence. Options include (a) a first application of water with intermediate salinity, (b) application of gypsum or other amendments with irrigation water either on the soil surface, or by mixing in the topsoil and (c) possibly, very small applications of soil conditioners in nonswelling soils. Further research is needed to evaluate soil conditioners that might be effective in swelling soils.

4. Use of highly alkaline water cannot be sustained, except with the use of appropriate amendments and good management practices. Further research is needed to develop criteria and standards for assessing hazards from use of alkaline water.

5. After harvest, immediate shallow cultivation with crop residues left on the surface where feasible and other mulching practices minimize wasteful evapotranspiration and the accumulation of salts in the surface.

ii. System level management

1. In the design of new irrigation areas prior questions should be asked including (a) whether different water qualities should be made available to farmers and if so, in fixed sequence or on demand; and (b) if certain drainage waters are to be reused or if all drainage water is to be safely disposed of.

2. The drainage water from sensitive crops could be reused for progressively more tolerant crops, until no further use is possible, in order to maximize crop production and income, to optimize water use efficiency, to keep drainage volume minimal and to minimize disposal or treatment costs.

3. Halophytic crops could be produced using water too saline for conventional agricultural crops, this would at the same time further reduce final drainage volume. The choice of crops for the less saline water would be somewhat wider, including some eucalypts.

4. If horizontal drainage is used effectively to skim off effluent for reuse, as in the case of perched water tables, the natural groundwater quality would be protected from salinization and pollution. However, if this water is not intercepted but allowed to mix with deeper water, as in the case of tubewells, then quality problems may be greater.

5. Options to manage drainage effluents include: on-farm reuse for a variety of salt-tolerant crops, use on halophytic crops or vegetation, 'harvesting' of toxic ions by certain plants (toxic ion scavengers), disposal into evaporation ponds, direct discharge into the ocean or into rivers at high stages with surplus flow.

iii. Basin level management

Strategies for the efficient use of water supplies in a drainage basin including saline and non-saline water should aim to:

- conserve usable water supplies;
- maximize effectiveness of using each water resource;
- minimize drainage volume and maximize salt concentration of drainage water from agricultural land;
- leave unusable saline groundwaters undisturbed as far as possible.

These strategies will minimize off-site impacts of irrigation.

Water quality management policies and programmes should take into consideration the drainage basin as a whole. Policies at the level of canal commands and management at the level of individual farms should be as compatible as possible within this overall drainage basin policy.

Table 3-39

Table 36-10. Equivalent amounts of common amendments for reclaiming sodic soils.

Amendment	Amount equivalent to 1 kg gypsum
	kg
Gypsum	1.00
S	0.19
H_2SO_4	0.57
CaS_5 (24% S)	0.77
$CaCO_3$	0.58
Calcium chloride dihydrate ($CaCl_2 \cdot 2H_2O$)	0.85
Ferrous sulfate ($FeSO_4$)	1.61
Aluminum sulfate [$Al_2(SO_4)_3$]	1.29

Source: in Stewart ed. 1990

Table 3-40a

Genetic type	Relation with groundwater	Water soluble salt content in the surface layers in saturation extract	Amelioration*
1 solonchak-solonetz meadow solonetz meadow solod (shallow and middle)	permanently linked	more than 0.2% (about 4 mmhos/cm)	drainage and chemical amendments
2 meadow solonetz and solod soils turning into steppe formation	temporarily linked	about 0.2% (about 4 mmhos/cm)	chemical amendments, deep ploughing and drainage if necessary
3 deep solonetz and solod soils, solonetz-like meadow soils	not linked	less than 0.2% (about 4 mmhos/cm)	low amount of chemical amendments proper agrotechnics and suitable crop (deep ploughing, alfalfa, etc.)

* The necessity of irrigation depends on local conditions

Tab. 2: *A schematic grouping of solonetz and solod soils with regard to their amelioration.*

Source: Szabolcs 1989

Table 3-40b

TABLE 21. Schematic grouping of solonetz and solod soils and suggested methods of amelioration.

Genetic type	Relation with ground water	Water-soluble salt content in the surface layer	Amelioration[1]
1. Solonchak-solonetz Meadow solonetz Meadow solod (shallow and middle)	Permanently linked	More than 0.2 per cent (about 4 mmhos)	Drainage and chemical amendments
2. Meadow solonetz and solod soils turning into steppe formation	Temporarily linked	About 0.2 per cent	Chemical amendments, deep ploughing and drainage if necessary
3. Deep solonetz and solod soils Solonetz-like meadow soils	Not linked	Less than 0.2 per cent	Low amount of chemical amendments, proper agrotechnics (deep and suitable crop (alfalfa, etc.) ploughing)

1. The necessity for irrigation depends on local conditions.

Source: Szabolcs 1979

Table 3-41

Table 8.3. Soil conservation practices

Practice	Control over					
	Rainsplash		Runoff		Wind	
	D	T	D	T	D	T
Agronomic measures						
Covering soil surface	*	*	*	*	*	*
Increasing surface roughness	–	–	*	*	*	*
Increasing surface depression storage	+	+	*	*	–	–
Increasing infiltration	–	–	+	*	–	–
Soil Management						
Fertilizers, manures	+	+	+	*	+	*
Subsoiling, drainage	–	–	+	*	–	–
Mechanical Measures						
Contouring, ridging	–	+	+	*	+	*
Terraces	–	+	+	*	–	–
Shelterbelts	–	–	–	–	*	*
Waterways	–	–	+	*	–	–

– no control; + moderate control; * strong control (adapted and enlarged from Voetberg, 1970)
D = Detachment, T = Transport.

Source: Kirkby/Morgan ed. 1980

Table 4-1

Table 2 Health Protection Measures: Overview of the Practice

Country/Location	Kind of Reuse	Health Protection Measures Practised
MEXICO Mezquital Valley	Irrigation of alfalfa, maize, cereal crops, tomatoes and beans mostly with untreated wastewater	Crop restriction, some exposure control for agricultural workers
CHILE Santiago	Irrigation of raw-eaten vegetables, cereal crops and grapes with untreated wastewater	None (treatment being planned)
INDIA Kanpur	Irrigation of rice, wheat, forage and flowers with diluted untreated wastewater	None
Calcutta	Fish growing in ponds receiving untreated wastewater at low loading rates	Cooking of the fish
PERU Lima (S. Martin de P.)	Irrigation of vegetables and non-food crops with raw wastewater	None
Ica (Cachiche)	Irrigation of maize and cotton with primary pond effluent	Partial wastewater treatment and crop restriction
Tacna	Irrigation of maize, alfalfa and fruit trees with effluent from overloaded WSP	Partial treatment and crop restriction
ARGENTINA Mendoza	Irrigation of raw-eaten vegetables with settled sewage	Partial treatment
TUNISIA Tunis	Irrigation of non-vegetable crops and fruit trees with secondary effluent	Partial treatment and crop restriction
SAUDI ARABIA Riyadh	Irrigation of wheat, forage and date palms with tertiary (filtered and chlorinated) effluent	Full treatment and crop restriction
SOUTH KOREA Pusan	Use of sludge from nightsoil treatment plants in agriculture	Dewatering and composting of the sludge
JORDAN Wadi Dhuleil area	Indirect use of the Al-Samra/Amman WSP effluent for the irrigation of trees, fodder and industrial crops	Full wastewater treatment, seasonal dilution and crop restriction
Zarqa Valley (downstream of Jerash bridge)	Indirect use of WSP and STP effluent for unrestricted vegetable irrigation	Full/partial treatment and seasonal dilution
Salt (Wadi Shu'eib)	Indirect use of STP effluent for the irrigation of vegetables eaten cooked	Partial treatment, seasonal dilution and crop restrictions

Source: Shuval (WB) 1991 (?)

Table 4-2/1

Figure 1-4. Example of a summary assessment.

Project Title	An example
Project Type	Commercial Irrigation
Location	Somewhere in Africa
Date of Assessment	month/year
Community Group	Construction workers
Project Phase	Construction phase

Disease	Vulnerability of community	Receptivity of environment	Vigilance of health services	Health Hazard
Malaria (*falciparum*)	high	moderate	treatment only	high
Schistosomiasis (*mansoni*)	low	moderate	none	low
Filariasis (onchocerciasis)	low	none	none	none

For example

The accompanying worksheet (figure 1-4 on page 1- 11) indicates how the assessment might have been completed for the construction phase of an irrigation scheme somewhere in Africa. The summary could be interpreted as follows:

Malaria is expected to represent a health hazard during the construction phase because susceptible people will be exposed to the vector and no preventative measures are planned. A large percentage of the workforce may be incapacitated.

Schistosomiasis does not occur near the project site but a potential vector is present. The health hazard is moderate but will increase unless immigrants or construction workers and their families are screened on arrival for infection, or other preventative measures are instigated.

Onchocerciasis occurs in the region but there is no vector at the project site and none is expected to become established during construction.

Such a summary assessment is insufficient in itself. Each conclusion must be justified by reference to the answers obtained to the questions in the flowchart.

Source: Birley 1992

Table 4-2/2 to 6

see next pages

Table 4-3

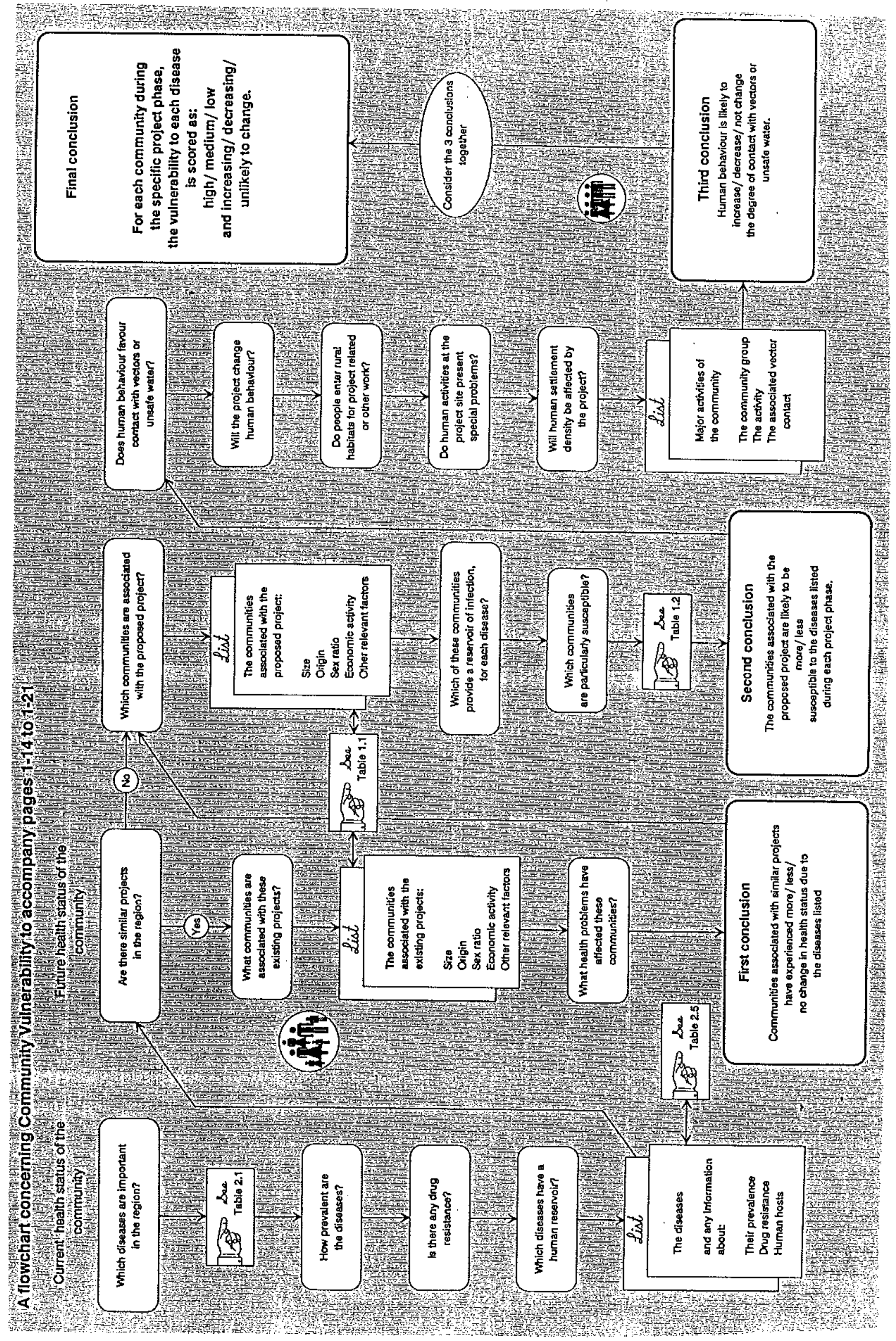
Table 1-5

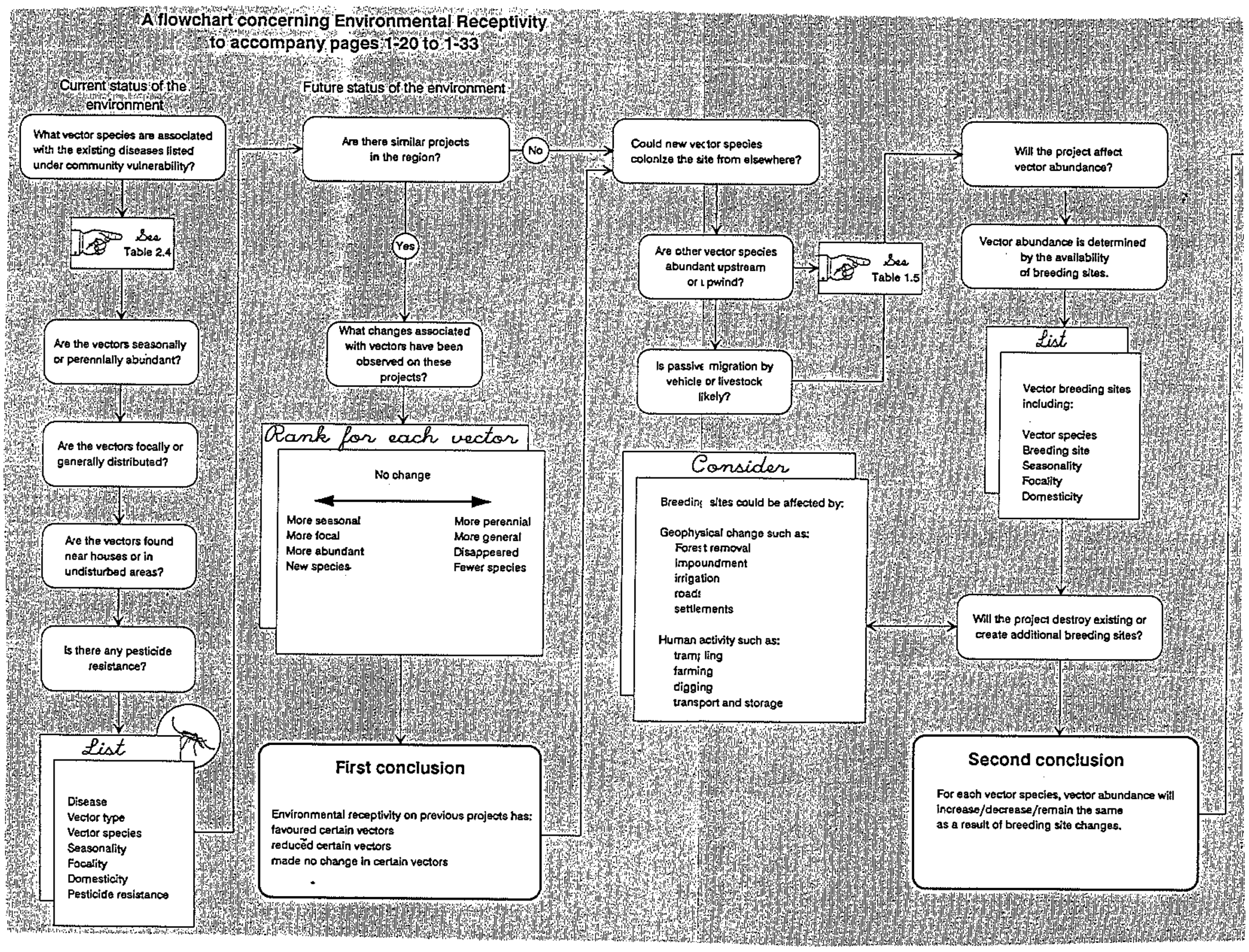
The flight range of vectors (kms). Migratory flights are often aided by prevailing winds and occasionally much longer flights have been recorded. Local movement is indicated as a guide to settlement siting. Where a range is indicated, the majority of vectors will only travel the shorter distance.

Vector	Local movement	Migration
Simuliid blackflies	4-10	400
Anopheline mosquitoes	1.5-2.0	50
Culicine mosquitoes	0.1-8.0	50
Tsetse	2.0-4.0	10
Phlebotomine sandflies	.05-0.5	1

Source: Birley 1992

Table 4-2/2




A flowchart concerning Environmental Receptivity
to accompany pages 1-20 to 1-33
Current status of the environment
Future status of the environment
What vector species are associated with the existing diseases listed under community vulnerability?
See Table 2.4
Are the vectors seasonally or perennially abundant?
Are the vectors focally or generally distributed?
Are the vectors found near houses or in undisturbed areas?
Is there any pesticide resistance?
List
Disease
Vector type
Vector species
Seasonality
Focality
Domesticity
Pesticide resistance
Are there similar projects in the region?
Yes
No
What changes associated with vectors have been observed on these projects?
Rank for each vector
No change
More seasonal
More focal
More abundant
New species
More perennial
More general
Disappeared
Fewer species
First conclusion
Environmental receptivity on previous projects has:
favoured certain vectors
reduced certain vectors
made no change in certain vectors
Could new vector species colonize the site from elsewhere?
Are other vector species abundant upstream or upwind?
See Table 1.5
Is passive migration by vehicle or livestock likely?
Consider
Breeding sites could be affected by:
Geophysical change such as:
Forest removal
impoundment
irrigation
roads
settlements
Human activity such as:
tramp ling
farming
digging
transport and storage
Will the project affect vector abundance?
Vector abundance is determined by the availability of breeding sites.
List
Vector breeding sites including:
Vector species
Breeding site
Seasonality
Focality
Domesticity
Will the project destroy existing or create additional breeding sites?
Second conclusion
For each vector species, vector abundance will increase/decrease/remain the same as a result of breeding site changes.

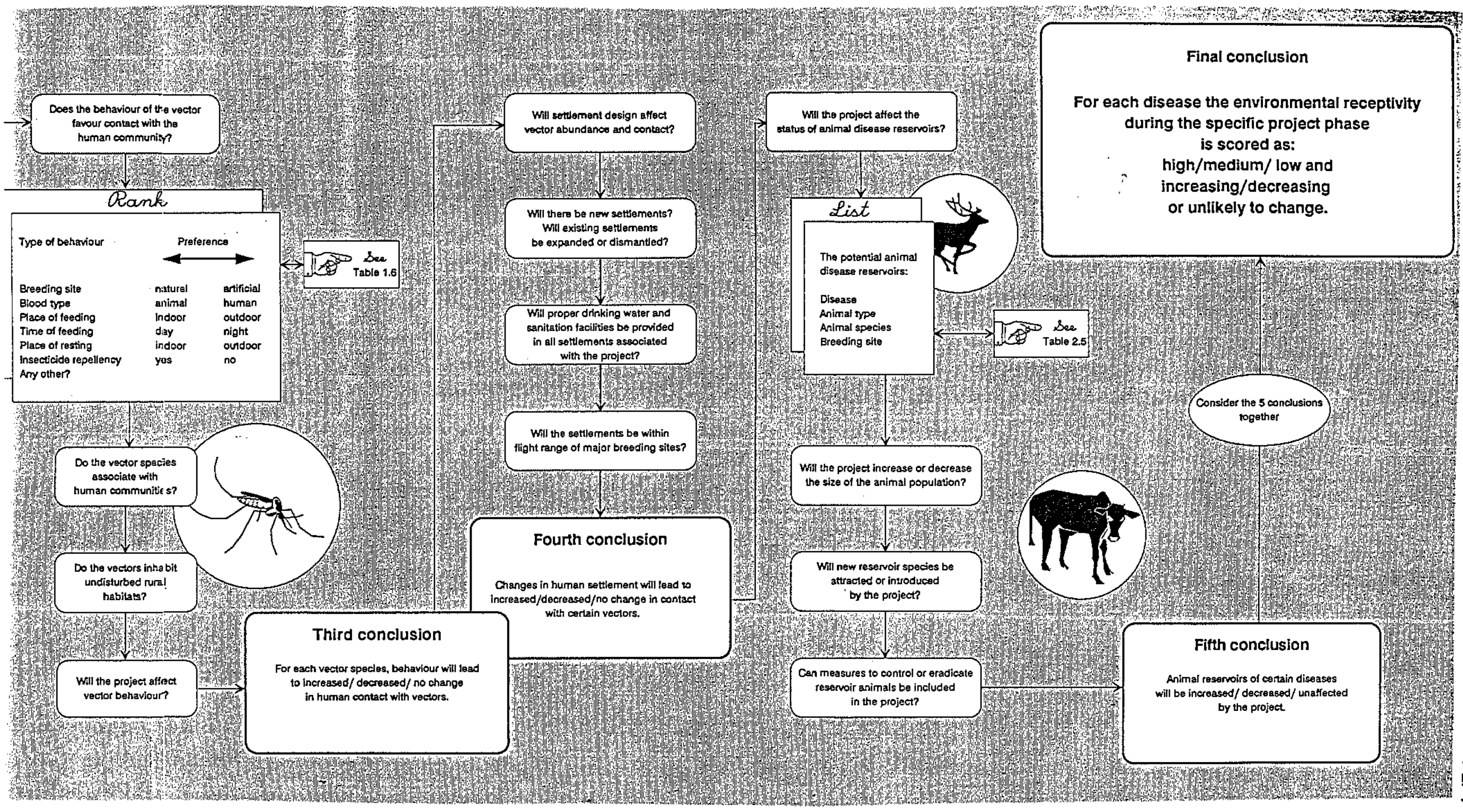

Does the behaviour of the vector favour contact with the human community?
Rank
Type of behaviour
Preference
Breeding site natural artificial
Blood type animal human
Place of feeding indoor outdoor
Time of feeding day night
Place of resting indoor outdoor
Insecticide repellency yes no
Any other?
See Table 1.6
Do the vector species associate with human communities?
Do the vectors inhabit undisturbed rural habitats?
Will the project affect vector behaviour?
Third conclusion
For each vector species, behaviour will lead to increased/ decreased/ no change in human contact with vectors.
Will settlement design affect vector abundance and contact?
Will there be new settlements? Will existing settlements be expanded or dismantled?
Will proper drinking water and sanitation facilities be provided in all settlements associated with the project?
Will the settlements be within flight range of major breeding sites?
Fourth conclusion
Changes in human settlement will lead to increased/decreased/no change in contact with certain vectors.
Will the project affect the status of animal disease reservoirs?
List
The potential animal disease reservoirs:
Disease
Animal type
Animal species
Breeding site
See Table 2.5
Will the project increase or decrease the size of the animal population?
Will new reservoir species be attracted or introduced by the project?
Can measures to control or eradicate reservoir animals be included in the project?
Fifth conclusion
Animal reservoirs of certain diseases will be increased/ decreased/ unaffected by the project.
Consider the 5 conclusions together
Final conclusion
For each disease the environmental receptivity during the specific project phase is scored as: high/medium/ low and increasing/decreasing or unlikely to change.

Table 4-2/5

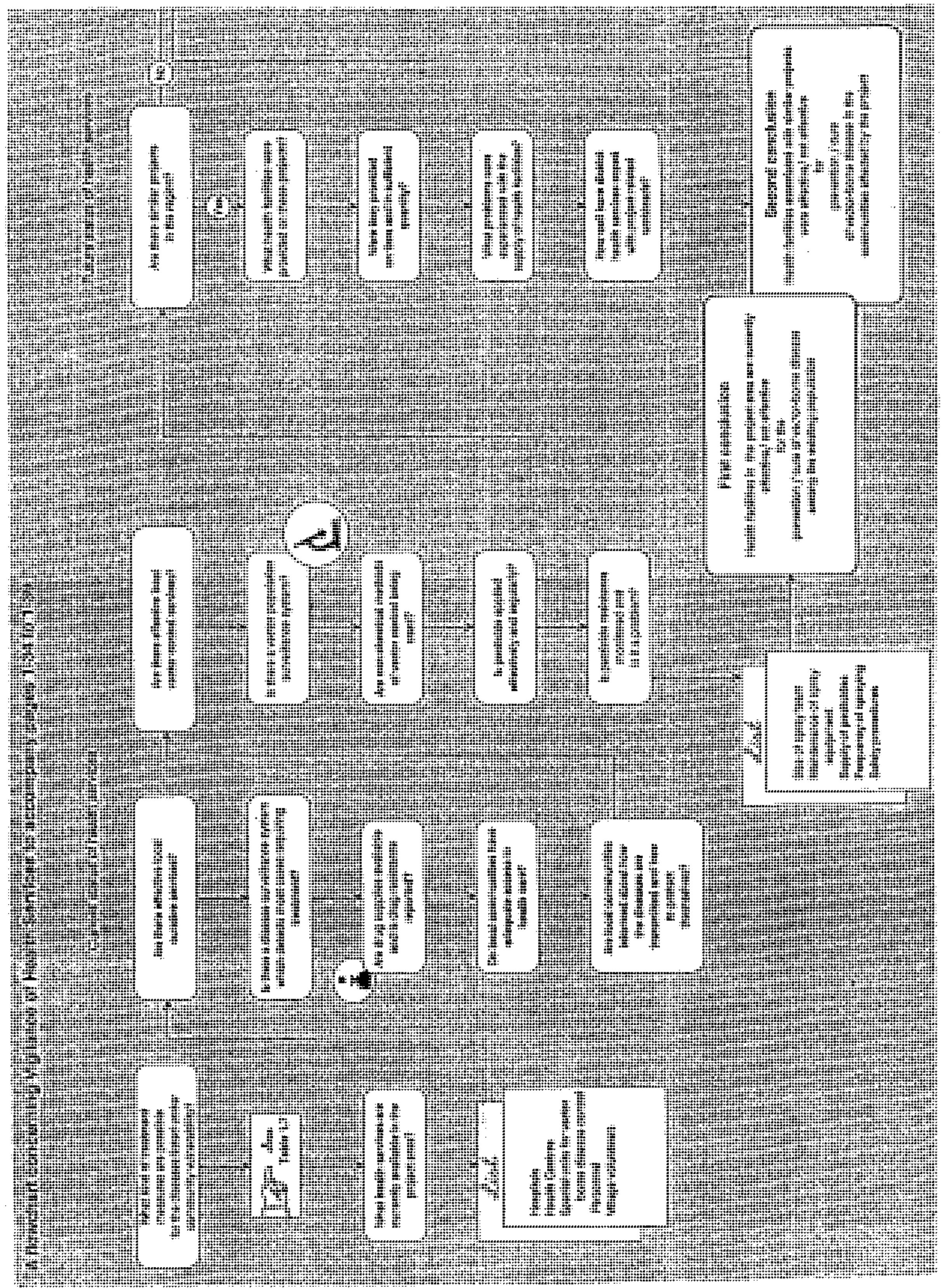
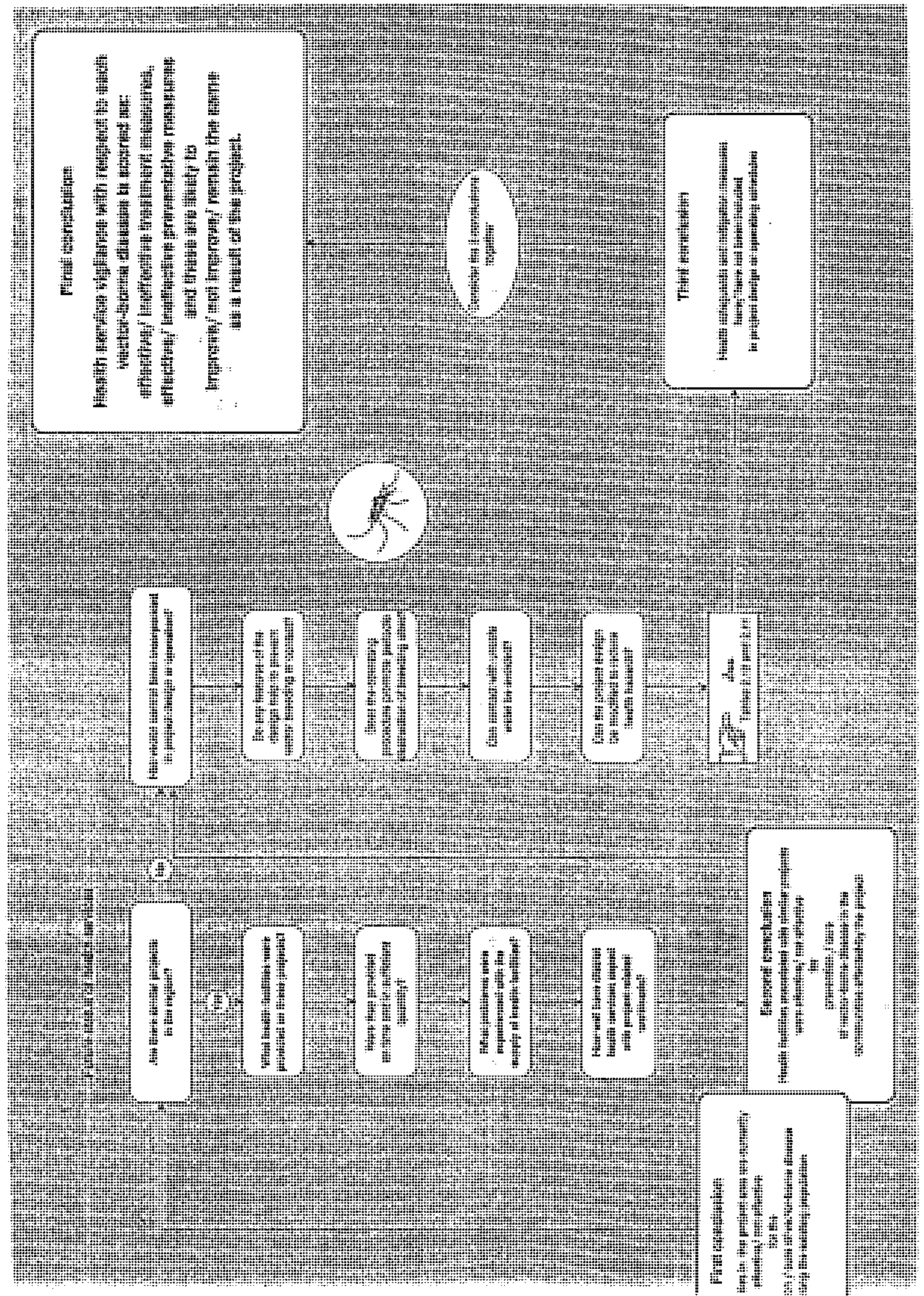


Table 4-2/6



Source: Birley 1992

Geophysical

Table 4-4

Soil type

If soil is compacted or ground cover is removed or soil is exposed to excessively dry conditions then soil loses its permeability or porosity and rainpools last longer.

If ground cover is removed then soil is eroded.

If soil is eroded then shallow pools are created by silt deposition.

If there are loess soils and semi-arid conditions then rodent reservoirs of leishmaniasis may be abundant.

If the soil is structurally poor then shallow latrine pits will collapse and provide vector breeding sites.

If the soil type is ferralsol or acrisol then there may be a lower incidence of malaria as compared with luvisols (because deep, free draining soils provide fewer pools for mosquitoes to breed).

Water Scarcity

If water is scarce or supply is irregular then there will be domestic water storage.

If tap water is too hot then it may be stored in domestic containers to cool.

If water is stored in domestic containers without good covers then container breeding mosquitoes such as *Aedes aegypti* will increase in abundance.

If there is a piped water supply and inadequate waste water disposal then there will be muddy surrounding water (in which mosquitoes and snails may breed).

If water pipes leak then mosquito breeding sites are created.

Irrigation Schemes

If an irrigation scheme is sited in a previously semi-arid region then health hazards are created because major ecological changes occur.

If molluscicide treatment is required then focal application can be very effective.

If old irrigation ditches are filled and new ones constructed alongside then snail populations are eradicated (oncomelanian snails were controlled in China by this method).

If canals are lined then the recurrent cost of vegetation and erosion control is reduced.

If water is piped then capital, maintenance and pumping costs are higher but health hazards are removed.

If sprinkler or drip feed irrigation is used then mosquitoes and snails are deterred.

If irrigation schemes are managed to provide the minimum of standing water for the minimum consecutive period then breeding can be controlled.

If canals and night stores are drained in a 7 day rotation with 2 days dry then mosquito breeding is reduced.

If a scheme is surrounded by afferent canals then the invasion of rodent populations is reduced.

Canalisation

If canal linings are imperfect then seepage pools will provide important breeding foci.

If rivers are crossed by fords, causeways or bridges then vector blackflies may be provided with new breeding sites.

If damage to canal banks is to be avoided then overpasses should be provided.

If the project is in West Africa then crossing points may attract tsetse flies.

If the mean flow rate is greater than 0.6 m/s and the channel is free of vegetation then snails are deterred (but erosion of unlined channels may occur).

If fast flow rates are to be maintained then regular desilting, bank repair and deweeding is necessary.

If the water is relatively clean and aerated and flowing then blackfly vectors may breed (Preferred habitats range from tiny streams and irrigation ditches to large rivers, to a depth of 0.15m. In W. Africa preferred flow rates are 0.7-1.2 m/s)).

If channels are designed for rapid draw-down and adequate drying-out then pooling during periods of low flow rate may be avoided.

If miracidia and cercaria are released in moving water then they cause infection downstream.

If solid waste collection facilities are inadequate then drains will be blocked by domestic waste.

If water is channeled through numerous small ditches then maintenance is more difficult than for a few large canals.

If an irrigation system contains night storage dams or canals then snail breeding should be expected (these habitats are difficult to treat with molluscicide).

If night storage dams become infested with aquatic vegetation then *Mansonia* mosquitoes should be expected.

Water Collections

If there are numerous small collections of clean water (such as are found in discarded cans, tyres, containers, leaf axils, tree holes, bamboo and rock pools) then *Aedes* mosquitoes may be abundant.

If borrow pits result from construction activities and fill with water then snails and mosquitoes may breed in them.

If borrow pits are deliberately planned as water holes then they should be enclosed and/or treated with larvicides or molluscicides.

Source: Birley 1992

Geophysical

Table 4-4 cont

Season

If the climate is seasonal then vectors may vary in abundance through the year.

If malaria is stable then additional vectors may not affect the incidence of the disease significantly.

If there is a season during which vectors and snails are unable to breed then disease transmission may be interrupted during that season.

If the seasonal abundance of standing water is increased then the period of interrupted transmission is reduced.

If domestic animals such as cattle, buffaloes and pigs are seasonally abundant then they may divert vectors away from human hosts.

If a development project alters the abundance of domestic animals then the diversionary effect is altered.

If people sleep outside during hot weather then they may attract outdoor biting mosquitoes.

If there are seasonal food shortages then there may be a seasonal increase in susceptibility to infection.

If there is a water development scheme then seasonal food shortages may be reduced.

If there is increased contact with limited dry season water supplies then intense focal transmission of schistosomiasis may occur.

Temperature and Altitude

If the mean temperature is below 17°C then parasite development in the vector or intermediate host ceases (20°C for *falciparum* malaria, 14°C for schistosomiasis).

If the temperature is very high then parasite development ceases and the activity of vectors is reduced.

If a development project is planned at altitudes at which pathogen transmission is rare then the potential increase will be negligible.

Wind

If the project is in West Africa and there are blackfly vectors breeding within 400 km upwind then recolonization of seasonal streams may be expected.

If wind assists the drift of floatage then the dispersal of snail vectors may be increased.

If the site is generally windy then insect biting activity will be greatly reduced.

If there are exposed shores subject to wave action then the breeding of snails and mosquitoes will be greatly reduced.

Humidity

If the microclimate humidity is low then insect lifespans may be low.

If the insect lifespan is low then it is less effective at disease transmission.

If humidity is low then the survival of filarial parasites may be reduced when they escape from the insect proboscis and transmission of this disease is reduced.

If the development project is in an area of low humidity and there will be a large scale increase in surface water then microclimate humidity will increase.

If the region is arid or semi-arid then schistosomiasis due to *S. mansoni* or *S. haematobium* is a potential health hazard.

Topography

If a river has a steep gradient then stream flow exposes bedrock (which provide breeding sites for various vectors).

If there is a flood plain and slowly meandering streams deposit silt then more permanent pools and marshes are created.

If there are fast currents and an unstable stream bed then the site is unfavourable for snails.

If bedrock is non-sedimentary then it is more suitable for blackfly breeding.

If land is levelled for road construction then borrow pits will be created.

If borrow pits fill with water then mosquito and snail habitats are created.

Rainfall

If there is plenty of rain then water contact may be reduced but snail breeding rates may be increased.

If an area has distinct dry and wet seasons then both insect vector density and disease prevalence are likely to have seasonal patterns.

If rainfall is plentiful in the river basin and hydrological conditions promote stream flow then stream margin breeding mosquito larvae will be flushed out but blackfly breeding sites may be enhanced.

If hydrological conditions cause rapid alterations in stream depth then rock pool breeding sites will be created as the stream falls and blackfly breeding sites may be created as the stream rises.

If there is plenty of rainfall and the soil is not too porous then temporary rainpools will be abundant.

If the vectors breed in temporary rainpools then their breeding sites will be very difficult to control.

If rainfall is less than expected then dried up river beds may serve as mosquito breeding sites.

Surface Water

If there is an abrupt margin between land and water then breeding sites are minimised.

If there is wave action and a steep shore or an unstable shore then mosquitoes and snails are deterred.

Geophysical

Water Chemistry

If surface water is subject to high evaporation rates then salinity increases.

If a coastal site is occasionally inundated with seawater then saline pools are abundant.

If salinity is high then some species of mosquitoes are attracted and other mosquito species are repelled.

If nitrogen content is high then culicine mosquitoes may be more abundant than anophelines (exceptions include *An. vanma* and *An. annularis* in India).

If insecticide spraying kills non-target organisms then algal blooms may stimulate vector production.

If there is a lake outflow and algal blooms provide high nutrient levels then vector blackfly larvae may be abundant at the outflow.

If the calcium content is about 80ppm and there is a balance of calcium, potassium and magnesium and pH is slightly acid then aquatic snails may be abundant.

If stream nutrient content and chemistry is suitable then vector blackflies may be abundant.

If the water is turbid then important malaria vectors may be attracted but snails may be deterred (eg: by puddling soils in ricefields).

Drainage and Sullage

If domestic water is supplied without adequate provision for waste water disposal then a major public health hazard is created.

If an irrigation system has better maintained water supply ditches than drainage ditches then excess standing water may create a public health hazard.

If water is moderately polluted then snail populations are favoured.

If water is heavily polluted with human or animal faeces then culicine mosquitoes will be abundant.

If an approved latrine design is used then mosquito breeding may be minimised (recommended designs include ventilated improved pit latrines, vault latrines and pour-flush latrines).

Ground Water

If the water table is close to the surface then latrine pits will fill with water and promote culicine mosquito breeding.

If trees with high evapotranspiration potential are planted then the level of the water table may be reduced.

If the water table is very deep then vertical drainage may be used.

Impoundments

If a reservoir floods a stream course then blackfly breeding sites may be destroyed but new breeding sites may be created at the spillway.

If the spillway is constructed of undressed stone then blackfly breeding is likely.

If the spillway is vertical or overhung or siphoned then blackflies are deterred.

If the spillway flow is interrupted for at least 1 day in 7 by using twin spillways then blackfly breeding is unlikely.

If continuous discharge from a reservoir scours the stream bed then new blackfly breeding sites may be created downstream.

If blackflies disrupt dam construction then larvicide should be applied upto 20km up- and down-stream during periods of rising and falling flood.

If the water level of a reservoir can be varied then the breeding of mosquitoes and snails can be reduced (but fluctuating water levels favour some species of mosquito).

If a reservoir is deep then mosquitoes and snails will be deterred (they rarely occur in lakes and large ponds, except at shallow margins).

If land can be cleared before it is flooded then breeding sites may be much reduced (because there is more exposure to wave action).

If complete land clearance is too costly then clearance should be restricted to the vicinity of human habitation or water margins (clearance should extend above the projected shore-line).

If land is flooded then wild rodent populations are displaced and may be brought into closer contact with human communities.

If a dam is constructed for hydroelectricity generation then its water may not be available for irrigation when it is most required and water level variation is likely to be unpredictable.

If a dam is constructed without adequate vegetation clearance then rotting organic material will pollute downstream water and make it unsuitable for domestic use.

If habitations adjacent to water margins are sited facing prevailing on-shore winds then wave action renders the margin unsuitable for vector breeding.

If land is newly flooded then old mosquito breeding sites are flushed out but new breeding sites are eventually created (so mosquito abundance may initially fall before rising to new levels).

Biotic

Vegetation on site

If the banks of water courses are covered in vegetation then water flow rates are reduced and refuges provided for mosquitoes and snails.

If water is shaded or partly shaded by vegetation then certain mosquito species will be attracted (eg: *An. minimus* in Asia and *An. funestus* in Africa).

If water is not shaded then certain mosquito species will be attracted (eg: *An. gambiae* in Africa).

If there is tropical rain forest vegetation and shaded or partly shaded margins of forest pools and streams then *Anopheles* mosquitoes should be abundant.

If tropical rain forest is clear felled then shade breeding species are eliminated (but soil erosion and loss of resources occurs).

If tropical rain forest is selectively felled then disturbance of the ground creates additional breeding sites.

If crop production simplifies the vegetation environment then more dangerous vector and snail species may be encouraged.

If emergent or floating vegetation grows in deep water then vector breeding sites are created. (*Mansonia* mosquito larvae only breed in association with rooted or floating vegetation, especially *Eichhornia, Pistia* and *Salvinia*).

If the species of vegetation provide natural water containers then mosquitoes will breed in them (eg: Bromeliads including pineapples; bananas; bamboo; Colocacia and rotting tree stumps).

If there is halophytic[1] vegetation then there may be reservoir hosts of leishmaniasis (eg: the rodent *Psammomys obesus*).

Bird fauna

If wild ardeid birds such as herons are attracted to an irrigation project then there is a risk of arbovirus transmission such as Japanese encephalitis.

Aquatic and terrestrial succession

If land or water is cleared of vegetation during the construction process then an orderly process of vegetational succession (regrowth) will occur.

If there is succession then vegetation will increase in size, density, cover and shade area (each phase in the succession will favour different species of animals, including vectors and their natural enemies).

If there are dense stands of vegetation then there are relatively humid resting places which are favoured by vectors.

Farming systems

If oxen are replaced by tractors then mosquitoes which were feeding on oxen may be forced to bite people (a resurgence of malaria in Guyana was attributed to this factor).

If water buffaloes are replaced by tractors in a rice production system then removal of their bathing pools may affect dry season vector density.

If agricultural insecticides are used on a large scale then vectors may develop resistance to a wide range of insecticides (eg: *An. sinensis* in China, *An. sacharovi* in Turkey and *An. albimanus* in Central America).

Rodent fauna

If an irrigation scheme is under development then rodent species which are closely associated with human settlements and are potential disease reservoirs will increase in abundance (eg: at Hola in Kenya abundance increased 10-50 times).

If an irrigation project raises the water table then rodents such as gerbils may become less abundant but associated sandflies may become more abundant (eg: a reservoir of cutaneous leishmaniasis which affected construction workers in Uzbekistan).

If previously unpopulated areas are settled then increased human contact with wild fauna may promote zoonoses.

If land is ploughed then colonial rodents such as *P. obesus* and *R. opimus* are eliminated but secondary reservoirs of leishmaniasis such as *Meriones* spp. may become more abundant.

If fodder crops are irrigated and it is a semi-arid region then rodents may increase in abundance.

Rice cultivation

If human settlements are close to rice fields then high rates of mosquito-borne disease may occur.

If a belt of dryland crops is established around a village then people are protected from rice-field breeding mosquitoes.

If paddy rice has been transplanted and is less than 75cm tall then malaria mosquitoes which prefer sunlit water will breed (eg: *An. arabiensis* in Africa, *An. freeborni* and *An. albimanus* in Central America).

If the paddy rice is taller than 75cm then shade loving malaria mosquitoes will breed (eg: *An. funestus* in Africa, *An. umbrosus* in S.E. Asia, *An. punctimaculata* in S. America).

If insecticides are used to kill rice pests and they kill aquatic predators then abundant mosquito breeding may result (eg: use of Dimecron at Ahero in Kenya).

If old plant debris is allowed to rot in newly flooded rice fields then mosquito breeding may be promoted (eg: *C. tritaeniorhynchus* in Sarawak).

If rice is planted in trenches through which water flows then mosquito breeding may be prevented (eg: *An. pseudopunctipennis* in Mexico).

Large fauna

If a settlement is planned and the settlers keep domestic animals then hygienic animal pens should be included in the settlement design.

If domestic animals are penned between human communities and mosquito breeding sites then mosquito vectors may bite the animals instead of the people and disease transmission is reduced.

Aquatic fauna

If natural predators such as dragonfly nymphs and fish are numerous then they will contribute to the control of vectors.

If natural predators are contributing to vector control then they should be protected by careful choice of vector control measures such as insecticide and application schedule.

If certain fish are introduced into irrigation schemes then they can contribute to the control of vectors.

If fisheries are drained or rotated periodically then schistosomiasis hazards may be reduced.

Source: Birley 1992

Demographic and socio-cultural factors

Table 4-5

Settlements

If there is inadequate provision for maintenance then piped water supplies and village pumps will be unreliable.

If the water supply is unreliable then water will be stored in the home (see water scarcity).

If water sources are far from the home then water will be stored in the home.

If water points are fitted with self-closing taps or handpumps then excess water discharge will be avoided.

If water supply and sanitation facilities are communal then there may be no incentive to maintain them properly.

If domestic waste water is not disposed of properly then vector and snail breeding sites are created.

If there are septic pools or surface grey water drainage or poorly maintained latrines then the mosquito vector of lymphatic filariasis may flourish.

If houses are designed to prevent mosquito ingress then much potential disease transmission can be avoided.

If house construction materials are absorbent then residual insecticide sprays will be less effective.

If settlements are sited 2km from swamps and forest margins then they are outside the flight range of most mosquitoes.

If settlements are sited far from agricultural zones then watchmen will be required to deter theft.

If there are locally breeding blackflies in a savannah or forest habitat then settlements should be sited at least 10km from the river.

If a dry-crop zone is sited around a settlement then contact with vectors which breed in irrigated sites is reduced.

If cultivation sites are far from permanent settlements then temporary settlements without proper sanitation will develop there.

Water contact

If small children bathe in irrigation systems where there are snails then schistosomiasis transmission will be intense.

If the climate is hot then the desire to bathe will outweigh any health education.

If snail-free bathing areas are provided and they are more convenient to use and their use is promoted by health education then schistosomiasis transmission can be reduced.

If bathing areas are sited in the centre of the village and they are closer to the home than irrigation canals then they are more likely to be used.

If bathing areas are to be kept free from snails then they should be refilled periodically and treated with molluscicide.

If the use of water sources near settlements is deterred by fencing, culverts, bridges and steep-sided canals then water contact is reduced.

If the daily cycle of water-related activities coincides with peak cercarial densities (the peaks are often during the middle of the day) then the risk of schistosomiasis infection is intensified.

If the seasonal cycle of activity (such as farming or fishing) coincides with peaks of vector or cercerial density then the risk of disease transmission is intensified.

Susceptibility to infection

If the demographic characteristics of the population are known then potential disease problems can be forecast with greater precision.

If a new settlement is developed then there will be more young fertile women and young children than in the rest of the population.

If there is a large population of children then schistosomiasis transmission is particularly favoured.

If future settlers are screened for parasitic disease then the chances of introducing new strains of parasites can be reduced.

If future settlers are screened on arrival, rather than at their place of origin, then anxiety, evasion and corruption may be reduced.

If the community has a high frequency of certain blood types such as haemoglobin S positive or Duffy group negative then malaria infections will be less severe.

If the population is largely immune to malaria then children and immigrants will be the main groups to suffer clinical illness.

If a labour force is assembled then the epidemic potential is increased.

If a susceptible community are translocated to a region with Japanese encephalitis and pig production is encouraged near to irrigation systems or reservoirs then there is a potential hazard of an epidemic (this has happened in Sri Lanka).

If use of antimalarial drugs is widespread then results of parasite surveys can be misleading.

If immigrants have no previous exposure to filariasis then clinical symptoms should be expected sooner than in communities from endemic areas (within 2 years in Indonesia).

If economic activities force certain people to expose themselves to the risk of infection then their health should be carefully monitored.

Vector contact

If mosquito nets and screens are badly maintained then they are not effective.

If the climate is hot, humid and windless then mosquito nets and screens are unbearable.

If the farms are within 15km of a blackfly breeding site then farm workers will be bitten.

If a vector is largely confined to feeding on animals and it is not very abundant then it does not pose a major health hazard.

If a biting insect cannot support development of parasite then it may be a nuisance but it is not a health hazard.

If there are no local blackfly breeding then seasonal migration of potentially infected blackfly may cause a hazard within at least 1.5km of the river bank.

Social categories

If there are large groups of construction workers then up to ten times as many spontaneous immigrants may be attracted informally to provide goods and services.

If communities are displaced then they may be exposed to hazards to which they have no prior experience.

Customs

If rights to use a water source are traditionally vested in different interest groups then development of the water source may produce intergroup conflicts leading to the destruction of the project.

If anal cleansing customs involve wiping and a waste disposal system is designed which assumes washing then wiping materials may block the system.

Source: Birley 1992

Table 4-6

CHECKLIST OF MAJOR STEPS FOR THE PREVENTION AND CONTROL OF VECTORBORNE DISEASES AT EACH PHASE OF WATER RESOURCES DEVELOPMENT PROJECTS

Planning phase

(1) Review of existing information on health and related subjects

- (*a*) Epidemiology: morbidity and mortality rates, geographical distribution, vector ecology.
- (*b*) Health and medical services: facilities, staff, special projects and programmes; degree of development, capacity and coverage.
- (*c*) Human population and its characteristics: agricultural, migrant, nomadic, etc.; population growth, importance of migratory movement, displacement within the project area.
- (*d*) Cattle: numbers and economic importance, prevalent diseases.
- (*e*) Community and housing patterns: location, design, construction materials.
- (*f*) Water supply, excreta and wastes disposal facilities.
- (*g*) Climatic patterns: temperature, rainfall, humidity, wind, etc.
- (*h*) Water: surface water and groundwater, quality, pollution, abundance and seasonal variation, floods and droughts, seasonal variation in temperature.
- (*i*) Soil: physical and chemical characteristics, including permeability, stability, salt content, etc.
- (*j*) Natural and cultivated aquatic and land vegetation; domestic and wild animals.
- (*k*) Economy: national and local, sources and levels of income.
- (*l*) Topographical maps: contour lines, roads, villages, etc., of the region and the watershed, design plans of proposed project, etc.

(2) Surveys: To check existing information or fill in gaps in knowledge; assessment and collection of basic data by specialists

- (*a*) Detailed epidemiology of major existing diseases and biology and ecology of principal vectors.
- (*b*) Health and medical services, disease and vector control programmes and activities, evaluation of effectiveness and resources.
- (*c*) Human and cattle movement: migratory currents, their origin and paths.
- (*d*) Sanitation: actual and potential sources of water supply, investigation of groundwater sources, actual and potential sources and routes of pollution, practices involving water contact, and methods of excreta disposal, cattle watering and manure disposal.
- (*e*) Existing and proposed agricultural crops and practices: irrigation methods, suitable crops, rotation in cultivation and irrigation, use of pesticides and fertilizers, their kind and amount.
- (*f*) Local economy: present status and prospects for future development.
- (*g*) Sociocultural patterns: present level and possible disturbance produced by the project.
- (*h*) Engineering and operational reconnaissance and mapping for ecological, hydrological, and geological or soil studies.
- (*i*) Contact with agencies operating in the project area, their type of activities and possibility of assistance and coordination.

(3) Decision-making for the prevention and control of diseases

- (*a*) Review of project proposals and preliminary designs and options.
- (*b*) Identification of existing health problems.
- (*c*) Prediction of possible future problems and of their health effects.
- (*d*) Determination of the importance and extent of actual and potential health problems to establish an order of priority in prevention and control operations.
- (*e*) Feasibility studies of control measures, including cost-effectiveness and cost-benefit analyses.
- (*f*) Selection of village sites and types of water supply and excreta disposal installations.
- (*g*) Selection of methods of vector and disease control and estimates of manpower and organizational requirements.
- (*h*) Organization of field trials and pilot projects.
- (*i*) Settlement of displaced and immigrant population and estimates for the provision of water supply, sanitation and other health facilities.

Design phase

(1) Establishment of design criteria to minimize health hazards and to achieve the objectives of the health programme.

(2) Evaluation of preliminary project designs and alternatives.

(3) Establishment of proposed practices of water-system management and their effects on vector habitats.

(4) Preliminary design and options for canal lining overpasses and other health structures.

(5) Final detailed design of works in the reservoir

- (*a*) Shoreline modification and improvement.
- (*b*) Clearance and disposal of trees and brush, of man-made structures and fences.
- (*c*) Relocation of roads, villages, cemeteries, shrines, etc.
- (*d*) Discharge structures sized for water-level regulation and downstream flushing.

(6) Final detailed design of works in irrigation schemes

- (*a*) Equalizing reservoirs and night-storage ponds, when necessary.
- (*b*) Canals and drains.
- (*c*) Regulating structures, gates, sluices, etc., and distributing chambers.
- (*d*) On-farm water use.
- (*e*) Groundwater use and control.
- (*f*) Potential for incorporating domestic water supply.

(7) Final detailed design of measures and works in communities

- (*a*) Selection of sites for new communities distant from water sources.
- (*b*) Provision of safe, adequate and convenient water supply and sewage disposal systems.
- (*c*) Recreation: provision of safe ponds as alternative to infected water bodies, sports grounds, etc.
- (d) Other protective measures, such as house-screening, surface-water drainage, general sanitation, and public laundry installations.

(8) Provisions for maintenance activities and their financing.

(9) Environmental management

- (*a*) Regulating structures for measurement and control of water discharge and velocity.
- (*b*) Gates required for rapid drying and flushing of irrigation subsystems.
- (*c*) Adjustment of water salinity in coastal breeding-sites through the installation and operation of gates.
- (*d*) Water-level regulation in small reservoirs by means of automatic siphon spillways.
- (*e*) Safe crossings and bridges over canals and drains.
- (*f*) Lining of canals and drains, closed or subsurface conduits.

(10) Enhancement and simplification of chemical and biological control

- (*a*) Design of dispensers for chemical application attached to or incorporated into regulating structures, metal rakes and screens against snails.
- (*b*) Access roads and paths for surveillance and spraying, clear water lanes and landings for boats.

(11) Health education of the public and development of community participation.

(12) Health facilities: dispensaries and hospitals.

Source: WHO 1980

Construction phase

(1) Health protection of the construction labour force.

(2) Special facilities for disease control and treatment at the construction site.

(3) Adequate housing and sanitary facilities for construction workers and their families.

(4) Surveillance of infections in imported manpower and local population.

(5) Monitoring, vaccination, treatment of local population and elimination and control of endemic diseases, especially those with potential for intensification with project operation.

(6) Environmental protection, erosion, spillage, air and water pollution, disposal of wastes, aesthetic alterations, etc.

(7) Inspection to ensure that construction is carried out according to health designs.

(8) Health education of the public and development of community participation.

Operations phase

(1) Allocation of funds, assignment of staff and implementation of disease control programmes.

(2) Surveillance, screening and treatment of infected persons.

(3) Establishment of rule curves and schedules for the control of mosquitos, snails, flies, weeds, etc.

(4) Establishment of practices and schedules for water-level regulation.

(5) Maintenance and modernization of structures and other works.

(6) Application of chemical and biological methods for vector and weed control.

(7) Drainage of all water collections around the reservoir.

(8) Prevention and correction of excessive seepage.

(9) On-farm water management.

(10) Operation, maintenance, improvement and development of water supply and sewage disposal systems, general sanitation.

(11) Health education of the public and development of community participation.

(12) Evaluation of vector and disease pattern changes, efficacy of control programmes, study and implementation of amendments or alterations to improve results.

(13) Preparation of periodic and special reports for information purposes.

Annex 3

LIST OF ENVIRONMENTAL MANAGEMENT MEASURES WHICH HAVE PROVED TO BE USEFUL IN THE PREVENTION AND CONTROL OF MALARIA AND SCHISTOSOMIASIS

The following environmental management measures have been applied for the prevention and control of malaria and schistosomiasis. They serve to create conditions unfavourable to the breeding and propagation of vectors and intermediate hosts, to reduce opportunities for man/mosquito contact or man/cercaria-infested water contact, and to assist in the application of insecticides and molluscicides. Although specifically addressed to water resources development projects, the measures are equally applicable to other situations.

The letters (M) or (S) indicate that the measure is particularly applicable to malaria or schistosomiasis control respectively. No indication is given where the measure is equally applicable to the control of both diseases.

During the design and construction phases

A. In reservoirs and surrounding areas

1. Removal of all trees, bushes and other plants that would emerge at maximum drawdown water level of the reservoir.

2. Selective clearing of vegetation in the zone of water level fluctuation about 8 m beyond the normal full reservoir contour at heads of bights for stranding of drifts (see subchapter IIIA), and much further on open shorelines.

3. Straightening of margins through cutting, deepening and filling of the reservoir edge.

4. Construction of dikes and levees to separate shallow bays from the reservoir and dewatering of the low areas behind the dikes by the operation of gates, so that the water flows by gravity when the reservoir is at low level or by pumping. Dewatering of runoff from drainage areas behind the dikes.

5. Removal of earth from higher areas that would protrude as small islands at maximum drawdown water level of the reservoir.

6. Filling of natural or man-made depressions in the vicinity of the reservoir, or draining of these depressions by ditches leading to the reservoir.

7. Provision in the dam design for the periodic fluctuation of water level. Large size crest gates (Tainter gates).

8. Paving or lining of spillways and diversion channels where they are exposed to wave action and erosion.

9. Use of waterproof membranes of clayey or plastic material at the base and surroundings of the dam to reduce water seepage, and provision of drainage for possible seepage water.

10. Building of boat operating bases, either by the construction of jetties or by the digging of small channels for the docking of boats. Ramps for launching of boats.

11. Provision of paths and other means of access to the reservoir edge for vegetation clearance and pesticide application.

(S)12. Extension into the reservoir of the drawout structure or outlet conduit so that water is not taken from the edge.

(S)13. Screening of intakes to prevent the passage of snails.

(S)14. Locating intakes of large lakes and reservoirs below the euphotic zone. Below this zone, where sunshine does not penetrate, there should be no snails.

(S)15. Fencing of the reservoir in the vicinity of villages to discourage people from using the reservoir.

Source: WHO 1982

B. In irrigation systems

1. Design of main canals, laterals and sublaterals to follow straight lines with the minimum number of bends; any necessary bends should be of ample curvature.

2. Design of canal gradients and cross-sections to ensure water velocities that prevent both silting and scouring.

3. Design of canal grids without interconnexions so that water enters at the head (or upper) end and flows in one direction only.

4. Provision of a gate, siphon or other water control device at the tail (or lower) end of canals so that they can be flushed and emptied to the nearest drain when necessary.

5. Provision of an effective drainage system to collect and dispose of surface and ground surplus water.

6. Elimination of disused canals and drains, and of natural streams intercepted by the new system.

7. Filling or draining of borrow pits along canals and roads. Land levelling.

8. Paving or lining of canals as extensively as possible; this is an irrigation improvement as well as an effective health protection measure.

9. Consideration in the design to using covered conduits or pipes for water distribution to cultivated plots and for surplus water drainage.

10. Provision of a sufficient number of bridges across canals so that the villages are not isolated from the main roads; this will also help the maintenance work and the application of insecticides and molluscicides.

11. Protection of the canal section at the entrance and exit of culverts, drops, chutes, control structures, etc. against scouring that may form depressions.

12. Designation of "dry belting" areas around villages, and land occupancy and restriction measures.

During the maintenance and operation phases

A. In reservoirs and surrounding areas

1. Clearing of submerged, emerging and floating vegetation to keep a bare zone of water level fluctuation and a clean shoreline.

2. Dredging of the reservoir margin to deepen it and produce steeper slopes.

3. Repair of dikes and levees to keep them in proper condition.

4. Filling or draining of natural and man-made ground depressions of recent formation or those that were unnoticed at the time of construction.

5. Straightening of courses and rectification of gradients of natural streams conveying water from the catchment area to the reservoir.

6. Provision of proper management for the punctual operation of water level fluctuation.

7. Repair of spillways, diversion channels and other structures scoured by water, and paving of the damaged sections.

8. Repair of drains that collect and convey the seepage water coming from the dam or other structures.

(S) 9. Repair of grids and screens at the intake structures or suction pipes.

(S)10. Fencing of the reservoir may be advisable when the communities have been provided with a proper water supply.

11. Repair of roads and paths of access to the reservoir edge.

B. In irrigation systems

1. Dredging of canals and drains to bring them back to their original dimensions and correct gradients, reshaping of cross-sections, and filling of bed depressions that may retain water when empty.

2. Frequent clearing of vegetation to ensure that the canals and drains are free from aquatic plants, weeds, etc.

3. Avoidance of the use of canals for night storage.

4. Repair of control structures and gates to ensure their proper functioning.

5. Repair of culverts, siphons and bridges, and filling of bed depressions formed by scouring at their entrances and exits.

6. Effective control of water quantity at the intake of the irrigation reservoir and at the gates to prevent over-irrigation.

7. Levelling and grading of cultivated land, particularly where it is exposed to flooding, or provision of drainage when levelling and grading is too extensive.

8. Gradual lining of canals, starting in the sections most exposed to scouring and those where seepage losses are greatest.

9. Gradual transformation of open channels to covered conduits and pipes, starting in the sublaterals and feeding canals. Promotion of subsurface drainage.

10. Gradual improvement of irrigation practices and methods (intermittent irrigation, localized sprinkler irrigation, etc.); gradual improvement in agricultural practices.

(M)11. Restriction of land use to daytime work in order to reduce the opportunities for mosquito biting.

12. Periodic flushing of canals and drains.

Table 4-8

Table 8.2 Properties of some molluscicides (Source: WHO 1965; 1973; 1980; 1983)

Characteristics	Niclosamide (Bayluscide)	N-trityl-morpholine (Trifenmorph)	NaPCP (Sodium penta-chlorophenate)	Yurimin	Copper sulfate	Nicotinanilide
Physical properties						
- Form of material	Crystalline solid	Crystalline solid	Crystalline solid	Crystalline solid	Crystalline solid	Crystalline solid
- Solubility in water	230 mg/l	very low	300 mg/l	Very low	320 mg/l	?
Toxicity						
- Snail LC_{90} (mg/l·h)*	3-8	0.5-4	20-100	4-5	20-100	5
- Snail eggs LC_{90}*	2-4	240	3-30	.	50-100	20-50
- Cercaria LC_{90} (mg/l)	0.3	No effect	–	..	–	?
- Fish LC_{90}(mg/l)	0.05-0.3	2-4	–	0.16-0.83	–	>30
Stability (affected by)						
- U.V. light	No	No	Yes	No		–
- Mud, turbidity	Yes	No	No	Yes		–
Formulations	70% W.P. 25% E.C	16.5% E.C. 4% granules	75% Flakes 80% Pellets 80% Briquettes	5% Granules	980 g/kg Pentahydrate crystals	Not yet formulated
Field dosage						
- Aquatic snails (mg/l·h)*	4-8	1-2	50-80	?	20-30	?
- Amphibious snails on moist soil (g/m^2)	0.2	–	0.4-10	5	Ineffective	?

* (mg/l·h) indicates that the figures given are the product of the concentration and the number of hours of exposure
LC Lethal concentration
LD Lethal dose
W.P. Wettable powder
E.C. Emulsifiable concentrate

Source: Oomen et al 1990

Table 4-9

Table 8.3 Comparison of molluscicide program costs for ten schistosomiasis control projects

Country / Locality	PUERTO RICO Vieques	Patillas	ST LUCIA Guayama Arroyo	Cul de Sac	Sao Lourenco	BRAZIL Belo Horizonte	Taquarendi	EGYPT Kom El Birka	IRAN Dez Scheme	TANZANIA Misungwi
Hydrology	i*	i and ii	i and ii	i	i	i and ii	ii	ii	ii	i
Annual rainfall (cm)	115	179	140	250	150	160	50	30	30	100
Controlled area (km^2)	130	122	207	18	80	200	2.5	52	220	100
Population	8,400	17,100	47,000	6,000	4,280	20,000	1,500	17,000	18,000	4,300
Annual volume of snail habitat treated (m^3)	65,000	89,000	106,400	182,000	80,000	39,000	15,000	1,354,000	500,000	200,000
Habitat volume per surface area (m^3/km^2)	500	739	514	10,000	1,000	195	6,000	16,000	2,300	2,000
Population density (persons/km^2)	64	140	227	333	54	100	600	330	82	43
Habitat volume per person (m^3)	7.8	5.2	2.3	30	18.5	2.0	10	80	28	46
Molluscicide	NaPCP	NaPCP	NaPCP	Niclosamide	Niclosamide	Niclosamide	Niclosamide	NaPCP + Niclosamide	Niclosamide	Niclosamide
Cost period (years)	10	7	1	1.1	10	4	5	1	1	1
Currency	US$	US$	US$	US$	US$	US$	US$	Egypt pound	US$	Sh.T
Total cost of program	63,600	60,380	8,298	32,500	316,800	34,000	6,800	20,700	17,000	30,000
Base year for costs	1960	1960	1955	1972	1972	1968	1968	1963	1972	1972
Annual cost in 1972 US$	13,000	17,000	20,000	25,000	32,000	10,000	1,500	58,600	17,000	4,178
Annual cost per 100 m^3 treated	20	19	19	17	40	26	10	1.40	3.40	2.10
Annual cost per km^2	100	139	97	1,700	400	50	600	1,130	77	42
Annual cost per person	1.50	1.00	0.43	4.00	7.40	0.50	0.70	3.45	0.94	0.75
Program cost breakdown										
Labour	65%	61%		50%	80%	50%	36%	5%	6%	
Molloscicide	3%	6%	11%	12%	10%	11%	40%	85%	19%	25%
Transport and equipment	7%			16%	5%	15%	24%		21%	
Supervision	22%			16%		24%			54%	
Others	3%	33%	89%	6%	5%			10%		75%

*; Natural drainage systems, comprising small streams, pools, or small water collections (either natural or man-made), seepages and marshy areas
ii Irrigation systems

Source: Oomen et al. 1990

Table 4-10

Table 4.1 Epidemiological variables for monitoring and evaluating the integrated control of vector-borne diseases

CONTROL METHODS	EPIDEMIOLOGICAL VARIABLES									
	Breeding habitat	Larvae/ pupae	Adult vectors density	Vector survival	Man-biting rate	Water contact	Population coverage	% infected	% diseased	Mortality
Environmental modification	x	x	x					x	x	x
Environmental manipulation	x	x	x		(x)			x	x	x
Residual insecticides control			x	x	x		x	x	x	x
Non-residual biochemical control		x	x		x			x	x	x
Biological control		x	x	x				x	x	x
Reduction man-vector contact					x	x	x	x	x	x
Prophylaxis/immunization							x	x	x	x
Treatment							x	x	x	x
Corresponding type of EVALUATION					I (and II)				III	

Source: Oomen et al. 1990

Table 4-11

Table 5.2 Classification of the most common potential breeding places in Zone 2, System C

Category	Description	Index
A	Large bodies of fresh water in full or partial sunlight Floating or emergent vegetation, especially near edges	1 Ulhitiya Reservoir, buffer reservoirs, large borrow pits, waterlogged pools behind bunds of distributary channels constructed in fill, large natural surface depressions. 2 Marshes
B	Small watercollections, stagnant and often muddy, but not polluted, full to partial sunlight 1 Vegetation present: scattered or at fringes 2 Vegetation absent	Marginal pockets along irrigation canals semi-permanent rain pools in natural or man-made surface depressions (e.g. in between road and canal bund), seepage pools behind buffer reservoir or canal bund, old borrow pits, clogged drainage ditches 2 Recent borrow pits, rock pools on excavation sites, new road ditches, wheel ruts, foot or hoof prints, rainwater pools
C	Marshy patches, often polluted with organic matter; mostly abundant vegetation (oily monolayers, iron-coloured water, smell of decomposition)	1 Seepage ponds/depressions along irrigation canals constructed in fill, poorly drained shallow but extensive surface depressions 2 Roads saturated with water from overtopped field channels bunds 3 Muddy broad sections of natural drains where the waterflow stagnates (mainly in upper parts of intermediate drains).
D	Paddy fields	1 Swampy and poorly drained fallow lowland paddy fields, prior to land preparation. 2 Recently tilled fields 3 Fields during seeding (levelled fields, no water layer, but small shallow pools) 4 Fields during transplanting (levelled fields, shallow water layer) 5 Fields during crop growth 6 Washing pits
E	Partially or heavily shaded water under abundant vegetation	1 Sluggish irrigation drainage streams (slow waterflow from one pool to another), pools at the interception of drains in distributary channels, ponds. 2 Stagnant pools in spillway drainage beds
F	Running water courses, clear fresh water, direct sunlight	1 Pools in drying stream beds (natural streams or irrigation canals), seepage pools from irrigation structures in canal beds, pools in stream-eroded canal depressions directly behind dropstructures, turnout structures and cross-regulators 2 Irrigation ditches and lowland grassy/weedy field-drainage ditches 3 Small side-pockets along embankments or irrigation canals (erosion gullies, bund breaches, etc.)
G	Man-made containers	1 Stilling basins of irrigation structures (turnouts, cross-regulators), silt catcher of reservoir spill 2 Wells, cisterns, discarded receptacles, old tyres, gutters

Source: Oomen et al. 1988

Table 4-12

	Pre-irrigation	Land-preparation	Crop Establishment	Vegetative growth	Harvest	Post-irrigation
Reservoir	A1; G1	A1; G1	A1; G1	A1; G1	A1; G1	A1; G1
Main/Branch Canal	F1	F3	F3	F3	F3	F1
Level Crossing/Tanks	A2	A1; B1; C1	A1; B1; C1	A1; B1; C1	A1; B1; C1	A2
Distributory Channel	A1; C1 G1; F1	A1; B1; B2 F3; E1	A1; B1; B2 F3; E1	A1; B1; B2 F3; E1	A1; G1; C1; F1	A1; G1; C1; F1
Field Channel	C1; F1	B1; C1; C2	B1; C1; C2	B1; C1; C2	C1; F1	C1; F1
Field Ditch		F2	F2	F2		
Field	D1	D2; D6	D4;D6;D3;D6	D5; D6	D6	D1
Field Drainage		F2	B1; F2	B1; F2	B1; F2	
Natural Stream/Major Drainage	E1; F1	C3; E2	C3; E2	C3; E2	C2; E2	E1
Domestic Environment	G2	G2	G2	G2	G2	G2
Natural Environment	A1; B1; B2; C1	A1; B1; B2; C1	A1; B1; B2; C1	A1; B1; B2; C1	A1; B1; B2; C1	A1; B1; B2; C1

Figure 5.5 Matrix II, Phases of the irrigation and crop husbandry cycle and locations in the irrigation area proper and in the remaining area in relation to potential breeding places

Source: Oomen et al. 1988

Table 4-13

	Irrigation feature					
	Hydrology	Farm water Management	Design	Construction	Operation	Maintenance
Reservoir	A1		G1		A1	A1
Main/Branch Canal				F3		F1; F3
Level Crossing/Tanks	A2; C1			B1	A1	A1
Distributory Channel			A1; E1; G1	A1;B1;B2;C1 E1;F1;F3	C1	B1;C1;F1 F3
Field Channel			F1	B1; C1; C2; F1	B1; C1; C2; F1	B1; C1; C2; F1
Field Ditch		F2		F2		F2
Field		D1; D6				
Field Drainage		F2				F2; B1
Natural Stream/ Major Drainage	A1; C3; E1 E2; F1			C3; E1; E2		C3; E1; E1
Domestic Environment				G2		G2
Natural Environment	A1; B1; C1		B1	B2		B2

Figure 5.6 Matrix III, Relationship between irrigation feature and breeding place

Source: Oomen et al. 1988

Table 4-14

Table 38-1. Lifetime Health Advisory Levels (HAL) for pesticides in drinking water (USEPA, 1989a, b).

Common and chemical name	Concentration, μg/L
Acifluorfen Sodium 5-[2-chloro-4-(trifluoromethyl) phenoxy]-2-nitrobenzoate	1
Alachlor† 2-Chloro-2'-6'-diethyl-*N*-(methoxy methyl) acetanilide	0.4
Aldicarb 2-Methyl-2(methylthio) propionaldehyde *O*(methylcarbamoyl) oxime	10
Ametryn 2-(Ethylamino)-4-(isopropylamino)-6-(methylthio)-1,3,5-triazine	60
Ammonium Sulfamate Ammonium sulfamate	1500
Atrazine 2-Chloro-4-ethylamino-6-isopropylamino-1,3,5 triazine	3
Baygon (Propoxur) 2-(1-Methylethoxy)phenyl methylcarbamate	3
Bentazon 3(1-Methylethyl)-1*H*-2,1,3-benzothiodiazin-4(3*H*)-one-2,2-dioxide	20
Bromacil 5-Bromo-3-*sec*-butyl-6-methyluracil	90
Butylate *S*-Ethyl diisobutylthiocarbamate	700
Carbaryl 1-Napthyl methylcarbamate	700
Carbofuran 2,3-Dihydro-2,2-dimethyl-7-benzofuranyl methylcarbamate	40
Carboxin 5,6-Dihydro-2-methyl-*N*-phenyl-1,4-oxathiin-3-carboxamide	700
Chloramben 3-Amino-2,5 dichlorobenzoic acid	100
Chlordane† 1,2,3,4,5,6,7,8,8-octachloro-2,3,3a,4,7,7a-hexahydro-4,7-methanoindene	0.03
Chlorothalanil† Tetrachloroisophthalonitrile	2
Cyanazine 2-{[4-Chloro-6-(ethylamino)-*S*-triazin-2-yl]amino}-2-methylproprionitrile	10
Dacthal (DCPA) Dimethyl tetrachloroteréphthalate	3500
Dalapon 2,2-Dichloropropionic acid	200
2,4-D (2,4-Dichlorophenoxy) acetic acid	70
DBCP† 1,2-Dibromo-3-chloropropane	0.03
Diazinon *O,O*-Diethyl *O*-2-isopropyl-6-methylpyrimidin-4-yl phosphorothioate	0.6
Dicamba 3,6-Dichloro-*o*-anisic acid	200
1,2-Dichloropropane 1,2-Dichloropropane	0.6
1,3-Dichloropropene (Telone) 1,3-Dichloropropene	0.2
Dieldrin† 1,2,3,4,10,10-Hexachloro-6,7-epoxy-1,4,4a,5,6,7,8,8a-octahydro-*endo*-1,4,-*exo*-5,8-dimethanonaphthalene	0.002
Dimethrin 2,4-Dimethylbenzyl-2,2-dimethyl-3(2-methyl propenyl) cyclopropanecarboxylate	2100
Dinoseb 2-(*sec*-Butyl)-4,6-dinitrophenol (alkanolamino salts)	7
Diphenamid *N,N*-Dimethyl-2,2-diphenylacetamide	200
Disulfoton *O,O*-Diethyl *S*-[2-(ethylthio)ethyl] phosphorodithioate	0.3
Diuron 3-(3,4-Dichlorophenyl)-1,1-dimethylurea	10
Endothall 7-Oxabicyclo-(2,2,1)heptane-2,3-dicarboxylic acid	140
Endrin 1,2,3,4,10,10-Hexachloro-6,7-epoxy-1,4,4a,5,6,7,8,8a-octahydro-*exo*-1,4,-*exo*-5,8-dimethanonaphthalene	0.3
Ethylene Dibromide (EDB)† 1,2-Dibromoethane	0.0004
Ethylene Thiourea† 2-Imidazolidinethione	0.2
Fenamiphos Ethyl 3-methyl-4-(methylthio) phenyl (1-methylethyl) phosphoramidate	2
Fluometuron 1,1-Dimethyl-3-(α,α,α-trifluoro-*m*-tolyl) urea	90
Fonofos *O*-Ethyl-*S*-phenylethylphosphonodithioate	14
Glyphosate *N*-(Phosphono-methyl) glycine	700
Heptachlor† 1,4,5,6,7,8,8-Heptachloro-3a,4,7,7a-tetrahydro-4,7-methanoindene	0.008
Hexachlorobenzene Hexachlorobenzene	0.02
Hexazinone 3-Cyclohexyl-6-(dimethylamino)-1-methyl-1,3,5-triazine-2,4(1*H*, 3*H*)-dione	200
Maleic Hydrazide 1,2-Dihydropyridazine-3,6-dione	3500
Methomyl *S*-Methyl-*N*-[(methylcarbamoyl)oxy] thioacetimidate	200
Methoxychlor 1,1,1-Trichloro-2,2-*bis*(4-methoxyphenyl)ethane	400
Methyl Parathion *O,O*-Dimethyl-*O*-4-nitrophenyl phosphorothioate	2
Metolachlor 2-Chloro-*N*-(2-ethyl-6-methylphenyl)-*N*-(2-metboxy-1-methylethyl) acetamida	100
Metribuzin 4-Amino-6-(1,1-dimethylethyl)-3-methylthio-1,2,4-triazin-5(4*H*)-one	200
Oxamyl S-Methyl *N',N'*-dimethyl-*N*-(methylcarbamoyloxyl)-1-thiooxamimdate	200
Paraquat 1,1'-Dimethyl-4,4'-bipyridinium-dichloride	30
Pentachlorophenol Pentachlorophenol	200
Picloram 4-Amino-3,5,6-trichloropicolinic acid	500
Prometon 2,4-Bis(isopropylamino)-6-methoxy-*s*-triazine	100
Pronamide 3,5-Dichloro-*N*(1,1-dimethyl-2-propynyl) benzamide	50
Propachlor 2-Chloro-*N*-isopropylacetanilide	90
Propazine 2-Chloro-4,6-*bis*(isopropylamino)-*S*-triazine	10
Propham Isopropyl carbanilate	100
Simazine 2-Chloro-4,6-bis(ethylamino)-*s*-triazine	4
2,4,5-T 2,4,5-Trichlorophenoxy-acetic acid	70
Tebuthiuron *N*-[5-(1,1-dimethylethyl)-1,3,4-thiadiazol-2-yl]-*N,N'*-dimethylurea	500
Terbacil 3-tert-Butyl-5-chloro-6-methyluracil	90
Terbufos *S-tert*-butylthiomethyl *o,o*-diethyl phosphorodithioate	1
2,4,5-TP (Silvex) 2-(2,4,5-Trichlorophenoxy) propionic acid	50
Trifluralin α,α,α-Trifluoro-2,6-dinitro-*N,N*-dipropyl-*p*-toluidine	2

† No HAL established: Lifetime exposure at this level represents an excess cancer risk of one in one million.

Source: in Stewart ed. 1990

Annex 1

MATRIX FOR THE STUDY AND ASSESSMENT OF IMPACTS RESULTING FROM ENVIRONMENTAL MANAGEMENT FOR VECTOR CONTROL

Main elements and sectors of the environment likely to be affected		Main proposed actions																	
		Environmental modification							Environmental manipulation										
		In man-made reservoirs and other still waters				In man-made courses and other flowing waters			In man-made reservoirs and other still waters					In man-made courses and other flowing waters			In all types of water bodies		
		Cutting, deepening and filling	Dyking and dewatering	Drainage in catchment area	Consolidation of shores	Rectification of courses and cross-sections	Consolidation and lining	Conversion of open to closed conduits	Basin preparation and maintenance	Cutting of trees and shrubs	Vegetation clearance	Shore maintenance	Water level fluctuation	Dredging and desilting	Vegetation clearance	Intermittent flow and flushing-drying	Manipulation of biological pollution	Manipulation of salinity in coastal areas	Manipulation of vegetation to provide shade or sunlight
Topsoil structure	Erosion/silting																		
	Disintegration/dust																		
	Acidity/alkalinity																		
	Ion exchange/salinity																		
	Aeration																		
	Microbial content																		
	Helminths and insects																		
Water	Surface flow and seepage																		
	Groundwater flow and recharge																		
	Water quality/pollution																		
Vegetation cover	Trees and shrubs																		
	Grass and weeds																		
	Aquatic plants																		
	Cultivated crops																		
Wildlife	Fish																		
	Birds																		
	Other animals																		
Human activities and interests	Irrigation																		
	Agriculture																		
	Fisheries																		
	Flood control																		
	Land reclamation																		
	Recreation																		
	Communications																		
	Cultural assets																		
	Aesthetic assets																		

Notes on the use of the matrix

The effects on the environment resulting fron environmental management measures for vector control can be assessed subjectively and shown quantitatively in this matrix, by using a rating for "magnitude" (the extent of the effect in space, time, population affected, etc.) and another for "importance" (the intensity or the relative seriousness of the effect).

1. Rate magnitude and importance between 1 and 10, 1 for the least and 10 for the greatest impact. Use a plus sign to indicate a beneficial effect and a minus sign for a detrimental effect.
2. Show the ratings in the relevant blocks of the matrix by recording two numbers, separated by a diagonal line, one for the magnitude and one for the importance of the impact; each pair of numbers should have its own plus or minus sign.
3. Actions that offer the most beneficial effects and the least adverse effects should be preferred in the choice and design of a control strategy.

Source: WHO 1980

Table 27: Crop Management Methods (Bailey and Waddell, 1979)

A. Crop Management
   1. Tillage
      - Conventional - moldboard plow, disc, harrow
      - Timing - fall, spring
      - Chisel plowing
      - Conservation - minimum, no-till
   2. Crop Sequencing
      - Mono-crop
      - No-meadow crop
      - Relay cropping
      - Double cropping
   3. Seed/Plant Improvement
      - Weather resistance
      - Salt tolerance
      - Production efficiency
      - Early or late maturation

B. Soil/Water Management
   1. Runoff and Erosion Controls
      - Contouring
      - Terraces
      - Cover crops
      - Grassed waterways
      - Tile drains
      - Diversions
      - Land forming
      - Row spacing
      - Harvesting and planting times
   2. Moisture Conservation Practices (e.g., fallow cropping)
   3. Wind Erosion Controls
      - Strip cropping
      - Barrier rows
      - Windbreaks

C. Nutrient Management
   1. Formulation, Granular, Liquid
   2. Species (e.g., NH_4 vs. NO_3 form of N, animal vs municipal)
   3. Amount Applied
   4. Application Methodology
   5. Timing of Application

D. Pest Management
   1. Scouting
   2. Pesticides
      - Application methodology
      - Amount applied
      - Timing of application
   3. Pest-Resistant Crops
   4. Integrated Controls
   5. Cultural/Mechanical Methods
   6. Biological Controls

Source: Canter 1986

Table 5-2

Table 1. Physiological processes interesting the crop manipulation for droughts and water stress resistance: A summary

Processes	References
Cell growth, dynamics of cell water (relative water content, water potential, wall dehydration)	Boyer, 1983; Hsiao & Bradford, 1983; Rascio et al, 1987
Cell and tissue turgor; osmotic regulation	Radin, 1983; Turner & Burch, 1983.
Stomatal opening	Hsiao & Bradford, 1983; Kirkham, 1984; Planchon, 1987.
Water and Co_2 exchanges	Krieg, 1983a; Rosenberg et al, 1983; Shalevet & Hsiao, 1986.
Photosynthesis, protein synthesis	Boyer, 1983; Kramer, 1983; Krieg, 1983b; Pearcy, 1983.
Changes in concentration of growth regulators	Austin et al, 1982; Hsiao & Bradford, 1983; Davies et al, 1987.
Leaf development and leaf senscence patterns	Boyer, 1983; Kramer, 1983; Shalevet & Hsiao, 1986.
Root development patterns	Passioura, 1982, 1983; Kramer, 1983; Jones & Zur, 1984.
Shoot - root relations	Turner, 1986.
Water fluxes : xylem conductancy	Wenkert, 1983; Jones & Zur, 1984.
Water fluxes : leaf water potential kinetics	Turner & Burch, 1983; Kirkham, 1984; Jones, 1985; Lorens et al, 1987.
Water fluxes : capacitance behaviour	Wenkert, 1983; Katerji & Hallaire, 1985.
Stand establishment : germination and emergence	Kramer, 1983; Jordan 1983.
Yield process : flowering, yield potential, fruit/grain yield	Jordan, 1983; Krieg, 1983a.

Source: Pereira 1990

Table 5-3

Table 2. Drought resistance mechanisms and traits for plant breeding

Mechanisms	Characteristics/Traits	Benefits	Yield affected	Reversible
Drought escape				
Rapid phenological development	Short biological cycle	Lower total water demand	yes (?)	no
Developmental plasticity	Branching/tillering and variation in flower, floret and panicle	Lower reduction in seed numbers	no	yes
Drought avoidance (at high water potential)				
Reduction of water losses				
. stomatal resistance (+)	Size, number and opening of stomata	Less transpiration	yes	yes
. evaporative surface (-)	Leaf rolling, smaller and fewer leaves, senescence	Smaller loss surface end less radiation absorved	yes	limited
. radiation interception (-)	Leaf pubescence and leaf orientation	Higher reflectivity and less radiation	yes	limited
. cuticular resistance (+)	Thicker and tighter cuticules	Lower transpiration, higher resistance to dissecation	no	no
. epicuticular wax (+)	Waxiness	Lower transpiration, higher resistance to dissecation	no	no
Maintenance of water extraction.				
. root depth and density (+)	More extensive and intensive rooting	Lower root and soil resistances	no (?)	no (?)
. liquid phase conductance (+)	More or larger xilems in roots and stems	Lower resistances to water fluxes	no	no
Drought tolerance (at low water potential)				
Maintenance of turgor				
. osmotic adjustment	Water potential kinetics	Decrease osmotic potential in response to stress	no (?)	yes
. cellular elasticity (-)	Cell membranes	Large chenges in volume	no	?
. cell size (-)	Cell size	Increased bound water fraction (in cell wall)	yes	limited
Tissue water capacitance	Favourable water potential Kinetics	Ability to maintain the daily water balance	no	no
Dissecation toleranca	Protoplasmic and choroplast conditions	Maintaining photosynthetic activity	no (?)	?
Accumulation of solutes	Proline, abscissic acid, ethylene, betaine	Regulation of senescence and absicissin	no	yes

Adapted from Hsiao (1982), Turner (1982; 1986), Jordan et al. (1983), Clarke (1987), Marshall (1987) and Monti (1987).

Source: Pereira 1990

Table 5-4

Table 4. Soil management techniques, benefits and effectiveness for limiting drought and water stress impacts

Soil management techniques	Benefits	Effectiveness	References
Water retention on the soil surface/runoff control			
. Tillage/soil cultivation with surface roughness	Storage of rainfall excess in micro depressions; increased time for infiltration	Variable	Unger & Stewart, 1983.
. Loosening tillage	Increased porosity, higher infiltration and soil water retention	Variable	Unger & Stewart, 1983.
. Contour and graded furrows	Runoff and erosion control, increased infiltration	High	Unger & Stewart, 1983.
. Conservation tillage, mulching	Increased infiltration, lower soil and water losses	High	Sojka et al, 1984; Griffith et al, 1986
. Furrow dikes	Runoff control and increased infiltration	High	
. Bed surface profile	Idem	Limited/high	Spoor et al, 1987.
Water yield and water spreading and infiltration (arid lands)			
Microwatersheds combined with vertical mulches	Runoff from one area to be infiltrated in the cropped one	Limited	Unger & Stewart, 1983.
Water harvesting, runoff farming and water spreading	Maximize runoff to be utilized in the cropped area	Limited	Boers et al, 1986; Sharma, 1986.
Water infiltration and soil storage volume			
Organic matter for improving aggregation	Stability of aggregates and increased infiltration	Limited	Unger et al, 1981.
Chemicals for aggregates	Idem	Economic limits	Unger & Stewart, 1983.
Soil loosening or subsoiling for fragipans, hardpans and plowpans	Increased water penetration and soil depth explorable by roots	Variable	Unger et al, 1981; Reicosky, 1983; Spoor et al, 1987.
Deep tillage/profile modification in presence of clay horizons	Idem	Variable	Unger et al, 1981; Reicosky, 1983; Spoor et al, 1987.
Chemical and physical treatments of salt-affected soils	Increased infiltration and available soil water	High	Hoffman, 1981; 1986.
Crop rotations including grasses and legumes	Higher organic matter, better aggregation, increased infiltration	Variable	Loomis, 1983

Soil management techniques	Benefits	Effectiveness	References
Mulches, crop residues	Soil protection, higher infiltration reduced erosion	Very high	Larson et al, 1983; Sojka et al 1984; Griffith et al, 1986.
Traffic control	Decrease compaction, improve water penetration	High	Reicosky, 1983; Spoor et al, 1987.
Water retention in the soil profile			
Deep soil treatments	Deeper roots and water storage volume	High	Unger et al, 1981; Reicosky, 1983.
Adding fine materials to sandy/coarse soils	Increase water retention	Economic limits	Unger et al, 1981.
Mixing fine and coarse horizons	Increase water retention	Variable	Unger & Stewart, 1983.
Asphalt barriers in sandy soils	Decrease deep percolation	Economic limits	Unger et al, 1981.
Compacting sandy soils	Slowing water penetration	Interesting	Agrawal et al, 1987.
Mulches	Decrease of soil evaporation	Variable	De et al, 1983; Rosenberg et al, 1983.
Chemical hydrophilics in sandy soils	Increase water absorption	Economic limits	Azzam, 1987.
Chemical surfactants	Decrease capillary rise	Limited	Unger et al, 1983.
Control of toxicity and acidity, liming	More intensive and deep rooting	Limited/high	Reicosky, 1983.

Source: Pereira 1990

Table 5-5

Table 5 . Techniques for crop management for coping with droughts and water stress conditions

Crop management techniques	Benefits	Effectiveness	References
Drought risk management			
Change of crop patterns replacing sensitive by tolerant crops (eventually decreasing the irrigation surface)	Limit effects of droughts	High	Section 4, Table 3.
Choice of drought tolerant instead of high productive crop varieties	Limit drought impacts	High	Section 4, Table 3.
Use of short cycle varieties	Low water requirements	High	Section 4, Table 3.
Early seeding	Avoidance of terminal stress	High	French, 1983.
Early cutting of forage crops	Avoid degradation of the stressed crop	High	Dawdy et al, 1983.
Grazing drought damaged fields	Alternative use; livestock support	High	Dawdy et al, 1983.
Supplemental irrigation of rainfed crops	Avoid stress at critical stages	High	
Management for controlling the effects of water stress			
Use of appropriate soil management techniques	Increase available soil water	High	Section 5, Table 4.
Adaptation of crop patterns to the environmental constraints and resource conservation	Coping with water stressed environments	High	Loomis, 1983.
Use of fallow cropping in rainfed systems	Increase in soil moisture	Controversial	Larson et al, 1983; Loomis, 1983.
Use of mixed cropping and intercropping, namely for forages	Better use of resources	Low	Loomis, 1983.
Increase plant spacing of perennials and for some row crops	High individual explorable soil volume	Limited/high	Gardner & Gardner, 1983; Loomis, 1983.
Cultivation techniques			
Minimizing tillage	Avoidance of evaporation from the soil	High	Larson et al, 1983.
Adequate seed placement	Prevention of rapid drying of soil layers around the seed	High	Larson et al, 1983.

Crop management techniques	Benefits	Effectiveness	References
Pre-emergence weed control	Alleviating competition for water; avoiding herbicide effects on stressed crop plants	High	Dawdy et al, 1983.
Reduced and delayed fertilization	Favorizing deep rooting; adaptation to crop responses under water stress	Variable	Loomis, 1983.
Dry soil land preparation and seeding of paddy rice	Water savings	High	Pereira et al, 1986.
Early defoliation (maize)	Decrease evaporative surfaces, so the water use by the crop	Limited	Crookston & Ouattar, 1987.
Antitranspirants	Reduction of plant transpiration	Controversial	De et al, 1983; Rosenberg et al, 1983.
Reflectants (increasing albedo)	Decrease energy available for transpiration	Limited/high	De et al, 1983; Rosenberg et al, 1983.
CO_2 enrichment (controlled environments)	Increased water use efficiency, higher yield per unit of water	Limited	Rosenberg et al, 1983; Allen et al, 1985.
Windbreaks	Decrease energy available for evaporation	Limited	Rosenberg et al, 1983.
Growth regulators	Improved responses of physiological processes to water stress	Promising	Reviewed by Davies et al, 1987.

Source: Pereira 1990

Table 5-6

TABLE 3

Specific technologies for sustainable management of soil and resources for different ecological regions

Humid	Sub-humid	Semi-arid	Arid
Soil management systems for improving water-use efficiency			
Mulch farming	No-till	Rough plowing	Water harvesting
No-till	Mulch farming	Tied ridges	Fallowing
Manual clearing	Contour ridges	Mulch	Early planting
Drainage and water management	Agroforestry	Micro-catchments	Grass hedges (Vetiver)
Erosion control	Drainage and water management	Diggets	Salinity
Water harvesting		Contour bunds	Irrigation
		Grass hedges (Vetiver)	Water conservation
		Fallowing	
		Early planting	
		Salinity control	
		Irrigation	
		Water harvesting	
Soil/crop management systems for increasing nutrient-use efficiency			
Perennial crops	Cover crops	Manure/kralling	Manure/kralling
Root crops	Mulch farming	Mulch farming	Irrigation
Agroforestry	Agroforestry	Cover crops	Water harvesting
Mulch farming	Mixed cropping	Relay-mixed cropping	N and P fertilizers
Fertilizers	Crop rotations	N and P fertilizers	Salinity and alkalinity control
In-situ burning	In-situ burning	Irrigation	
N and P fertilizers	N and P fertilizers	Leaching and salinity control	
Drainage and water management	Drainage and water management		

Source: Lal 1991

Table 5-7a

TABLE 4

Some examples of tillage-based technological packages for sustainable management of soil and water resources on small-scale farms (less than 5 ha) in the tropics

	Structurally active soils	Structurally inert soils
(a)	Grain crop–cover crop rotation Conservation tillage–mulch farming Strip cropping Chemical fertilizers (supplementary) Water management Irrigation	Conservation tillage and water management options will differ as follows: Contour ridges Tied ridges Periodic sub-soiling or chiseling Supplementary irrigation
(b)	Grain crop–alley cropping systems Conservation tillage Chemical fertilizers (supplementary) Water management Irrigation	
(c)	Ley/mixed farming Conservation tillage Grain crop–pasture rotation Growing woody perennials to supplement food Reservoirs for runoff storage Organic manures Chemical fertilizers (supplementary) Drainage and irrigation Water harvesting	
(d)	Agro-forestry systems Same as (c) but pasture replaced by shrubs and woody perennials	
(e)	Smallholder plantations Cover crops (Kudzu, Centro, etc.) Tangya system Chemical fertilizers Supplemental irrigation	

Table 5-7b

TABLE 5

Some examples of tillage-based technological packages for sustainable management of soil and water resources on medium sized farms (5–25 ha) in the tropics

	Structurally active soils		Structurally inert soils
(a)	Grain crop–cover crop rotation Conservation tillage with herbicides and periodic loosening to alleviate compaction Chemical fertilizers Planting trees or woody perennials at 1 m intervals Water management	(a)	Contour ridges Terraces and waterways Engineering structure Water management Supplemental irrigation
(b)	Grain crop–pasture rotation Water harvesting and reservoirs Conservation tillage with herbicides Tree hedges at 1 m intervals Chemical fertilizers Drainage and irrigation	(b)	Water reservoirs and engineering structures Supplementary irrigation Tied-ridge or basin tillage Water management
(c)	Plantation and cover crops Erosion control Fertilizer management Drainage and irrigation	(c)	Erosion control access on roads Fertilizer management Water harvesting Supplemental irrigation

Source: Lal 1991

Table 5-8

TABLE 9

Soil eco-regional guide to tillage methods for upland crops in West Africa

Moisture regime	Texture of soil surface	Constraints	Tillage methods
Per-humid and humid	Sandy, sandy loam, loam, sand	Soil erosion by water, low soil fertility low AWC[1], high soil temperature	No tillage, reduced tillage, mulch farming with cover crops, agroforestry with plantation/tree crops
Per-humid and humid	Silt loam, silty clay loam	Soil erosion, crusting compaction, high soil temperature	Reduced tillage or minimum tillage, cover crops, mulch farming, agroforestry
Per humid and humid	Clay loam, clay	Water logging, poor trafficability, erosion	Ridge/furrow system, surface drainage, raised beds or mounds, agroforestry
Sub-humid	Sandy loam, loamy sand, sandy clay	Soil erosion by water, crusting, compaction, drought, low soil fertility, low AWC	No tillage with periodic chisel plowing, mulch farming with cover crops and alley cropping
Semi-arid and arid regions	Sandy loam, loamy sand	Soil erosion by wind and water, drought, low AWC, high soil temperature, sand blasting	Chisel plowing, tied ridges, plowing at the end of rains, rough seed bed
Semi-arid regions	Clayey, sandy clay, swelling soils	Soil erosion, poor trafficability, water logging, drought	Ridge/furrow system broad beds, water harvesting
Arid regions	Sandy loam, loamy sand	Wind erosion, drought, sand blasting, low AWC	Wind breaks, reduced tillage, water harvesting techniques

[1]AWC is available water capacity.

Source: in Lal 1991

Table 5-9

Table 1. The rate of fertilizer use in regions of the world

Region	Kilo nutrients applied/ha kg ($N + P_2O_5 + K_2O$)	
	1964	1984
World	29.3	85.3
North America	47.2	93.2
Western Europe	124.4	224.3
Eastern Europe & USSR	30.4	122.1
Africa	1.5	9.1
Far East	6.4	45.8
Centrally planned economies in Asia	15.8	170.5

Source: [illegible]

Source: ESCAP 1991

Table 5-10

Table 3.5 Agricultural Inputs in Selected DMCs

	Irrigated Land (per cent of cropland)		Average Annual Pesticide Use (1000 metric tons)		Average Annual Fertilizer Use (kg/ha)	
	1975-77	1985-87	1975-77	1982-84	1975-77	1985-87
Korea	48	58	4.7	12.3	334	395
Indonesia	26	34	18.7	16.3	27	100
Lao PDR	6	13	...	...	0	2
Malaysia	7	8	...	9.7	68	154
Philippines	14	18	3.5	4.4	34	50
Thailand	15	20	13.1	22.3	14	26
Viet Nam	18	28	1.7	0.9	58	61
Bangladesh	15	23	...	0.2	29	68
India	20	25	52.5	53.1	22	52
Myanmar	10	11	3.7	15.3	5	18
Nepal	12	28	...	...	6	20
Pakistan	70	77	2.1	1.9	32	81
Sri Lanka	25	30	...	0.7	49	106
China	43	46	150.5	159.3	74	195

Source: World Resources Institute, *World Resources 1990-91* (New York, 1990).

Source: ADB 1991

Table 5-11

Table 1. Cd content of phosphate rocks

Source	Cadmium content		Approximately Cd content
	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]

[illegible]

Source: ESCAP 1991

Table 5-13

Table 1

CHANGES IN THE USE OF PESTICIDES FOR FOOD CROPS IN INDONESIA, 1980-89

Year	Pesticide use (tons)	Rice fields (000 ha)	Production (000 tons milled rice)
1980	6 366	9 105	20 161
1981	9 006	9 382	22 286
1982	11 256	8 988	22 837
1983	13 887	9 162	24 006
1984	13 816	9 764	25 933
1985	14 980	9 902	26 547
1986	17 216	9 988	27 014
1987	17 342	9 923	27 253
1988	10 840	10 090	28 340
1989	8 660	10 531	29 072

Source: Ministry of Agriculture, Indonesia.

Source: Kasrunyo in OECD 1991d

Table 5-12 →

Table 5-12

Table 31: Practices for the Control of Nutrient Loss from Agricultural Applications and Their Highlights (Stewart, et al., 1975)

No.	Nutrient Control Practice	Practice Highlights
N 1	Eliminating excessive fertilization	May cut nitrate leaching appreciably, reduces fertilizer costs; has no effect on yield.
	Leaching Control	
N 2	Timing nitrogen application	Reduces nitrate leaching; increases nitrogen use efficiency; ideal timing may be less convenient.
N 3	Using crop rotations	Substantially reduces nutrient inputs; not compatible with many farm enterprises; reduces erosion and pesticide use.
N 4	Using animal wastes for fertilizer	Economic gain for some farm enterprises; slow release of nutrients; spreading problems.
N 5	Plowing-under green legume crops	Reduces use of nitrogen fertilizer; not always feasible.
N 6	Using winter cover crop	Uses nitrate and reduces percolation; not applicable in some regions; reduces winter erosion.
N 7	Controlling fertilizer release or transformation	May decrease nitrate leaching; usually not economically feasible; needs additional research and development.
	Control of Nutrients in Runoff	
N 8	Incorporating surface applications	Decreases nutrients in runoff; no yield effects; not always possible; adds costs in some cases.
N 9	Controlling surface applications	Useful when incorporation is not feasible.
N 10	Using legumes in haylands and pastures	Replaces nitrogen fertilizer; limited applicability; difficult to manage.
	Control of Nutrient Loss by Erosion	
N 11	Timing fertilizer plow-down	Reduces erosion and nutrient loss; may be less convenient.

Source: Canter 1986

Table 5-14

Table 39: Practices for the Control of Pesticide Loss from Agricultural Applications and Their Highlights (Stewart, et al., 1975)

No.	Pesticide Control Practice	Practice Highlights
	Broadly Applicable Practices	
P 1	Using alternative pesticides	Applicable to all field crops; can lower aquatic residue levels; can hinder development of target species resistance.
P 2	Optimizing pesticide placement with respect to loss	Applicable where effectiveness is maintained; may involve moderate cost.
P 3	Using crop rotation	Universally applicable; can reduce pesticide loss significantly; some indirect cost if less profitable crop is planted.
P 4	Using resistant crop varieties	Applicable to a number of crops; can sometimes eliminate need for insecticide and fungicide use; only slight usefulness for weed control.
P 5	Optimizing crop planting time	Applicable to many crops; can reduce need for pesticides; moderate cost possibly involved.
P 6	Optimizing pesticide formulation	Some commercially available alternatives; can reduce necessary rates of pesticide application.
P 7	Using mechanical control methods	Applicable to weed control; will reduce need for chemicals substantially; not economically favorable.
P 8	Reducing excessive treatment	Applicable to insect control; refined predictive techniques required.

Table 39: (Continued)

No.	Pesticide Control Practice	Practice Highlights
P 9	Optimizing time of day for pesticide application	Universally applicable; can reduce necessary rates of pesticide application.
	Practices Having Limited Applicability	
P 10	Optimizing date of pesticide application	Applicable only when pest control is not adversely affected; little or no cost involved.
P 11	Using integrated control programs	Effective pest control with reduction in amount of pesticide used; program development difficult.
P 12	Using biological control methods	Very successful in a few cases; can reduce insecticide and herbicide use appreciably.
P 13	Using lower pesticide application rates	Can be used only where authorized; some monetary savings.
P 14	Managing aerial applications	Can reduce contamination of non-target areas.
P 15	Planting between rows in minimum tillage	Applicable only to row crops in non-plow based tillage; may reduce amounts of pesticides necessary.

Source: Canter 1986

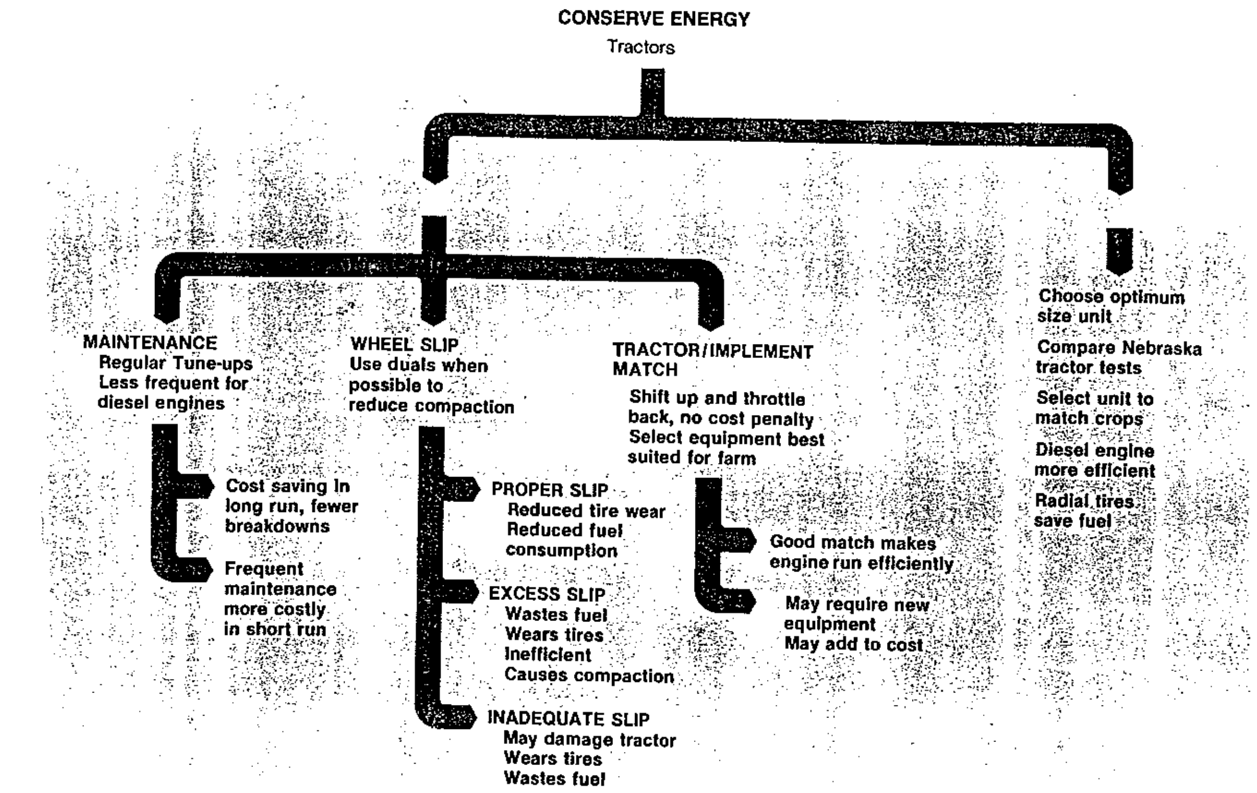


Chart 3-Tillage Systems

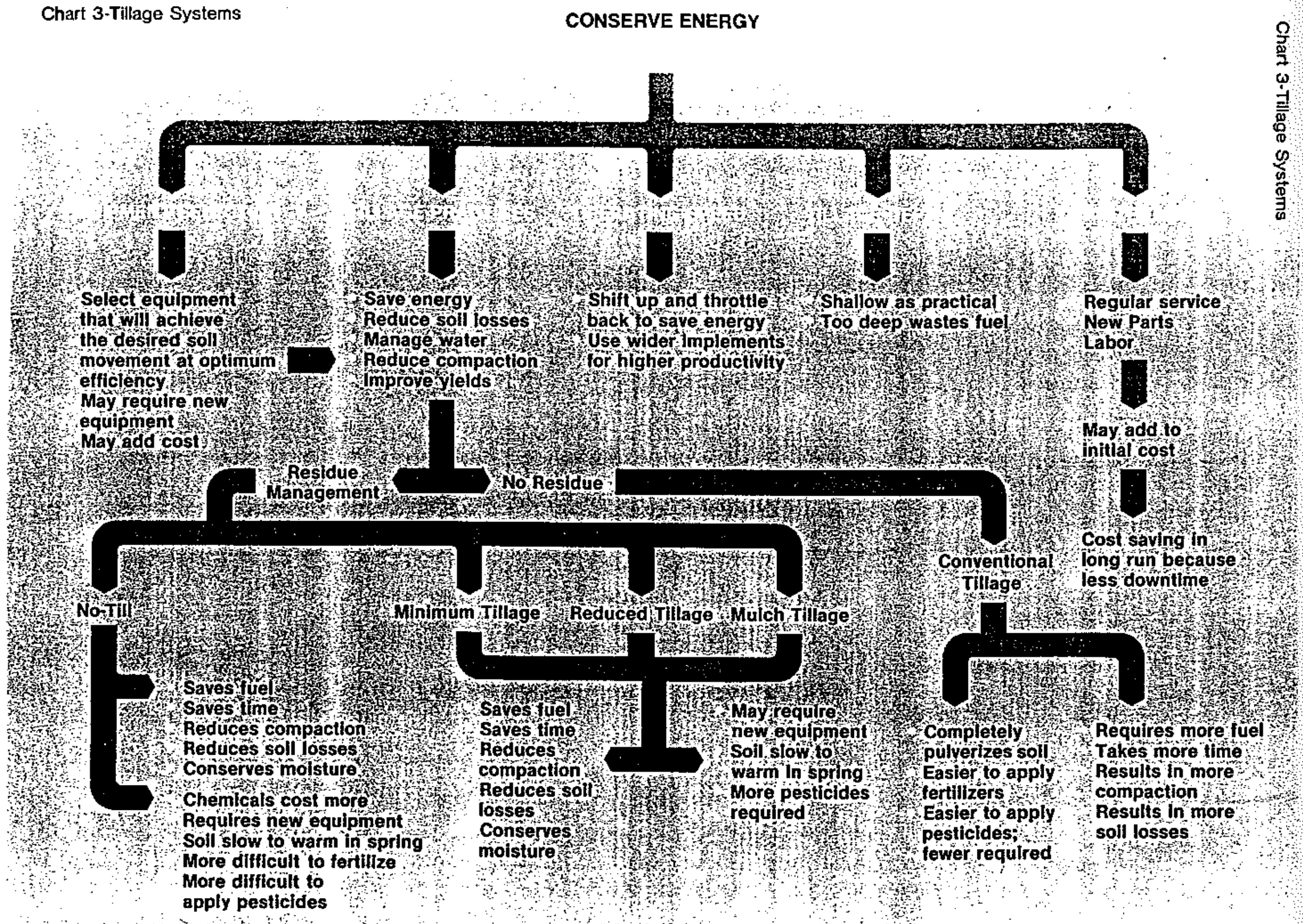
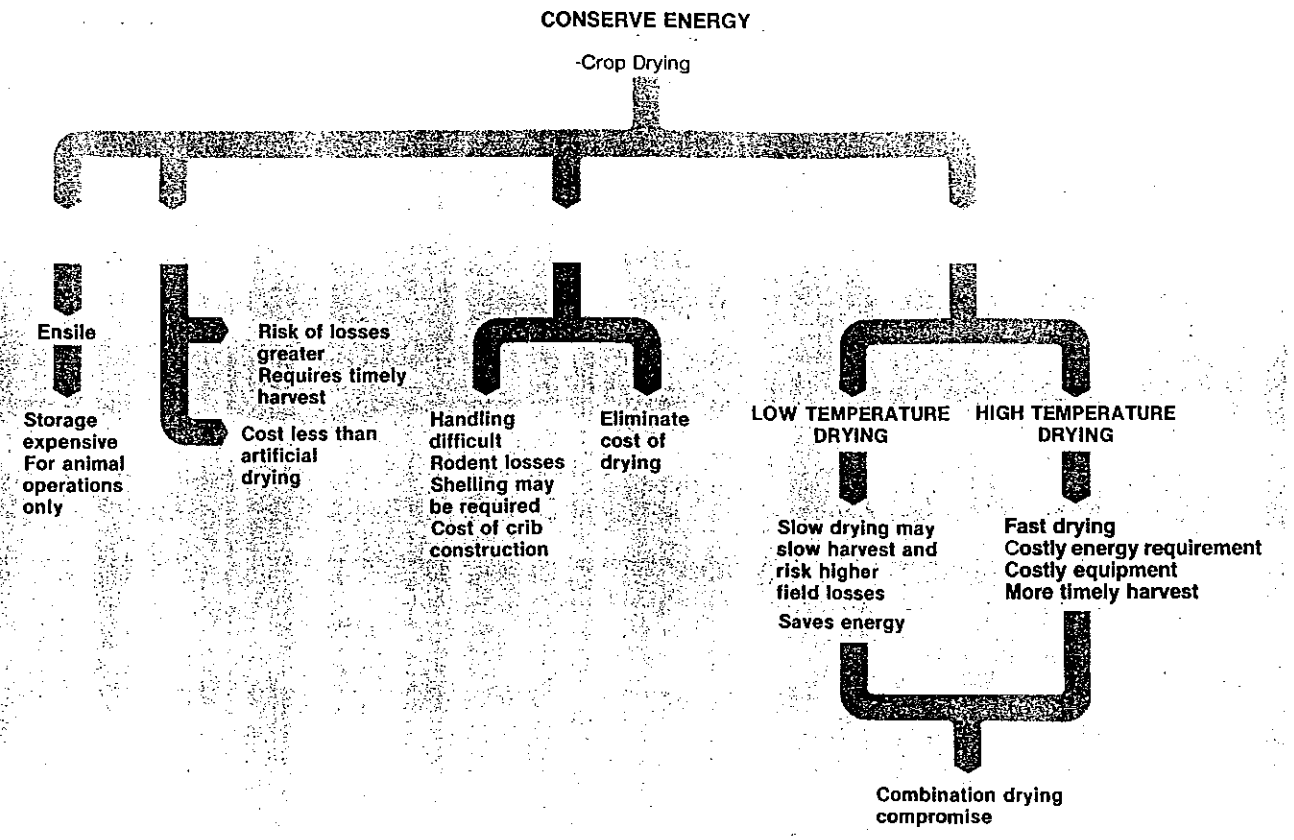


Chart 3-Tillage Systems

Source: Hughes 1980

Chart 5-Crop Drying



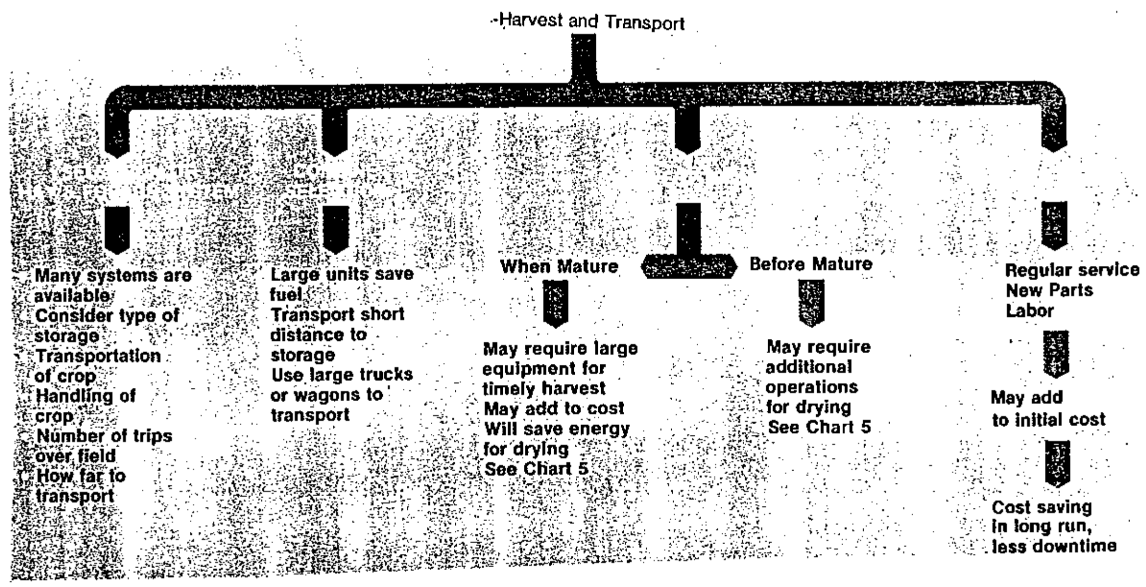


Chart 6-Alternate Energy Sources