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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

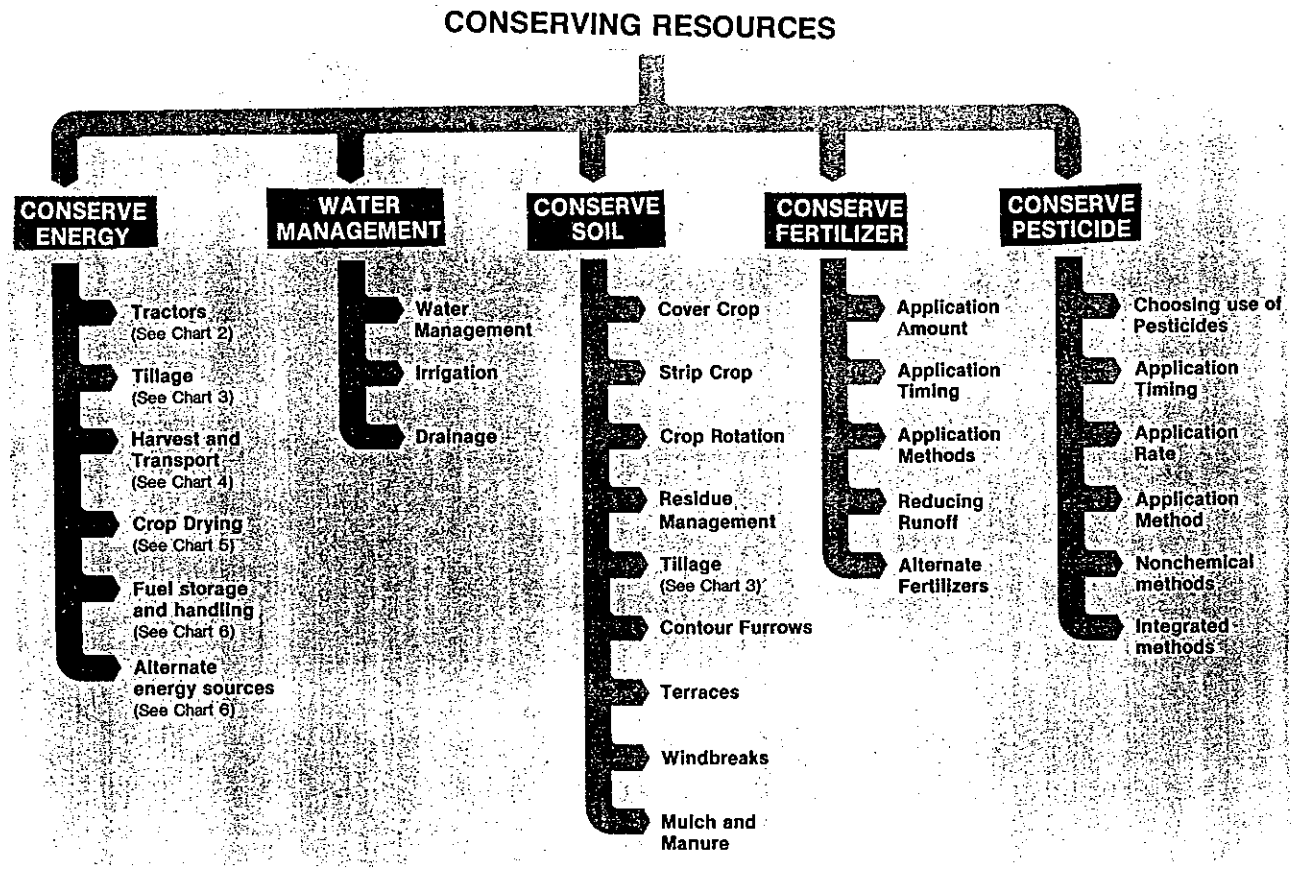
Tables

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

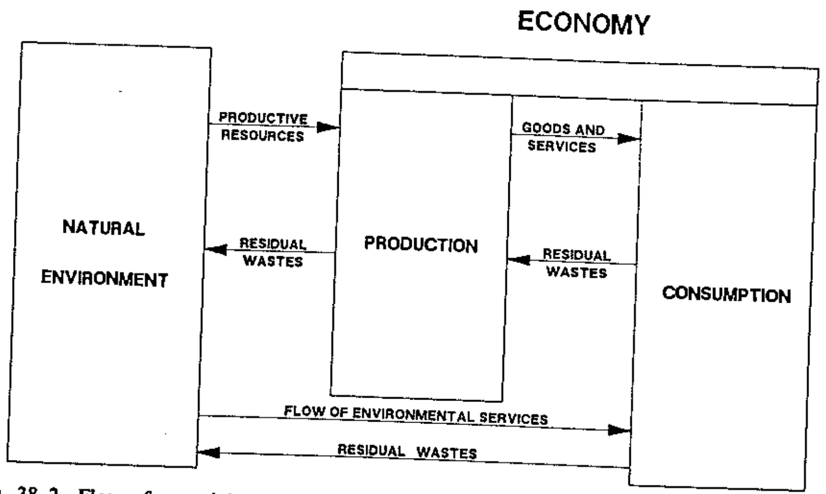


Fig. 38-2. Flow of materials between the natural environment and the economy (Gutema & Whittlesey, 1983).

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?

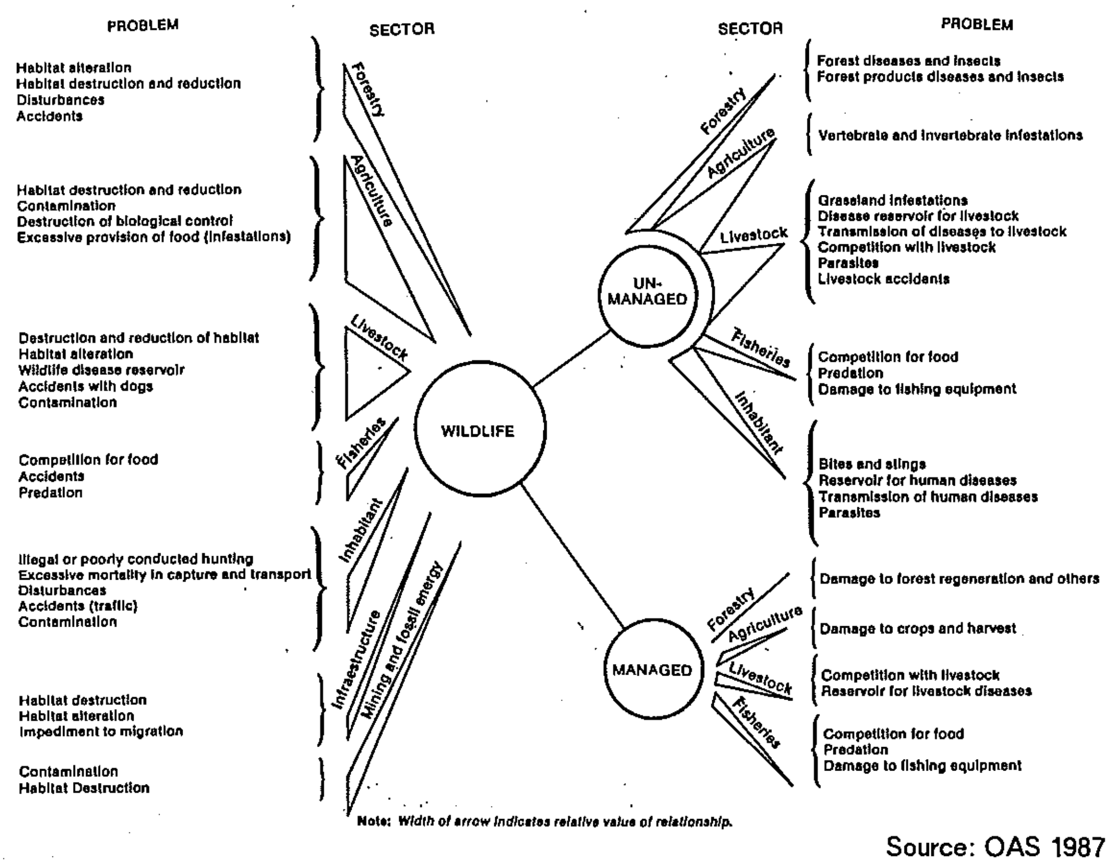
(iv) generalized criteria are not adequate: is carrying capacity of a given ecosystem relevant when it can be significantly increased through the application of even the simplest technical measures? For example the 'productivity' of an irrigated area may be increased by drainage, or rangeland can be 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

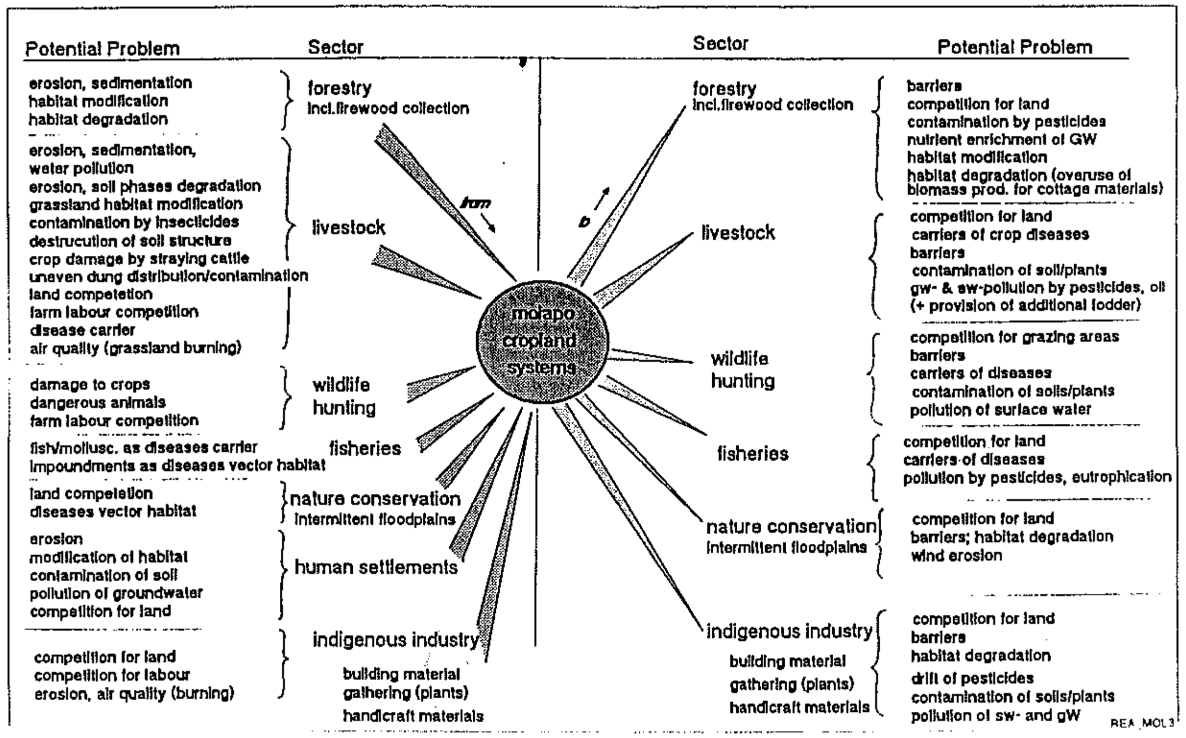
PRINCIPAL CONFLICTS BETWEEN WILDLIFE AND ACTIVITIES TO USE OTHER RESOURCES



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:

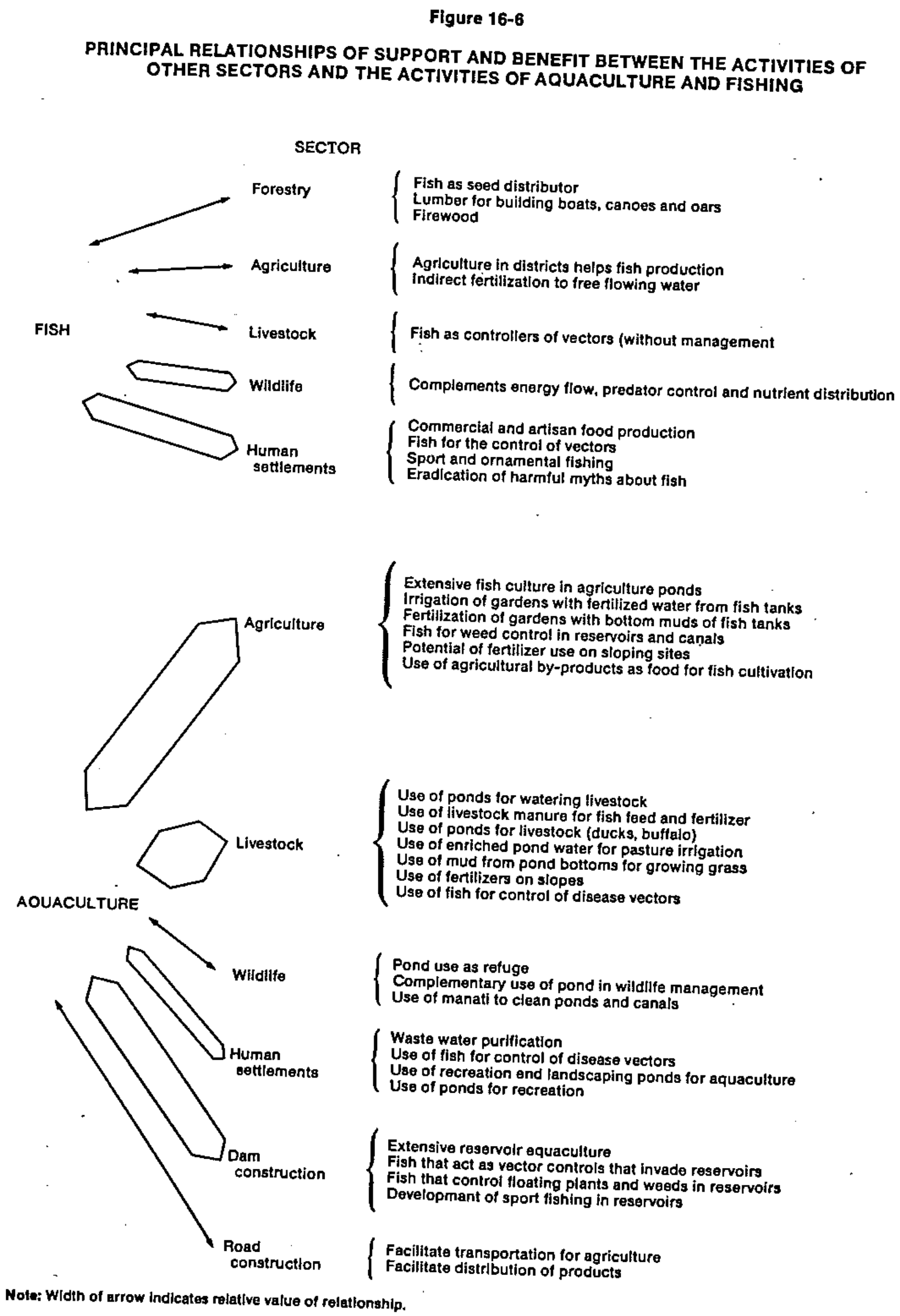
(1) Development of a **regional conceptual model** which describes the structure and function of the ecosystems in detail. The region (or any specific area) constists of producers and the consumers which are interrelated. The available information is obtained from various disciplines. The degree of detail 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



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.

IRRIGATION AND THE ENVIRONMENT
CONTEXT OF RESOURCES PLANNING

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

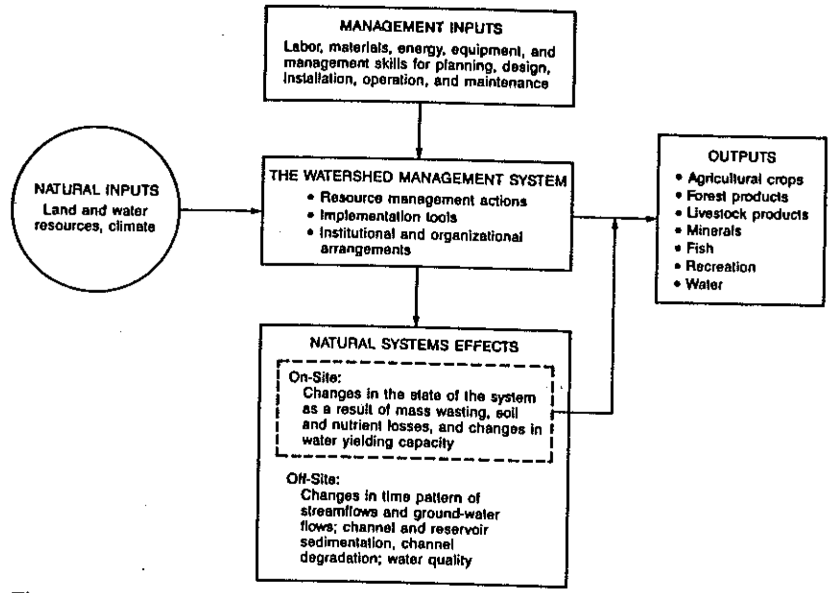


Figure 2.3
Generalized watershed management system in physical output terms.
Note: This schematic can be used to depict a system in the planning, design, installation, or operation stage.

Source: Easter ed. 1986

Fig. 1-6

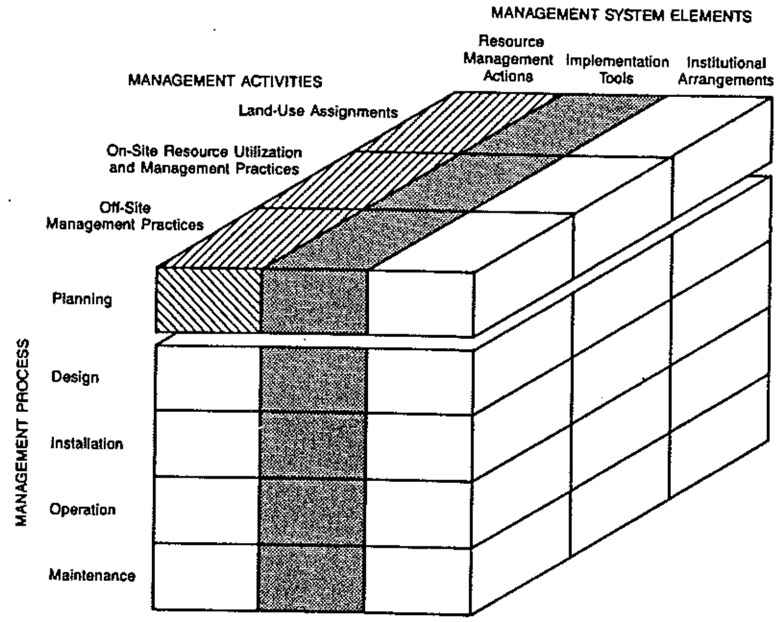


Figure 2.4
A three-dimensional analytical framework for watershed management.

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

13

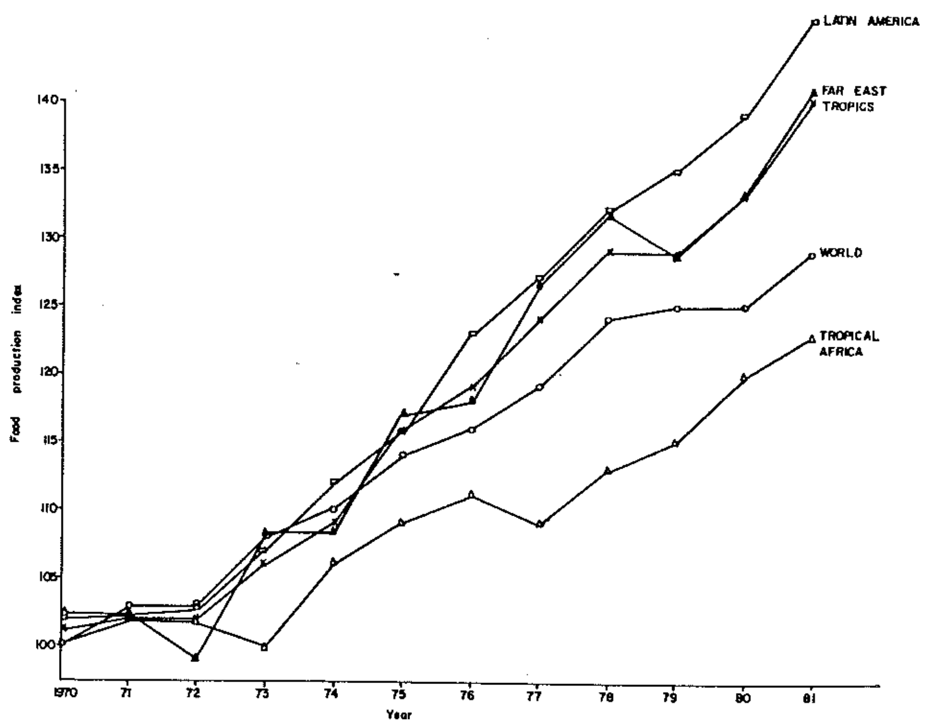


Figure 1.7 Food production index of tropical regions (FAO, 1981). *Reproduced by permission of the Food and Agriculture Organization of the United Nations*

Source: Lal ed. 1987

14

Fig. 1-7 b

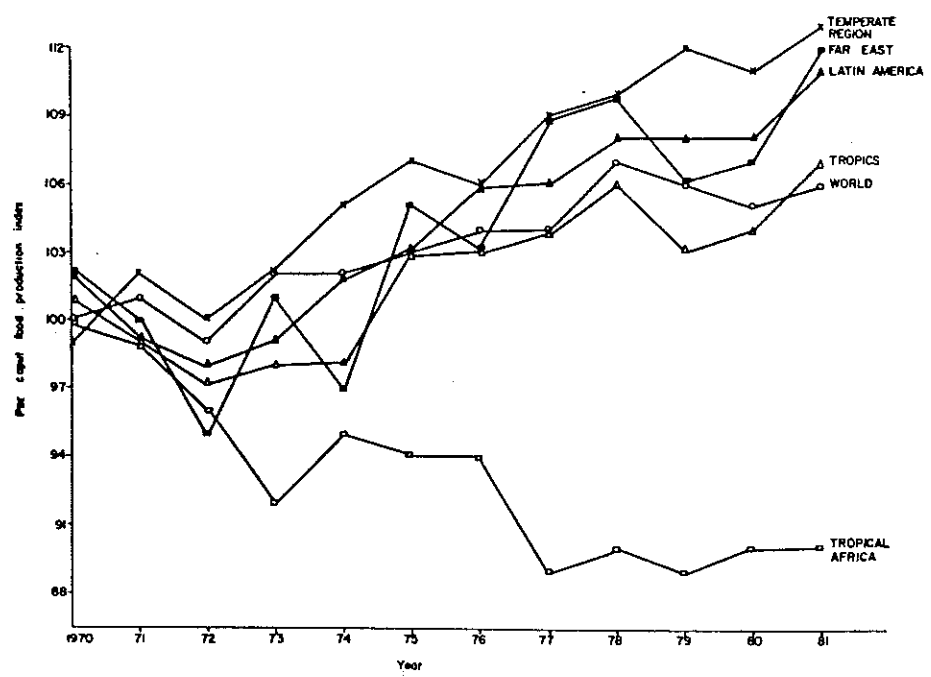


Figure 1.8 Per caput food production index (FAO, 1981). *Reproduced by permission of the Food and Agriculture Organization of the United Nations*

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 categories:

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

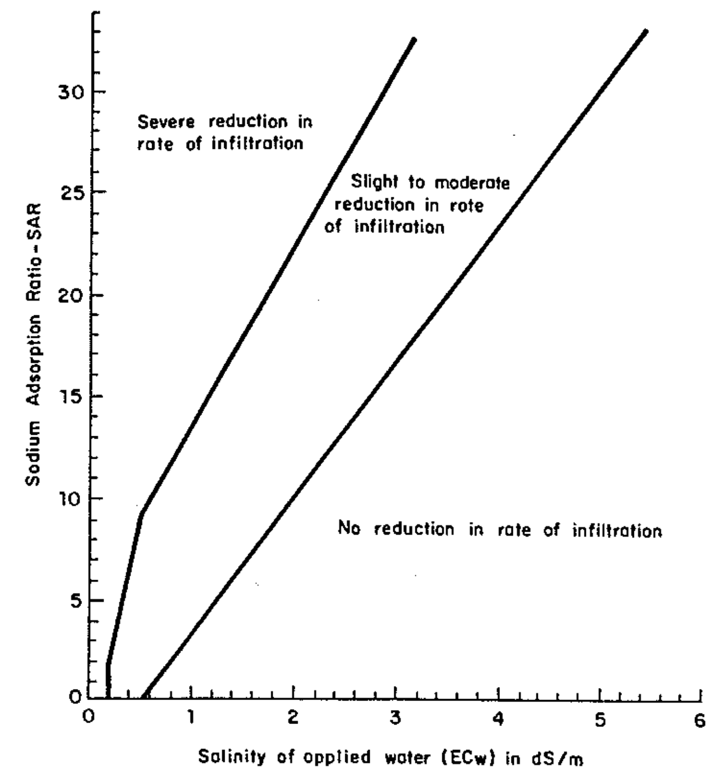
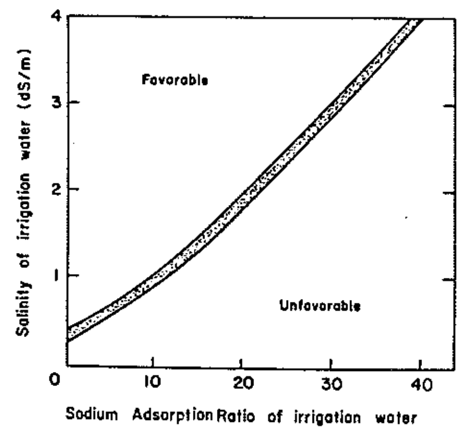


Fig. 21 Relative rate of water infiltration as affected by salinity and sodium adsorption ratio (Adapted from Rhoades 1977; and Oster and Schroer 1979)

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

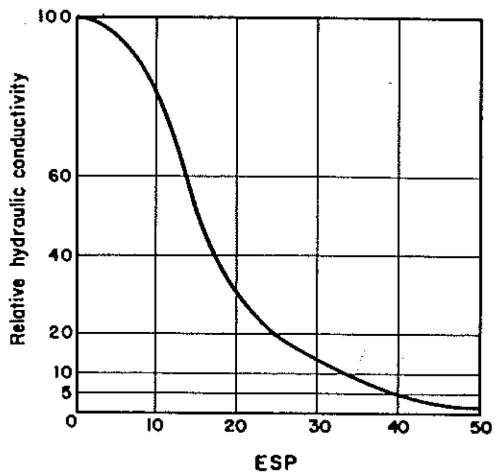


Figure 20 Schematic diagram showing the relative hydraulic conductivity of a soil as affected by increasing ESP

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

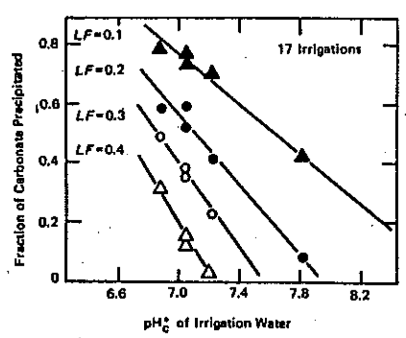


Figure II.7 Precipitation of $CaCO_3$ as related to pH_c^* of irrigation water and leaching fraction.

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.

<u>Corrosion and Encrustation Problems</u>

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 <u>reuse</u> 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).

<u>On-farm management options</u> 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

Management of Irrigation with Brackish Water 309

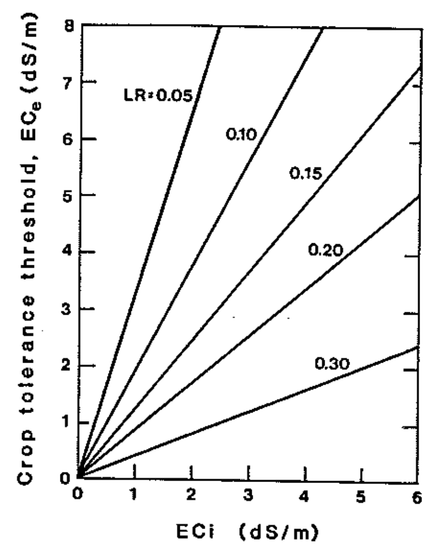


Fig. 10. Graphic solution for the leaching requirement (LR) as a function of irrigation water salinity (EC_i) and the salt tolerance threshold value (EC_e) for the crop (Hoffman and Van Genuchten 1983)

Fig. 2-4

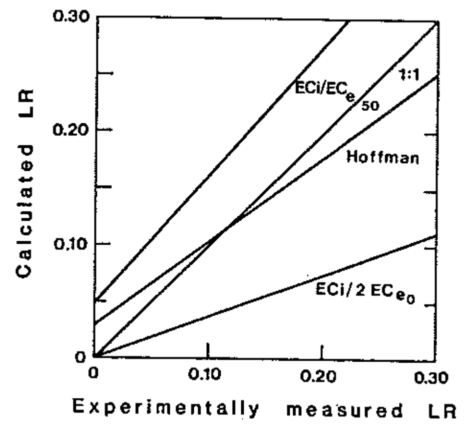


Fig. 11. Comparison of experimentally measured and calculated leaching requirements (LR), using three methods for calculating LR (Hoffman and Van Genuchten 1983)

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

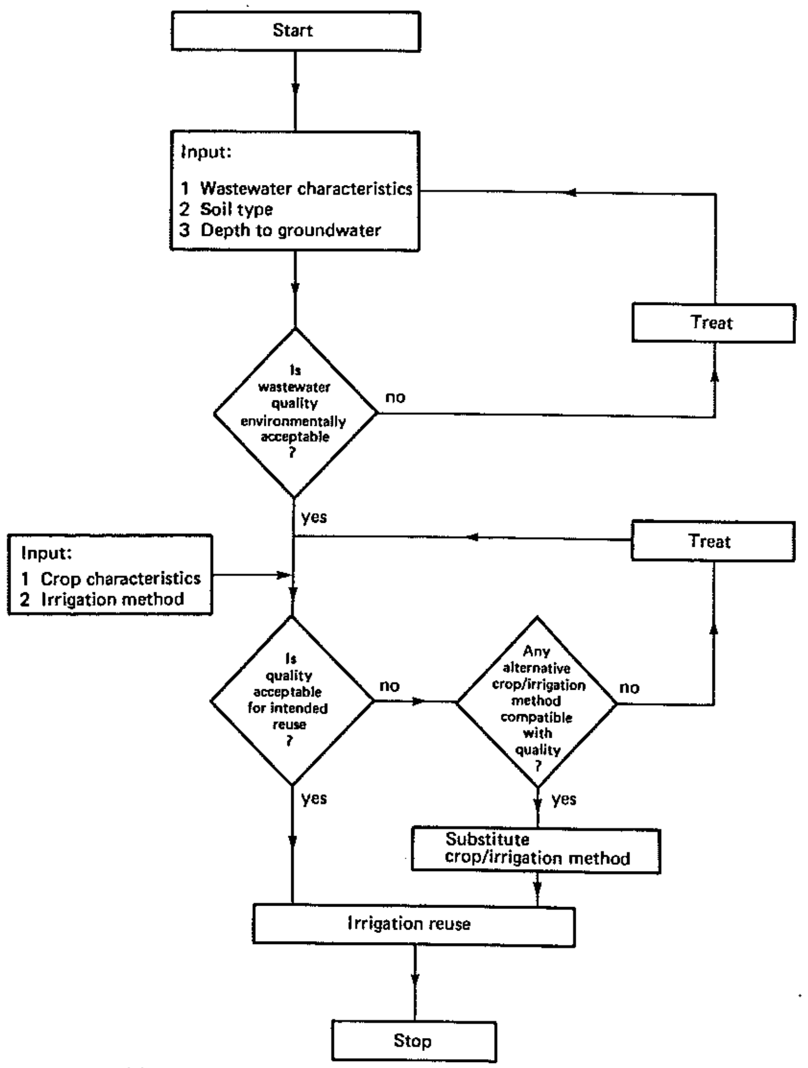


Figure 3.5 Decision model for wastewater treatment for reuse

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

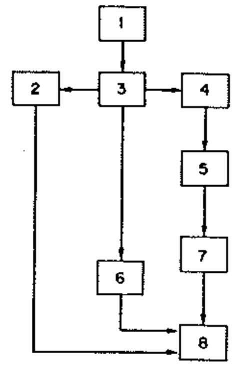


Fig. 2.12. Simplified block-diagram of the return water-quality model. (1) Irrigation régime: (2) drainage flow; (3) flow in the non-saturated medium; (4) chemical interaction; (5) chemistry of the non-saturated medium; (6) flow in the saturated medium; (7) chemistry of the saturated medium; (8) drainage-flow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

Source: ICID 1980

Fig. 2-7 a

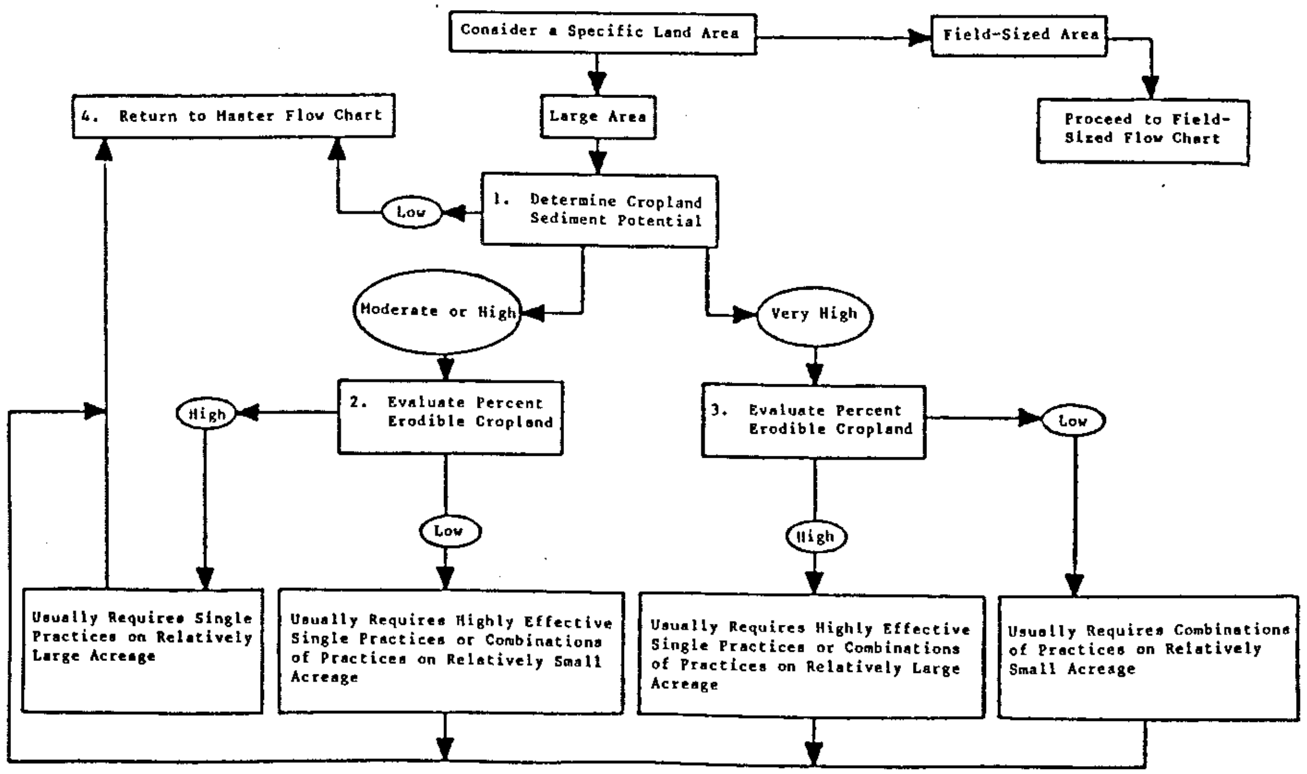


Figure 22: Flow Chart for Assessing Soil Erosion Problems and Controls Over Broad Areas (Frere, et al., 1977)

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

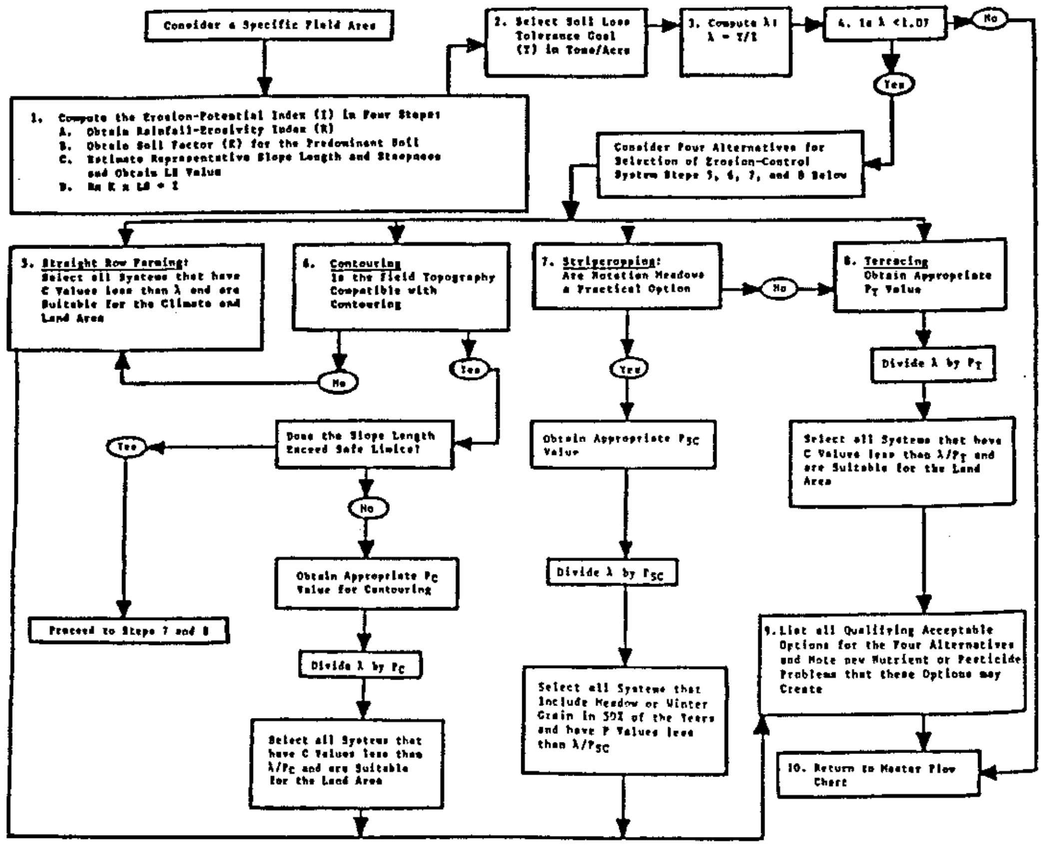
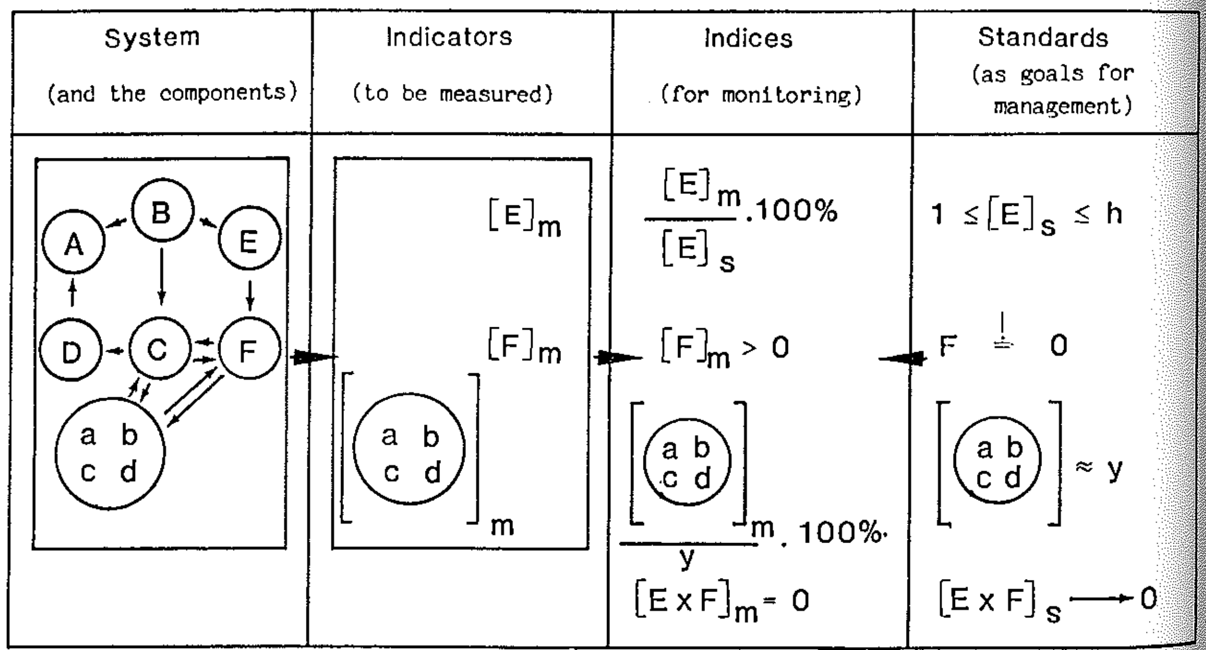


Figure 23: Flow Chart for Assessing Erosion Problems and Selecting Physically Feasible Control Practices for Field-Size Areas (Frere, et al., 1977)

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 Madsen (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 1986; 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

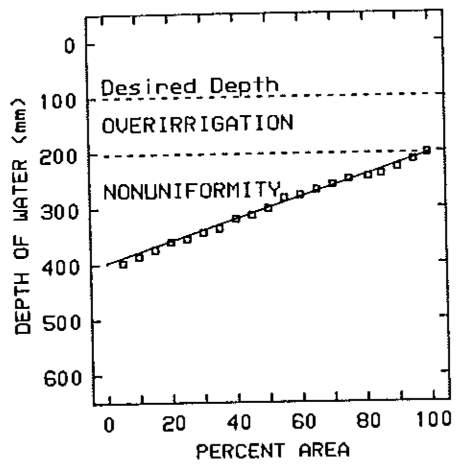


Fig. 35-7. Distribution of applied water showing amount of subsurface drainage because of overirrigation and amount due to irrigation system nonuniformity.

Source: Stewart ed. 1990

Fig. 2-11

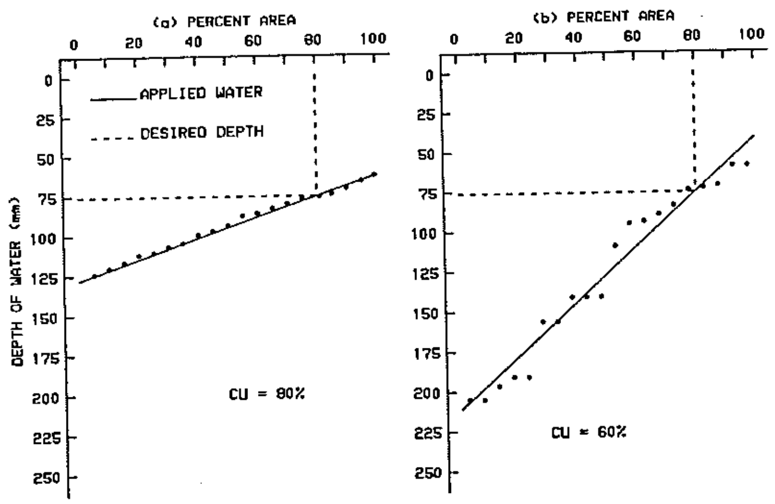


Fig. 35-8. Distributions of applied water for CU's of (a) 80 and (b) 60%. Area between dashed and solid line is the subsurface drainage.

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

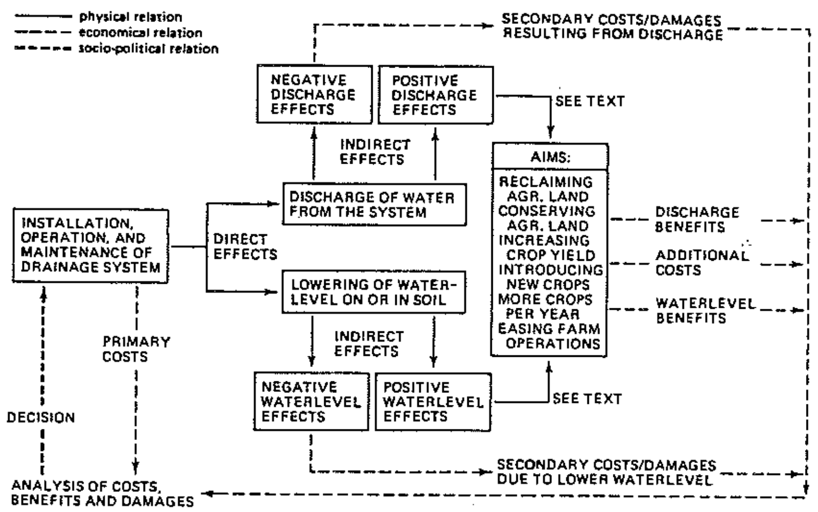


Fig. 1. Generalized diagramn of effects of subsurface drainage on agriculture, and their economic evaluation.

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; Oostérbann 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

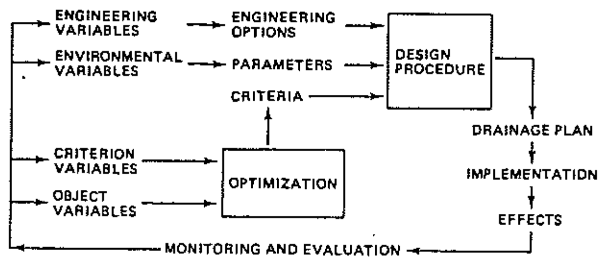


Fig. 2. The role of criteria in the optimization, design, and evaluation of drainage systems. There is a feed-back in the proces.

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.

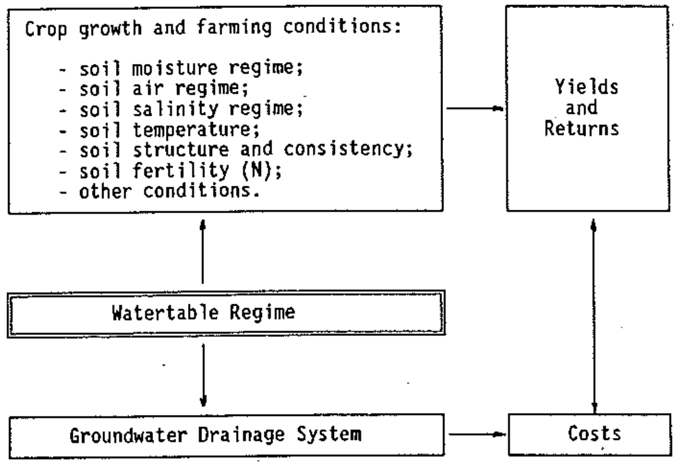
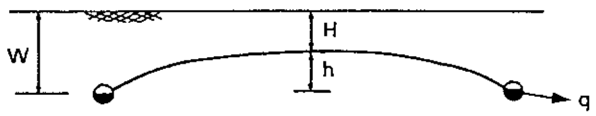


Figure 1 - Relationships to be considered in groundwater drainage design for agricultural land

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	1.00	0.002	2.50	1.50	1.3
salinity control	1.75	0.0005	2.50	0.75	0.7
aeration	0.50	0.007	1.20	0.70	10.0
subirrigation	1.00	-	1.00	-	-
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

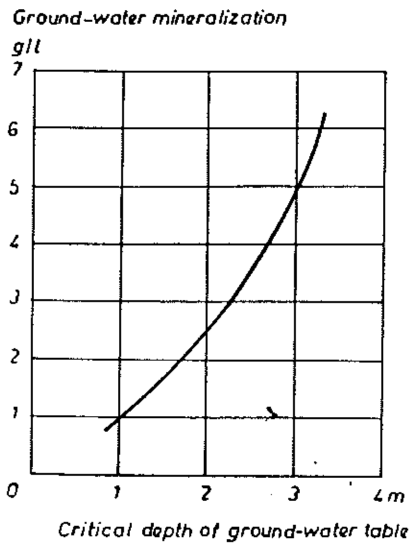


FIG. 16. Relation between ground-water salt content and the 'critical ground-water level'.

Source: Szabolcs 1979

Fig. 2-15 c

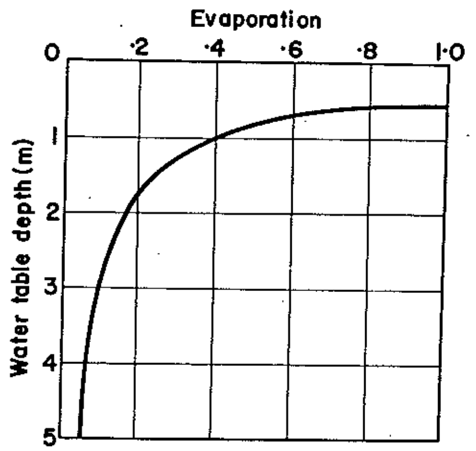


Figure 7
A schematic relationship between the depth of groundwater and relative evaporation rate from soil surface

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

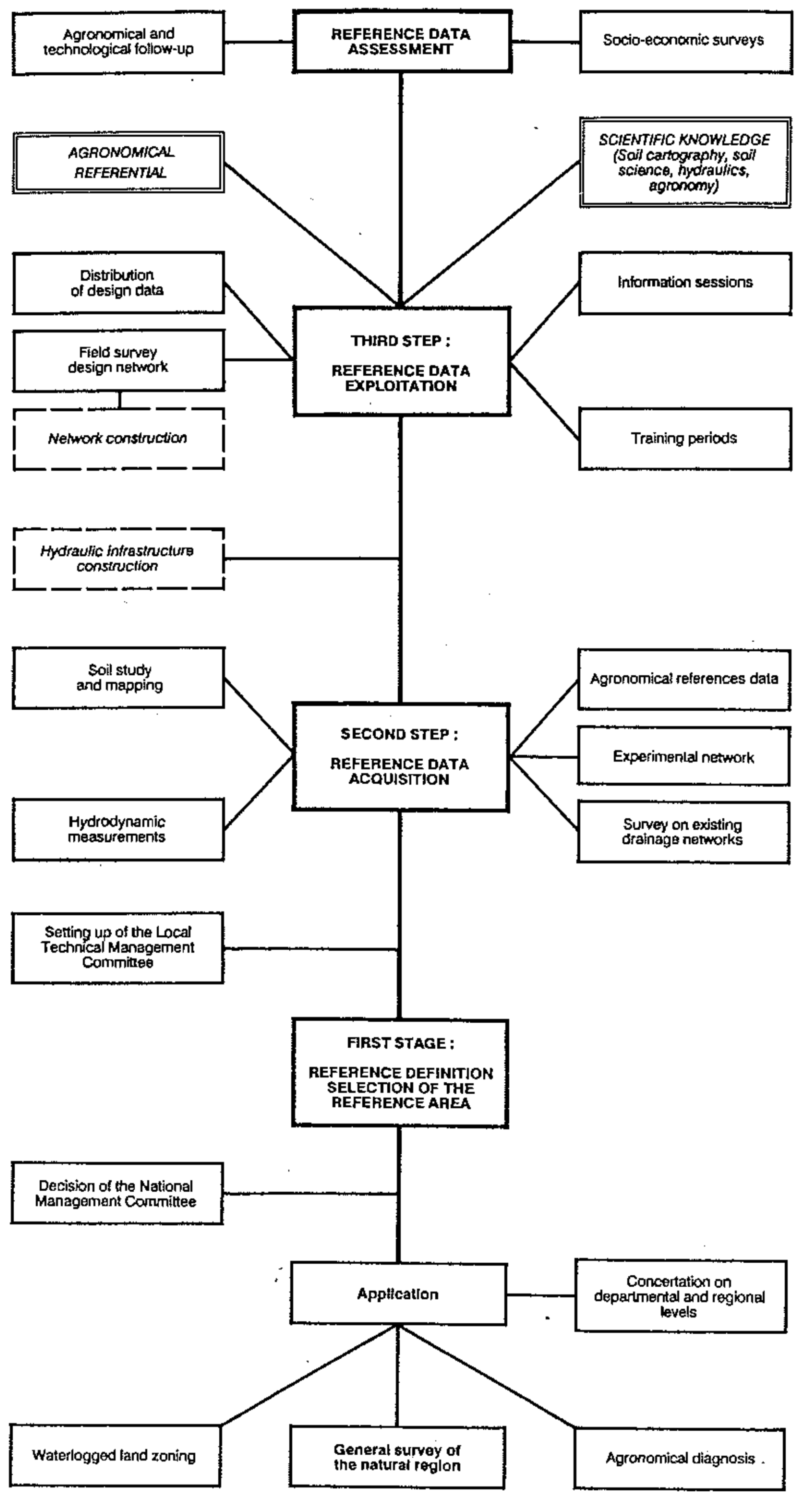


Figure 1 - The different steps of the reference area method

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 'ecological drainage criterion' 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.

Groundwater pumping 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

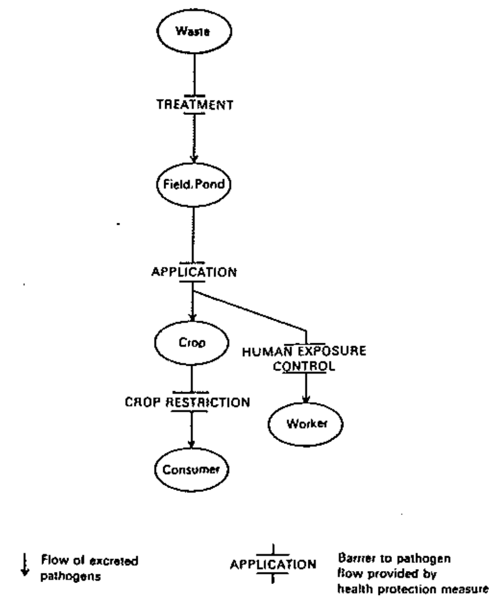
It is essential that the acceptance of excreta or wastewater reuse by farmers, farmworkers, consumers and people living in the vicinity is ensured before it is considered for irrigation. Socio-cultural studies or other information is required to ensure that there are no objections. Suitably designed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

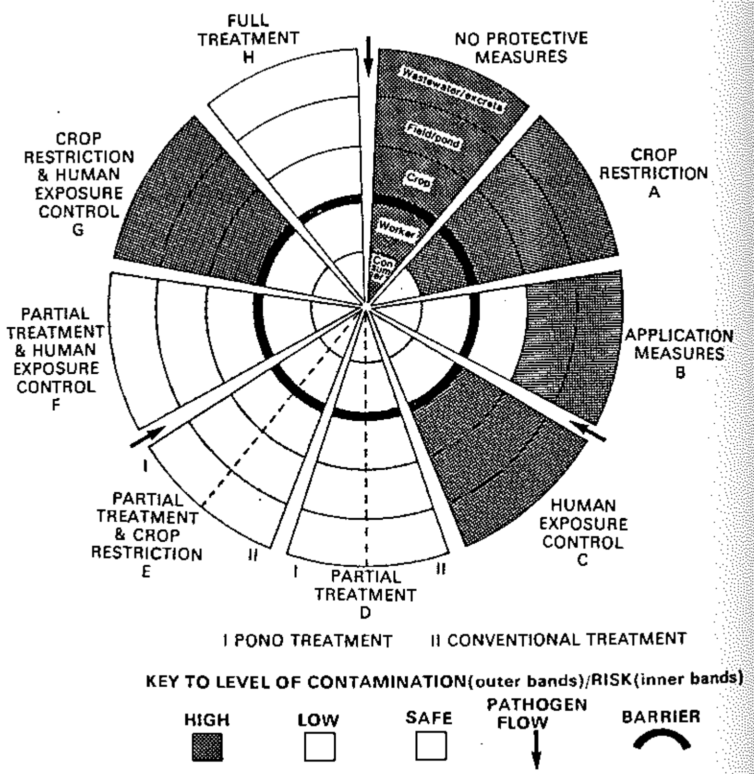
Fig. 2-17



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

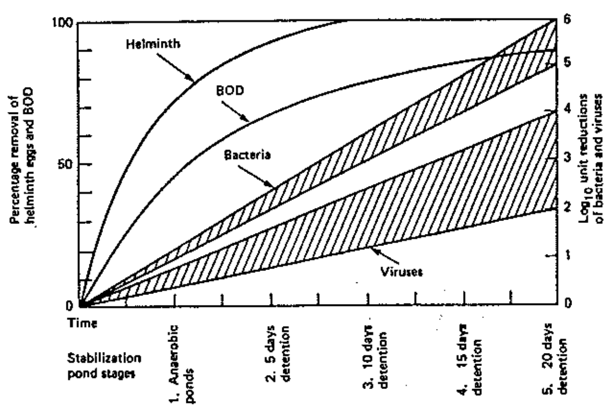


Figure 2.1 Generalized removal curves for helminth eggs, BOD, excreted bacteria and viruses in waste stabilization ponds at temperatures above 20°C

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

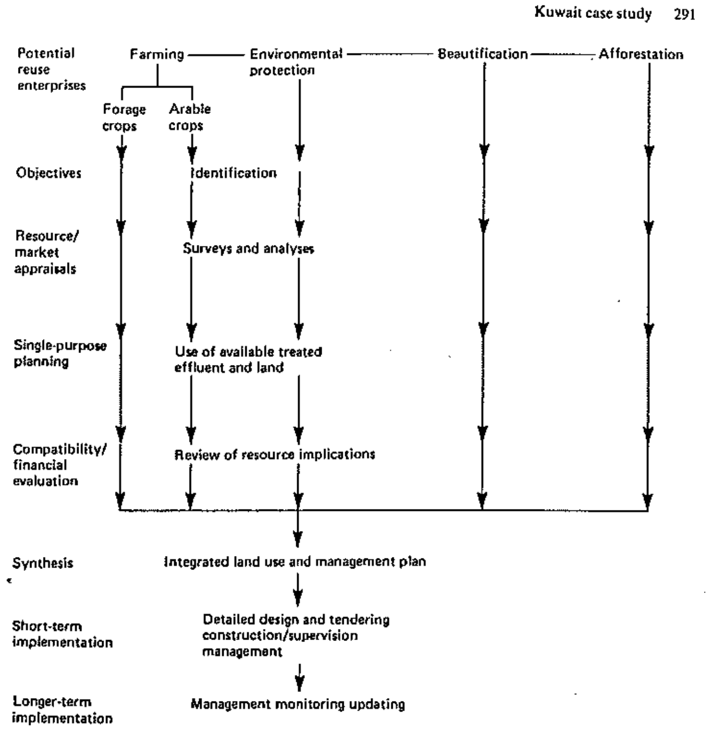


Figure 24.1 An outline of the resource planning and implementation processes

Source: Pescod/Arar 1988

Fig. 2-21

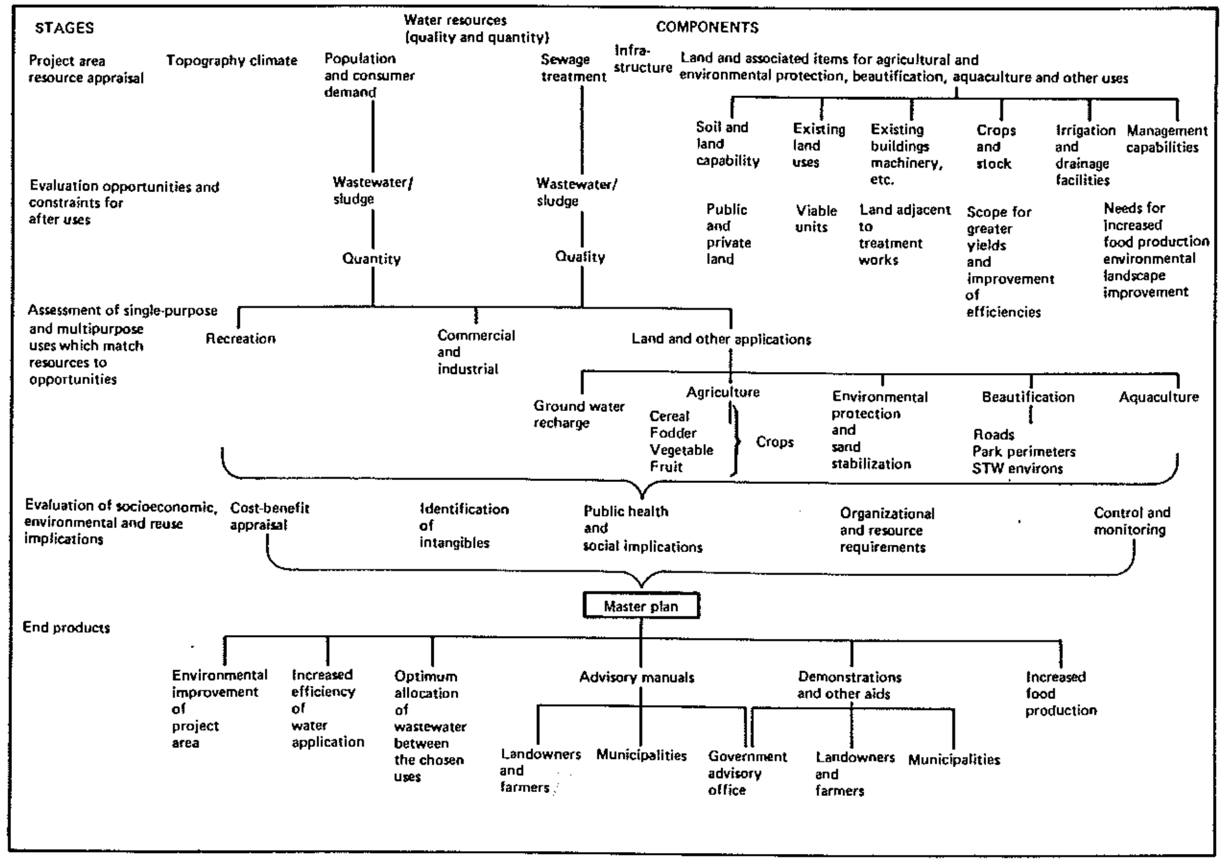


Figure 24.2 Main components of general planning guidelines for wastewater reuse

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

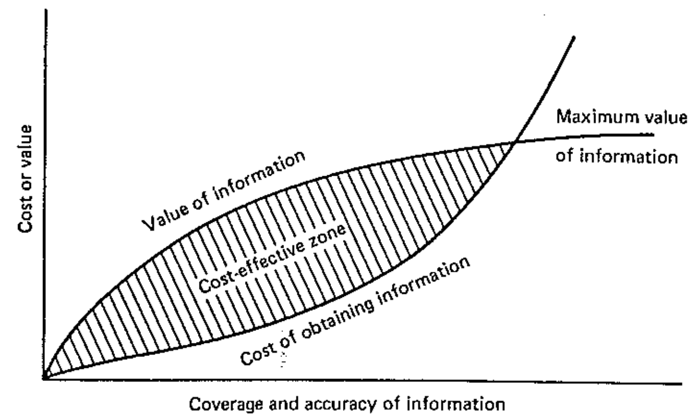


Figure 1.4 Cost-effectiveness of monitoring and evaluation information

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

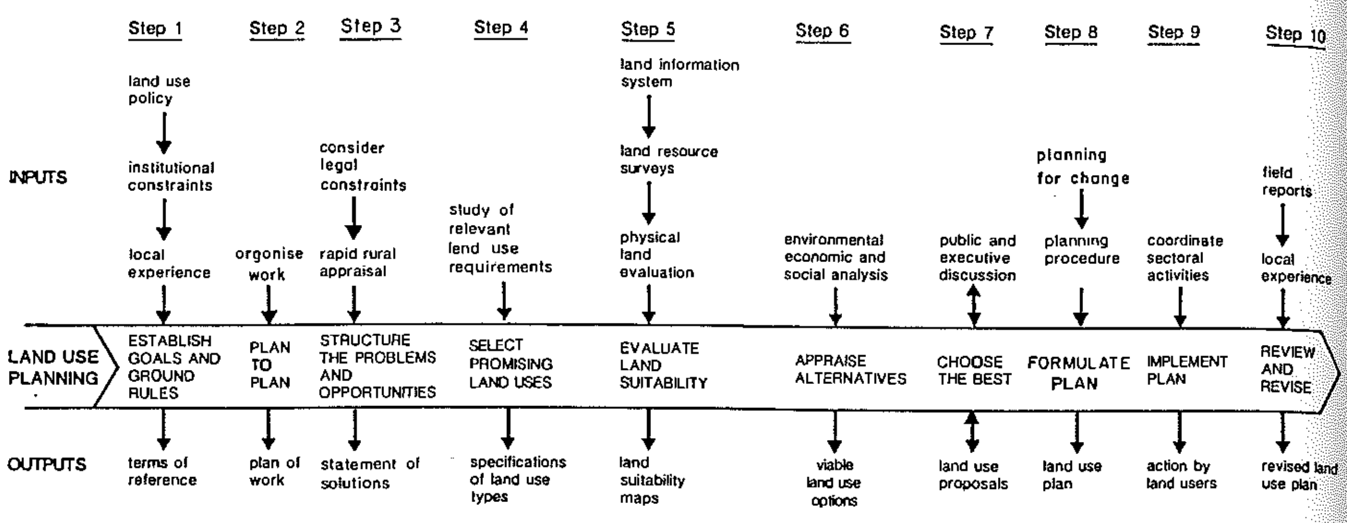


Figure 4
Synoptic view of the land use planning process
adapted from Dent and Ridgway 1986

Source: FAO 1989

Fig. 3-2

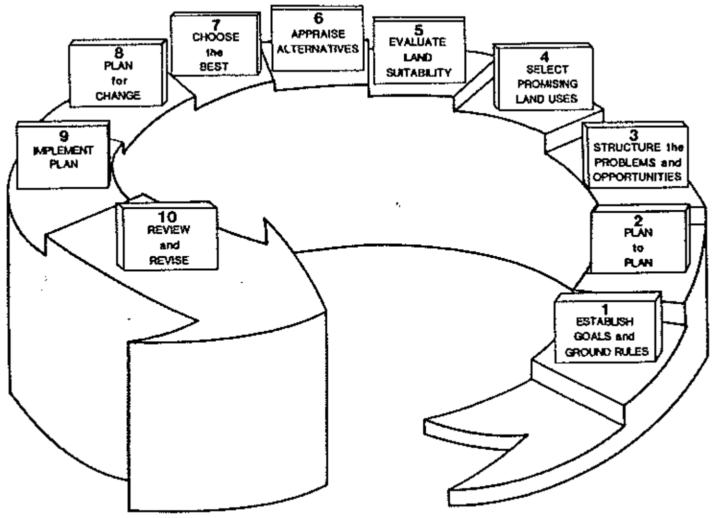


Figure 3. Steps in land use planning.

Source: FAO 1989

Fig. 3-3

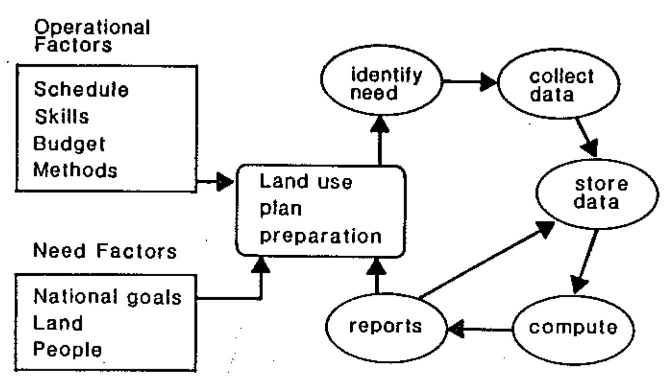


Figure 18 Elements of a land use planning information system

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

Fig. 3-4

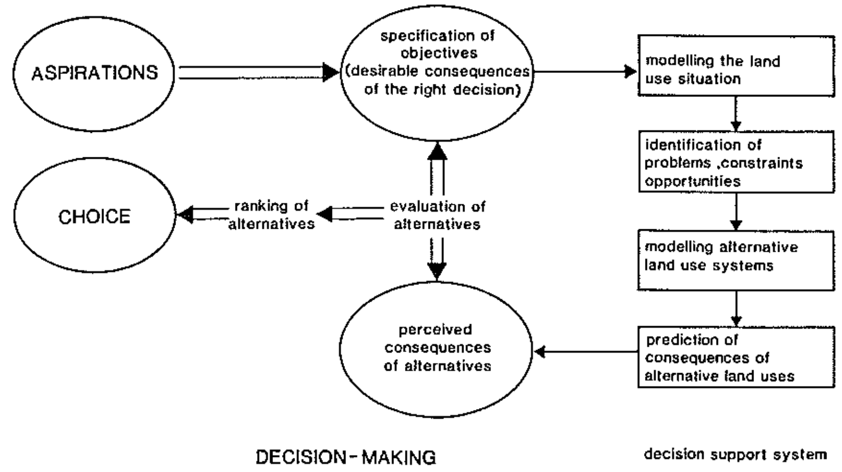


Figure 16 Schematic representation of decision-making

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

- 102 -

Fig. 3-5

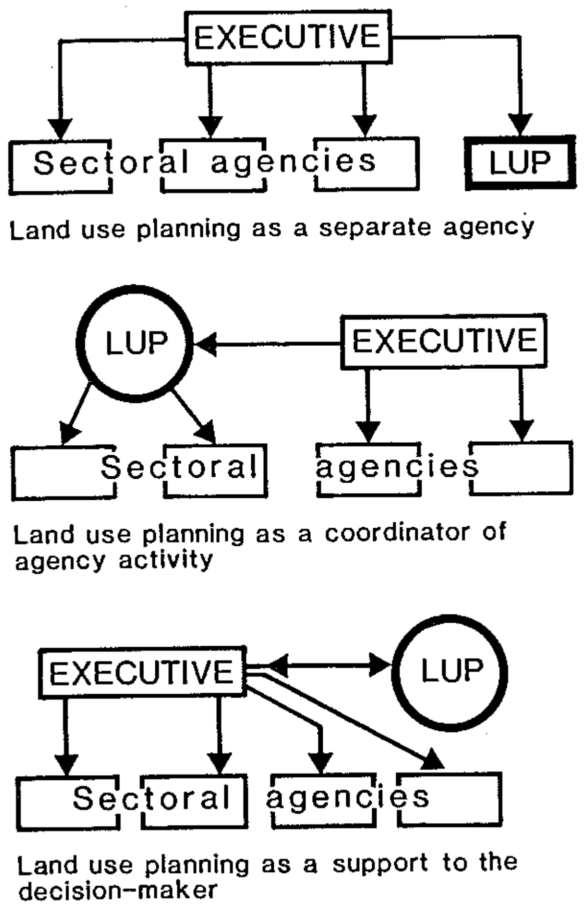


Figure 22 Alternative institutional structures for land use planning

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

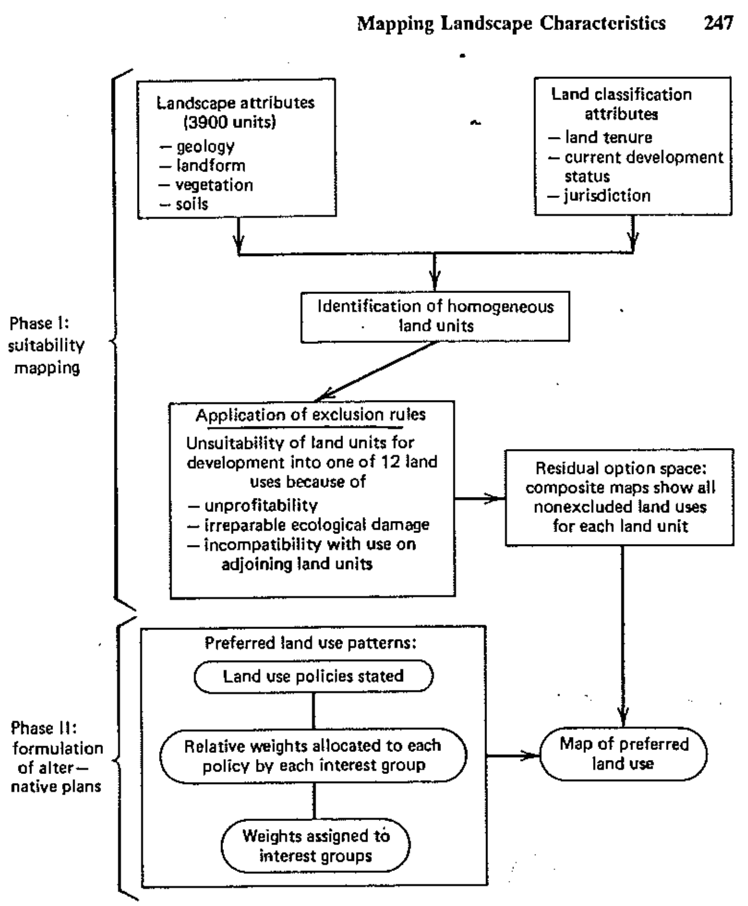


Figure 6.19. Steps in the CSIRO approach to land use planning (SIRO-PLAN), as applied to the south coast of New South Wales, Australia (from information in Austin and Cocks 1978).

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.

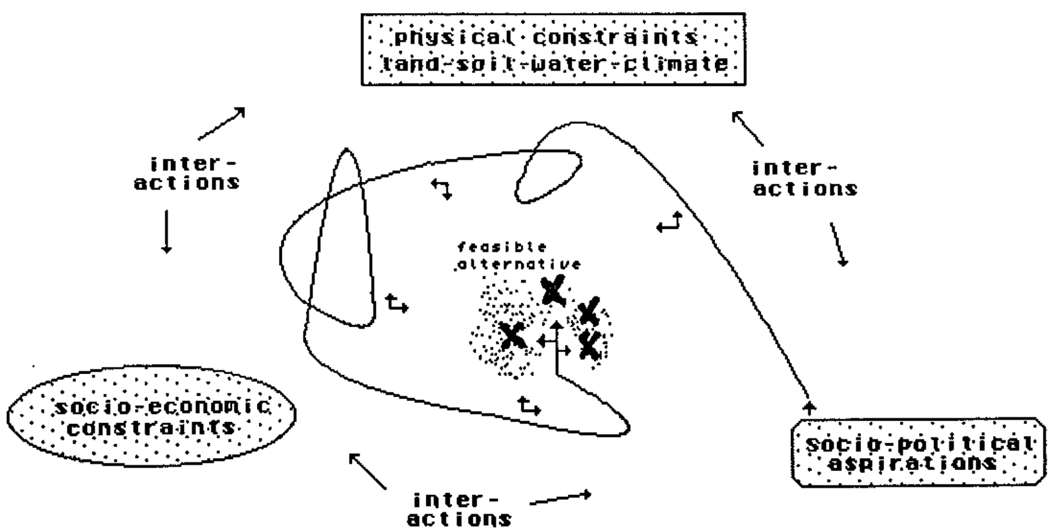
A strict **preservationist** view may assume that any development will exceed the carrying capacity. In any case, the succession and resilience of **ecosystems** and the consequences for specific species (humman, fauna, flora) must be considered when defining the carrying capacity. Also the **user's** 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



modified after:
Smyth in: USDA (Cornell Workshop) 1981

Dynamic Land Classification
Interactions between goals and constraining corners

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 le-

ad 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

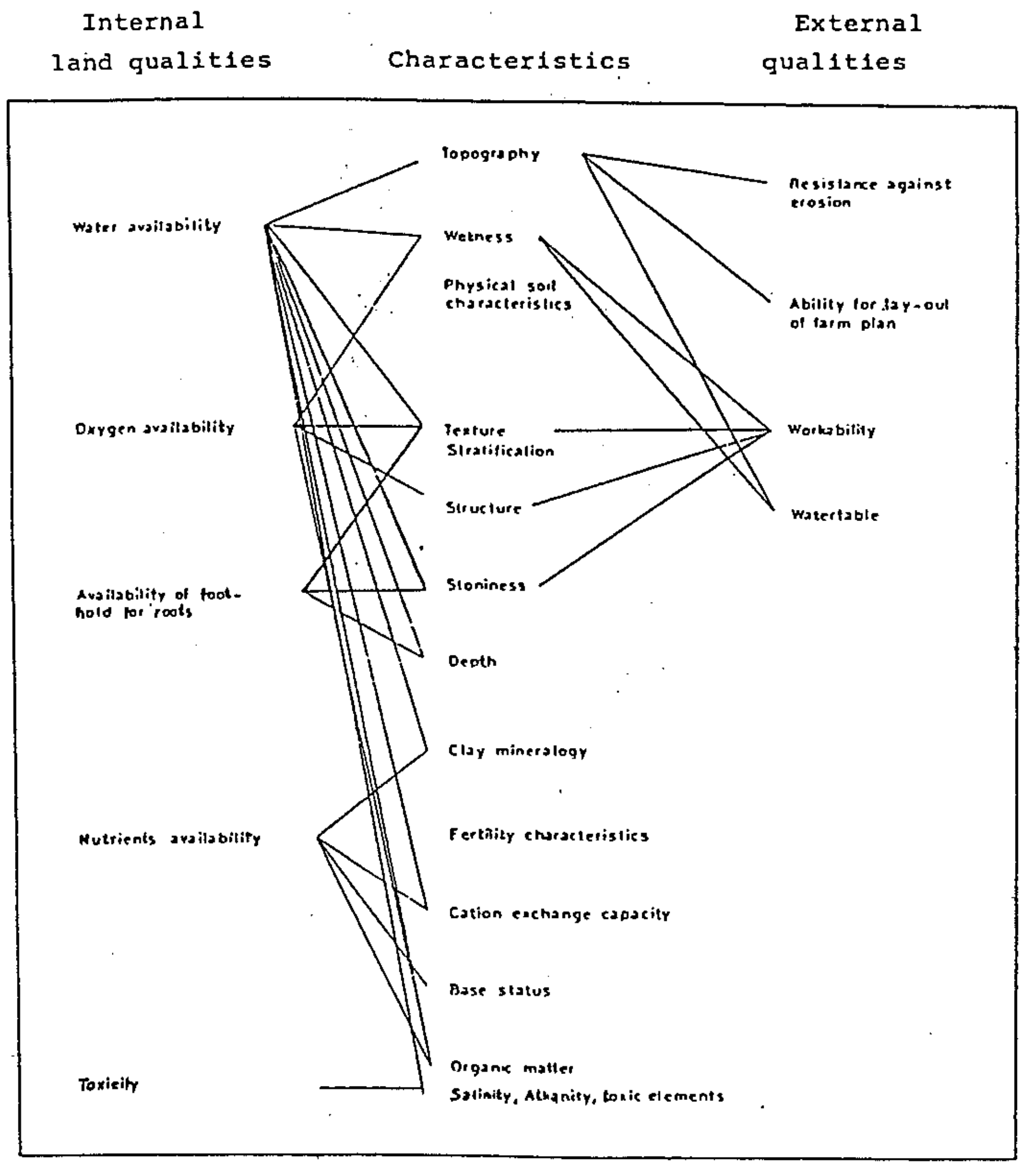


Fig. 9 : Relation between Land/Soil Characteristics and Land Qualities
(modified after Sys, 1978) ; Petermann

- 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-

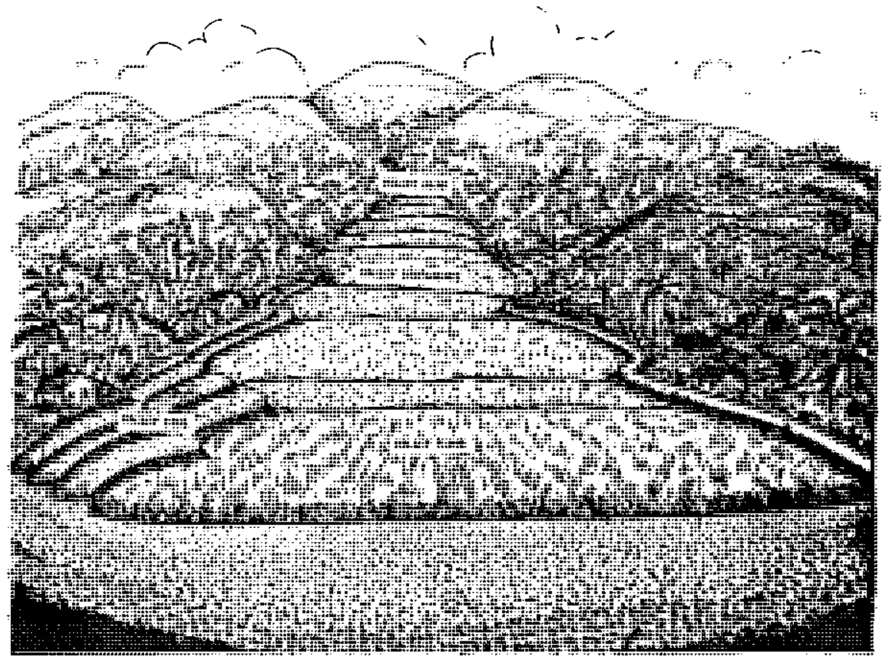


Figure 4. Land elements found in inland valley complexes.

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

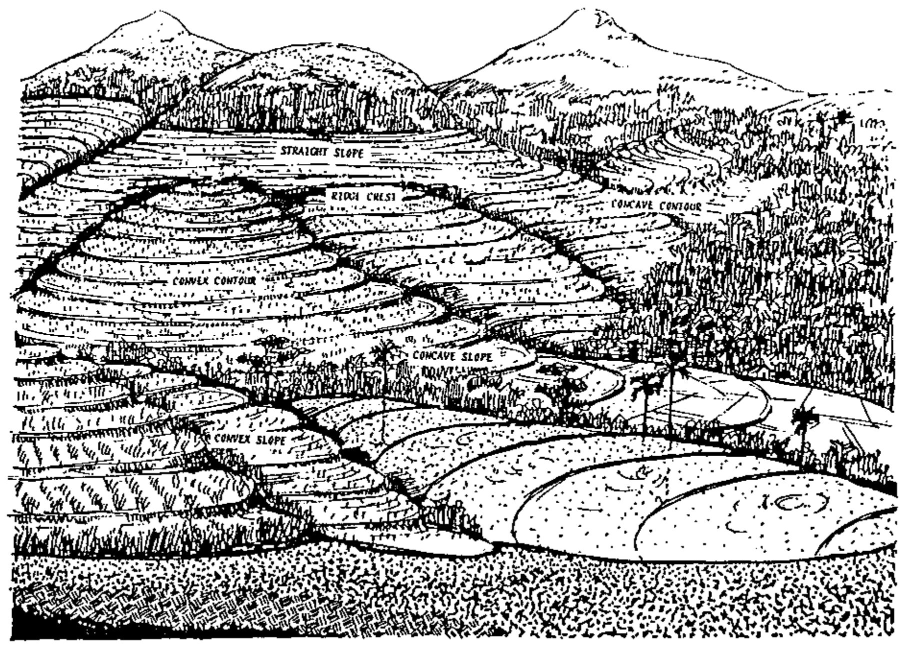


Figure 5. Land elements found in terraced slope complexes.

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

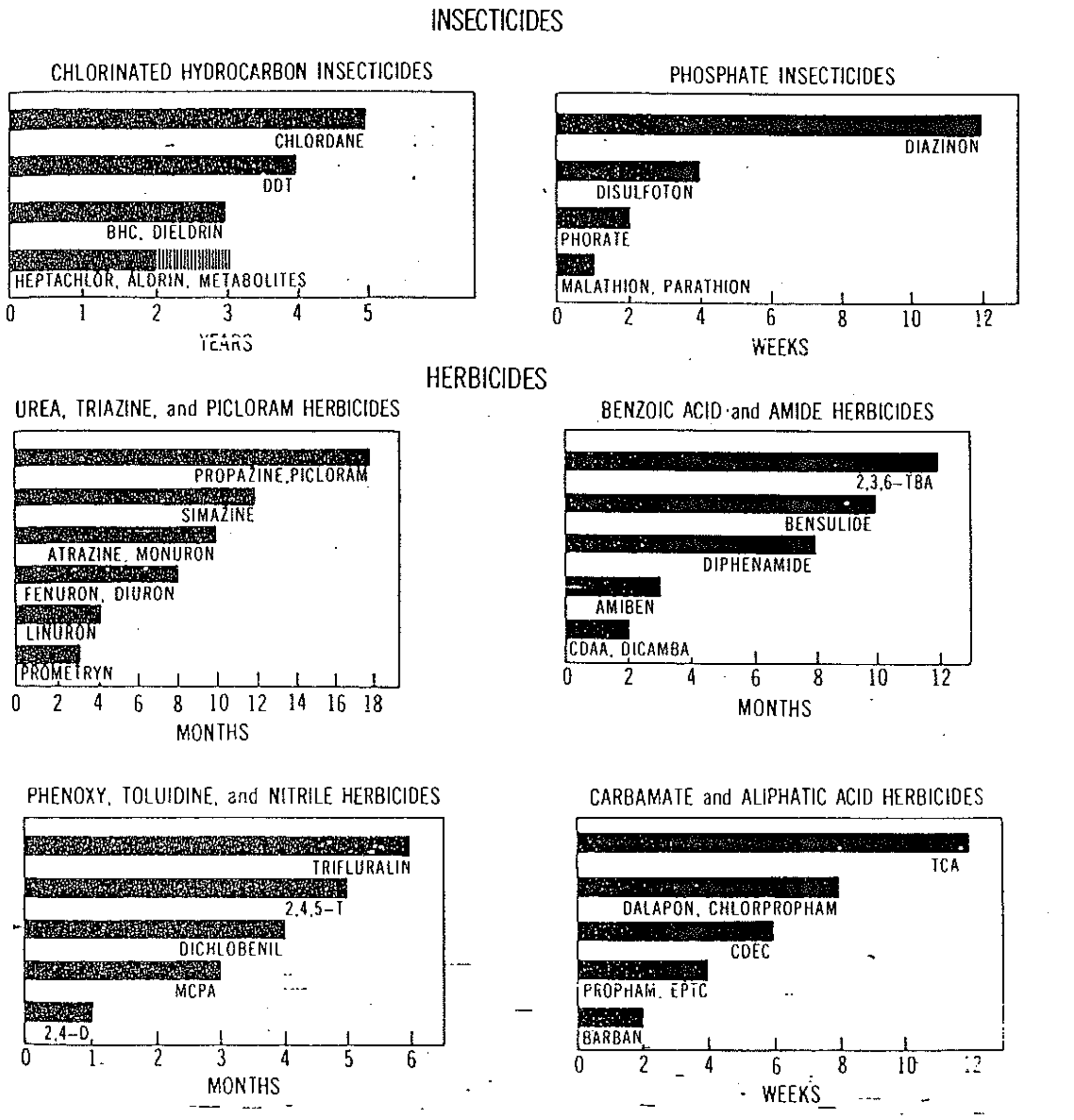


Figure 2 Persistece of certain pesticides in soils. The lengths of the bars represent the time required for loss of 75 to 100% of the biological activity under agricultural conditions with normal rates of application. The values were derived from a review of approximately 80 sources concerned with pesticide 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

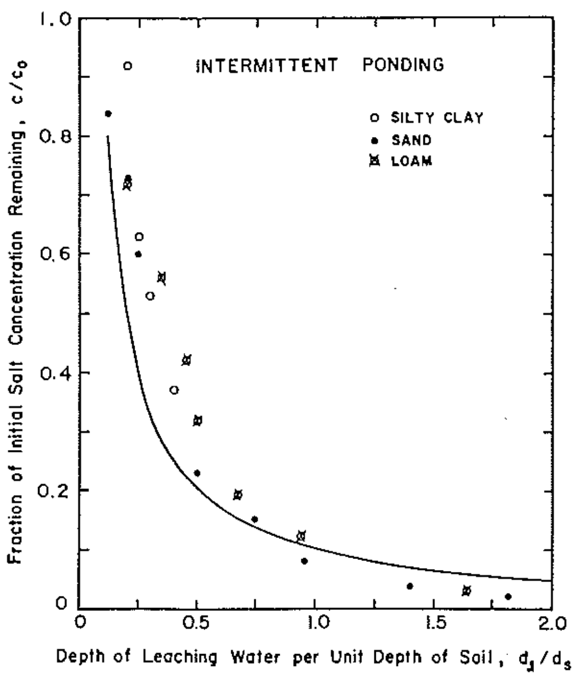


Fig. 36-13. Depth of leaching water per unit depth of soil required to reclaim a saline soil by ponding water intermittently. After Hoffman (1980).

Fig. 3-10 b

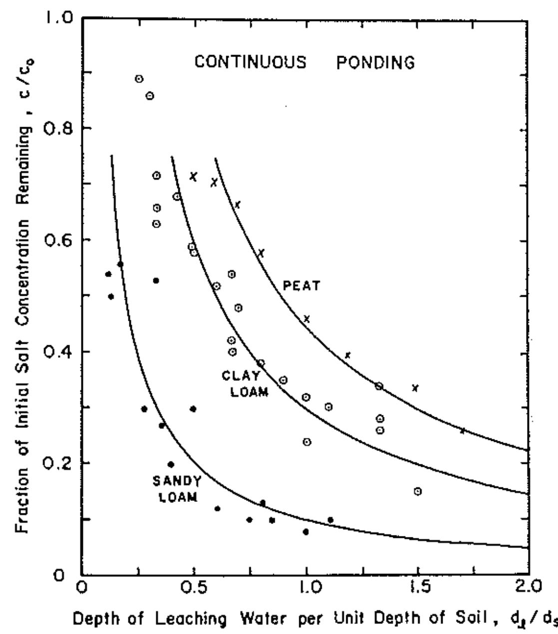


Fig. 36-12. Depth of leaching water per unit depth of soil required to reclaim a saline soil by continuous ponding. After Hoffman (1980).

Fig. 3-11 a

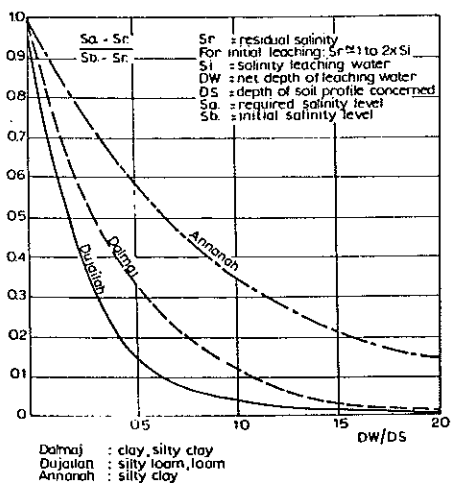


Fig. 5.3/1. Leaching curves of soils in Iraq

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
$C = 2{\cdot}2$ Annanah curve
$C = 1{\cdot}1$ Dalmaj curve
$C = 0{\cdot}67$ 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 valuės 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

1124 RHOADES & LOVEDAY

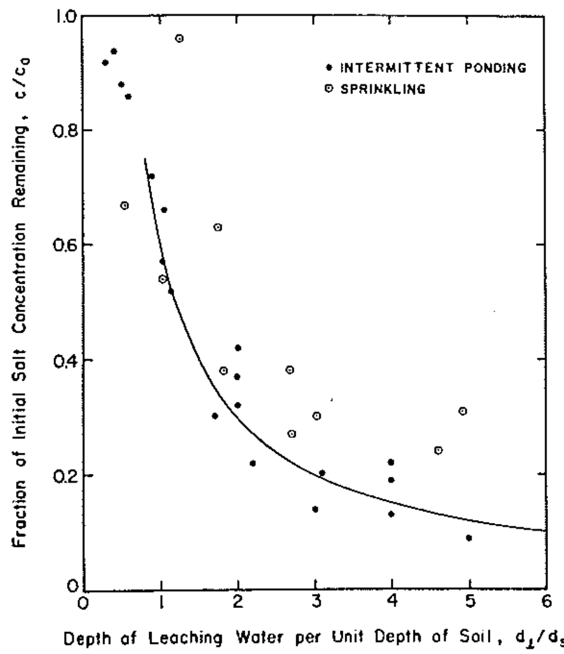


Fig. 36-14. Depth of leaching water per unit depth of soil required to reclaim a soil inherently high in B. After Hoffman (1980).

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 <u>reclamation</u> 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).

<u>Leaching efficiency</u> 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.

<u>Leaching Requirement for Controlling the Salt Balance</u>

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:

$$VivCiw + VgwCgw + Sm + Sf - VdwCdw - Sp - Sc = d\,Ssw$$

Fig. 3-13

SALINITY IN IRRIGATED AGRICULTURE 1109

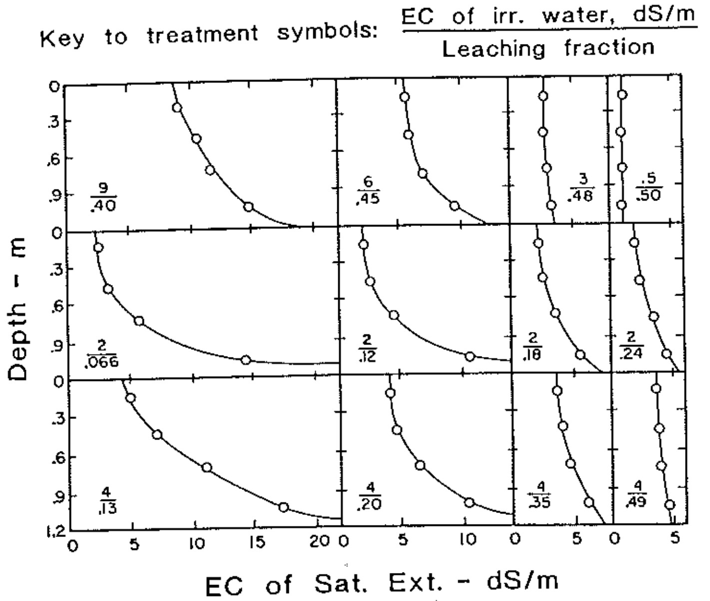


Fig. 36-5. Steady-state salt profiles expressed as electrical conductivity (EC) of the soil-saturation extract, as influenced by EC of irrigation water and leaching fraction. Key to treatment symbols: EC of irrigation water, dS/m per leaching fraction (Bower et al., 1969a).

Source: Stewart ed. 1990

Fig. 3-14 a

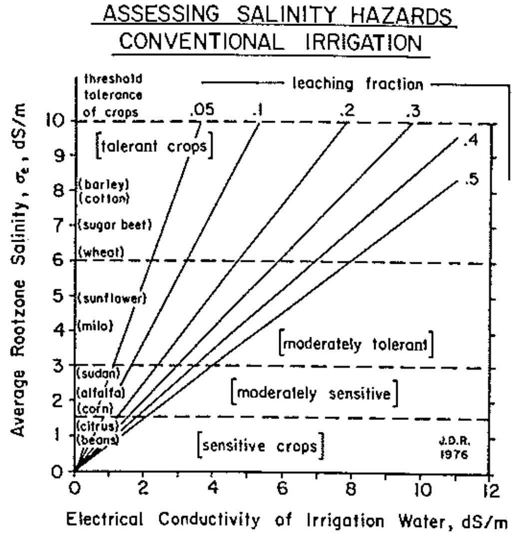


Fig. 36-10. Relations between average root zone salinity (saturation extract basis), electrical conductivity of irrigation water, and leaching fraction to use for conditions of conventional irrigation management (Rhoades, 1982b).

Fig. 3-14 b

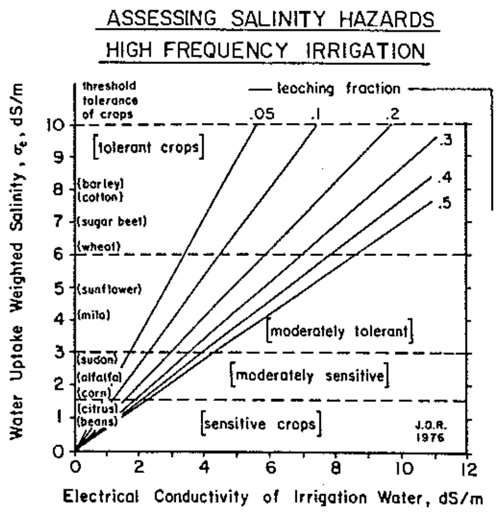


Fig. 36-11. Relations between water uptake-weighted salinity (saturation extract basis), electrical conductivity of irrigation water, and leaching fraction to use for conditions of high-frequency irrigation (Rhoades, 1982b).

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

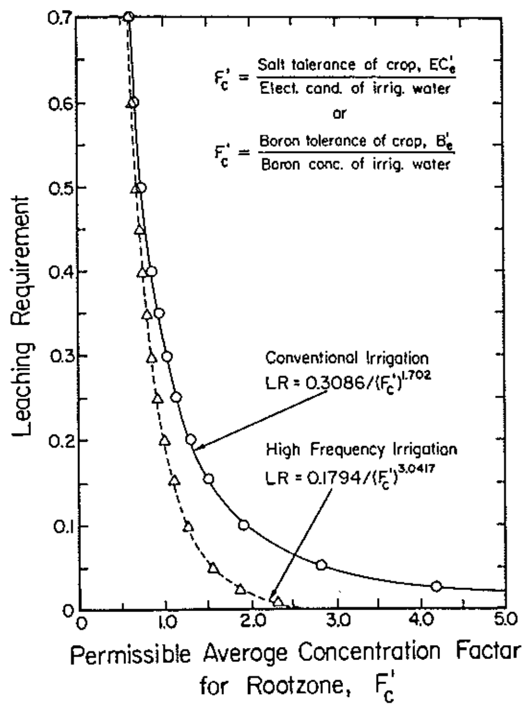


Fig. 36-9. Relation between leaching fraction and permissible root zone concentration factor for use in determining leaching requirement for conventional irrigation. After Rhoades (1982b).

Source: Stewart ed. 1990

Fig. 3-16 a

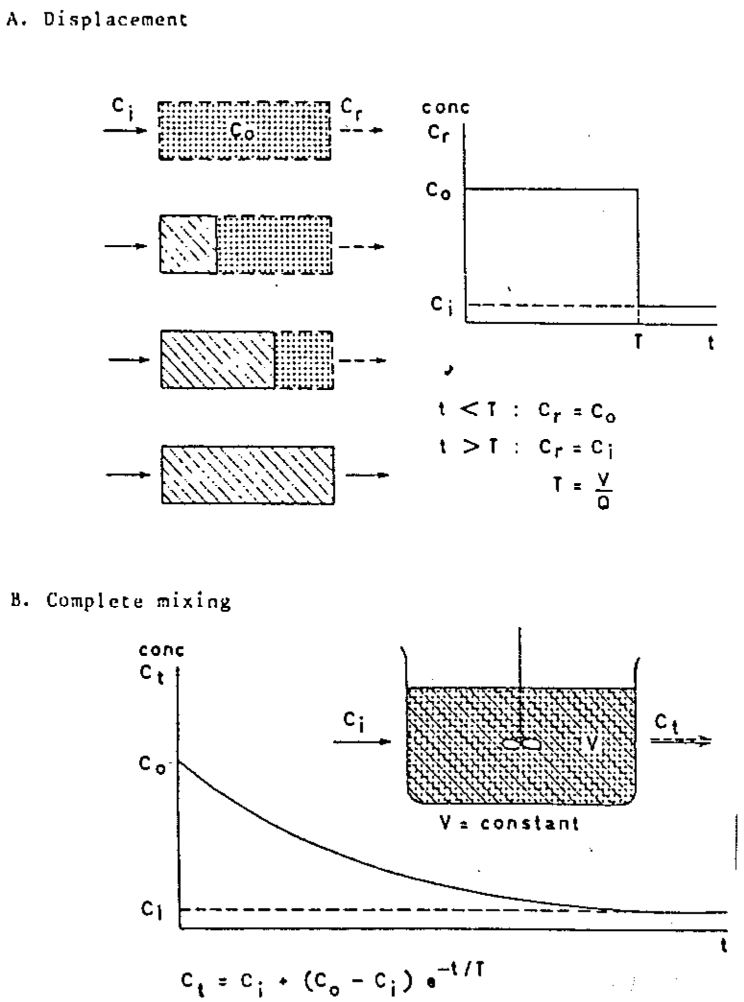


Figure 11.Desalinization of a reservoir.

Fig. 16 b

Source: van der Molen/van Hoorn 1979

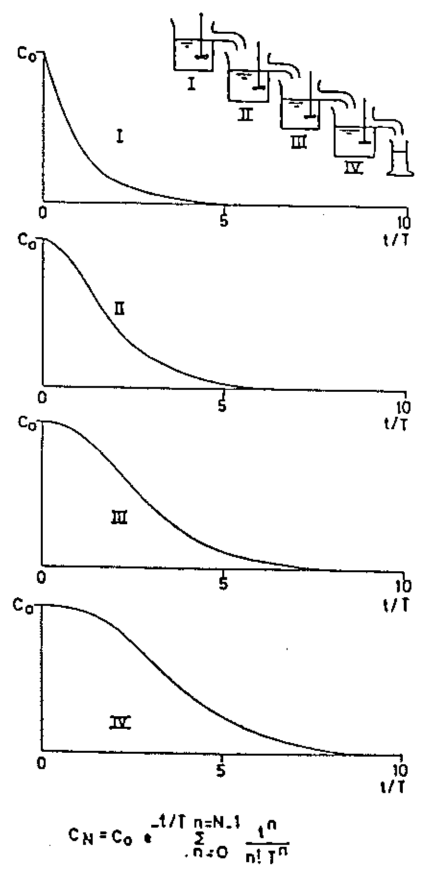


Figure 12.Desalinization of 4 reservoirs in series by rainfall.

* 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 'minimum leaching' 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:

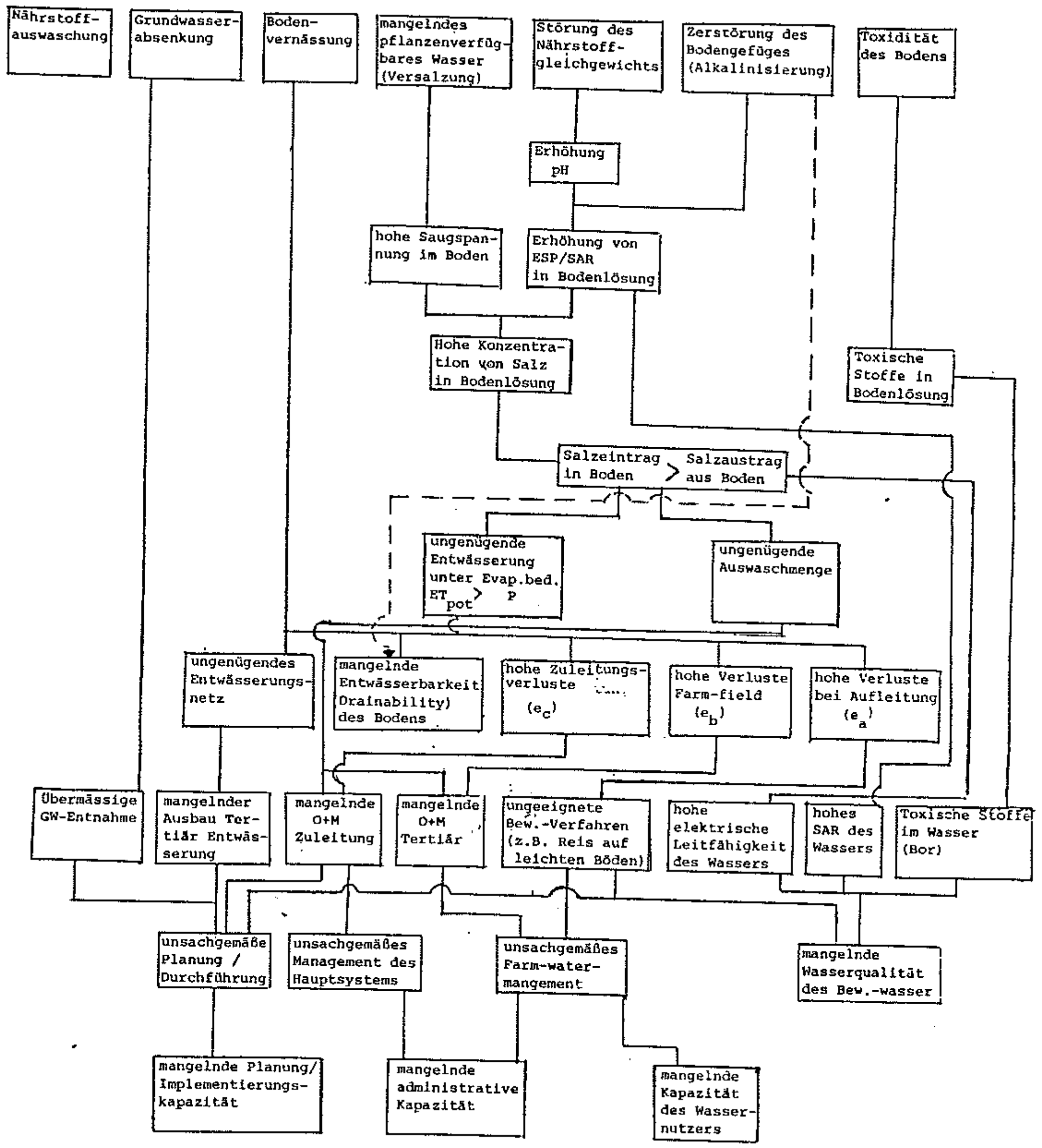
- applying sufficient water at each irrigation to meet the LR,
- applying, once or on several occassions, an additional 'leaching irrigation' sufficient to remove the salt that has accumulated from previous irrigations.

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 salt control analyses 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

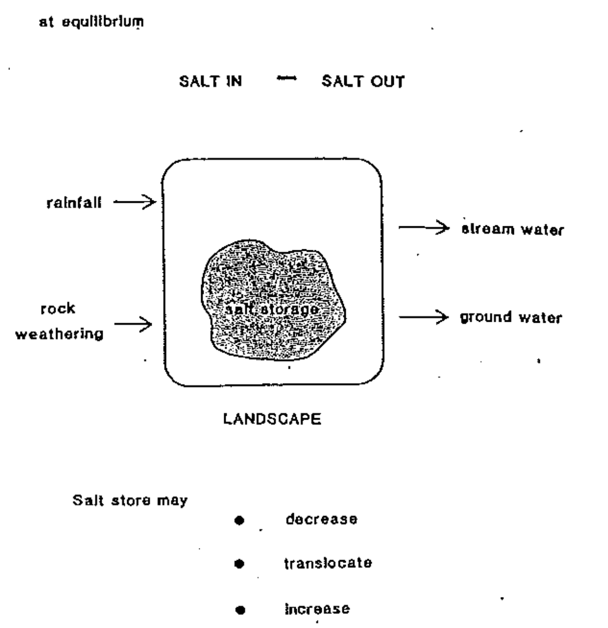


Figure 1 Conceptual model of a salt-balance in a landscape, from Shaw *et al.* (1987).

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.

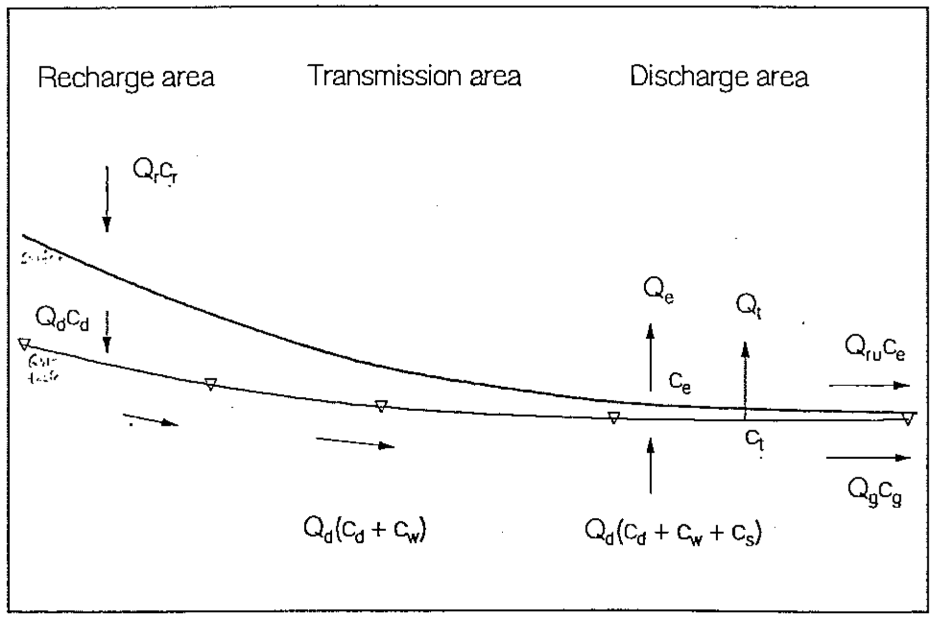


Figure 1 Components of the steady state water and salt mass balance in a salted landscape.

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

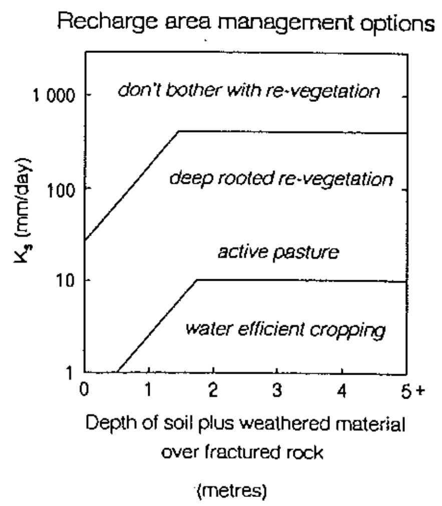


Figure 2 Potential dryland salinity control options for recharge areas based on the depth of soil plus weathered rock and saturated hydraulic conductivity K_s.

Source: Shaw 1992 b

Fig. 3-19 b

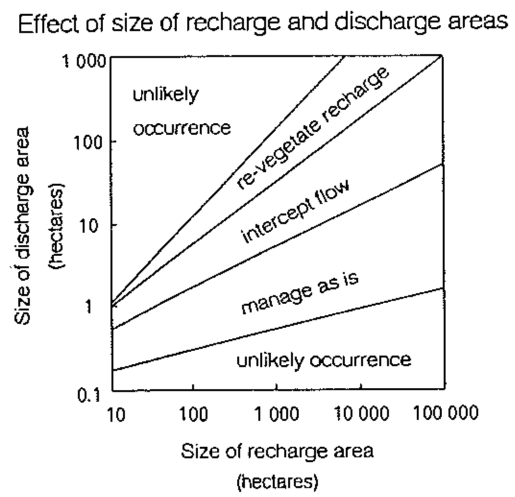


Figure 3 Possible dryland salinity control options based on the relative sizes of recharge and discharge areas. These options need to be considered in conjunction with the information in Table 2.

Source: Shaw 1992 b

Fig. 3-19 c

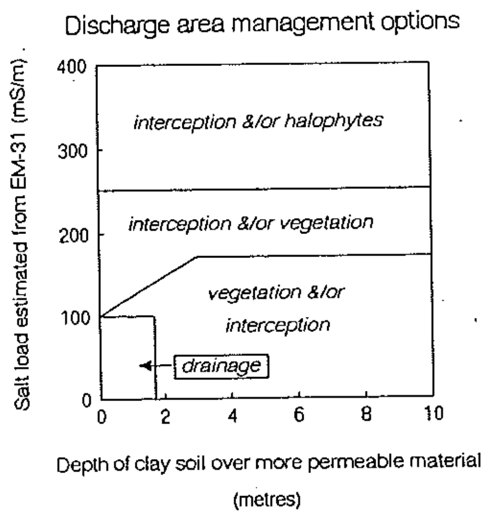


Figure 4 Possible dryland salinity control options for the discharge area, or by interception of water flow to the discharge area, based on the depth of soil and the estimated salt load in the discharge area.

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

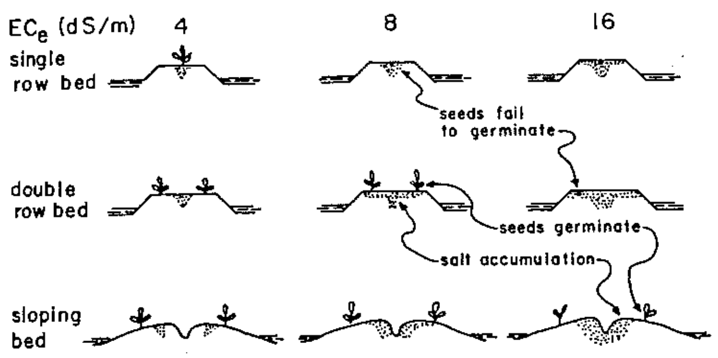


Fig. 36-2. Pattern of salt buildup as a function of irrigation management, bedshape, and level of soil salinity. After Bernstein et al. (1955).

Source: Stewart ed. 1990

Fig. 3-20 b

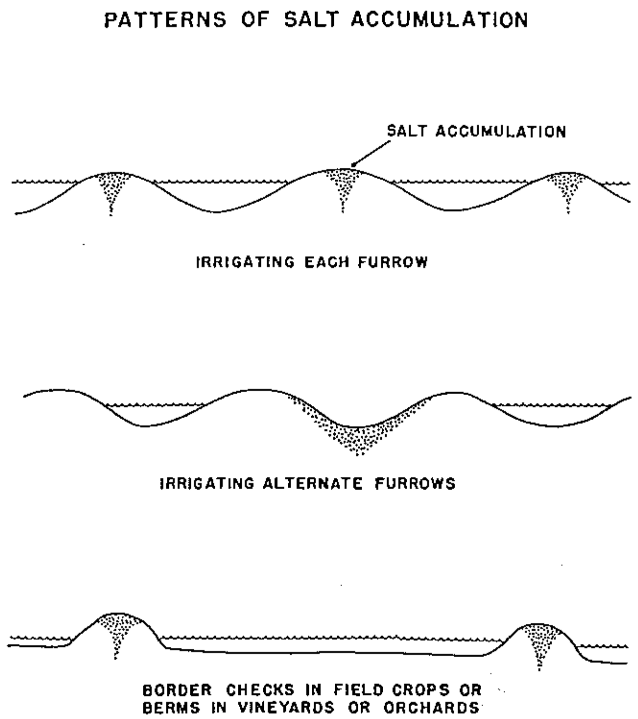


Fig. 2-4. Irrigation management can affect salt accumulation.

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

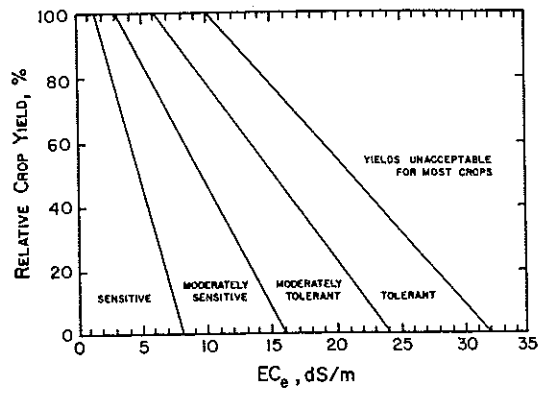


Fig. 36-1. Divisions for classifying crop tolerance to salinity. After Maas (1986).

Source: Stewart ed. 1990

Fig. 3-22

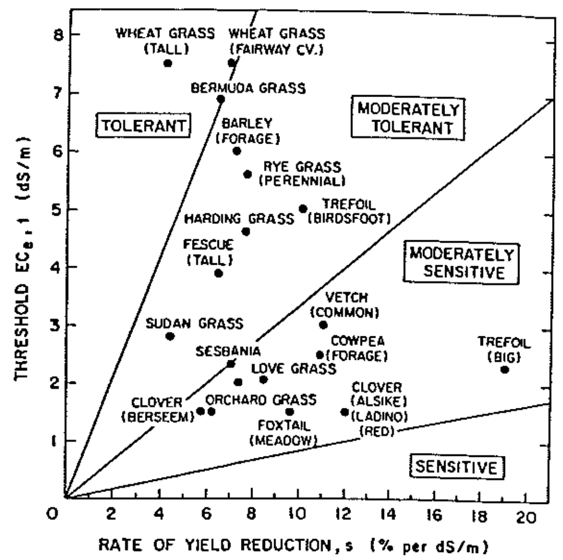


Fig. 3.7 Salt tolerance (threshold ECe and % yield reduction with increasing salinity) of forage crops (Maas 1986)

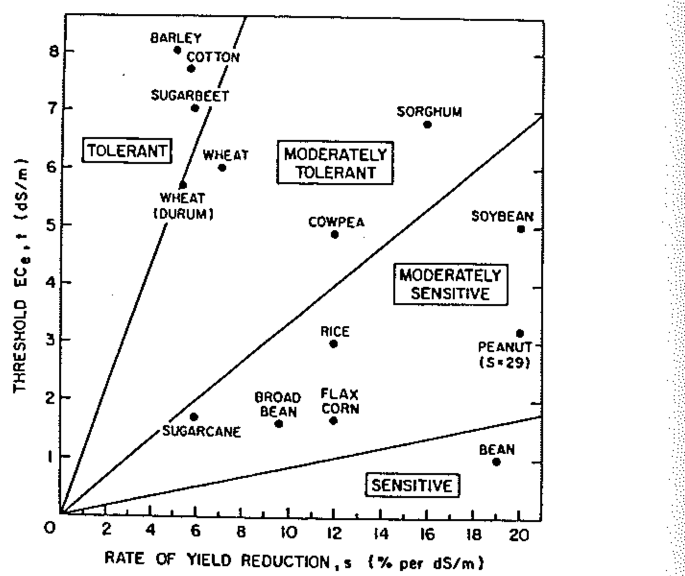


Fig. 3.6 Salt tolerance (threshold ECe and % yield reduction with increasing salinity) of field crops (Maas 1986)

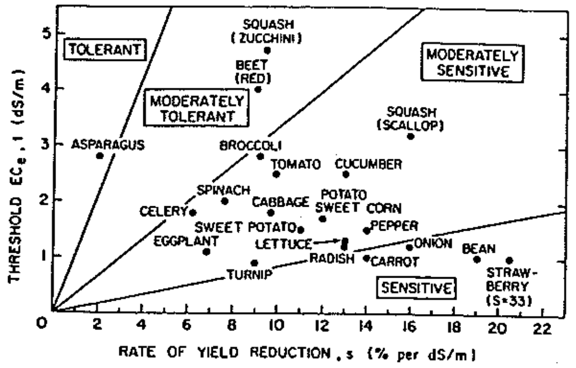


Fig. 3.8 Salt tolerance (threshold ECe and % yield reduction with increasing salinity) of vegetables (Maas 1986)

44 Effect of Irrigation with Treated Sewage Effluent on Soil, Plant and Environment

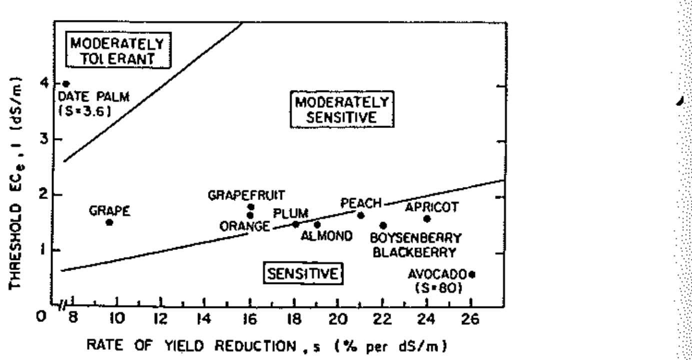


Fig. 3.9 Salt tolerance (threshold ECe and % yield reduction with increasing salinity) of trees (Maas 1986)

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

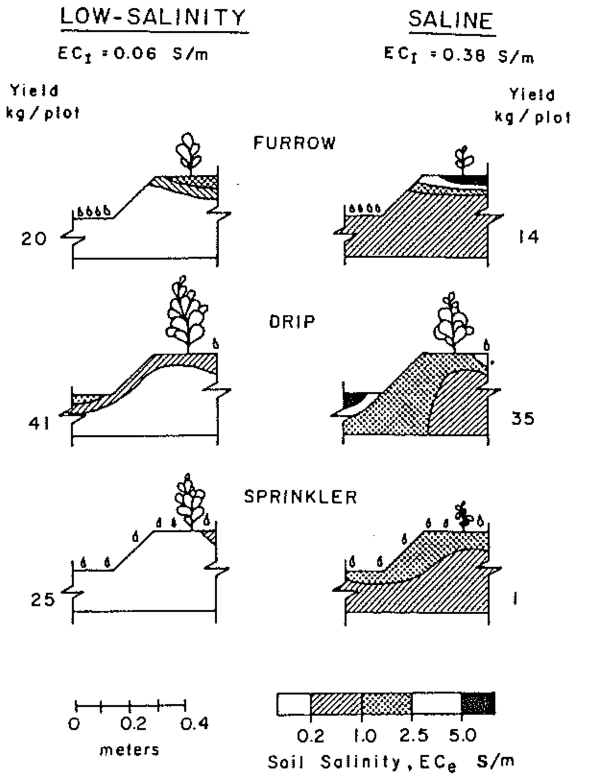


Fig. 36-3. Influence of the irrigation system on the soil salinity pattern and yield of bell pepper (*Capsicum anuum* L.) at two levels of irrigation water quality. After Bernstein and Francois (1973).

Source: Stewart ed. 1990

Fig 23 b

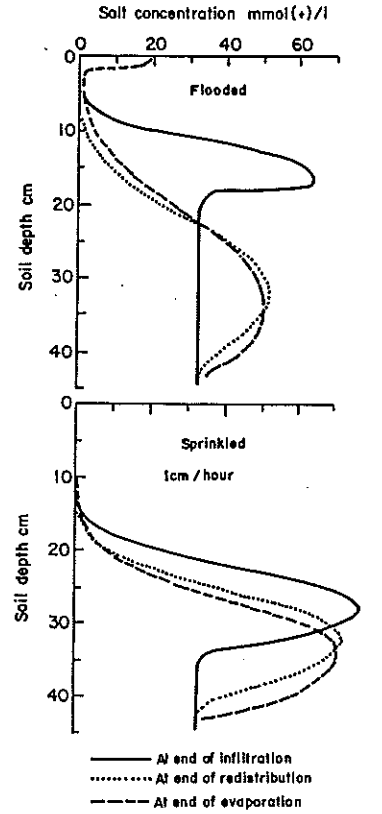


Figure 3
Effect of method of irrigation (flooding vs. sprinkler) and water redistribution following irrigation[2] and evaporation[3] on the salt concentration profiles (Bresler and Hanks, 1969)

Source: FAO (SB 39) 1988

Fig. 23 c

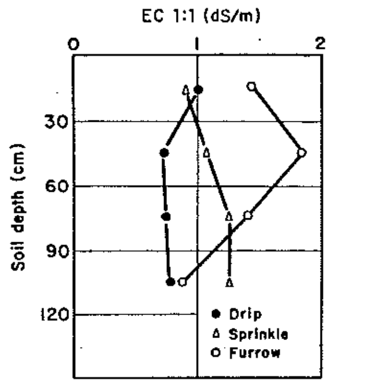


Figure 12
Salinity profiles in sweet corn under drip, sprinkler and furrow irrigation methods
(Goldberg et al., 1976)

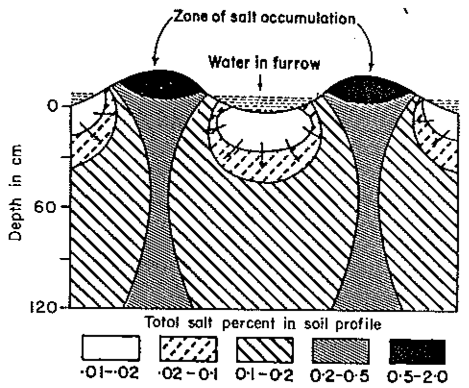
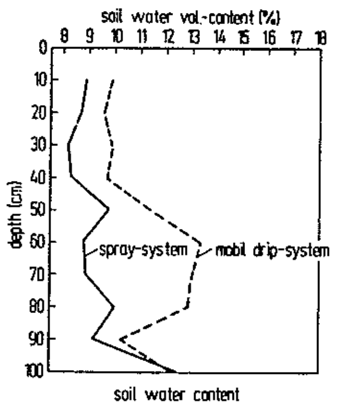
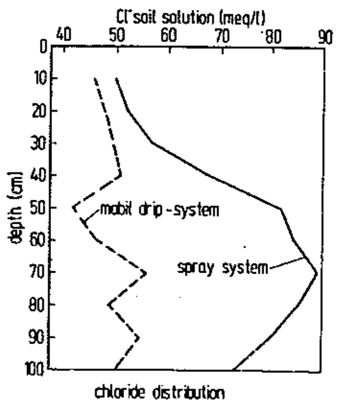


Figure 13
Direction of salt flow and salt accumulation in furrow irrigation. The zone of maximum salt accumulation is in the top of the ridges

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.

Irrigation Management

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 delivery system and field irrigation practices 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.

Conclusion

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.

Management practices 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

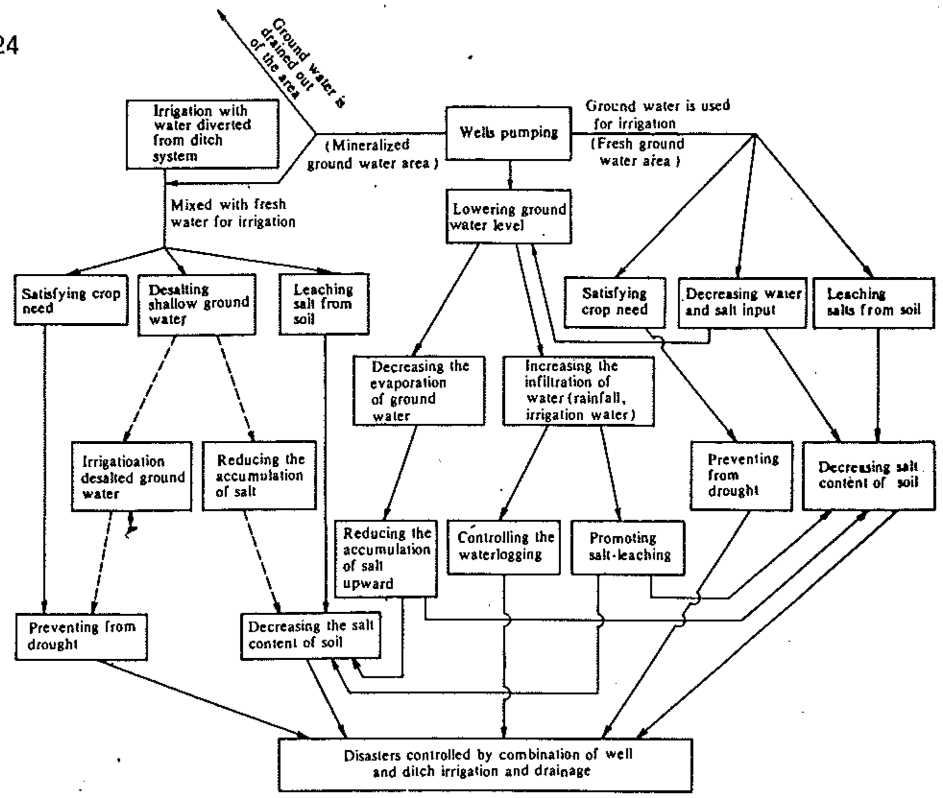


Figure 34
Schematic diagram of the effect of pumped well irrigation and drainage on control of drought, flooding, salinization and sodication (You and Wang, 1983)

Source: FAO (SB 39) 1988

Fig. 3-25

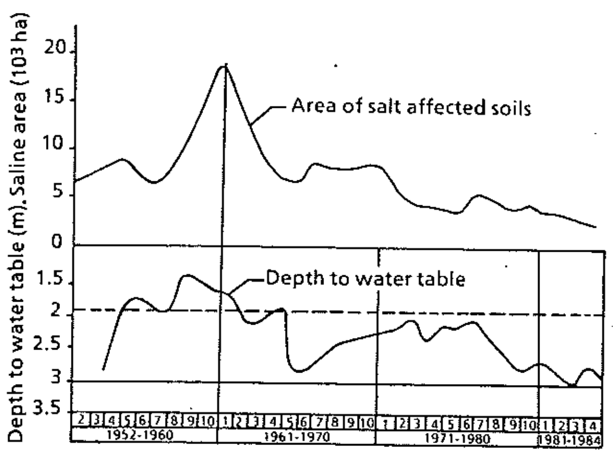


Figure 2 - Evolution of the area of salt-affected soils and of depth to watertable in the People's Victory Canal Project

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

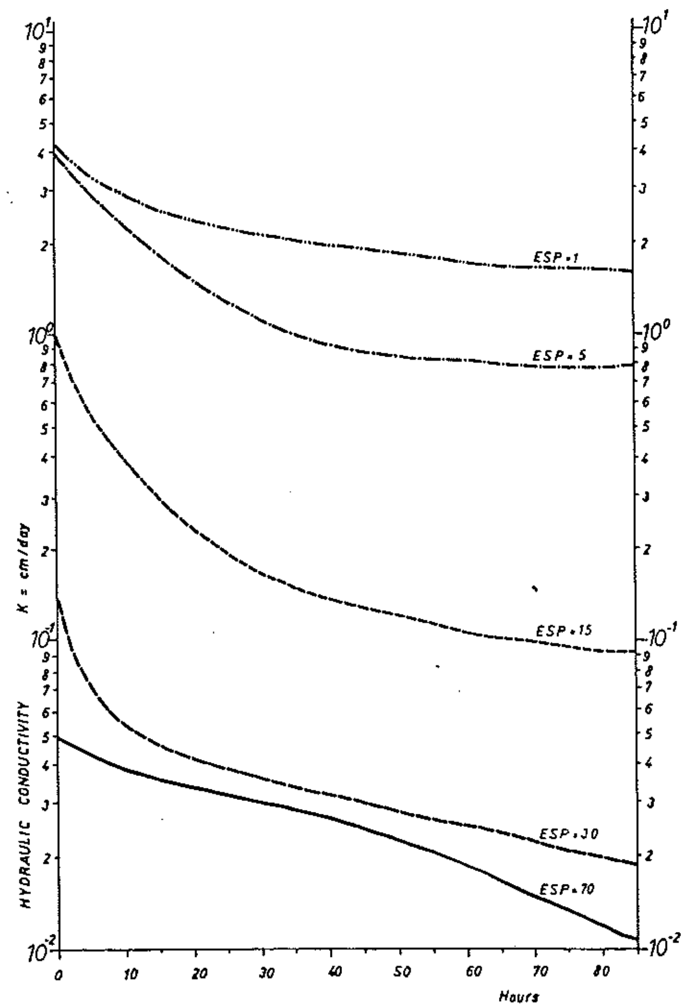


FIG. 55. Hydraulic conductivity of a chernozem soil saturated with sodium to various degrees.

Source: Szabolcs 1979

Fig. 26 b

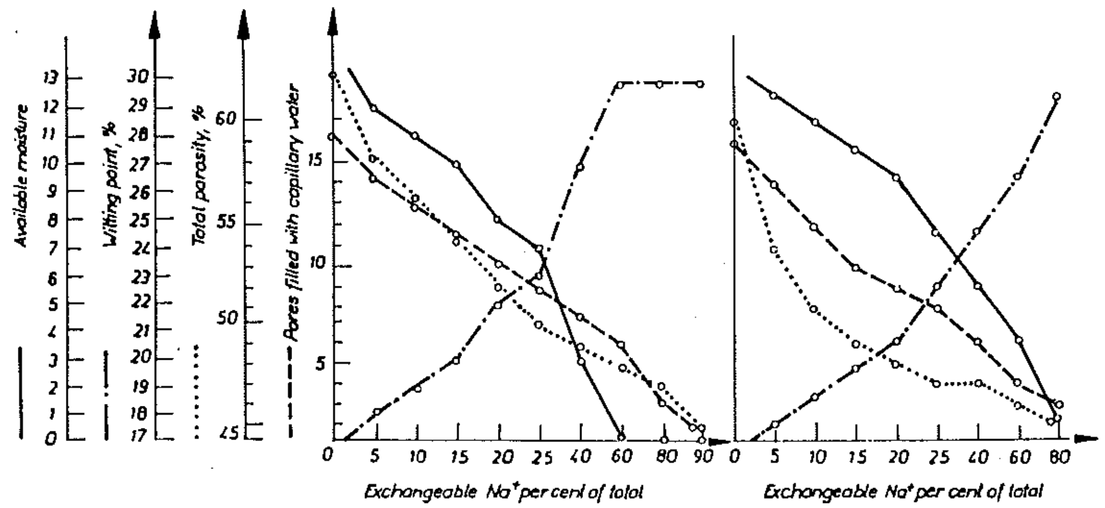


FIG. 54. Exchangeable cations and water properties of a soil according to a ratio of (Ca⁺ + Mg⁺) to Na⁺ in sandy and clayey soils.

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 by-products 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 '<u>gypsum requirement</u>':

$$\text{kg gypsum/ha} = (8.5)d \times db \times Ec\,(RNai - RNaf),$$

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 <u>common practice</u> 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 <u>sodic soils</u> 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). <u>Conservation measures</u> 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 <u>furrow erosion</u> 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

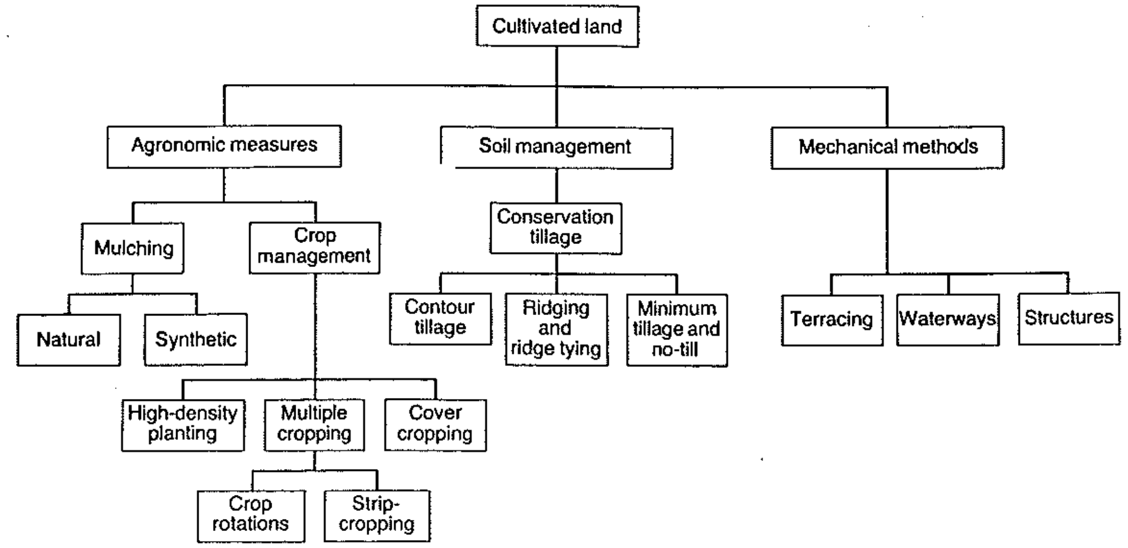
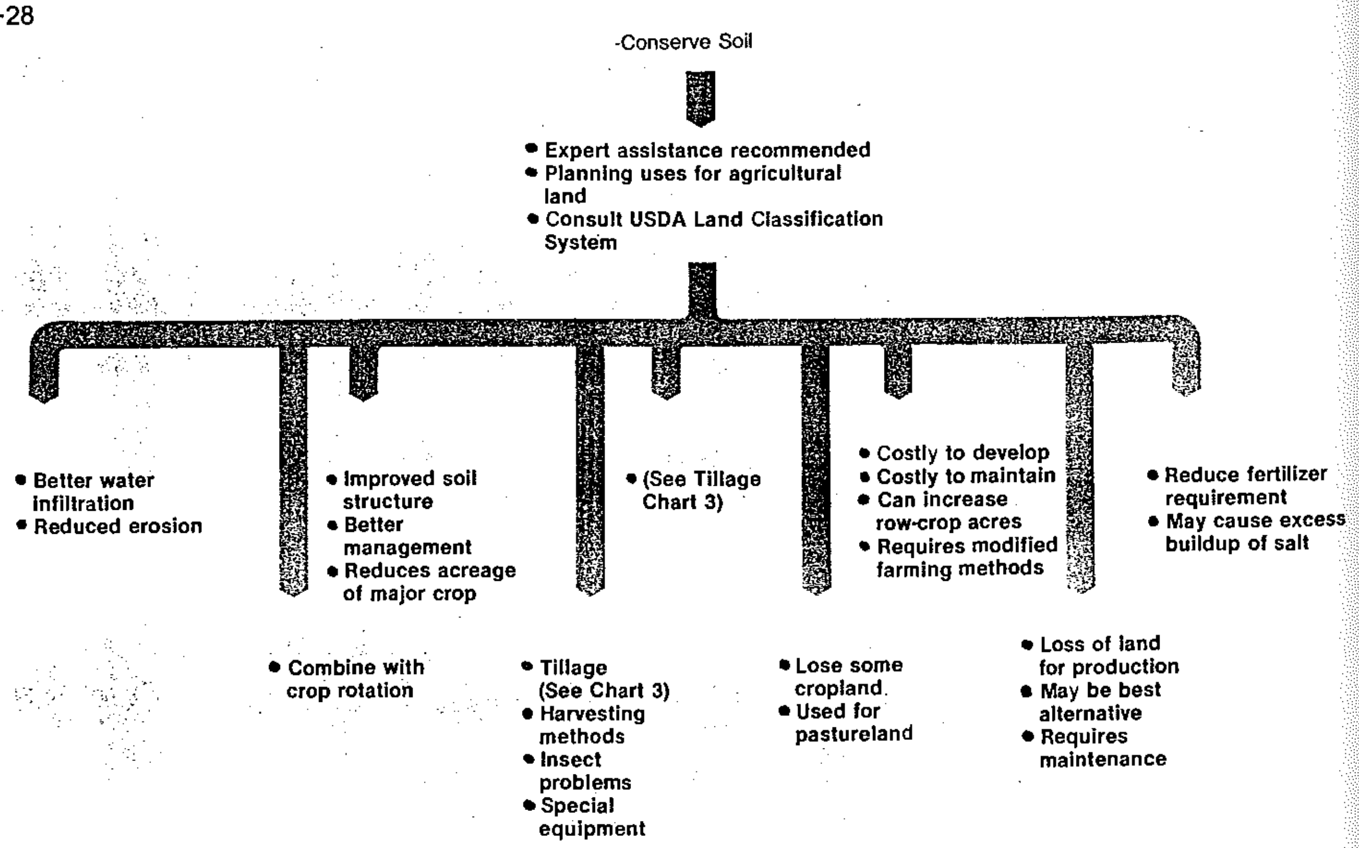


Fig. 7.2 Soil conservation strategies for cultivated land (after El-Swaify, Dangler and Armstrong, 1982).

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 sprinkler irrigation 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

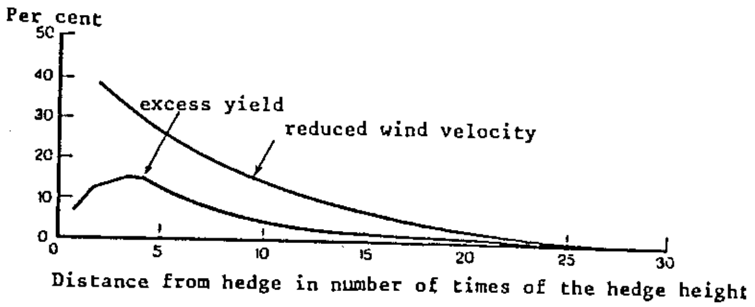


Figure 4

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

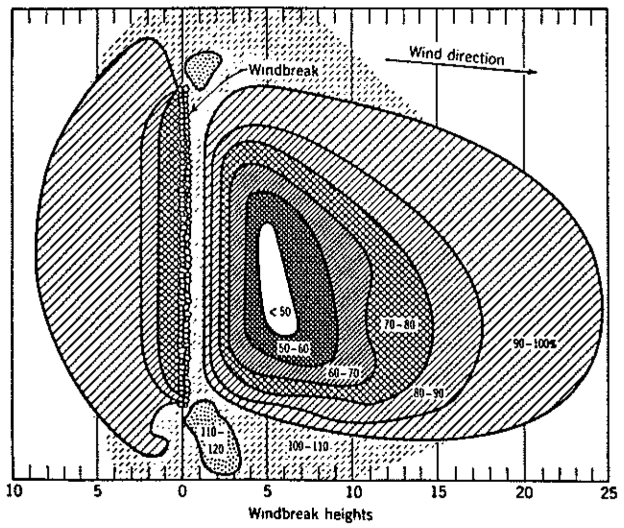


Fig. 6.7. Percentage of normal wind velocity near a windbreak having an average density of 50 percent. (Redrawn from Bates, 1944.)

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

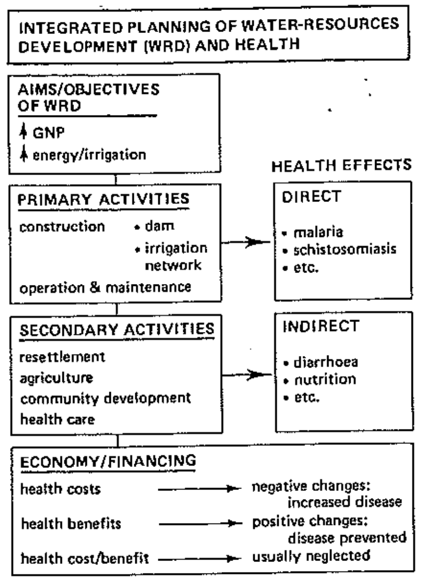


Figure 1.1 Integrated planning of water-resources development and health

Source: Oomen et al. 1990

Fig. 4-2

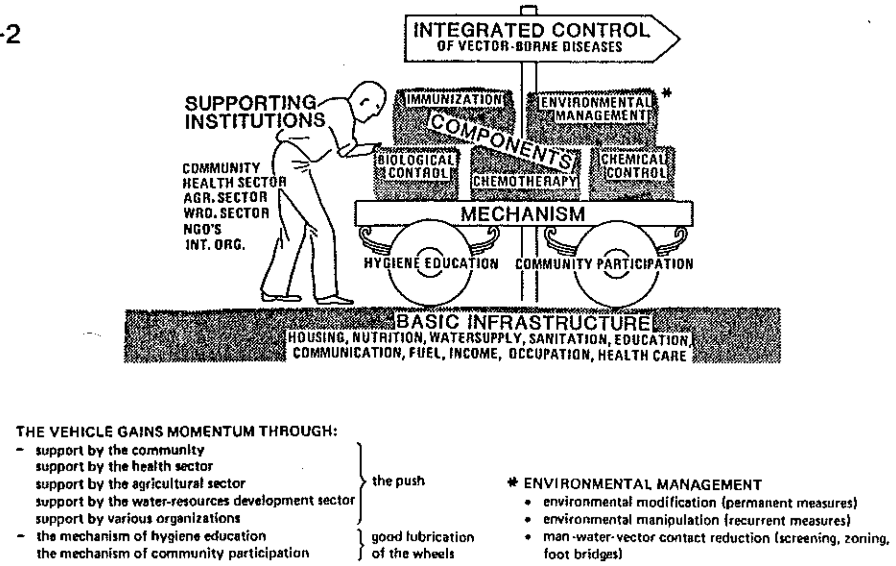


Figure 1.4 Integrated control of vector-borne diseases

Source: Oomen et al. 1990

Fig. 4-3

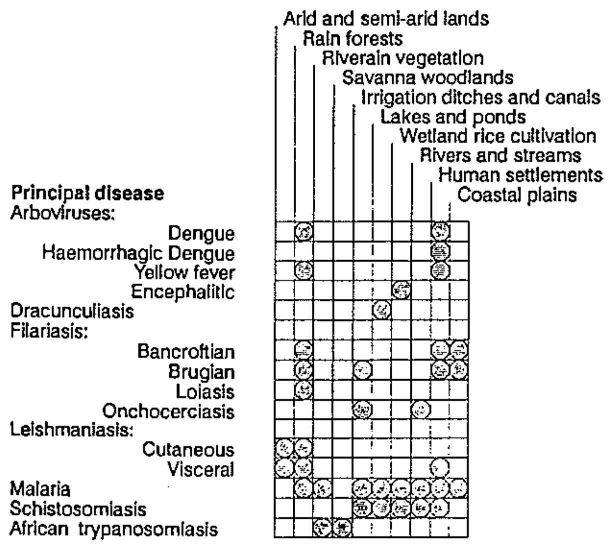


Table 2-3
The principal diseases associated with water in relation to the principal habitats of the vectors.

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

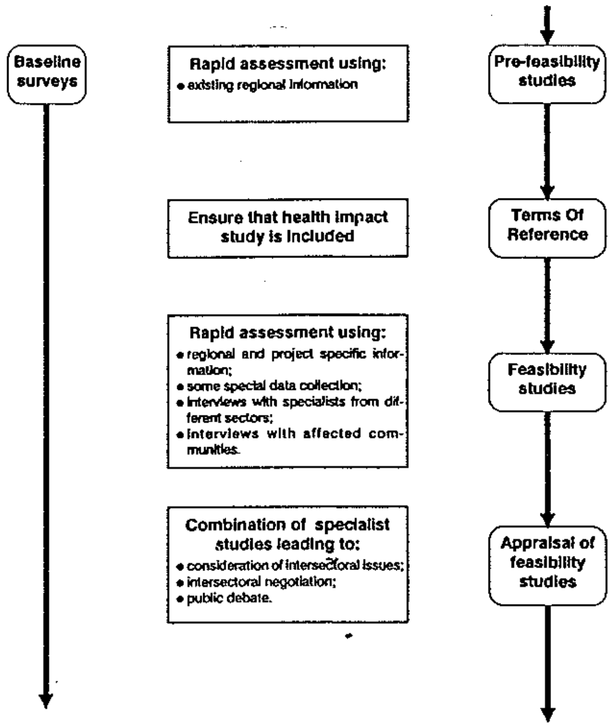
- type of vector-borne diseases in the region,
- their relationship to water,
- capacity of the existing health service to implement control programmes.

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:

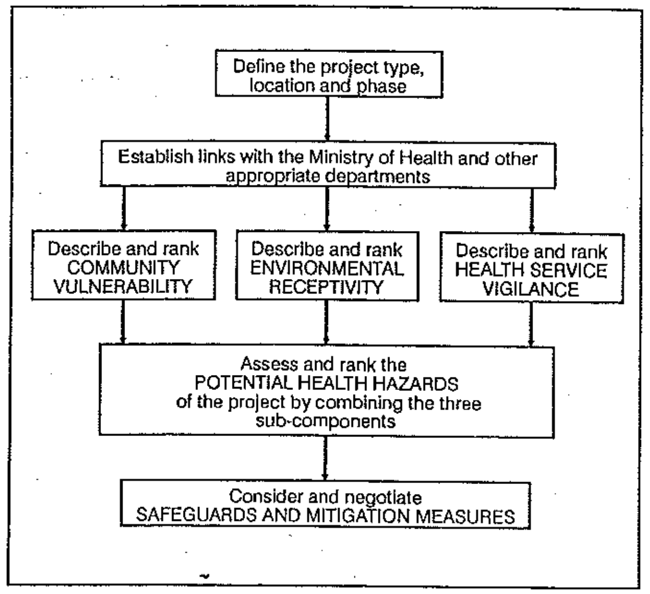
'very good': the health service includes effective preventive measures (vector control, chemoprophylaxis) and effective treatment (trained personnel, access, case detection, drug supply),

'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,

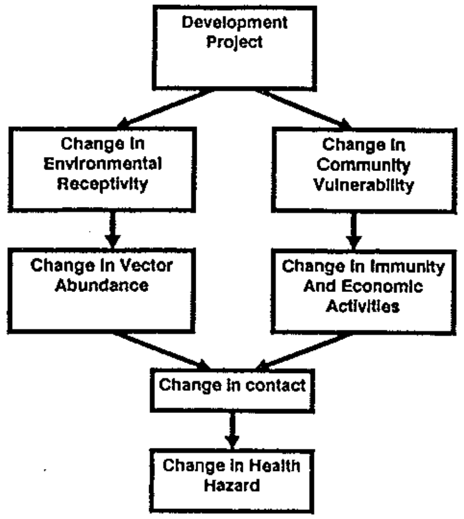
Fig. 4-5 a

Figure 1-3. An overview of the assessment procedure.



Source: Birley 1992

Fig. 4-5 b



Source: Birley 1992

Fig. 4-6 a

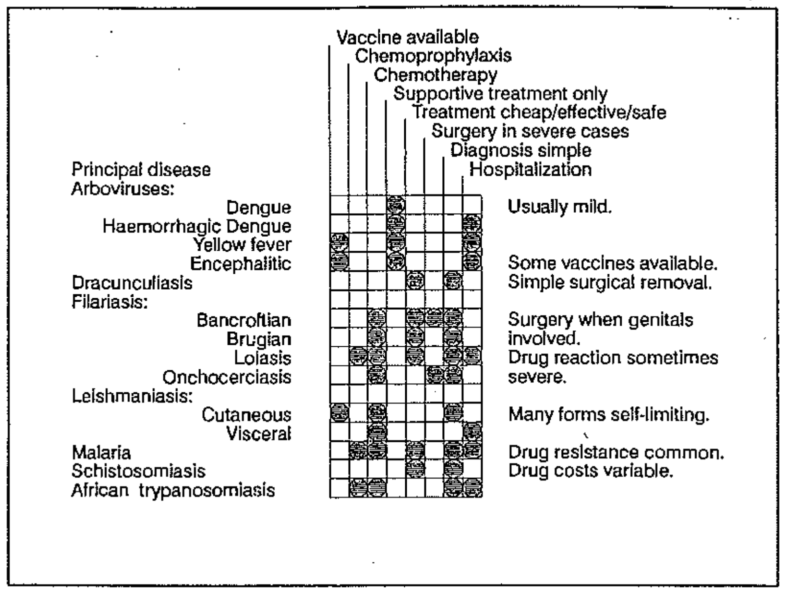


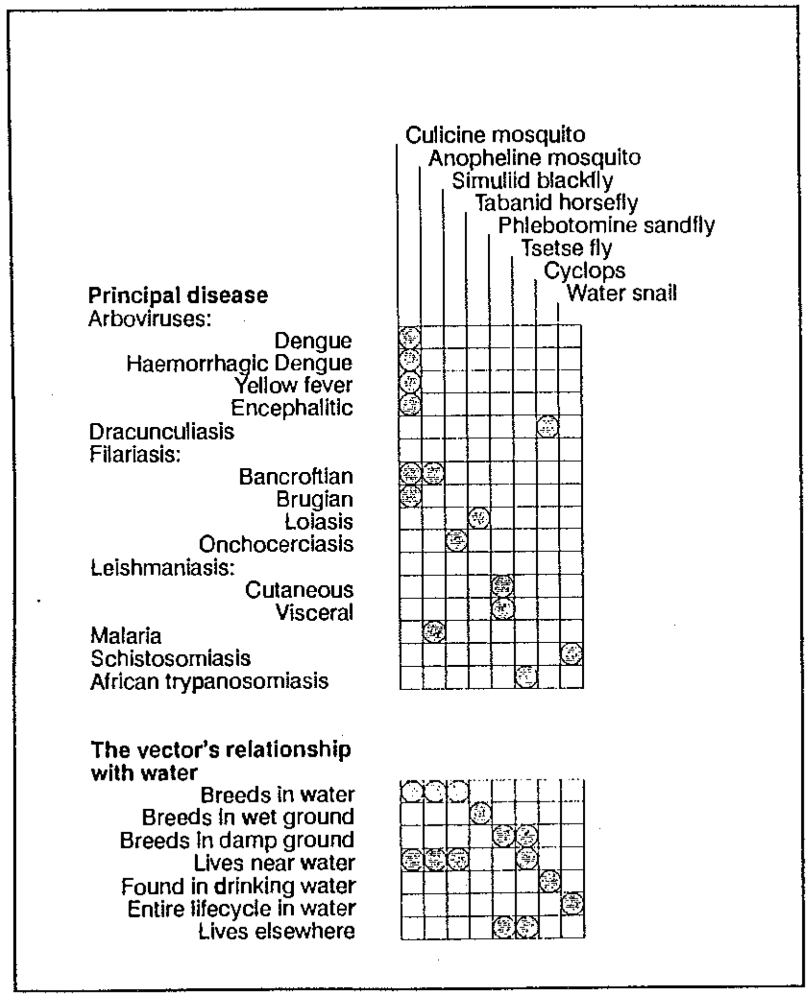
Table 1-7

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.

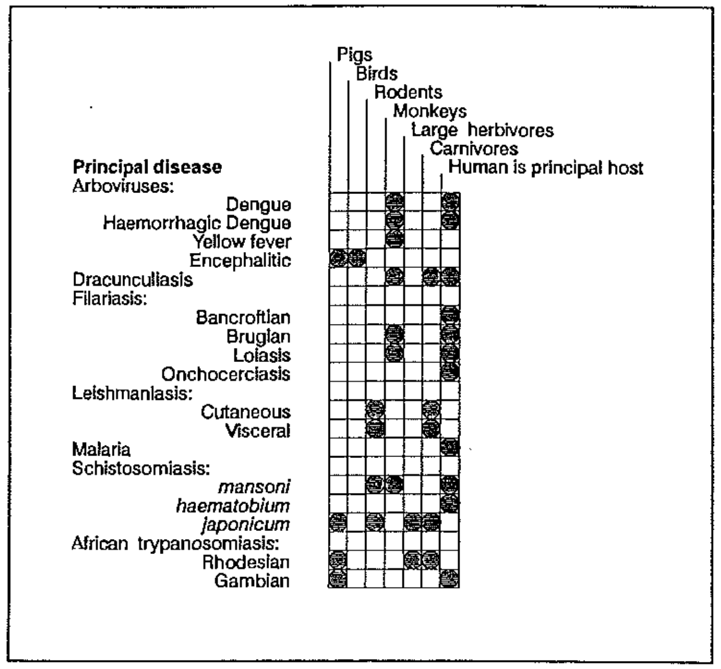
Special reading with regard to inter-institutional cooperation: Tiffen 1989

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

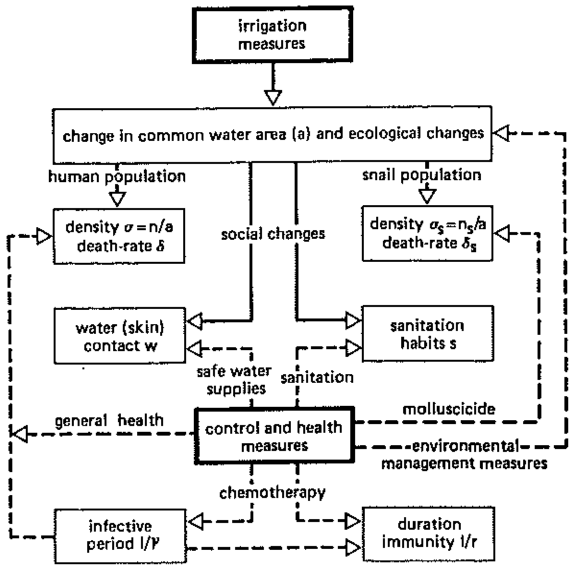


Figure 2 Irrigation, health, and control measures, and the nine parameters in the model that can be changed by these intervention measures

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

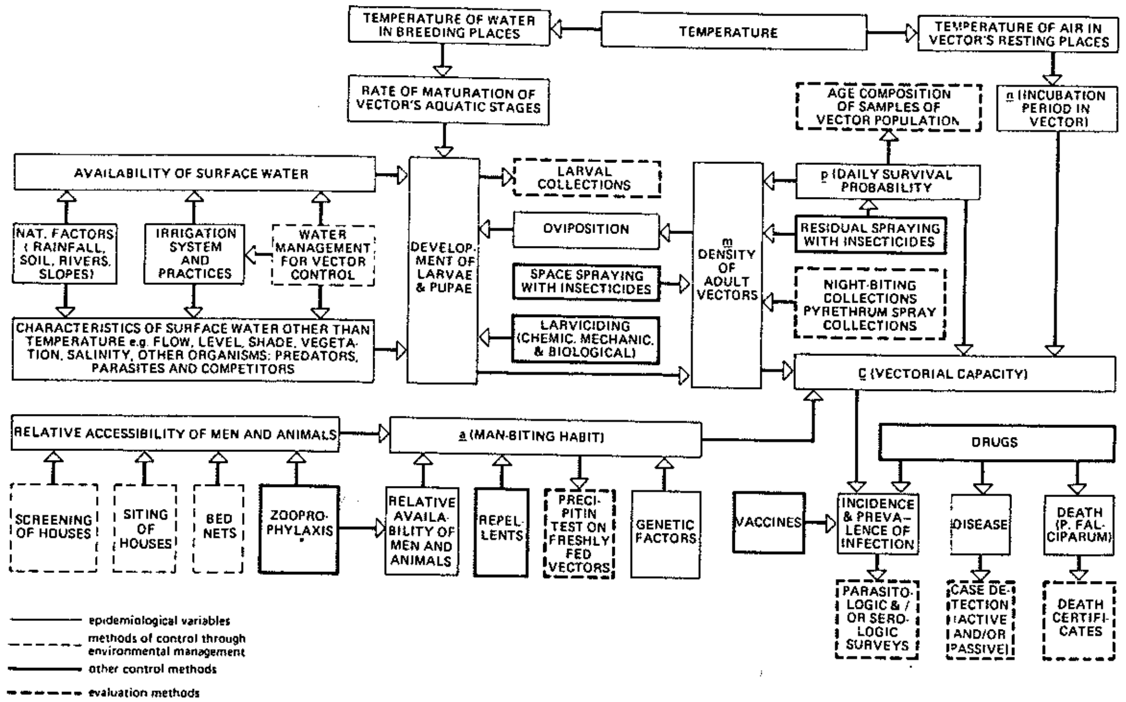


Figure 6 Malaria: natural and man-made factors, control measures, and evaluation methods, with particular reference to environmental management

Source: Oomen et al 1990

Fig. 4-9

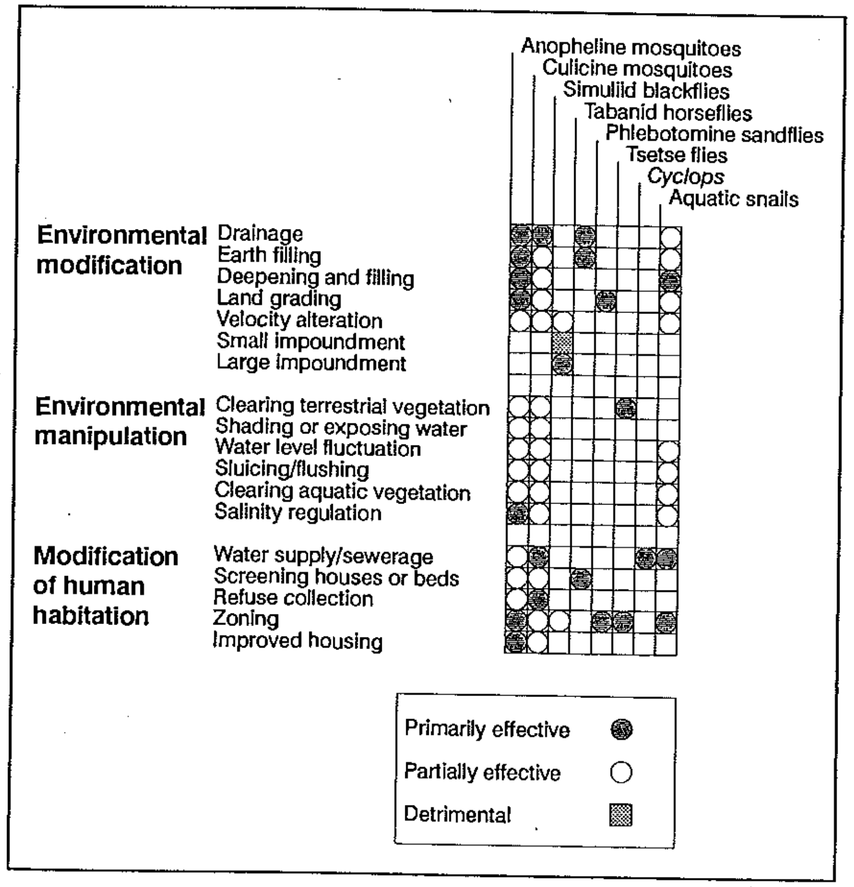


Table 2-11
Examples of interventions which are designed to control vectors and the vector groups which may be affected (WHO, 1980).

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

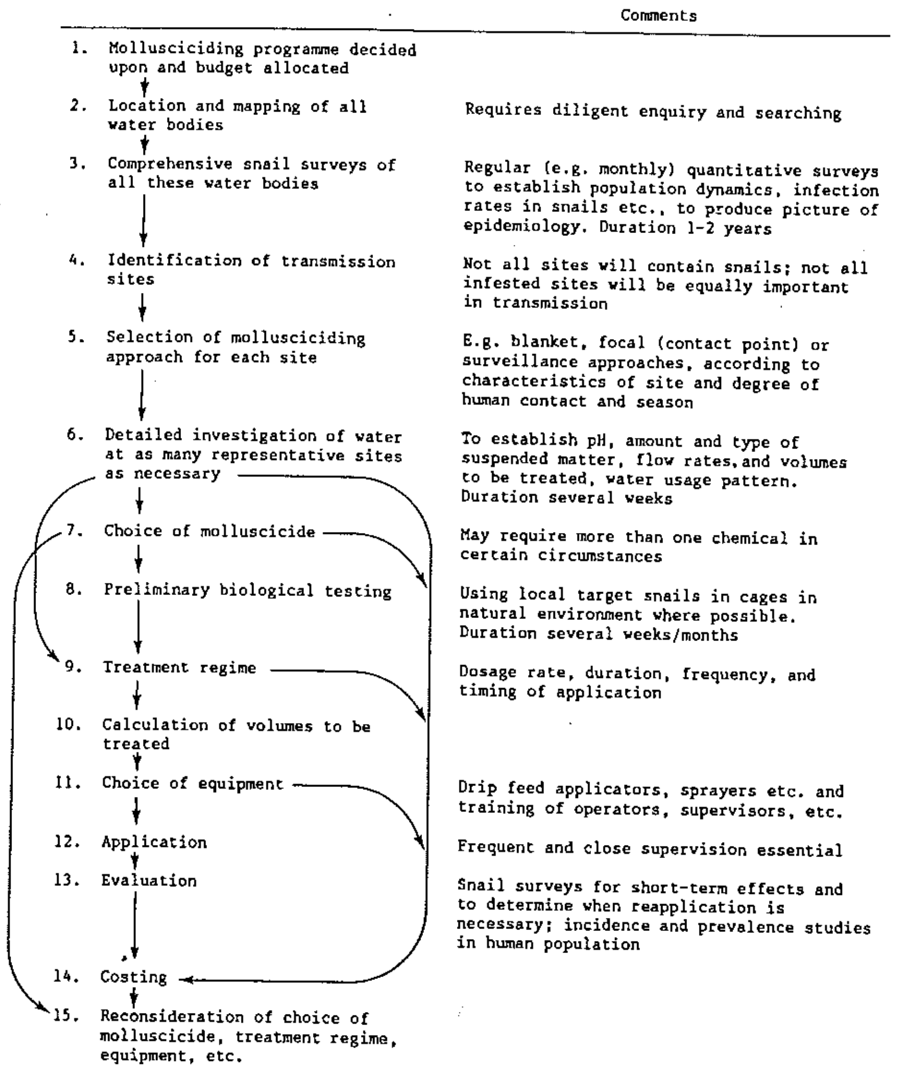


Figure 8.4 Sequence of events in a molluscicliding program (after Jewsbury 1985)

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

Molluscicliding 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

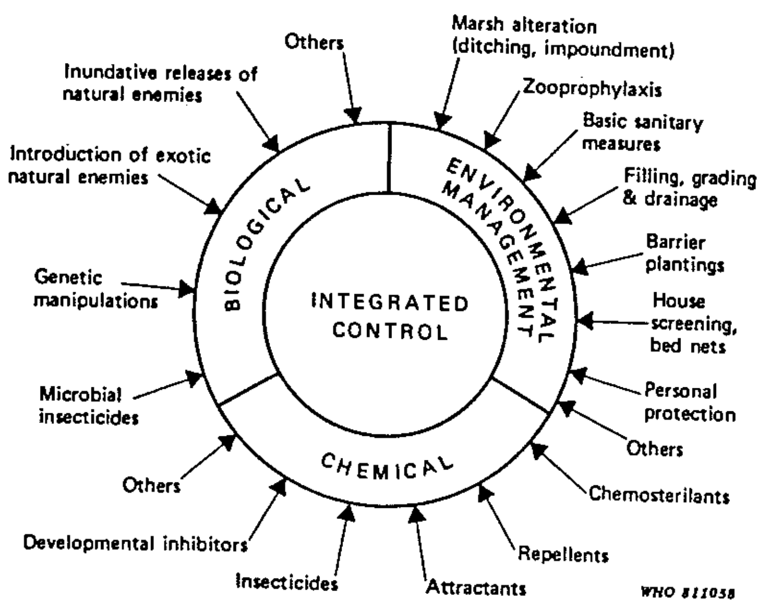


Fig. 6 Diagram of the components (environmental management, chemical, biological) and their potential constituent methods to be considered in an "integrated control" approach to mosquito control (Adapted from Axtell 1979)

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

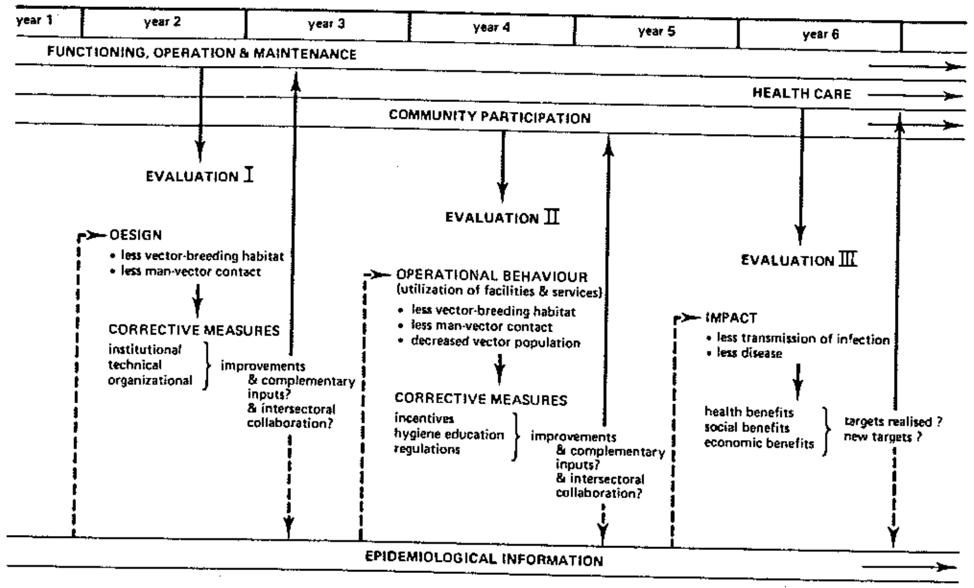


Figure 4.4 A schematic representation of monitoring and evaluation in the integrated control of vector-borne diseases

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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,