African Dams Project

Adapt planning and operation of large dams to social needs and environmental constraints

An integrated water resource management study in the Zambezi Basin

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Foreword

The African Dams project (ADAPT) aims at enhancing the scientific basis of integrated water resource management in the Zambezi River Basin. To reach this goal, ADAPT combines expertise from biogeochemistry, aquatic physics, ecology, economy, political sciences, hydraulic engineering, and hydrology. During its main phase (2008-2011) this interdisciplinary project developed new models that can be used to improve the operation of existing large hydraulic structures and to design future water use schemes at the basin-scale. These models incorporate new concepts of multi-objective optimization and real-time control and are calibrated with novel data resources. Capacity building has been included through exchanges and joint supervision of master students, training activities in our partner countries and involvement of governmental agencies and NGOs in the research process.

Our study investigates water resource management with regard to large reservoirs and wetlands on a basin-wide (Zambezi) scale and on a regional (Kafue Flats) scale. The following pages give a short summary of the research outcomes on the hydrology, politics, water allocation, and sediment and nutrient transport for the Zambezi River Basin, and ecology, biogeochemistry, hydrology, economics and water governance in the Kafue Flats. The published scientific papers, PhD, Master and Bachelor theses from ADAPT can be found on the memory stick handed out together with this brochure.

Until the end of 2013, most projects within ADAPT will be finished. This last year represents a synthesis phase where the research results will be integrated and new future activities will be identified. A more detailed report on the outcomes of this project will be addressed to and discussed with our African partners.

The last five years have only been possible due to fruitful collaboration and exchange of Northern and Southern expertise. We hope we can extend our collaborations in future projects.

Content

Outcomes of the ADAPT stakeholder meeting

During the ADAPT stakeholder meeting held on 24th January 2011 in Lusaka, representatives of governmental, non-governmental, and educational institutions have identified critical research needs to address problems of water demands for agriculture, hydropower, and the environment.

The activities within ADAPT are closely related to stakeholder needs:

Identified stakeholder needs	Activities of ADAPT
Include irrigation needs more explicitly in hydrological models.	Undergoing scenario analyses using a hydrological open-source SWAT model address irrigation as well as hydropower schemes and environmental demands.
Address the social, economic and ecological potential, challenges and risks of expanding irrigation in different parts of the river basin.	• A multi-objective hydro-economic optimization model has been developed for the Kafue River Basin to analyze competing water demands. • Suggestions for crop production based on economical water values in different parts of the basin can be given by a hydro-economic model.
Improve dam operation specifically in terms of flood management in a comprehensive way by including new planned hydropower schemes.	• Based on a model including new planned hydropower schemes for Itezhi-Tezhi reservoir, suggestions can be given to improve dam management for environmental needs and fisheries. • Currently, the development of a hydrological model linked to ecology is developed for the Kafue Flats to address optimum flood management for the preservation of ecosystems. • A new routine has been implemented in a basin-wide SWAT model to calculate the turbined and the spilled outflow at dams in the basins depending on the reservoir level and the operation rule curve. • Dam management at basin-wide scale was modeled including existing and planned hydropower schemes with regard to the hydropower, ecosystems and economical values.
Study the impact of mining operations on water quality and human health.	Mining was only included from an economical perspective.
Improve the knowledge base for ecosystem conservation, specifically for floodplains and for fish resources.	The knowledge of wetland ecology, nutrient and water transport in the reservoirs and wetlands has been substantially expanded.
Stronger support in know-how transfer and capacity building.	• During the run of ADAPT 4 MSc students have been supervised jointly by Swiss and Zambian researchers, and spent part of their studies in Switzerland. • Interview training was given to small-groups collaborating in water-use surveys. • Currently, a webpage is under development to share research results and databases with stakeholders.

Hydrologic-hydraulic model for water resources management*

An adapted version of the open source SWAT hydrological model was set up and calibrated for the Zambezi River Basin. Incorporating the most advanced input data sets and using state-of-the-art calibration techniques its target applications are future scenario assessment and short-term reservoir management.

The publically available SWAT (Soil and Water Assessment Tool) model was adapted to the Zambezi River Basin (Fig. 1) by modifying the source code to meet the hydrological constraints found in Sub-Saharan African basins. The model was successfully calibrated and could be identified as stable at the daily time step. The large inter-annual flow variations in the Zambezi River and the variable channel geometry in the flood plains, together with few direct measurements of the discharge, even at key locations, pose a challenge on discharge reliability.

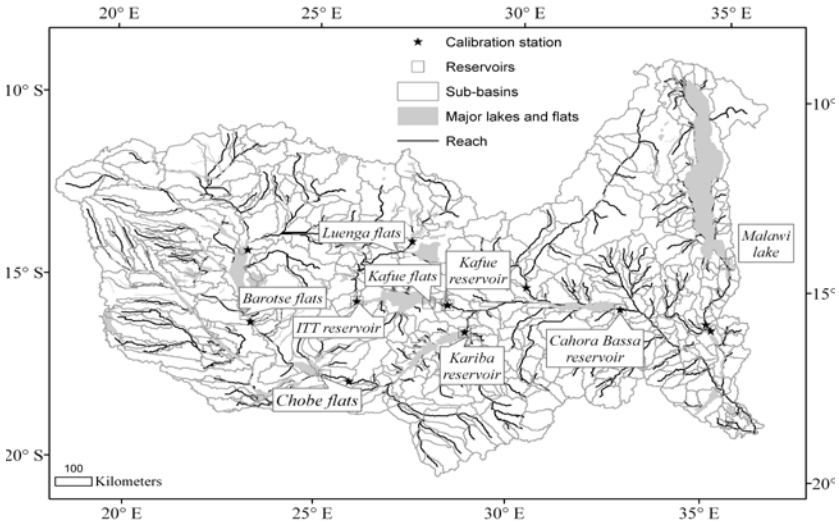


Fig. 1: SWAT model scheme for the Zambezi River Basin. © Cohen Liechti et al.[1]

To overcome this, the adapted version of the model includes a floodplain sub-model which calculates the outflow from the floodplain as a combination of a base flow through the main channel and an upper flow during flooding season. This adapted SWAT version performs better than the original version in simulating the discharge downstream of large floodplains. Moreover, a new routine has been implemented to calculate the turbined and the spilled outflow at the dams depending on the reservoir level and the operation rule curve. The model will be employed to analyze scenarios incorporating new hydropower schemes, irrigation, environmental flows and climate change.

The quality of the input data and discharge observations is of high importance to achieve good model performances. While discharge records are essential for calibration and validation, rainfall outstands as the most relevant among the different types of input data. In this light, results have been produced regarding the quality of several satellite rainfall estimates over the Zambezi basin area[2]. More precisely, three high resolution satellite-derived precipitation estimates, the *Tropical Rainfall Measuring Mission product 3B42 version 6 (TRMM 3B42 v6), the National Oceanic and Atmospheric Administration/ Climate Prediction Centre (NOAA/CPC)* Morphing Technique (*CMORPH*), and the *NOAA/Famine Early Warning System Rainfall Estimate 2.0 (FEWS RFE 2.0),* have been compared with ground data measurements. At monthly time scale, all estimates have a good correspondence, although *CMORPH* is the least precise as it overestimates rainfall volume by about 40%. *TRMM 3B42 v6* and *FEWS RFE2.0* show a very similar performance when compared to ground data. The lack of long records of input data constrains the success of hydrological models of the Zambezi. To overcome this, a newly developed model recreates historical areal rainfall maps based on the non-linear patterns identified from modern sources such as satellite estimates. This approach performs substantially better than other interpolation methodologies.

*Prepared in collaboration with Theodora Cohen Liechti and José Pedro Matos.

[1] Cohen Liechti et al. (unpublished) Hydraulic-hydrological modeling framework for water resources management of a large African river basin.

[2] Cohen Liechti et al. (2012) Comparison and evaluation of satellite derived precipitation products for hydrological modeling of the Zambezi River Basin.

Water policy across country borders*

Impacts of potential future water scarcity within the Zambezi River Basin (ZRB) can only be mitigated through better and more efficient international cooperation across country borders. This includes the definition of water allocation rules for the riparian countries and the establishment of a basin-wide monitoring system to manage water interdependence and water use externalities throughout the Zambezi River catchment.

The ZRB is one of the largest freshwater catchments in Africa and worldwide, and it experiences only minor water stress today. However, current water abundance in most parts of the ZRB is unlikely to last. Population and economic growth as well as expansion of irrigated agriculture and water transfers are likely to have very important transboundary impacts on water availability, while climatic changes probably only will have relatively small effects. Negative impacts include drastically reduced runoff in the dry season at sensitive key locations and changing (relative) shares of ZRB countries in the basin's total water demand.

Without addressing these impacts through effective international cooperation, there could be strong consequences: On a local scale, hydroelectric power production, wetlands and tourism could be affected. At a regional scale, large shifts in relative shares of water demand and total ZRB runoff could trigger allocation conflicts among the eight riparian countries of the ZRB[3]. Highest conflict potential exists between Mozambique, Zambia, and Zimbabwe, where Mozambique and Zimbabwe could challenge Zambia if the latter expands its consumptive water use[4]. Mitigation of such water-related challenges can only be addressed through effective basin-wide cooperative governance mechanisms[5]. This includes joint rules for water allocation, improved information flows and common strategies to deal with flow variability and flow uncertainty.

[3] Beck, L. and Bernauer, T. (2009) Water scenarios for the Zambezi River Basin, 2000-2050.
[4] Subramanian, A., Brown, B., and Wolf, A. (eds.) (2012) Zambezi, 2000-2004. In: Reaching across the waters: facing the risks of cooperation in international waters, p. 23-25.
[5] Beck, L. and Bernauer, T. (2011) How will combined changes in water demand and climate affect water availability in the Zambezi River Basin?

Today, the agreement on the establishment of the Zambezi water course commission (ZAMCOM) is the only international convention covering the ZRB. It has entered into force in June 2011 and provides a platform for sharing plans and motivating cooperative action on recurring flood problems. Zambia, with 90% of its' population and 77% of its' area in the ZRB is the most dependent country on the Zambezi River. It remains the only country that has not signed the agreement, mainly because of missing allocation rules for costs and benefits from water use that could weaken the position and development possibilities of Zambia. Hence, with the current water governance structure including ZAMCOM, regional cooperation is still very critical. It is likely that the Zambezi countries will want to accelerate the implementation of their ambitious individual development plans and trigger distributional conflicts within the ZRB. Fostering the influence of ZAMCOM and reducing the risk of autonomous development of the riparian countries is urgent and implies in essence two major activities: 1) Allocation rules should be set up to be able to account for a fair distribution of costs and benefits from water use. 2) Improving information flows for better accountability of costs and benefits from water use. This requires the establishment of a better monitoring system to trace and control interdependencies as well as external impacts of water use in the ZRB[6].

*Prepared in collaboration with Lucas Beck.

[6] Beck, L. (2010) Transboundary water allocation in the Zambezi River Basin, ETH Zürich, Dissertation Nr. 19048.

Optimizing water allocation for energy, irrigation and environmental demands*

The economic value of water varies throughout the Zambezi River Basin, and depends largely on the existence of reservoirs. Downstream river discharges for aquatic ecosystems can be increased by changing the operating rules of reservoirs.

A hydro-economic model that considers the largest existing and planned hydraulic infrastructures and irrigation schemes in the basin was used to derive optimal basin-wide allocation policies. Results indicate that planned irrigated areas in the Lower Zambezi and the Shire can be fully developed and supplied. However, the presence of large hydroelectric dams in the Middle Zambezi implies that the competition between different water sectors is likely to increase in the upper parts of the Zambezi Basin where the marginal value of water is the highest. The study also reveals that the storage services of the three largest existing reservoirs Kariba, Itezhi-Tezhi, and Cahora Bassa have an economic value of US$ 443 million per year, which represents 17% of the expected total benefits for the entire system[7].

A varying flow regime including flow pulses provides the best condition to maintain aquatic ecosystems. This condition is disturbed in hydropower-dominated river basins, especially when reservoirs are managed to maximize revenues from energy generation regardless of ecological demands. Under current operation, the discharges of the Lower Zambezi are reduced in February and March. Increasing peak discharge in the delta can only be achieved through larger release from Cahora Bassa (HCB) by spillage outflows since the reservoir is already discharging at maximum capacity (Fig. 2). The implementation of reservoir operating policies that explicitly consider environmental benefits would reduce, on average, the annual energy output by 6% or 1.4% when environmental flows are assigned a high or low value, respectively. Operating existing reservoirs to meet environmental demands and restoring floods in the Zambezi delta can be achieved through the coordinated operation of the multireservoir system. Lake Kariba for instance, would be re-operated so as to increase outflows and therefore supplies to downstream HCB during critical months. However, to ensure coordination and share of the corresponding benefits and costs adequate policies need to be in place[8].

The opportunity cost associated with unilateral irrigation development in the Zambezi basin was also assessed. This cost reflects the economic costs of noncooperation in the basin, and would reach in average 350 million US$ per year, which is 10% of the annual benefits of the basin system. It must be stressed that the distribution of gains and losses among riparian countries is uneven and constitutes a major obstacle towards efficient sharing of water resources. However, it might also be seen as an incentive for the development of adequate benefit sharing mechanisms[9].

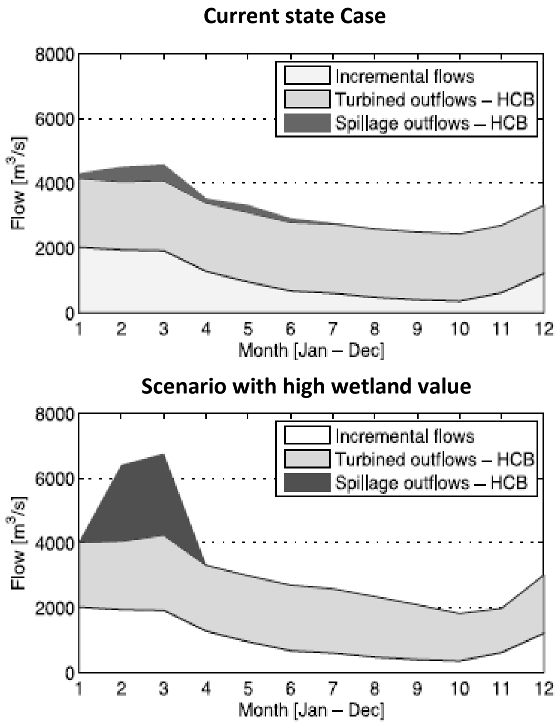


Fig. 2: Water release at Cahora Bassa for the current state and for considering environmental benefits[7].

*Prepared in collaboration with Amaury Tilmant.

[7] Tilmant et al. (2012) Economic valuation of benefits and costs associated with the coordinated development and management of the Zambezi River Basin.

[8] Tilmant et al. (2010) Restoring a flow regime through the coordinated operation of a multireservoir system: The case of the Zambezi River basin.

[9] Tilmant, A., Kinzelbach, W. (2012) The cost of noncooperation in international river basins.

Effect of large dams on sediment, carbon and nutrient fluxes*

Hydropower reservoirs along the Zambezi substantially reduce nutrient availability for downstream ecosystems. Ebullition is the most important pathway for methane release. Dam management can be amended to improve nutrient outflow and to reduce methane emissions.

In a global context, reservoir sedimentation is important because it reduces the transport of organic matter (OM), carbon (C), nitrogen (N) and phosphorus (P) from land to ocean (Fig. 3). Due to the decrease in sediment transport in the Zambezi River to the wetlands downstream of dams, more erosion at the river banks can be expected. The time it takes until the reservoirs are filled with sediment is relatively long based on our estimated sedimentation rates in the lakes (ca. 1 cm yr^{-1}). Kariba and Itezhi-Tezhi reservoirs have low absolute burial rates of organic C, N and P in comparison to other reservoirs worldwide[10]. However, in this nutrient-poor region, the relative reduction of these substances in the river is substantial. E.g., in the Itezhi-Tezhi reservoir (ITT), approximately 50% of N and 60% of P inputs to ITT are removed. Downstream ecosystems may be adversely affected by a lower C, N and P availability. Effects could include lower ecosystem productivity, lower fishing yields, or impacts on subsistence farming in the Kafue Flats[11].

Biogeochemical cycling (Fig. 3) within ITT was shown to be characterized by a strong increase of primary production and fast turnover rates of OM, meaning that most of OM produced within the reservoir was buried in the sediments. ITT stratifies seasonally, resulting in a low-oxygen bottom water layer and in the accumulation of nutrients[12]. The planned installation of new turbines releasing bottom water at ITT will result in a period of low-oxygen outflow during up to ~200 d and in average outflow oxygen concentrations as low as 4.1 mg L^{-1} compared to the current 7.6 mg L^{-1}, potentially causing fish killings. On the other hand, this practice has the advantage of higher nutrient outputs that partly compensate for losses to the reservoir sediments. To permanently prevent low-oxygen conditions and to optimize nutrient outputs we suggest to release 50% of the total outflow from 13 m and 50 m each[13]. This environmental-friendly dam operation would compensate for 40% of the P burial in the sediments.

Areas of river inflows in Lake Kariba receive relatively high OM inputs, which generate the formation of the greenhouse gas methane (CH_4; Fig. 3). In these locally restricted areas, CH_4 is mainly released to the atmosphere by ebullition (bubbling). Overall emissions are moderate in comparison to other tropical reservoirs thanks to the release of low-methane surface water through turbines and spillways. It is suggested to limit CH_4 emissions by preventing the release of bottom water with high CH_4 concentrations from tropical reservoirs.[14]

*Prepared in collaboration with Manuel Kunz.

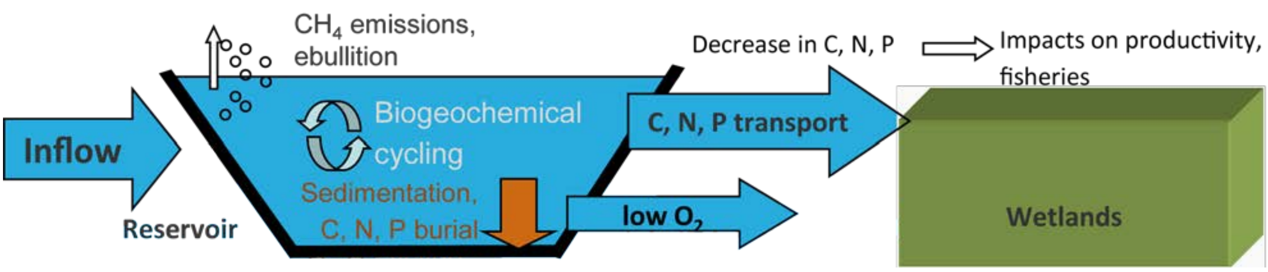
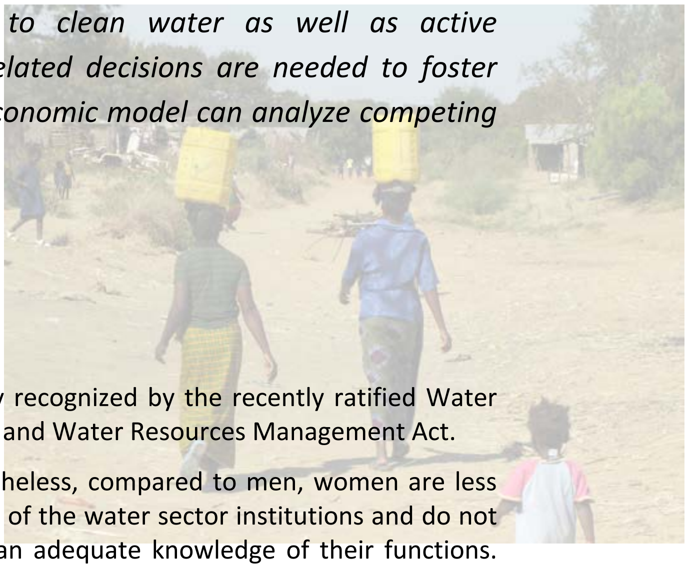


Fig. 3: Changes in sediment and nutrient fluxes through a hydropower reservoir (© ADAPT, 2013)

[10] Kunz et al. (2011) Sediment accumulation and carbon, nitrogen, and phosphorous deposition in the large tropical reservoir lake Kariba (Zambia/Zimbabwe).
[11] Kunz (2011) Effect of large dams in the Zambezi River Basin: Changes in Sediment, Carbon and Nutrient Fluxes, ETH Zürich, Dissertation Nr. 19441.
[12] Kunz et al. (2011) Impact of a large tropical reservoir on riverine transport of sediment, carbon, and nutrients to downstream wetlands.
[13] Kunz et al. (submitted) Optimizing turbine withdrawal from a tropical reservoir for improved water quality in downstream wetlands.
[14] DelSontro et al. (2011) Spatial heterogeneity of methane ebullition in a large tropical reservoir.

Water economics and governance*

To implement good water governance in Zambia more financial support is needed for training and infrastructure. Irrigation and access to clean water as well as active participation of stakeholders and women in water-related decisions are needed to foster water resource development in rural areas. A hydro-economic model can analyze competing water demands in the Kafue River Basin.



The Zambian National Water Policy approved in 2010 aims at improving water resources management by setting institutional coordination and defining roles and responsibilities of various ministries. The implementation of good water governance in the country is challenging because human and financial resources are too scarce to sustain the required legal and administrative changes. The conflicting interest and water use objectives within the basin, the lack of reliable information systems to provide accurate hydro-economic data, the low stakeholder participation in decision-making, and the ineffectiveness of the Sector Advisory Groups constitute drawbacks to the water management proposed in the Water Policy. Based on stakeholder interviews, the main identified need was the increase of financial support for training of professionals to manage decentralized institutions and for infrastructure development to enforce decentralization in the different basins and to enhance economic growth.[15].

A rural household survey on water use and governance conducted in 15 villages in the Southern Kafue River Basin highlighted that merely 50% of the population have basic water access; only ~19% have access to clean and safe water. Water is used for irrigation only by 30% of the farmers in this area. Most of the food production relies on erratic rainfalls, threatening the smallholders' food security. To develop water resources, efforts are advised to be directed towards full implementation of the irrigation policy, which stresses the role of smallholders in food production, and to ensure adequate access to safe water in the rural areas[16]. Women are key actors in water collection and use with significant influence on water use decisions, particularly concerning domestic water consumption, as is clearly recognized by the recently ratified Water Policy and Water Resources Management Act.

Nonetheless, compared to men, women are less aware of the water sector institutions and do not have an adequate knowledge of their functions. In addition, only ~5.5% of the respondents are aware of the institutions introduced with the recent Water Act, demonstrating that the reforms have not yet been implemented on the ground. Moreover, women are less involved in the water governance participation mechanisms and generally have less trust in the influence of smallholders' participation on water-related decisions. To implement an effective reform process, it is necessary for the Government of Zambia to improve smallholders' and women's awareness and participation in the water sector[17].

A multi-objective hydro-economic optimization model has been developed for the Kafue River Basin to analyze the competing water demands and provide clear indications on the tradeoffs arising from the often conflicting stakeholders' objectives. It includes three components: (1) hydrology, including water balances in reservoirs, river reaches and aquifers; (2) water demand functions, including water use for agriculture, mining, industry, municipalities; and (3) economy (optimization), including benefit calculations from each water-using sector. The optimization model suggests a range of efficient solutions to the water allocation problem but also takes into consideration fairness in the distribution of water resources and the need to allocate water for environmental functioning.

*Prepared in collaboration with Claudia Casarotto.

[15] Uhlendahl et al. (2011) Good water governance in IWRM in Zambia: challenges and chances.

[16] Simfukwe et al. (submitted) Rural household water use in the Kafue River Basin in Zambia.

[17] Casarotto and Kappel (2012) A half empty bucket: woman's role in the governance of water resources in Zambia.

River-floodplain exchange and dam impacts in the Kafue Flats*

The exchange of river and floodplain water is a crucial process for the biogeochemistry of the Kafue Flats. The floodplain system represents a hotspot for nutrient and carbon cycling, resulting in high exports of carbon, nitrogen, and phosphorous, and low oxygen levels in the Kafue River during flooding season.

The magnitude and direction of water exchange between the Kafue River and the floodplain varies substantially in space (Fig. 4), and is governed by the morphology of the river channel. A channel constriction diverts most of the river water into the floodplain during flooding in the wet season. A channel expansion further downstream allows water to flow back from the floodplain into the main channel of the Kafue River. As a result, >80% of water exiting the Kafue Flats passed through the floodplain[18]. Temporal and spatial variations in river-floodplain exchange remained similar before and after dam closure, but dam operation has reduced the lateral water flows and downstream recharge now decreased to 50%. The lateral exchange of floodplain and river water significantly impacts river water quality. In an area of intense river-floodplain exchange 250 km downstream of the Itezhi-Tezhi dam, dissolved oxygen (DO) concentrations strongly decline (Fig. 4) to below the minimum concentration for fish (2 mg/L), and remain low for 150 km. The cause was identified to be mainly low-oxygen floodplain water flowing into the river[19].

During transit through the floodplain, river waters mobilize substantial amounts of organic carbon and organic nitrogen. The dissolved organic matter in the river is mainly derived from terrestrial sources (upstream wetlands), despite travelling through the large Itezhi-Tezhi reservoir. While the Itezhi-Tezhi reservoir has little impact on the characteristics of dissolved organic matter, it efficiently traps terrestrially derived particulate organic matter (POM) and discharges relatively bioavailable POM that is produced in the reservoir to the river[20]. Despite reduced nutrient input due to removal in the upstream reservoir and efficient nitrogen and phosphorus retention in the floodplain, the Kafue Flats export 220 t phosphate, 1'300 t nitrogen and 50'000 t organic carbon. Hence, the Kafue Flats act as a net source of dissolved organic carbon and nutrients to downstream ecosystems[21].

*Prepared in collaboration with Roland Zurbrügg.

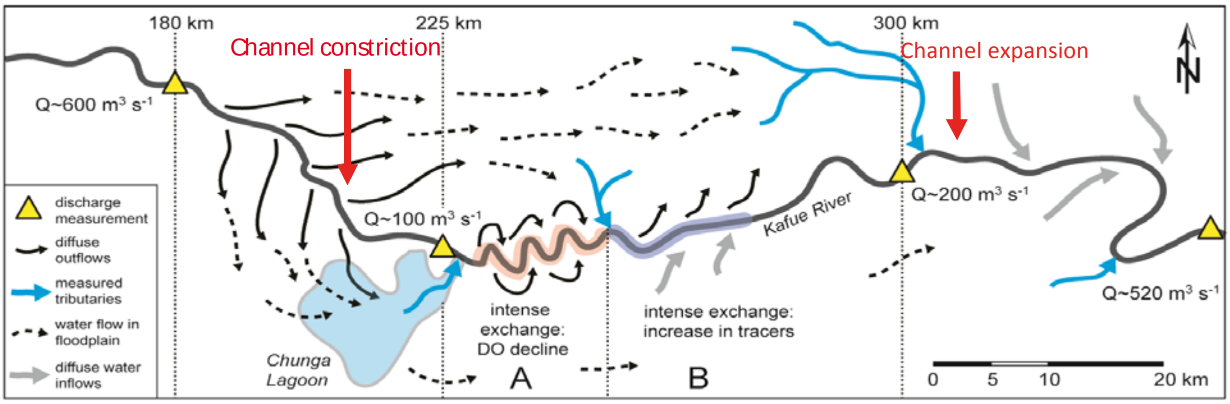


Fig. 4: River-floodplain exchange and its effects along the Kafue River between 160 km and 380 km downstream of the Itezhi-Tezhi reservoir (modified after Zurbrügg et al.[18]).

[18] Zurbrügg (2012) Biogeochemistry of a large tropical floodplain system (Kafue Flats, Zambia): River-floodplain exchange and dam impacts, ETH Zürich, Dissertation Nr. 20309.

[19] Zurbrügg et al. (2012) River-floodplain exchange and its effects on the fluvial oxygen regime in a large tropical river system.

[20] Zurbrügg et al. (2012) Organic carbon and nitrogen export from a tropical dam-impacted floodplain system.

[21] Wamulume et al. (2011) Exploring the hydrology and biogeochemistry of the dam-impacted Kafue River and Kafue Flats (Zambia).

Hydrologic modeling and floodplain modeling in the Kafue River Basin*

Dam operation has altered the hydrology of the Kafue River, but does not suppress seasonal flooding in all but the driest years. An adapted operation of hydropower reservoirs requires reliable information on future inflows to the reservoirs and on the downstream effects of reservoir releases. Models forecasting the inflows to the Itezhi-Tezhi reservoir and simulating the flooding patterns in the Kafue Flats have been developed in the ADAPT-project. Short-term (< 1 month) forecasts have been improved to high quality, while good prediction of longer (i.e. seasonal) inflow is ongoing work.

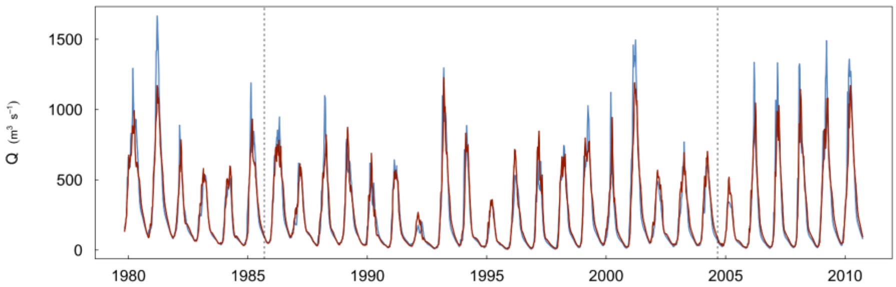


Fig. 5: Discharge at Kafue Hook Bridge: Observation data (blue) and 21-day forecast of the ANN model (red). © Köck, ETH Zürich.

Two model approaches have been investigated for short-term forecasting inflows to Itezhi-Tezhi (ITT) reservoir. Based on a conceptual model with surface and subsurface storage components, remote sensing data products of rainfall and soil moisture are used in a real-time forecasting framework[22]. In addition, a number of artificial neural networks (ANN) were set up in order to test if the different available remote sensing and ground data sources could be used independently of a conceptual model structure. Results show that the existing long-term measurements of discharge, rainfall and evaporation in the basin are essential inputs that allow the ANN model to derive reliable short-term inflow forecasts in a climate marked by high inter-annual variability (Fig. 5).

Current work focuses on improving the quality of a seasonal forecast that is based on climate pattern indices (e.g. sea-surface temperature anomalies).

Timing and extent of the regulated releases from ITT directly affect the seasonal flooding downstream of the reservoir. Since few direct observations in terms of flood maps are available, flooding in the Kafue Flats is simulated by means of a distributed hydraulic groundwater and surface water model based on the software *MODFLOW2005* [23, 24]. The model has a spatial resolution of 1 km^2 and is calibrated using flooding patterns derived from Synthetic Aperture Radar data (ASAR). It reproduces well the seasonal progression of the total flooding in the simulation period 2002-2010 (Fig. 6). However, the calibration process also pointed out the need for a higher quality digital elevation model.

*Prepared in collaboration with Philipp Meier and Florian Köck.

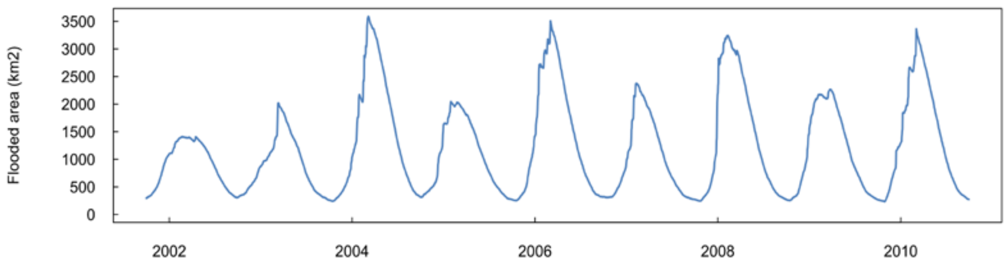


Fig. 6: Simulated total flooded area in the Kafue Flats (modified after Meier[23]).

[22] Meier, P., Frömelt, A. and Kinzelbach W (2011) Hydrological real-time modelling in the Zambezi river basin using satellite-based soil moisture and rainfall data.

[23] Meier, P. (2012) Real-time hydrologic modelling and floodplain modelling in the Kafue river basin, Zambia, ETH Zürich, Dissertation Nr. 20421.

[24] Meier, P., Wang, H., Milzow, C. and Kinzelbach, W. (2010) Remote sensing for hydrological modeling of seasonal wetlands concepts and applications.

Wetland ecology*

Dam induced hydrological changes in the Kafue Flats can have cascading effects on vegetation and animal populations.

Fig. 7: Changing ecology in Lochinvar national park: The encroaching shrub species *Dichrostachys cinerea* (a) and *Mimosa Pigra* (b), and the Kafue Lechwe (c).

The dam-induced alterations in the hydrology of the Kafue Flats with lower maxima, higher minima, reduced seasonal amplitude have lead to changes in the vegetation[25]. Mapping the spread of woody encroachment in Lochinvar National Park using a remote sensing approach revealed that woody cover increased from 26 to 45%, while open areas decreased from 50 to 33% of the park area between 1986 and 2010. The main species invading Lochinvar National Park are the exotic the native *Dichrostachys cinerea* (Fig. 7a) and *Mimosa pigra* (Fig. 7b)[26].

Laboratory analysis of soil and nutrient parameters along cover and age gradients of *D. cinerea* and *M. pigra* showed that encroachment of the shrub species *M. pigra* has little effect on soil nutrients. However, *D. cinerea* increases soil carbon, nitrogen and phosphorus pools and availabilities, and hence might represent a C-sink for at least several decades[27]. Both shrubs largely reduce plant species richness, grass cover and the available biomass of the understory vegetation. While *D. cinerea* lead to a more than doubling of herbage quality (N and P concentrations), *M. pigra* density had no net effect on herbage quality[26]. Differences in the observed effects likely depend to a large extend on the growth form of the species[28].The encroachment of the shrubs hence reduces food for grass-eating herbivores (e.g. Lechwe, Zebra) but might provide a valuable food resource for mixed feeders (e.g Impala) and browsers (e.g. Kudu). However, the reduction in food induced by shrub encroachment is not sufficient to explain the decline in the Lechwe population (Fig. 7c) observed since the mid-seventies[26].

In order to understand how the Lechwe population depends on the seasonal inundation of the Kafue Flats we mapped Lechwe movements by ground and aerial surveys. The produced maps showed that Lechwe migration is closely linked to flood levels and food supply. Fecal analysis implied that Lechwe suffer nutritional stress during the early dry season when they are forced to remain on higher grounds and that Lechwe follow the decreasing flood in search of qualitatively better food. We conclude that Lechwe rely on the seasonally inundate floodplain as an important food resource and that the right time of decreasing flood levels is crucial for the survival of the Lechwe population[29].

*Prepared in collaboration with Wilma Blaser.

[25] Blaser et al. (unpublished) Vegetation-hydrology interactions before and after dam construction in the Kafue Flats, Zambia.
[26] Shanungu et al. (unpublished) Impact of shrub encroachment on the understory vegetation differs among shrub species in the Kafue Flats, Zambia.
[27] Blaser et al. (unpublished) N-fixing shrub encroachment abolishes N and P limitation for growth and C sequestration in the Kafue Flats, Zambia.
[28] Blaser et al. (unpublished) N-fixation and growth form determines impact of woody encroachment on understory vegetation; a meta-analysis.
[29] Blaser et al. (unpublished) The semi-aquatic antilope Kafue Lechwe shows a remarkable food adaptation upon changed flooding conditions and shrub encroachment.

Future work

In the coming year we will organize further activities to enhance communication and capacity building during the synthesis of this project. Further discussion will concern feasible solutions for data sharing and training needed in tools and models. A complete report on the outcomes of ADAPT will follow in the end of 2013. A rough outline includes the following parts:

Part 1: Dam operation at Zambezi River Basin scale

- Scenarios including operation for irrigation, environmental demands and possibly climate change

Part 2: Dam operation at Kafue Flats scale

- Dam impact on the environment and improvement scenarios
- Economical multi-objective optimization
- Best-case dam operation rules for optimization

Part 3: Recommendations

- How to implement better operation rules
- How to choose dam sites
- How to close research gaps

ADAPT Publications

All published material from ADAPT researchers is distributed on a memory stick together with this brochure, and includes

- Journal Articles: ordered after the name of the first author
- Dissertations, Master theses, Bachelor theses: ordered after the author's name
- Researcher presentations from the ADAPT stakeholder meeting

A database with more information and publications is also available online at http://www.cces.ethz.ch/projects/nature/adapt

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