Adapted reservoir management in the Zambezi river basin to meet environmental needs

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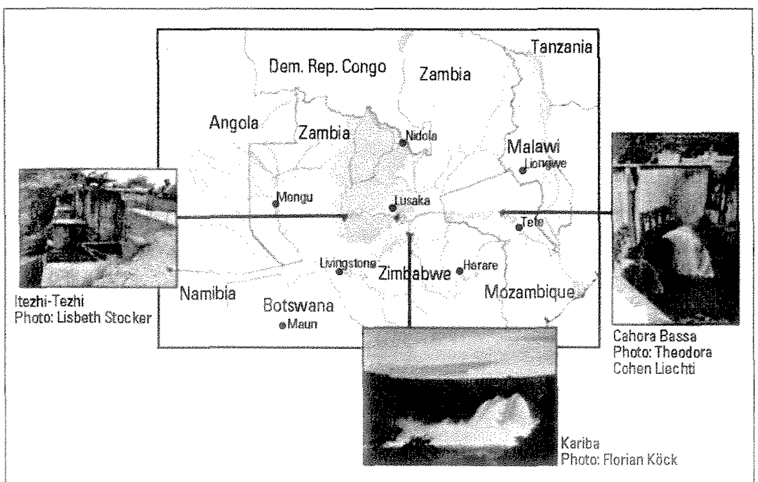
A number of major hydropower schemes have been developed in the Zambezi river basin to ensure a stable energy output. Although this main objective is well met, there is considerable scope to optimize operation of the plants. This paper presents the results of an integrated water resource management study, called the African Dams Project (ADAPT), and focuses on how hydropower schemes can be adapted to meet environmental needs.

The Zambezi river basin (ZRB) with an area of $1.4 \times 10^6 m^2$ is one of the largest river basins on the African continent. From its headwaters in Angola and Zambia to the delta in Mozambique, the Zambezi river flows for more than 2600 km and connects eight African nations, with approximately 40 per cent of the total catchment area located in Zambia. The largest tributary to the Zambezi is the Kafue river. Large wetland systems, which represent valuable ecosystems, such as the Kafue Flats, shape the basin's topography.

To meet the increasing energy demand, four large dams have been constructed along the Zambezi and Kafue rivers over the past 50 years: Kafue Gorge (1971; 900 MW) and the water storage reservoir Itezhi-Tezhi (1978; 120 MW currently installed) in Zambia; Kariba (1958; originally 1200 MW recently upgraded to 1470 MW) at the border between Zambia and Zimbabwe; and, Cahora Bassa (1974; 2075 MW) in Mozambique, see Fig. 1 [Zurbrügg, 2012[1]].

Unexploited hydropower potential still exists, and several new hydro schemes are currently being proposed. Objectives of hydropower production, flood mitigation, navigation, fisheries, water supply and agricultural irrigation compete for water use in the river basins. It is generally accepted that, in addition to these requirements for industry and people, the river ecosystems also provide 'goods and services' such as food, tourism, recreation, flood mitigation and removal of pollutants.

Fig. 1. The Zambezi river basin in Southern Africa. The Kafue river basin (in Zambia) is outlined in the darker colour. Existing dams are marked with red triangles, planned dams with white triangles, and the green areas are the major wetlands in the basin, modified after Zurbrügg [2012[1]].



This paper presents the African Dams Project (ADAPT), an integrated water resource management study, and some of its key results on the effects of current dam operation on sediment and nutrient transport processes in the ZRB. It also focuses on the evaluation of hydro-economic and hydrologic-hydraulic models as useful tools for water resources management. With this contribution possible adaptations of dam operation are outlined, which could optimize water quality and management.

1. The African Dams Project

The African Dams Project (ADAPT*), aims at enhancing the scientific basis of integrated water resources management (IWRM) in the ZRB with regard to large reservoirs and wetlands on a basin-wide (Zambezi) scale and on a regional (Kafue) scale. This trans-disciplinary effort operates on two levels:

- clearly defined research activities are generating knowledge through data collection, concepts and numerical models; and,
- a science-policy interface organizes capacity building efforts (student exchanges and training activities), and interdisciplinary integration of research results in interaction with stakeholders and policy makers in the ZRB.

The research partners involved include the Integrated Water Resources Management Centre at the University of Zambia, the Centre for Engineering Studies of the Eduardo Mondlane University (Mozambique), the Laboratory of Hydraulic Constructions at Ecole Polytechnique Fédérale de Lausanne (Switzerland), the department of Surface water – research and management of the Swiss Federal Institute for Aquatic Science and Technology, the institutes of Integrative Biology, Environmental Engineering, Environmental Decisions, Biogeochemistry and Pollutant Dynamics, the Center for Comparative and International Studies, and Advanced Studies in Development and Cooperation at the Swiss Federal Institute of Technology in Zurich.

* See https://www.cces.ethz.ch/projects/nature/adapt

ADAPT researchers and stakeholders at the stakeholder meeting in Lusaka, in January 2011 (photo: Bernhard Wehrli).

The interconnection between hydrology, socio-economics, biogeochemistry, water management and ecology related to large dams is vital for environmental sustainability. With new data sources, enhanced conceptual understanding and quantitative models the research teams contribute to the emerging science of river basin management. To maximize integration, governmental institutions, NGOs and private companies in the ZRB are involved in the data collection and discussion processes (see photograph).

2. The effects of large dams on sediment, carbon and nutrient fluxes

In a global context, reservoir sedimentation is important because it reduces the transport of important nutrients for ecosystems, such as organic matter (OM), carbon (C), nitrogen (N) and phosphorus (P), from land to ocean. In the ZRB, the ADAPT studies were able to demonstrate that the construction of dams decreased sediment transport to the wetlands downstream of large reservoirs. Mass balances of organic C, P, and N and modelling results were used to evaluate the relevance of the Itezhi-Tezhi reservoir (ITT) for riverine nutrient transport. In total, approximately 50 per cent of N and 60 per cent of P inputs are removed by the reservoir [Kunz *et al.*, 2011[2]].

2.1 Assessing the ecological effects

Sedimentation was not the only reason for the reduction in nutrients: N and C were lost to the atmosphere (see Fig. 2) through increased denitrification and efficient recycling of OM. Mass balance calculations also showed that measurements underestimate riverine nutrient inputs. Biogeochemical cycling within ITT is characterized by a strong increase of primary production and fast turnover rates of OM, meaning that most

Aerial view of the Kafue Flats (photo: Griffin Shanungu).

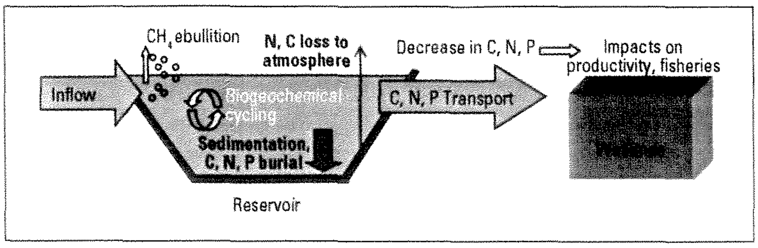


Fig. 2. Changes in sediment and nutrient fluxes through a hydropower reservoir, modified after Mertens, [2013[6]].

of OM produced within the reservoir was buried in the sediments (Fig. 2). For Lake Kariba, mass balance calculations suggest that approximately 70 per cent of total N and 90 per cent of total P are eliminated from the water column by sedimentation (N and P) and denitrification (only N) [Kunz *et al.*, 2011[3]]. Although the Kariba and Itezhi-Tezhi reservoirs have low absolute burial rates of organic C, N and P in comparison with other reservoirs worldwide, the relative reduction of these substances in the river is substantial for this nutrient-poor region. Downstream ecosystems may be adversely affected by a lower C, N and P availability. The effects could include lower ecosystem productivity, lower fishing yields, or impacts on subsistence farming in the Kafue Flats.

The Kafue floodplain system (see photograph) represents a hotspot for nutrient and carbon cycling, resulting in high exports of carbon, nitrogen, and phosphorous, as well as low oxygen levels in the Kafue river during the flood season. More than 80 per cent of the water that leaves the Kafue Flats has passed through the floodplain [Zurbrügg, 2012[1]]. Dam operation has not significantly affected the temporal and spatial variations in the river-floodplain exchange. However, it has reduced lateral water flows, and lateral exchange over an annual cycle has been decreased by 50 per cent [Zurbrügg *et. al*, 2012[4]].

Tropical reservoirs have been identified to be important emitters of the greenhouse gas methane (CH_4) through turbines and downstream degassing. Areas of river inflows in Lake Kariba receive relatively high OM inputs, which generate the formation of CH_4. In these locally restricted areas, CH_4 is mainly released to the atmosphere by ebullition (gas bubbling, see Fig. 2). Overall emissions are moderate in comparison with other tropical reservoirs thanks to the release of low-methane surface water through turbines and spillways [DelSontro *et al.*, 2011[5]].

2.2 Adapting dam operation to environmental constraints

The Itezhi-Tezhi reservoir (ITT) stratifies seasonally, resulting in a low oxygenated hypolimnion and an epilimnion with low nutrient concentrations for most of the year. Therefore, the location of water release from the reservoir determines downstream water quality.

Current operation of the ITT involves discharges which are almost exclusively surface water through the spillways (Fig. 1). Bottom water is withdrawn only in times of low storage. In the near future, the installation of new turbines releasing bottom water with a maximum discharge of 306 m^3/s for hydropower generation is planned. In these new operating conditions, the river water quality will be determined by the characteristics of hypolimnetic water. As a result, low dissolved oxygen concentrations will persist over longer periods of time, potentially affecting subsistence fishery in the downstream Kafue Flats [Kunz *et al.*, 2011[2]]. In addition, the release of bottom water with high CH_4 concentrations could contribute to global warming. It is therefore proposed to prevent the outflow of bottom water, so as to limit greenhouse gas emissions from tropical reservoirs. On the other hand, this practice has the advantage of higher nutrient outputs that partly compensate for losses to the reservoir sediments, and which could result in increased productivity. The simulation of outflow water quality of the ITT under different dam management scenarios provides decision support for optimizing turbine intakes.

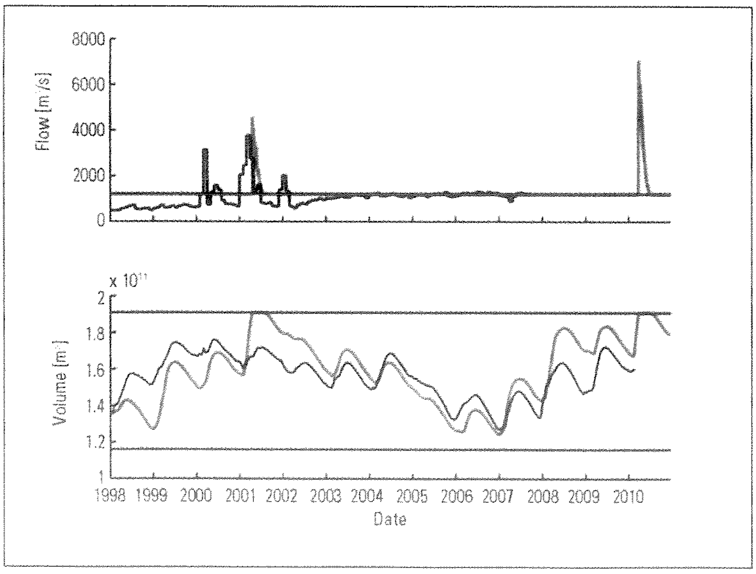
3. Hydrological-hydraulic model for water resources management

Until now, no model studies have been done of the Zambezi below the monthly time step, which is important for hydropower production. The existing water resources management studies have been conducted without resorting to global rainfall-runoff models.

For the present work, two criteria were defined to select the tool used for hydrological modelling: the application of a source code available in the public domain, so as to be able to transfer the model to the stakeholders, and the choice of a model already applied in Southern Africa with promising results, which would contribute to an appropriate definition of the hydrological processes. Therefore, the Soil and Water Assessment Tool (SWAT), a river basin scale model available in the public domain and actively supported by the USDA Agricultural Research Service at the Grassland, Soil and Water Research, was chosen. SWAT 2009 is a semi-distributed physically based continuous time model, constituted in multiple components, including a hydrological module. The broad principle of the tool is to simulate the water balance in each of the geographical sub-units for four storage volumes: snow, soil profile, shallow aquifer and deep aquifer, by considering precipitation, interception, evapotranspiration, surface runoff, infiltration, percolation and subsurface runoff.

To adapt the model to the large floodplains commonly found in African river basins, the source code of the reservoir object was completed. A double equation has been introduced for the outflow computation, dependent on the water depth in the reservoir, for the base flow constantly flowing out of the reservoir, and in the form of an open crest weir formula for the upper flow occurring during high flow periods. Moreover, because of the unusually large size of the main floodplains and lakes relative to the sub-basins where they are located, the sub-basin surfaces were made to be dependent on reservoir surfaces, to take into account the expansion and reduction of the flooded surfaces in the water budget calculation. Finally, a new routine was implemented to calculate the turbine water and the spilled outflow at the dams, depending on the reservoir level and the operating rule curve.

Fig. 3. Simulated (grey) and observed (black) outflow (upper panel) and volume (lower panel) at Kariba dam.



The quality of the input data and discharge observations is of great importance to achieve good performance of the model. While discharge records are essential for calibration and validation, among the different types of input data, rainfall stands out as the most relevant. In the light of this, TRMM 3B42 version 6, NASA's standard precipitation product, available since 1998, was chosen as the precipitation source, based on a detailed study of the various satellite products.

The temperature grids (daily minimum and maximum) are compiled from the NCEP/DOE 2 Reanalysis data. For the model set-up, the following data sets, available for Africa and a large part of the world, were chosen:

- the Digital Elevation Model (DEM) from the US Geological Survey's (USGC) public domain geographic database HYDRO1k, which is derived from the 30° digital elevation model of the world GTOPO30 at a resolution of 1 km;
- the soil map produced by the Food and Agriculture Organization of the United Nations at a resolution of 10 km; and,
- the land-use grid from the Global Land Cover Characterization at a 1 km resolution.

The most extensive available database containing historical discharge records in the Zambezi river basin is managed by the Global Runoff Data Centre (GRDC). In the global database, 67 daily and 30 monthly stations located within the Zambezi basin are identified. In addition, the Department of Water Affairs of Zambia provided a list of 34 stations with the associated discharge data over the Zambian part of the basin. The Zambezi River Authority (ZRA), managing the Kariba dam and Hidroeléctrica de Cahora Bassa (HCB), which manages the Cahora Bassa dam, shared some of the information recorded at the dams. Based on all this information, the model set-up resulted in the delineation of 405 sub-basins and 778 hydrological response units.

For the calibration, two years were required to stabilize the model (1998-1999) because of the size of the basin. The initial reservoir volumes were reset at the end of the stabilization period, to match the observed historical volumes at the artificial reservoirs. The same years were then re-used for calibration (1998-2003), starting from the initial conditions reached at the end of the two-year stabilization period. The remaining years (2004 to 2006) were kept for validation.

The multi-algorithm genetically adaptive multi-objective method (AMALGAM) was used as the automatic optimization algorithm to select the best parameter sets. The results were then evaluated in terms of Nash-Sutcliffe coefficient, percentage of error and volume ratio at all the discharge and water level stations available. The calibrated model showed a good agreement with the observed data for the calibration and the validation periods (see Fig. 3).

The model is currently being used to analyse scenarios incorporating new hydropower schemes and three extensions of existing hydropower plants, environmental flows and climate change. The objective of the scenario analysis is mainly to determine the impacts of new hydropower plants on energy production, as well as on the environmental flows. The scenarios are then compared in terms of average annual energy production, firm energy production and alteration of the hydrograph at some key locations. A finer evaluation of the economic implication of environmental flows, as well as an optimization of the reservoirs' operating regimes will be an added value.

4. Optimizing water allocation for energy and environmental demands

Hydro-economic models typically link water allocation to economics, with the aim of maximizing net economic benefits across the basin, while taking the governing equations of hydrological processes as constraints. One such model, Stochastic Dual Dynamic Programming (SDDP), can provide a useful guide for maximizing economic benefit while balancing complex competing water demands over a long planning period.

Taking the example of hydropower-dominated basins, large negative impacts of storage structures have been observed [World Commission on Dams, 2000[7]], including resettlements, ecosystem degradation, and a disrupted hydrological regime. However, the storage of water has clear economic benefits in terms of energy generation but also contributes to the reduction of human exposure to flood and droughts. The storage services of the three largest existing reservoirs Kariba, Itezhi-Tezhi, and Cahora Bassa have an estimated economic value of US$ 443 million per year [Tilmant *et al.*, 2012[8]]. This analysis focuses on ecological requirements in the delta area downstream of Cahora Bassa with an attached economic value of 10 US$/1000m^3 during flood pulses. Downstream river discharges can be increased during critical wet months by changing the reservoir operating rules. While previous studies have been limited in scope, assessing the impacts only on Cahora Bassa, this study reveals that one of the upstream reservoirs (Kariba) will be significantly affected by the coordination of the multireservoir system. This emphasizes the need for a basin-wide approach to investigate the potential trade-off in a holistic manner. Lake Kariba will have larger fluctuations in storage levels and contribute in a different way to the flow downstream depending on the status of the system, that is, the storage levels and inflows: during dry years, Kariba can increase its releases to refill Cahora Bassa as a result of its huge storage capacity, allowing Cahora Bassa to increase the total outflows to the delta. During wet years, this contribution is not required and Kariba can keep a high pool elevation to maximize its own hydropower generation.

The trade-off relationships between hydropower generation and e-flows illustrate the sacrifices in terms of reduced firm energy if society chooses to restore a flow regime downstream of major dams. For example, if a 5 per cent reduction of firm energy were socially acceptable (from 27 to 25.65 TWh), then a 4500 m^3/s discharge (reported bank-full discharge as opposed to the current constant discharge of 2690 to 3000 m^3/s) in the delta could already be achieved or exceeded in February and/or March 70 per cent of the time (hydrological risk of 30 per cent).

To ensure coordination of dam operation and sharing of the corresponding benefits and costs of water use, adequate policies need to be in place. Effective basin-wide cooperative governance mechanisms could also mitigate future water-related challenges such as population and economic growth, as well as expansion of irrigated agriculture [Beck and Bernauer, 2011[9]].

The economic costs of non-cooperation in irrigation development in the basin would reach on average 10 per cent 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 [Tilmant and Kinzelbach, 2012[10]].

5. Conclusions and outlook

It is important to emphasize that hydropower has benefits and drawbacks, and sustainable water management should achieve a balance between energy revenue and environmental constraints. Studies within the ADAPT initiative demonstrated the effects on sediment and nutrient transport induced by current dam operation in the Zambezi river basin. The presented hydrologic, economic and biogeochemical models are effective tools towards optimizing IWRM practices. The intake height of turbine withdrawals may be adjusted to improve water quality downstream. To optimize water allocation in the ZRB, it is crucial for water management to be addressed at a basin-wide level through the coordination of the major reservoirs by riparian countries. Moreover, equilibrium between environmental demands and energy production should be defined, to adapt the new hydropower structures to future needs.

In this light, the models which have been described are now being implemented further to provide integrative insights for sustainable water resource management in the Zambezi river basin. Within the ADAPT framework more detailed investigations on the effect of altered hydrology on the ecology in the Kafue river basin are currently being undertaken. ◊

References

1. **Zurbrügg, R.**, "Biogeochemistry of a large tropical floodplain system (Kafue Flats, Zambia): River-floodplain exchange and dam impacts", Dissertation No. 20309, ETH Zürich, Switzerland; 2012.
2. **Kunz, M. J., Wüest, A., Wehrli, B., Landert, J., and Senn, D.B.**, "Impact of a large tropical reservoir on riverine transport of sediment, carbon and nutrients to downstream wetlands", *Water Resources Research*, No. 47; 2011.
3. **Kunz, M. J., Anselmetti, F.S., Wüest, A., Wehrli, B., Vollenweider, A., Thüring, S., and Senn, D.B.**, "Sediment accumulation and carbon, nitrogen, and phosphorus deposition in the large tropical reservoir Lake Kariba (Zambia/Zimbabwe)", *Journal of Geophysical Research*; 2011.

4. **Zurbrügg, R., Wamulume, J., Kamanga, R., Wehrli, B., and Senn, D.B.,** (2012), River-floodplain exchange and its effects on the fluvial oxygen regime in a large tropical river system (Kafue Flats, Zambia), *Journal of Geophysical Research*, 117.
5. **DelSontro, T., Kunz, M.J., Kempter, T., Wüest, A., Wehrli, B., and Senn, D.B.** (2011). "Spatial heterogeneity of methane ebullition in a large tropical reservoir", *Environmental Science & Technology*, 45, 9866-9873.
6. **Mertens, J.** (ed.), "African Dams Project – adapt planning and operation of large dams to social needs and environmental constraints", CCES/ADAPT, Switzerland, 2013.
7. **World Commission on Dams**, "Dams and development - New Framework for Decision-Making". The Report of the World Commission on Dams, published by Earthscan, London, UK; 2000.
8. **Tilmant, A., Kinzelbach, W., Juizo, D., Beevers, L., Senn, D.B., and Casarotto, C.,** "Economic valuation of benefits and costs associated with the coordinated development and management of the Zambezi river basin", *Water Policy*, Vol. 14, 2012.
9. **Beck, L., and Bernauer, T.,** "How will combined changes in water demand and climate affect water availability in the Zambezi river basin?" *Global Environmental Change*, Vol. 21, 2011.
10. **Tilmant, A, and Kinzelbach, W.,** "The cost of non-cooperation in international river basins", *Water Resources Research*, Vol. 48; 2012.

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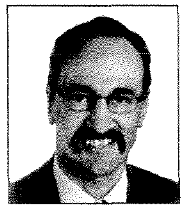

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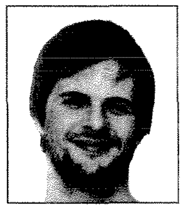

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