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Jointly thinking the post-dam future: exchange of local and scientific knowledge on the lakes of the Lower Rufiji, Tanzania

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Abstract A large dam is planned at Stiegler's Gorge in Tanzania. The change in the Rufiji River flood pattern will affect downstream ecosystems. This paper concentrates on the highly productive floodplain lakes that play a vital role in local livelihoods. A participatory monitoring system with village-based observers collected water level, rainfall, fisheries and food data from 2001 to 2011. Water balances of the lakes show dependence on the Rufiji River flood, with varying vulnerability. With the dam design flood of 2500 $m^3 s^{-1}$, lakes with a high threshold and small catchment will dry out quickly. Lakes with a lower threshold and substantial catchment are more robust but may still dry out during prolonged local drought. Analysis of rainfall (1923–2012) indicates a recent decrease. The data were analysed through feedback workshops with local observers, government technical staff and researchers. Through this collaborative approach, local capacity in preparing for the post-dam future was enhanced.

Key words Stiegler's Gorge Dam; lakes; participatory science; environmental flows; climate change; Rufiji River; Tanzania

Imaginer ensemble les impacts d'un barrage: interactions entre savoirs locaux et savoirs scientifiques sur les lacs de la basse vallée du Rufiji, Tanzanie

Résumé La construction d'un barrage est prévue à Stiegler's Gorge en Tanzanie. Les modifications du régime hydrologique du fleuve Rufiji auront des effets pour les écosystèmes et les économies locales en aval. Cet article s'intéresse plus particulièrement aux impacts du barrage sur les lacs des plaines inondables, écosystèmes productifs qui jouent un rôle économique crucial. Un système de suivi participatif a été mis en place avec des observateurs locaux. Des données de hauteur d'eau, de pluie, de pêche, et d'alimentation ont été acquises sur une période de 10 ans. Les bilans d'eau calculés montrent que les lacs dépendent de la crue du fleuve avec des vulnérabilités différenciées. Avec la conception actuelle du barrage (crue de projet de l'évacuateur de 2500 $m^3 s^{-1}$), les lacs au bassin versant peu étendu et au seuil élevé ont de fortes chances de s'assécher rapidement. Les lacs avec un bassin versant plus étendu et un seuil plus bas résisteront mieux mais présentent aussi des risques d'assèchement en cas de sécheresse locale. L'analyse de la pluviométrie à Utete (1923–2012) a montré une diminution des pluies au cours des 10 dernières années. Les données ont été analysées lors d'ateliers de restitution réunissant les observateurs locaux, les techniciens du gouvernement local et les chercheurs. Par cette approche collaborative les capacités des communautés locales à se préparer aux impacts du barrage ont été renforcées.

Mots clefs barrage de Stiegler's gorge ; lacs ; science participative ; débit environnementaux ; changement climatique ; rivière Rufiji ; Tanzanie

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1 INTRODUCTION

At the level of public discourse, there is a global push towards Integrated Water Resource Management (IWRM), defined as "a process which promotes the coordinated development and management of water, land and related resources in order to maximize economic and social welfare in an equitable manner without compromising the sustainability of vital ecosystems and the environment" (Global-Water-Partnership 2000). The main idea is, in a specific river basin or watershed, to improve collaboration between various sectors that often have conflicting agendas with regard to water development and also to involve stakeholders at all levels to participate in the decision-making about the water. As is often the case with lofty and morally attractive concepts, there is a substantial gap between the theory and the practice (Garcia 2008). In rural sub-Saharan Africa there are obvious constraints to the implementation of IWRM (Swatuk 2005), not least the power relations and inequitable access to knowledge about the resource use options between different kinds of stakeholders, e.g. institutions, agro-industrial actors, the urban elites and the local communities. In fact, the idealized harmonious, symmetrical and triangular interaction between state, markets and civil society required for water governance for the greater common good does not exist (Miranda *et al.* 2011). There is some confusion between water governance and IWRM (Lautze *et al.* 2011), but basically management is about what we do while governance is about who gets to decide on what we do. Effective IWRM therefore requires a "good governance" playing field, which means it is participatory, consensus oriented, accountable, transparent, responsive, effective and efficient, equitable and inclusive and follows the rule of law. It assures that corruption is minimized, the views of minorities are taken into account and that the voices of the most vulnerable in society are heard in decision-making. It is also responsive to the present and future needs of society (Graham *et al.* 2003).

From as early as the 1980s, Tanzania adopted river basin management principles in its law by creating Basin Water Boards (Maganga 2003, Komakech *et al.* 2011). The Rufiji Basin Office was established in 1993 (Komakech *et al.* 2011) and is located in Iringa. The Rufiji basin covers a large area (approx. 184 000 km^2) and the Office has a mandate for 25 districts (RBWO 2013). The Rufiji Basin Office has a field office in Utete, but the latter had no operations in the Rufiji District at the village level at the time of the study. Generally speaking, although Tanzania has been a frontrunner in passing laws on IWRM (Mehari *et al.* 2009), there is a gap between the national policy and local reality (Maganga 2003, Koppen *et al.* 2007, Komakech *et al.* 2011) where water abstraction is mostly done according to customary rules. To fill this gap, Water Users Associations were created by the New National Water Policy of 2002 and the Water Act of 2009 with the mandate to liaise with the Basin Water Offices and collect water fees at an individual level, but with little operationalization (Mehari *et al.* 2009, Komakech *et al.* 2011). To date, none seem to have been created in the study area (Rufiji District between Mloka and Ikwiriri) where flood recession agriculture is dominant and water fees would therefore seem difficult to implement.

Where devolution in the water sector took place, it concentrated on expanding water infrastructure (dams, wells, etc.) and handing over the management of water supply points to local user groups in towns and water-scarce rural areas in an effort to achieve the Millennium Development Goals (MWI 2008). On the ground, this means designated community volunteers have to collect payments for water services and channel them into maintenance of the water sources, the success of which remains to be demonstrated (Pals 2011). There has been rather less effort on building water governance and management capacity in stakeholder groups from the perspective of ecosystem service delivery for human well-being, which is what we have been attempting through participatory monitoring and research.

Environmental flows are an important component of IWRM (Korsgaard 2006). In Africa, the legislation has most often concentrated on maintaining a minimal flow in rivers, the "reserve flow" that helps to maintain the characteristic lotic biodiversity. Much less has been done on maintaining the vital peak flows (Richter 2010) and the ecosystem service delivery related to flooding (Maltby and Acreman 2011). This is particularly important in Africa in view of the renewed interest in hydropower dams. At least in theory, the "traditional" western donors and multilateral institutions were supposed to adhere to the recommendations of the World Commission on Dams (WCD 2000) with regard to managed flood releases from these dams. But in recent years, this drive has been diluted as we observe a new boom in dam building, with emerging nations, e.g. China (McDonald *et al.* 2009), Brazil and oil-rich countries

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that have not adhered to WCD guidelines (Briscoe 2010) coming in as funders or implementers of hydropower projects. By involving the stakeholders downstream of the planned Stiegler's Gorge hydropower dam (local users, local government, Ministry representatives) in research on and monitoring of potential ecosystem impacts, we have attempted to generate some collective thinking that may strengthen local capacity to meaningfully engage with the dam builders and the Rufiji Basin Development Authority (RUBADA) with regard to managed flood release scenarios (Acreman 1996) and also increasingly relevant climate change adaptation and mitigation (Conway *et al.* 2005).

The study area is located on the lower part of the Rufiji River that, with a mean annual flow of some 800 m^3 s^{-1}, is one of the largest rivers in Africa. At present, three dams have been constructed on its upstream tributaries (Fig. 1) but without a significant impact on the flow regime at Stiegler's Gorge (Yawson *et al.* 2006). The Rufiji River has a strongly seasonal flow pattern with a main flood peak around April. The flood pulse sustains floodplain fertility and the productivity of the natural resources on which local communities depend (Duvail and Hamerlynck 2007). The floods seem especially important to the floodplain-adjacent lakes, which are essential to the livelihoods of the approximately 100 000 inhabitants. Effectively, of the villages created during the "Ujamaa" (forced collective farming) period (Hedlund and Lundahl 1989), only those located close to a lake have survived. The lakes

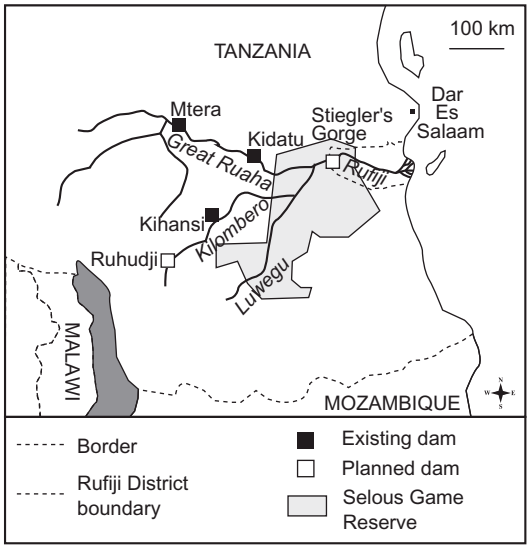


Fig. 1 The Rufiji River, its main tributaries and existing and planned dams.

concentrate many activities, e.g. they are the main fishing sites, providing animal protein and cash. As the river is crocodile-infested and highly turbid, and most of the groundwater brackish or geothermal, the lakes are a vital source of water for drinking and domestic use. They also have a high spiritual value with legends and divinities attached to them (Duvail *et al.* 2005). Riparian groundwater forests exist around most lakes, providing hardwood, fuel and non-timber forest products. They are part of the Eastern African lowland coastal forest hot spot (Myers *et al.* 2000) and harbour important biodiversity values in comparison to the surrounding miombo woodland. In the dry season, wildlife from a wide area, including the 55 000 km^2 Selous Game Reserve, moves to the lakes for grazing and drinking.

The floodplain-adjacent lakes (Fig. 2) are shallow (less than 8 m deep) remnants of old tributaries entering the Rufiji River dammed by alluvial deposits. Some of the lakes, therefore, have tributaries from local catchments entering on the side opposite to the main river. The water from the tributaries can be mixed with water from the Rufiji River when the flood peak exceeds the altitude of the threshold that separates the lake from the river. These thresholds, called "kingo" in Swahili, are a concept familiar with local users. The connection with the river can extend for several weeks, allowing exchange of water, suspended matter and biological material (e.g. fish) (Hamerlynck *et al.* 2011). At flood recession, excess water (above the threshold) flows back to the river until the connection is severed, and the water level in the lake evolves independently from the level in the Rufiji River until the next connection.

A large hydropower/multipurpose dam at Stiegler's Gorge, just upstream of the lower floodplain, has been planned for decades (Hoag 2006) and is regularly revived by the national water bureaucracy (Molle *et al.* 2009). An MOU between the RUBADA and Brazilian company Odebrecht was signed in July 2012 and funding of an estimated US$2 billion is to be sourced through a Public–Private Partnership (Tanzania Daily News 2012). Hydropower generation has always been the prime objective of the dam but, in order to suit potential donors, the project was subsequently relabelled as a multipurpose dam (Havnevik 1993) with flood control and the creation of some 80 000 ha of irrigated land downstream included in the objectives, even though the viability of the irrigation component is doubtful (Hamerlynck *et al.* 2010). The original design was prepared by the

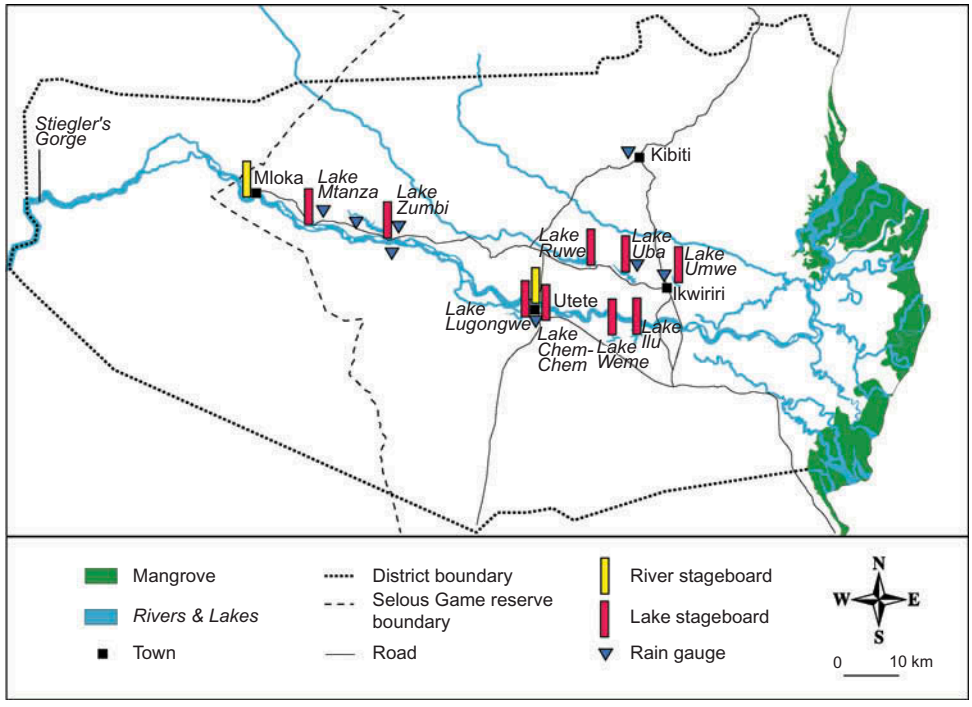


Fig. 2 Map of the Lower Rufiji with the floodplain-adjacent lakes.

Norwegian companies Norplan and Hafslund in 1980 and included low-level outlets permitting managed flood releases of 2500 m^3 s^{-1}. In 1983, Norplan recommended a higher flood release capacity of 4000 m^3 s^{-1}, but the safety of such releases was later questioned (Havnevik 1993) and never formally incorporated into the design. All recent mentions of the dam in the press (Haonga 2012) refer back to the original Hafslund/Norplan design with a 2500 m^3 s^{-1} flood release, hereafter referred to as "the design flood". The storage capacity of the reservoir will be 34 000 Millions m^3, which, considering that the Rufiji River has a mean annual runoff of 25 228 Millions m^3, is equivalent to a residence time of the water in the reservoir of 1.35 years. Many reservoirs have residence times in the range of 0.2–2 years and the longer the residence time, the stronger the disturbance of the natural flow regime (van der Zaag and Gupta 2008). The flood hydrograph of the Rufiji River will thus be strongly modified, affecting downstream ecosystems including 500 km^2 of mangrove (Mwalyosi 1988). At present, Mtera and Kidatu dams built on the Kilombero branch of the river have not significantly modified the flow regime in the lower floodplain. Contrary to expectations, the dams even tend to sharpen the flood peaks (Yawson *et al.* 2006), probably because of management issues. The Stiegler's Gorge Dam, immediately upstream of the study area and designed to control the floods, is likely to have a significant impact.

Other, smaller hydropower dams are planned in the upper catchment, e.g. on the Ruhudji, and in the second phase of the controversial Kihansi plant (Quinn *et al.* 2005). Still, the prolonged and recurrent droughts in East Africa have demonstrated the vulnerability of hydropower projects with severe power rationing in Kenya and Tanzania having had major impacts on the economy. Even though climate models in general predict increased runoff for the main Eastern African river basins (Milly *et al.* 2005), the likelihood of extreme events is also set to increase (Milly *et al.* 2002). In addition to the drought, the inappropriate management of irrigation schemes in the Great Ruaha catchment has been cited as the major cause of the decline in the flow to the Mtera and Kidatu hydropower stations (Lankford *et al.* 2004).

The probability of reduced flood peaks and increased abstraction in the future is therefore high. The impact of such changes on the functioning of the lakes was identified as a research priority during a workshop held in December 2001 that brought together scientists, villagers, NGOs, District Officers and Government Officials (Ochieng 2002) and had as an objective to collectively decide on the research priorities for the Lower Rufiji for the period 2001–

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2011. The main goal of the research was therefore to document the vulnerability of the lakes by

- developing a simple water balance model of the lakes;
- estimating the importance of the connection to the river during the flood for their water balance; and
- assessing the impact of modifications of the peak flow on the lakes.

2 MATERIALS AND METHODS

2.1 Data collection

At the beginning of this study only two hydrometric stations, at Mloka and Utete, part of the national monitoring system, existed on the Rufiji River (Fig. 2). Additional gauges were therefore installed in the floodplain lakes. Climate data were obtained from the Utete agriculture weather station, which has recorded daily rainfall since 1923. Annual average rainfall was calculated for the agricultural year (1 August of year N to 31 July of year $N + 1$). Data for pan evaporation, maximum and minimum temperature, humidity, wind speed and hours of sunshine at Utete have also been available since 1999, but progressively the instruments have failed and recording stopped in 2005. Other raingauges have been installed and operated at various schools in the Rufiji District, but readings and data collection have been less than perfect. Water-level data collection started in 2001 and ended in 2011 for the lakes.

For water-level monitoring, two approaches were followed:

- The River Basin Management and Small-scale Irrigation Improvement Project (RBMSIIP), supported by US$26.3 million from the World Bank, rehabilitated 43 hydrometric sites in the Rufiji Basin, including three sites in the lower floodplain (Mloka, Utete, Ikwiriri) where sophisticated automatic data loggers (Nimbus OTT) were installed. The Ministry of Water was in charge of data downloading, analysis and feedback to the District.
- In parallel, a participatory monitoring approach was designed. The eight most important lakes were equipped with sets of stageboards levelled by a topographic team from the Ministry of Water. Unfortunately, there was no availability of differential global positioning system (GPS) and the levels are therefore to a local datum for each lake and not linked to average mean sea level. A team of local village-based observers received training and some backstopping support from the Rufiji District Agriculture Department to take daily readings. Raingauges were also installed in 2001 at several primary schools and were monitored by the teachers and students. Three additional raingauges were installed in 2007 around Lake Zumbi, including one south of the river (Fig. 2). The hydro-climatic data acquired by the local observers were collectively analysed through annual feedback workshops bringing together the local observers, the District team and the research team.

During these workshops, records were verified, discussed and recommendations for improved recording provided. More importantly, hydro-climatic data records were analysed in combination with the stageboard readings, and discussions were held on the functional aspects of the lakes, including their fisheries, and on their future under the dam scenarios. The principle guiding the series of workshops has been that, through the active participation of the data collectors in the analysis of the results, they would both be motivated to ensure a high quality of their operations as well as becoming a repository and a centre of dissemination within their respective communities of the increased understanding on the functioning of the lakes and the values of the floods for local livelihoods. By inviting participation by personalities from academia and local and central government water departments, a cross-fertilization of local and broader national understanding of water and livelihood issues was also an expected outcome.

Additionally, rating curves for connecting channels of the lakes were established, flow measurements were made using a Nautilus current meter and bathymetry of the lakes was conducted from 2001 to 2003 using a GPS and an echo-sounder. Depths were linked to a stageboard reading. Storage–elevation relationships and surface–elevation relationships were then established through a cut-and-fill method using Surfer software.

2.2 Calculation of water balances

Hydraulic modelling was conducted with a 7-year data set covering the period 1 October 2001–30 June 2008. It consisted of a simple water balance

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model established for each lake in an excel spreadsheet using a daily step according to the equation:

$$Q_i + G_i + P + R + M - Q_o - E - I + \Delta S_t = 0 \quad (1)$$

where Q_i is daily inflow from Rufiji River; G_i is daily groundwater inflow; P is daily rainfall on the lake surface; R is daily runoff for each lake; M is daily water abstraction due to human activity; Q_o is daily outflow to Rufiji River; E is daily evaporation; I is daily infiltration; and ΔS_t is daily storage variation, all in $m^3\ d^{-1}$.

The different variables of equation (1) were estimated as follows:

- P: As initially no raingauges existed in proximity to most of the lakes for 2001–2003, rainfall records from nearby stations were weighted using a "reciprocal-distance-squared method" (Chow *et al.* 1988), in which rainfall at an ungauged point (the lake) is inversely proportional to the distance from a gauged point. From 2003, local rainfall data collected by the observers were favoured when judged accurate. Exceptional rainfall events were added on the basis of notes made by the observers.
- E: In general, the lakes have a very low vegetation cover. Therefore, an open water evaporation rate was calculated from the Utete weather station data using the Penman-Monteith formula. In the absence of data since 2005, a five-point moving average evaporation curve was computed from the 2001–2005 data and used for the period 2006–2008.
- R: In the absence of detailed topography, land use and soil types of the lake catchments, runoff was estimated by using the following equation (Shahin 2002):

$$R = k(P - H) \quad (2)$$

where R is runoff (m^3); k is a runoff factor (m^2); P is precipitation (m) and H is soil retention (m); k and H were estimated by comparing generated runoff with the lake hydrograph when the lake was not connected to the Rufiji River. The runoff factor k represents three components, i.e. the drainage area, the influence of soil, vegetation and land use, and the potential difference between precipitation in the catchment and precipitation as calculated for the lake. Zumbi and Ruwe have large catchments with intermittent rivers (Msangazi for Zumbi and Rambo for Ruwe). When daily rainfall exceeded 50 mm, runoff was multiplied by 3, representing flash floods signalled by the observers.

- I and G_i: Exchanges between the groundwater and surface water were estimated from the hydrograph. Darcy's law was applied in a simple manner with the stage of the lake being compared with the supposed head of the aquifer, using the following formula (Merritt *et al.* 2000):

$$Q = qA = c(h_1 - h_a) \quad (3)$$

where Q is the volumetric flux [L^3/T]; q is the specific discharge (seepage rate) [L/T]; A is the cross-sectional area perpendicular to the flow [L^2]; $c = KA/\Delta l$ in the conductance [L^2/T], with K the hydraulic conductivity [L/T] of materials between the lake and a location within the aquifer below the water table, and Δl the distance between the points at which h_1 and h_a are measured; h_1 is the stage of the lake [L] and h_a the stage of the aquifer [L].

- Q_i and Q_o: Water exchange between the lake and the Rufiji River required measurement of their relative altitude. For the lakes close to the Rufiji River (Mtanza, Zumbi, Lugongwe, Ilu), levelling measurements were performed in 2002. For the other lakes (Weme, Ruwe, Ilu, Uba, Umwe), it was assumed that their highest water level during the main flood peak was equal to that in the Rufiji River. Unfortunately, for the biggest flood (2001–2002), the maximum water level was not recorded for most of the lakes because it exceeded the highest stageboards. Therefore, flood marks (e.g. mud traces on trees) were used and levelled in relation to the stageboards. The hydrograph of the Rufiji at Mloka was used as the water level in the river taking into account a travel time between Mloka and Utete of approx. 2 d during low and medium discharge and 1 d during the flood (with linear extrapolation to lake entry points).

The contributions of each variable of the equation to the daily storage variation were converted to water levels using a storage–elevation relationship obtained from the bathymetry. The simulated water level was then deduced from the sum of the daily water-level variations. Calibration of the model was performed during the 2002 flood pulse (between October 2001 and October 2002), a very wet year when all components of the water balance were well represented, and

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during the 2008 flood pulse (from October 2007 to October 2008) for which good hydrological and rainfall data were available. Calibration was performed using two techniques: a visual comparison between the observed and simulated water levels and a calculation of the correlation between the simulated and observed values. The validation of the model was done both in a dry year ("2003 flood pulse", October 2002 to October 2003) and in a year of medium flood size ("2007 flood pulse", October 2006 to October 2007). The model was then used to reconstruct the 2004, 2005 and 2006 flood pulses for which some water-level data were missing for some of the lakes. Hydrological years started on 1 October of year N (corresponding to the lowest water level in the Rufiji River) to 30 September of year $N + 1$.

2.3 Predicting the future of the lakes

The current design of Stiegler's Gorge Dam would allow for flood releases of up to 2500 m^3 s^{-1}. Using the rating curve produced by the Water Resources Engineering Programme of the University of Dar es Salaam (WREP 2003), this corresponds to 4.4 m at Mloka. A 20-year simulation of the impacts on the lakes of an annual release of such a magnitude, to coincide with the current flood peak in April, was carried out. The water balance model was run for the period from October 1987 to October 2007 using daily rainfall at Utete, and evaporation at Utete for the same period (1987–2007), but with a flood peak corresponding to 2500 m^3 s^{-1} at Stiegler's Gorge Dam. In order to carry out the comparison, water level at the beginning of the period was set at 2 m.

3 RESULTS

3.1 Rainfall

In the Lower Rufiji, the past 14 years have been characterized by an unprecedented series of dry years, as recorded at the Utete weather station. For the period from 1923 to 1998, annual rainfall was around 900 mm (average 885.7 mm, 99% confidence limits 826.0 and 945.4 mm), while for the period 1999–2012, average annual rainfall was only 662.1 mm (99% confidence limits 568.1 and 756.1 mm), which represents a statistically significant ($p < 0.01$) 25% decrease (Fig. 3). Five of the 10 driest years on record have occurred since 2003 and, since 1999, rainfall exceeded the long-term (1923–2012) average of 850 mm only in a single year since 2008 (1021 mm). The trends for the main changes are a substantial decrease in the rainfall during the short rains (October–December) and a shortening of the long rains (March–May), with less or no rain in May.

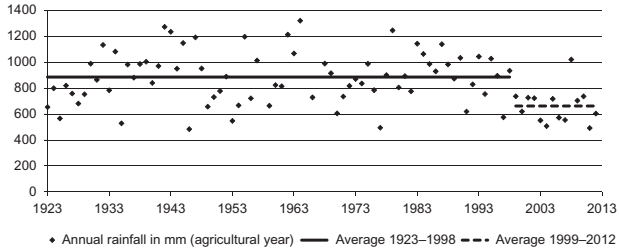


Fig. 3 Agricultural-year rainfall for Utete 1923–2012 and the averages for the two distinct time periods, 1923–1998 and 1999–2012 (significantly different at 99% level, $p < 0.01$).

3.2 Water-level records

The sophisticated monitoring system using data loggers rapidly failed for two main reasons:

- The dynamics of the Rufiji River make it difficult to find stable sites for the installation of a data logger and probe. At Ikwiriri (bridge), the data logger was installed under the new bridge but the high river flow in April 2002 deposited several metres of sand at the bridge pile, covering the data logger. In Utete, the meandering river claimed part of the river bank, destabilizing the data logger and washing away the probe.
- The RBMSIIP did not provide funds for maintenance, nor for travel for staff to come and download the data. Most of the 43 rehabilitated stations in the Rufiji Basin have ceased to function or have not been downloaded regularly.

The participatory monitoring system provided more consistent results. For each lake, two villagers (one woman, one man) were recruited as observers. Initially they volunteered and were given a bicycle for their travel to the stageboard. From 2004 onwards, they received a tiny cash compensation for the time spent reading the stageboard (approximately US$10 per month of data provided). Data were centralized by the District Agriculture Department. Ten years of water-level data have thus been collected. Initially, the quality of the data was uneven (e.g. Lake Ruwe and Lake Lugongwe) but the quality improved rapidly after the first feedback

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workshop and became reliable after a few months, as verified by observer-independent checks of the water level. Some technical problems affected stageboard readings, e.g. the 2001–2002 flood went unrecorded in most lakes as the level exceeded the highest stageboard. Additional stageboards were installed later in 2002. In contrast, after 4 years of small floods, the lowest stageboards were out of the water in some lakes (Uba, Mtanza, Zumbi), and the installation of an additional stageboard was required. With prices increasing for scrap metal, some stageboards were stolen but were replaced by a wooden pole design, making them less attractive. Despite an institutional gap between 2003 and 2005, and the series of very dry and tough years for local people, four observer teams out of nine continued monitoring. The Rufiji River stageboard readings were done by government employees up to 2005. From 2005 to 2011, the observations continued with support from the research projects. Some data are missing, but never during the flood season. The data set from Mloka (Fig. 4) is more consistent than the one from Utete where the stageboard requires frequent gauge replacement and levelling.

Through the feedback workshops, information was shared between locals, managers and scientists. At the first workshop (9 April 2002), emphasis was on conversion of readings into graphs and on how water levels, in combination with flow measurements during the connections, can be used to estimate the relative contributions of rainfall and floods to the water balance of the lakes. A debate was also initiated on the downstream effects of dams. In the second workshop (6 November 2002), emphasis was on the link between fish catches and floods, but also on how fisheries management such as practised in Lake Mtanza (with a closed season during the long rains and voluntary banning of beach seines and other destructive gear) led to higher and more sustained catches. A locally-made video on the lake fisheries was shown and proved to be a good starting point for a lively debate. During the third (30 March 2006, after 3 years of small floods) and fourth workshops (9 July 2007, after a moderate flood that connected most of the lakes to the river), the recorders jointly analysed and presented all the events that occurred in and around their particular lake and area of the floodplain over the past few years, with an emphasis on the differences between years with and without connections. The preliminary results of the model were presented and discussed, including impacts on fisheries. The fourth workshop was concluded by a role-play between five stakeholder groups in a hypothetical lower floodplain during a prolonged drought 20 years from now:

- two distinct villages, a lake-dependent and a rainfall-dependent one, each with two gender groups with different ambitions and opportunities;
- private irrigated agriculture operators with national and international management;
- the management team of an upstream hydropower dam;
- the local government authorities that are expected to integrate the various demands for water.

The participants made a very lively show of how they perceive each stakeholder group's strategies in a worst case scenario with humour, drama and a subtle understanding of human weaknesses and capacities. Most importantly, it demonstrated a thorough understanding of the issues at stake and of the vital importance of sustained flood peaks in the river.

During the fifth workshop in July 2010, a comprehensive version of the various monitoring systems, water levels, rainfall but also fisheries and food monitoring were presented and scenarios developed. Solutions for preventing the drying out of the lakes were collectively shared.

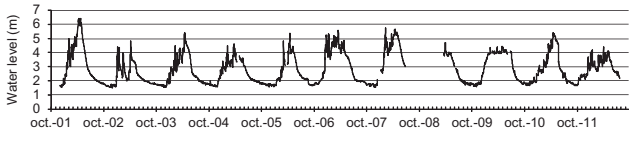


Fig. 4 Water levels at Mloka (relative altitude, not linked to mean sea level).

3.3 Water balance model results for each lake

The key characteristics of the different lakes are presented in Table 1, while observed and simulated water levels of the lakes are presented in Figs 5 and 6.

3.3.1 Lake Mtanza (Fig. 5). This lake has a high threshold (5.4 m at Mloka) and connects only during substantial floods. In 2002, it received a very high inflow from the river (nearly 550% of the initial volume), but did not connect for the next 3 years, only for a few hours in 2006 and 2007 and for about one week in 2008. It has a small catchment and no regularly flowing tributaries, so runoff and direct

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Table 1 Key characteristics of the different lakes. The surface area (km^2) was estimated from the aerial photographs of June 1999, the volume (hm^3) from depth measurements done in June 2000, the distance to the Rufiji River (km), also from the aerial photographs and the threshold (m), in comparison with the zero of the Mloka stageboard, as estimated by the model.

Lake	Surface (km^2)	Volume (hm^3)	Distance to Rufiji (km)	Threshold (m)
Mtanza	0.30	0.4	0.4	5.4
Zumbi	6.87	29.2	0.2	4.5
Ruwe	8.76	20.6	8.2	5.6
Uba	3.18	7.2	6.2	5.0
Umwe	1.43	1.4	7.6	5.7
Ilu	3.54	4.8	0.2	4.5
Weme	1.99	2.6	2.8	4.2
Lugongwe	2.47	5.9	1.0	3.7

precipitation cannot compensate for evaporation losses every year. The water balance was therefore negative in 2003, 2004 and 2005. An exceptional rainfall event occurred in 2006 (as reported by the observers) and saved the lake from drying out completely, as happened just prior to the 1997 El Niño–Southern Oscillation (ENSO) event. The correlation coefficient between the modelled water level and the stageboard readings is 0.84.

3.3.2 Lake Zumbi (Fig. 5). The Zumbi threshold is much lower than at Mtanza (3.4 m at Mloka) and the lake received inflow from the Rufji in 2002, 2004, 2007 and 2008. However, connections do not occur every year: none in 2001 and 2005, only a few hours in 2003 and 2006. Being the deepest and the second largest lake, the contribution of the connections with the Rufiji is relatively unimportant in comparison to the initial volume. The contribution from runoff is high due to the large Msangazi River catchment which, in rainy years, contributes substantially to the water balance. The correlation coefficient between the modelled water level and the stageboard readings is 0.97.

3.3.3 Lake Ruwe (Fig. 5). Ruwe has the largest surface area of the studied lakes but holds a third less water than Zumbi. Its threshold is high (5.6 m at Mloka) and the lake is far from the river (8.2 km). The lake did not connect between 2002 and 2008. The model fails to simulate the water level in Lake Ruwe (correlation coefficient 0.08), most probably as the inflow from the Rambo River is not properly taken into account. There is no raingauge in the Rambo catchment nor a stageboard on the Rambo River, and the weighted rainfall extrapolated from Utete does not correlate well with the inflow from upstream. The water balance of Lake Ruwe seems to be quite independent from the Rufiji River flood, but the conductivity of the water increased steadily during years of supply from the Rambo River only, indicating a possible connection to saline groundwater.

3.3.4 Lake Uba (Fig. 5). Though close to Lake Ruwe (distance to the Rufiji 6.2 km), Lake Uba has no upstream tributary and is highly dependent on the connection with the Rufiji River. Its threshold is high (5.0 m at Mloka) and Lake Uba connected in 2002 but not since. As is the case for Lake Mtanza, runoff and direct precipitation do not compensate for evaporation losses. Pumping from Lake Uba to provide freshwater for Ikwiriri town (>12 000 inhabitants) was stopped but the lake has now dried out, as happened in the 1930s. The water level has declined by over 6 m since the 2002 flood peak. The lake has also become increasingly saline, possibly through a connection with saline groundwater. The correlation coefficient between the modelled water level and the stageboard readings is 0.99.

3.3.5 Lake Umwe (Fig. 6). Lake Umwe is a small lake with a high threshold (5.7 m at Mloka) and quite far from the river (7.6 km). Inflows from the Rufiji occurred only in 2002. Unlike Lake Uba, the water level of Lake Umwe has remained comparatively stable for the past six years but there is no obvious surface inflow from an upstream catchment. Possibly, high precipitation events on the course sand terrace create groundwater flows which account for the relative stability of the water level. Moreover, the high conductivity of Lake Umwe (>2 mS cm^{-1}) may indicate a connection to salty groundwater. The correlation coefficient between the modelled water level and the stageboard readings is 0.98.

3.3.6 South bank lakes (Fig. 6). The lakes on the southern bank of the Rufiji River: Ilu (4.5 m at Mloka, correlation coefficient 0.88), Weme (4.2 m at Mloka, correlation coefficient 0.98) and Lugongwe (3.7 m, correlation coefficient 0.96) are all well connected to the river and, with the possible exception of Ilu in 2005, have connected annually.

3.4 Model predictions

Over the time period (October 2001–June 2008) used for model calibration and validation, it has become clear (Figs 5 and 6) that the small, high threshold lakes

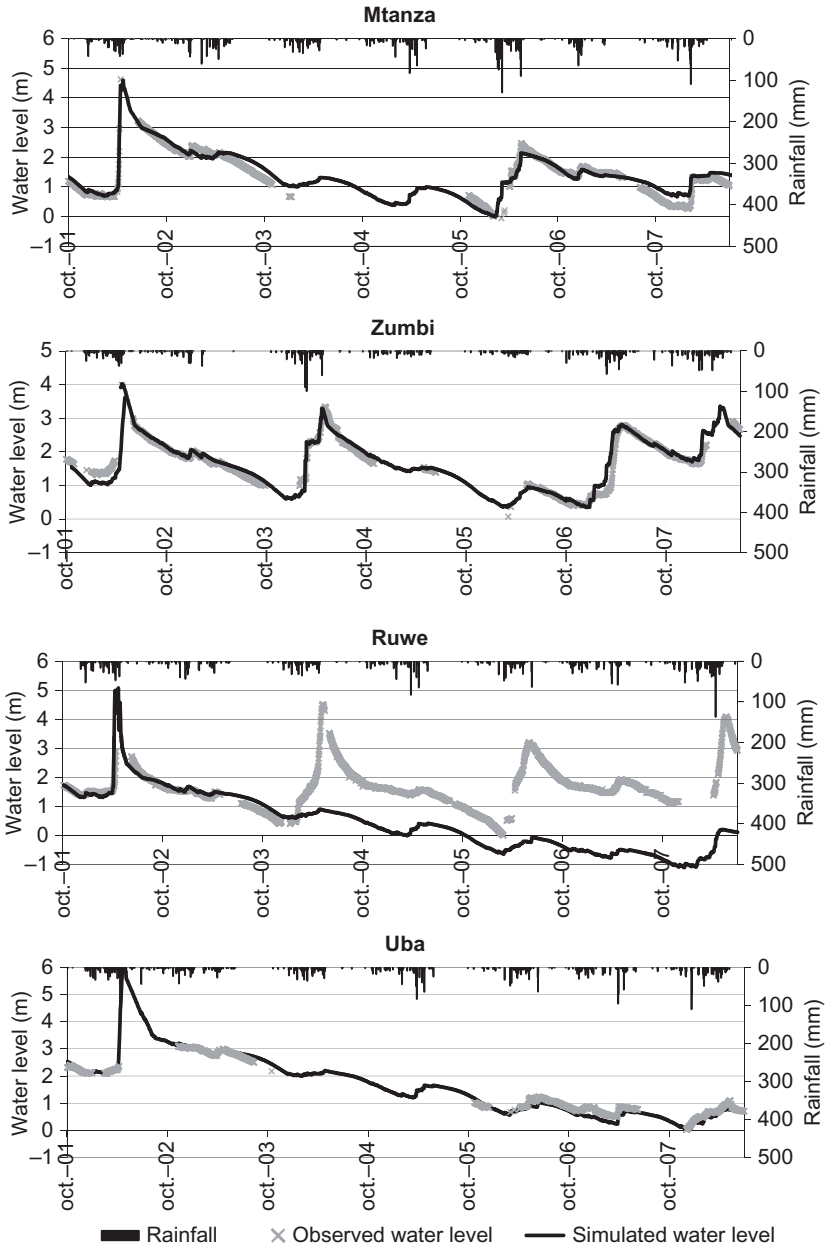


Fig. 5 Observed and simulated water levels and rainfall for lakes Mtanza, Zumbi, Ruwe and Uba.

on the north bank, Mtanza and Uba, cannot maintain their water-related livelihood functions without high floods or exceptional local rainfall. Under a post-dam scenario of an annual 2500 $m^3 s^{-1}$ flood peak and using the rainfall and evaporation data from Utete weather station for the 1987–2006 period (hence superior to the current rainfall trend and overestimated for the most western lakes considering the decreasing rainfall gradient from the ocean), Lake Mtanza would dry out in 4 years. However, the local rainfall will bring seasonal low water level in the lake (Fig. 7(a)). Lake Uba will dry in 13 years (Fig. 7(b)). Lake Umwe is an exception as it maintains its water level but its role for livelihoods is very limited because of its high salinity, which in itself is probably the main reason for its survival (connection to groundwater).

The large lakes, Ruwe and Zumbi, more or less maintained their water level over the study period, as did the well-connected lakes on the south bank. But under the post-dam scenario of an annual 2500 $m^3 s^{-1}$ flood peak starting in 1987, the average water level in Lake Zumbi would have fallen by over 1 m (Fig. 8(a)), leading to a considerable decline in water-dependent ecosystem service delivery. Lake Weme, which has a lower threshold, would maintain its water level

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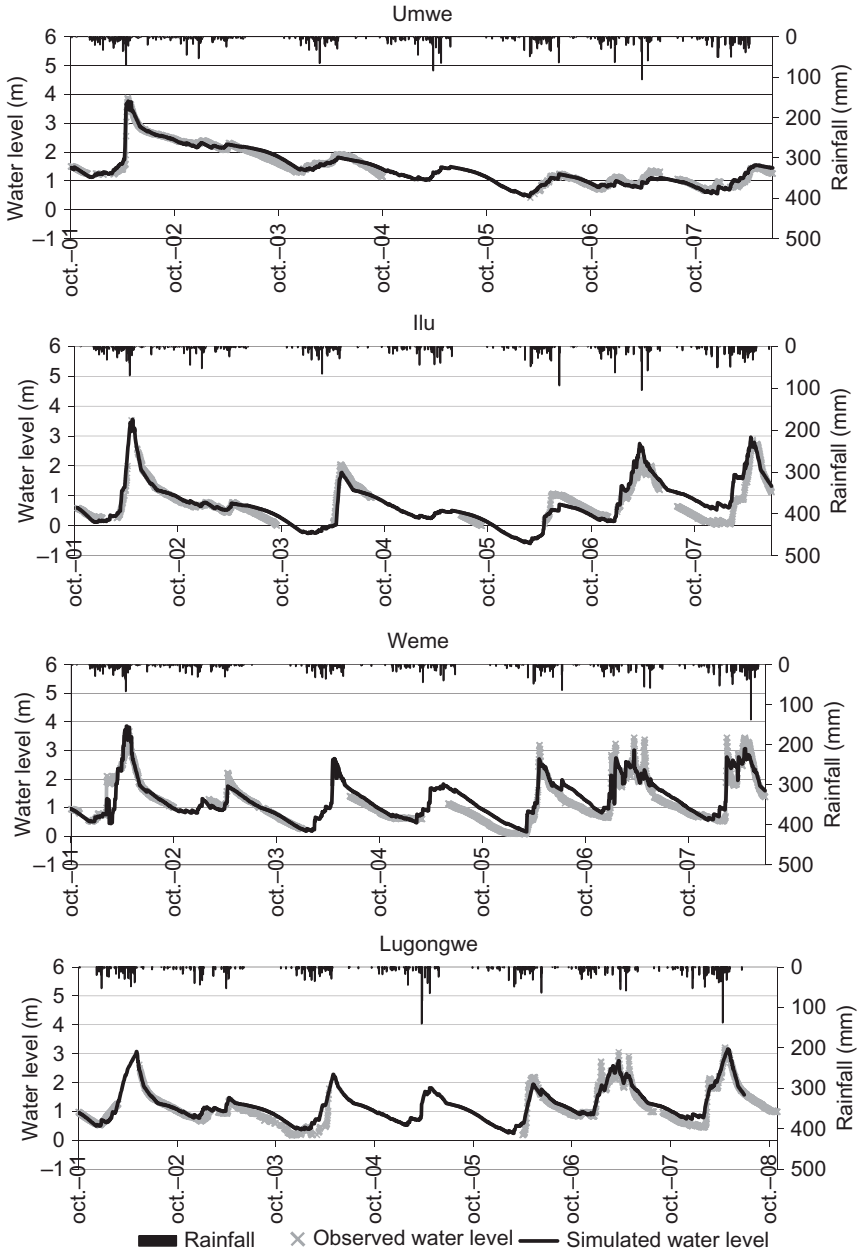


Fig. 6 Observed and simulated water levels and rainfall for lakes Umwe, Ilu, Weme and Lugongwe.

but with a slow tendency to a decreasing water level (Fig. 8(b)).

4 DISCUSSION

4.1 Expected impacts of the dam on the lake water levels

The impact of a reduced flood peak on the water levels in the lakes is dependent on the altitude of the lake thresholds, the size of the lake catchments (and the rainfall therein) and the connections with groundwater. Lakes with high thresholds, small catchments and no connection to groundwater are highly vulnerable to drying out. In fact, in 2010 lakes Mtanza and Uba were completely dry.

Under the design flood scenario (2500 m^3 s^{-1}), lakes with a lower threshold (e.g. Ilu, Weme, Lugongwe and Zumbi) will also experience a decline in many of their flood peak dependent ecosystem services. The lowering of the water level in Lake Zumbi in 2004, 2005 and 2006, even though connections to the river occurred annually, most probably reduced fisheries productivity and income for the

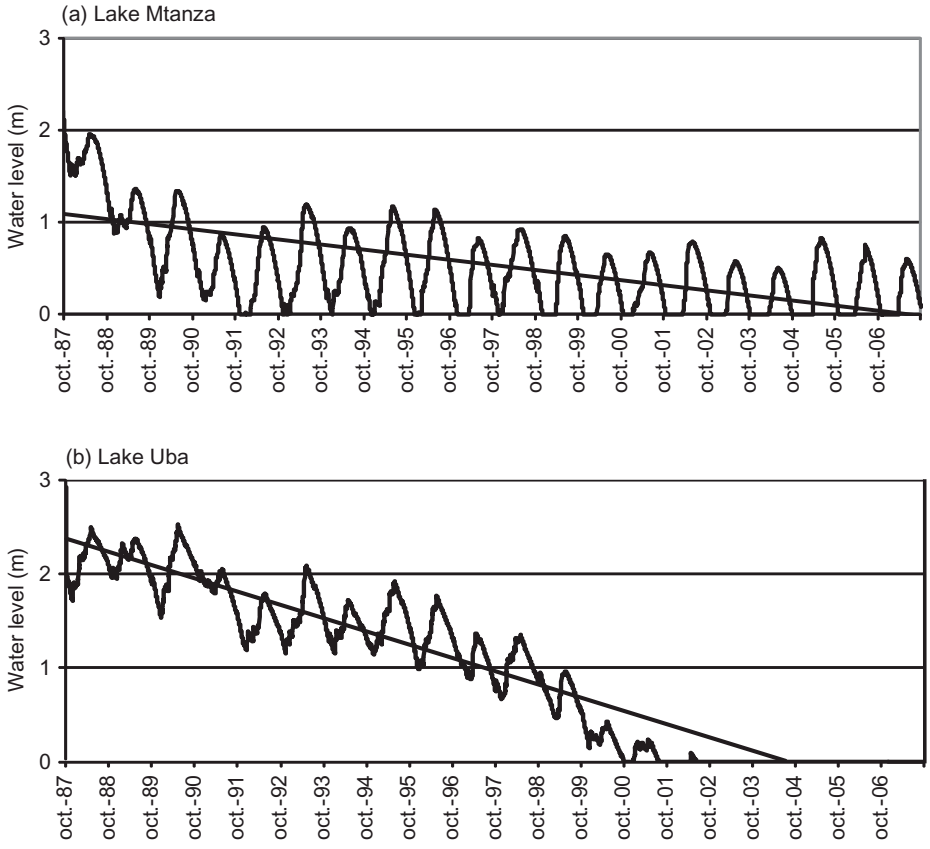


Fig. 7 Simulated water level and trend line in lakes (a) Mtanza and (b) Uba in a post-dam scenario with an annual 2500 m^3 s^{-1} flood release.

fishers (Hamerlynck *et al*. 2011). When productivity decreases, fishers adapt by putting in more effort (thus reducing the labour available for agricultural work) by using illegal active gear. It also pushes them towards more risky behaviour such as fishing inside the Selous Game Reserve (Paul *et al.* 2011). When the lakes do not connect, the diversity of their fish fauna decreases rapidly (Hamerlynck *et al*. 2011) making them more susceptible to detrimental regime shifts (Folke *et al.* 2004). In the easterly lakes, the increase of salinity makes them less and less suitable for domestic water supply. This increases dependency on the river, often at a greater distance from the village and, for the women and girls habitually tasked with water chores, a higher risk of harmful encounters with crocodiles.

Lakes with a high threshold but a large catchment independent from the water level in the Rufiji River (Ruwe) or supplied by groundwater (Umwe) are the only ones likely to maintain their water level. They will still lose part of their livelihood-supportive hydrological functioning as, in addition to decreased fisheries diversity and productivity, the increase in salinity risks making them unsuitable for domestic water supply.

The results of the modelling using the 2500 m^3 s^{-1} design flood are conservative: the model does not take into account the climate change trends mentioned above as it was calibrated on data from 1987 to 2007. The trends observed since the start of the observations indicate that, potentially, rainfall will decrease and evaporation will increase, linked to higher temperatures and changes in wind conditions. It also does not take into account the river bed degradation that is characteristic after dam construction (Galay 1983): as sediment is trapped behind the dam, the downstream river bed quickly erodes and the current flood peak level of 4.4 m at 2500 m^3 s^{-1} is set to decline, especially if the releases are made through low-level outlets as planned.

From these results and taking into account the fact that the floods have many other benefits (Duvail and Hamerlynck 2007), we can argue that a dam scenario with a flood peak at 2500 m^3 s^{-1} will have a huge impact on the livelihoods of the Rufiji floodplain inhabitants, potentially pushing many people to the brink of survival and increasing their dependence on poaching, non-sustainable hardwood harvesting (Milledge *et al.* 2007) and charcoal making

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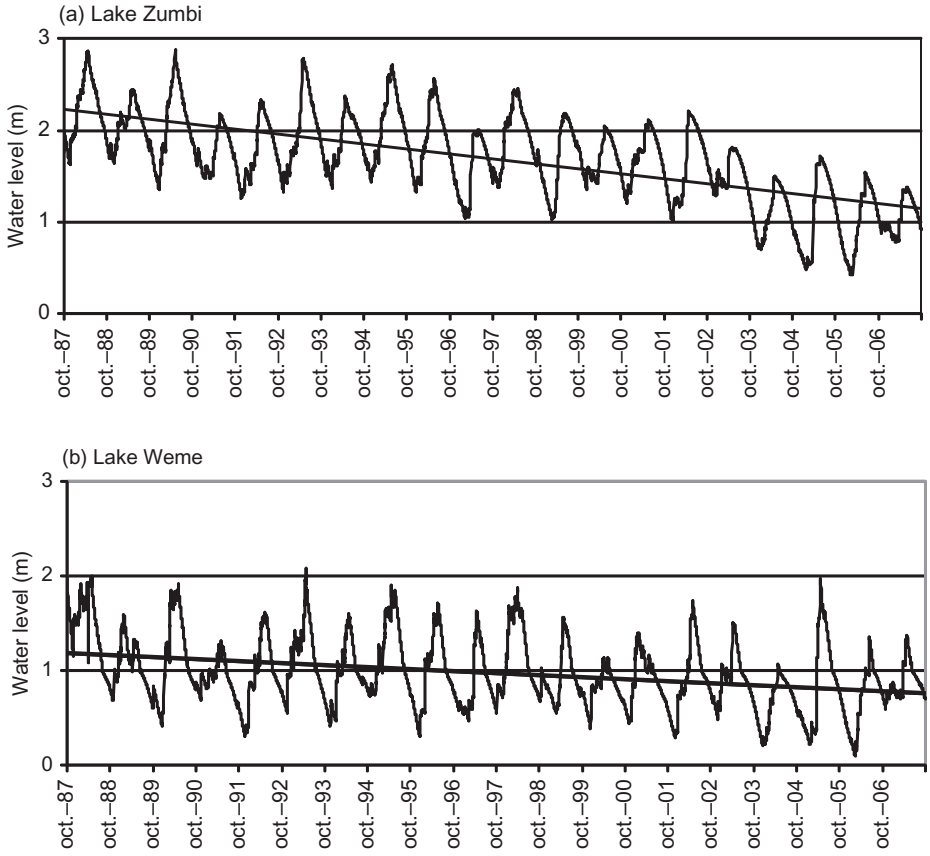


Fig. 8 Simulated water level and trend line in lakes (a) Zumbi and (b) Weme in a post-dam scenario with an annual 2500 m^3 s^{-1} flood release.

(Ahrends *et al.* 2010) leading to biodiversity loss (Sueur *et al.* 2008) in the exceptionally rich coastal forest and miombo biomes.

4.2 Expected impacts of climate change

The local drought in the Lower Rufiji was accompanied by a series of comparatively low flood peaks, with two out of seven being close to the design flood of 2500 m^3 s^{-1}. This meant that both the short rains maize and much of the long rains recession staple crops failed leading to severe food insecurity, which was partially alleviated by the distribution of some 500 tonnes of food aid in 2003 and 2006. After the main study period (2001–2008) three out of the next four flood peaks were again at or just below the design flood. It was clear from the discussion with the village elders that, for example, the lowering of the water level by some 3 m in Lake Zumbi (reducing lake volume from some 42 × 10^6 to 22 × 10^6 m^3) between April 2004 and December 2006 was unprecedented in living memory. The elders suspected there was a blockage on the Msangazi River, while in fact the lowered inflow from its own catchment was due to the local drought.

Whether Stiegler's Gorge Dam is built or not, the reduced flooding and rainfall trends, should they confirm themselves, require that serious attention be paid to implementing adaptation strategies such as small-scale irrigation along the natural channels in the floodplain, supplied by pumping from the river. This could be done using large mobile pumps that can be moved out of the floodplain quickly in the event of high flood peaks, e.g. by putting them on barges, and smaller pumps for individual fields. Indeed, it is not worthwhile to establish sophisticated irrigation infrastructure in the floodplain as it will be wiped away by the occasional extreme flood peaks. This is also the main reason why the planned post-dam irrigation scheme is likely to fail. Independent of the issues hampering the development of large-scale irrigation in the Lower Rufiji (Hamerlynck *et al.* 2010), the costs of embankments capable of resisting an El Niño type flood (Erftemeijer and Hamerlynck 2005) are prohibitive.

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Another option is the establishment of very simple water control devices on the connecting channels permitting rapid close-off of the lakes as soon as the flow inverses back to the river, e.g. a double series of wooden planks sliding into metal grooves with mud filling in between. It is important that they can be removed quickly as, in the Lower Rufiji, there are often successive flood peaks in a single year. With an operational flood prediction system transmitted by mobile phone, village-based managers could be warned in advance to prepare for the removal of the planks before the arrival of the flood peak. At least for the most vulnerable lakes north of the river, these could probably quite easily be put in place at the bridge structures or culverts crossing the main road from Ikwiriri to Mloka. In addition, when putting these control structures in place, some of the lake thresholds might be lowered and the channels widened to facilitate inflow. So far, the westerly lakes, Mtanza and Zumbi, have not shown any salinization problems, but for the more easterly lakes (Ruwe, Uba and Umwe) this needs to be carefully monitored. These measures will be even more necessary should the Stiegler's Gorge Dam be built, even if the design flood is increased.

At the local scale, lake-dependent livelihoods may also be affected by the agro-fuel boom, with several companies planning to develop sugarcane using water from the lakes for irrigation (Duvail *et al.* 2010).

4.3 Possible improvements of the modelling exercise

A very simple water balance model was chosen for the modelling exercise, a choice which had its advantages (in terms of reproducibility and didactics). But the exercise was hampered by the low density of rain gauges in comparison to the high spatial variability of rainfall, by the absence of a proper georeferencing of the stageboard elements and the subsequent imprecision on the altitude of the threshold (somewhat compensated by the notes taken by the observers) and by the absence of data regarding the evaporation (or temperature) after 2005.

The establishment and sustained management of a denser network of raingauges and the rehabilitation of the Utete weather station (for which an exceptionally long series of rainfall exists) would seem a necessity for the Rufiji District, not only for the modelling of the lakes but also as an early warning system for harvest failure and more generally in the light of climate change and its potential impacts on local livelihoods.

Information on groundwater exchange could also be improved by systematic measurements of conductivity in rivers, boreholes, wells and lakes. The establishment of a digital terrain model for the Lower Rufiji and associated hydrodynamic modelling of the flood extent, height and duration is expected to greatly improve the accuracy of predictions on natural resource productivity and local livelihoods.

4.4 Comparative advantage of participatory science over high-tech equipment projects

Even if the participatory approach has some disadvantages and constraints, it is our contention that long-term low-level funding and technical accompaniment are more effective at data collection, awareness-raising and empowerment of local communities than high-tech type projects.

High-tech solutions such as automatic data loggers are attractive to donors and water management institutions, especially for projects that have to spend the allocated funds within a short time period and where evaluations are carried out shortly after completion and not with a 5-, 10- or 20-year time lag. However, as can be seen from the Rufiji, they may be less well adapted to highly dynamic rivers in remote locations. They are also an obstacle to any knowledge exchange between local users and scientists, placing the data acquisition only in the hands of experts.

A participatory approach based on a simple stageboard design also has some constraints and disadvantages: the most obvious one is that the setting up of a functional network of local observers requires some time for the selection, training and backstopping. But even when the collection of data is achieved in a functional manner, sharing of knowledge faces additional barriers. For example, the representation of the water-level variation in a metric referential was a new concept. Prior to the set-up of the water-level observer network, no local system of water-level monitoring was in place. Its establishment required training of the local observers (done at the first workshop) and repeated sessions (including tests, where each recorder was required to read the same stageboard) during subsequent workshops.

In addition, the representation of the water level as a graph where water level is a function of time was another new concept that required explanation and training: water-level observers were asked to recall

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hydrological events of the year past and to relate them to the printed lake hydrograph. Once this common language was agreed and understood, it became easier to exchange views and jointly develop hypotheses on the functioning of the lakes. In addition to the meeting-room discussions, field visits were scheduled and each workshop was an opportunity to study a particular lake in more detail (Workshop 1: Uba, Workshop 2: Lugongwe, Workshop 3: Umwe, Workshop 4: Ruwe, Workshop 5: Zumbi).

Another constraint of this approach is the requirement for a technically competent and dedicated facilitator over a long time period.

On the positive side, in contrast to costly data loggers, stageboards are simple, flexible and cheap tools with a proven track record. For less than US $5000 per year a dozen stations can be maintained, monitored, the data centralized and entered in a computer and collectively analysed in a workshop.

Unlike data acquired with highly technical tools, the feedback sessions allowed an interesting interaction between scientific and local knowledge, which expanded over the years. On the one hand, scientific knowledge informed the observers on the hydrological functioning of the lakes, highlighting the importance of the connections during the floods relative to inputs from rainfall, the influence of the local catchments and the possible impact of flood peak reduction. On the other hand, local observation and knowledge led to improvements of model accuracy: the timing and duration of the connections to the river, the observations of inflow from upstream and the notes taken on intense local rainfall events helped to calibrate the model. Hypotheses on the functioning and on the relative importance of the various components of the water balance were formulated collectively. For example, the explanation for the failure of the water balance model of Lake Ruwe came from the local observers who stated that large volumes of water were occasionally entering from the upstream catchment. That these rises in water level were not originating from the Rufiji River (the connecting channels being filled by rain water during the flood season so connections were not easy to observe) was confirmed from the conductivity measurements. The discussions about the possible causes of the steep decline in water levels in Lake Zumbi between 2004 and 2006 similarly reinforced common understanding. For Lake Umwe, the hypothesis of a connection to groundwater was supported by local knowledge of an underground "river".

The whole process resulted in increased local understanding of water issues, thus contributing to building capacity in the water resource users, who can be organized into associations as promoted by IWRM processes in many countries (UN-Water 2008). For example, after the repairs to a bridge over the connecting channel of Lake Zumbi, the builders left the old bridge supports lying around. This created an obstacle to the flows into the lake, in fact, increasing the threshold by some 0.3 m. The water observer team alerted the village government and the obstacle was removed. The role-play in the fourth workshop also demonstrated that the observers had a good grasp of the importance of the maintenance of the floods for the long-term survival of the lakes and their associated livelihoods.

Still, even after 10 years of joint monitoring, scientific understanding of the functional aspects of the lakes is uneven and depends on the dedication and social insertion of the local observers and also on the social structure of the village itself. In some of the villages, knowledge is limited to the recorder team, while in others, where the community is comparatively homogeneous (Ujamaa villages that were simple translocations and not major re-assemblages of lineages from disparate areas) and where governance is open and participatory, understanding has more easily spread downward to the fishers and upwards to the village government.

4.5 Limits of the approach: information gaps and power disparities during negotiations

If a favourable socio-political environment at the village scale is a necessary condition for the success of participatory approaches, they can be hampered by constraints at other levels.

At local government level, decision-making in the Rufiji District is strongly determined by the perspective of short-term gains, e.g. increased income from taxation or project-related daily subsistence allowances, quite independently from existing scientific or local knowledge of the economic, environmental and social viability or sustainability. Examples include the Rufiji delta prawn farm (Ronnback *et al.* 2002), massive deforestation by "illegal" but condoned logging (Milledge *et al.* 2007), the establishment of hunting blocks or conservation areas (Igoe 2007) and the current privatization of village land by the agro-fuel boom (Sulle and Nelson 2009, Duvail *et al.* 2010). In the absence of a judicial system that holds decision-makers

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accountable for their actions, there are few or no incentives for good governance in both the legislative and executive branches of local government, except for the internal motivation of doing things honourably. This offers few alternatives to local communities wanting to defend their rights, and usually they have to resort to the mobilization of the press, of international NGOs and local campaigners to support High Court injunctions.

At the national level, Tanzania has a long and strong tradition of centralized top-down command and control governance (Havnevik 1993). In addition, a very substantial part of the government budget derives from foreign aid, which, on the one hand, has improved service delivery to society but, on the other hand, may have stifled the endogenous push for political reform (Tripp 2012). Tanzania engaged in the decentralization of natural resource management, which was accompanied by a plethora of donor-funded projects implementing participatory processes, but this has only been partially successful. For example, community-based forest management has taken off (Blomley *et al.* 2008) and, at least in cases of high intensity project related implementation, yielded some positive results for forest quality (Persha and Blomley 2009). Still, these conceptual devolutions of power have not led to substantial benefits accruing to the local communities, neither in the wildlife nor in the forest sectors (Nelson and Blomley 2009). Similarly, in the water sector, devolution seems to be more motivated by outsourcing the collection of water fees than by a drive for meaningful participation in thinking about water and jointly developing a common vision of the future under various infrastructure and climate change scenarios. Many of these failures, which contradict donor country and national government discourse on democratic decentralization, have to do with the lack of a level playing field between different stakeholders, with the local resource users at a disadvantage when negotiating. As demonstrated for the forest sector, the financial interests of the strongly intertwined local elites and government, as well as national commercial interests, often prevail (Ribot *et al.* 2010). But, in spite of these constraints, we have found willingness and even enthusiasm in government staff to participate in the process, which leads us to think that this approach could be mainstreamed.

5 CONCLUSION

A participatory monitoring system of the floodplain-adjacent lakes was set up in the Rufiji District and instrumental to the collection of a 10-year data series that gave better results than high-tech solutions. The results of the modelling exercise have shown that the lakes are sensitive to a modification of either the flood peak or the rainfall pattern. In terms of knowledge sharing, this participatory approach increased common understanding of the hydrological processes and, in particular, the importance of the flood. It also improved the communication and collaboration between the local users, the village leaders, the local government and the national water ministry. The monitoring of the water levels and a simple water balance modelling exercise was a good starting point for collective thinking on the future of the lakes under a post-dam scenario of 2500 m^3 s^{-1}. Such a participatory approach, with involvement of local stakeholders in the design of the research question, on the data collection and at each step of the data analysis is a good way to share local and scientific knowledge. In a context of climate change, where one of the challenges is to link science with decision-making (Conway 2011), it presents an opportunity to develop collective and prospective thinking supporting the local users in the adaptation of their decision-making processes to the post-dam and decreasing rainfall context.

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