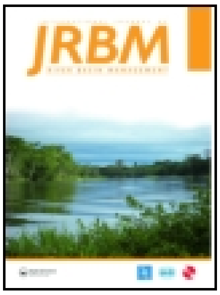

International Journal of River Basin Management
Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/trbm20

Assessing environmental flow requirements and trade-offs for the Lower Zambezi River and Delta, Mozambique

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Published online: 24 Jun 2010.

To cite this article: Richard Beilfuss & Cate Brown (2010) Assessing environmental flow requirements and trade-offs for the Lower Zambezi River and Delta, Mozambique, International Journal of River Basin Management, 8:2, 127-138, DOI: 10.1080/15715121003714837

To link to this article: http://dx.doi.org/10.1080/15715121003714837

Intl. J. River Basin Management Vol. 8, No. 2 (2010), pp. 127–138

Research paper

Assessing environmental flow requirements and trade-offs for the Lower Zambezi River and Delta, Mozambique

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ABSTRACT

The Zambezi Delta is vital to Mozambique's national economy and is a Wetland of International Importance. Large dams in the Zambezi catchment have substantially altered the magnitude, timing, duration, and frequency of flooding events in the delta, resulting in adverse ecological and socio-economic changes. We evaluated conflicts/trade-offs among various water uses and the potential for improving delta conditions through environmental flow releases from Cahora Bassa Dam, using the downstream response to imposed flow transformations (Brown, C.A. and Joubert, A., 2003. Using multicriteria analysis to develop environmental flow scenarios for rivers targeted for water resource development. *Water SA*, 29 (4), 365–374; King, J.M., Brown, C.A., and Sabet, H., 2003. A scenario-based holistic approach to environmental flow assessments for regulated rivers. *Rivers Research and Applications*, 19 (5–6), 619–640) model. Five variations in low flows, 18 alternatives for annual floods, and one extreme (1:5 year) flood were considered for a range of uses/concerns, including commercial and small-scale agriculture, estuarine ecology, coastal and freshwater fisheries, livestock, large mammals, waterbirds, vegetation, invasive species, natural resources, water quality, navigation, and groundwater recharge. The study revealed minimal trade-offs among different uses with regard to reinstating environmental flows. The majority of user-representatives perceive reinstatement of the annual flood to be beneficial and the perceived benefits increase with increased magnitude and prolonged duration, provided the timing of the annual flood occurs during the normal wet season. Simulation modelling of the Zambezi system dam operation indicates that these environmental flow releases can be realized within the constraints of firm power commitments and total energy demand. Of the 18 annual flood change levels considered, 7 can be generated with a firm power reliability >95% and hydropower reductions of <2.3%, and 16 require <10% reduction in annual energy production. This work illustrates the potential for environmental flows to overcome conflict in shared water resources and create opportunities for cooperation.

Keywords: Environmental flows; large dams; floodplains; biodiversity conservation; sustainable development

1 Introduction

Over the past century, water-resource development projects have substantially altered the hydrological regime of the Zambezi River Delta in Mozambique (Tinley 1975, Suschka and Napica 1990, Beilfuss 2001, Beilfuss and Bento in review; Figure 1). Prior to river regulation, Zambezi floodwaters spread over this 12,000 km^2 mosaic of vegetation communities, including permanently inundated papyrus swamp, reed swamp, and oxbow lagoon and seasonally flooded grassland and Savanna – one of the largest wetland systems in southern Africa (Beilfuss *et al.* 2000). The delta supported a remarkable biomass of large herbivores, including an estimated 46,000 African buffalo *Syncerus caffer*, 47,500 waterbuck *Kobus ellipsiprymnus*, 3000 hippopotamus *Hippopotamus amphibious*, and 400 African elephant *Loxodonta africana* during the 1970s (Tello and Dutton 1979). The delta was vital to the national economy of Mozambique for its lucrative prawn fisheries, sugar production, trophy hunting operations, and sustained flood-recession agriculture, fisheries, and other subsistence land uses (Da Silva 1986, Gammelsrød 1992, Negrão 1995, Turpie *et al.* 1999).

With the closing of Kariba Dam on the Middle Zambezi in 1959 and Cahora Bassa Dam on the Lower Zambezi in 1974, the natural flood cycles of the Lower Zambezi River are now a phenomenon of the past. Flooding events in the delta, when they occur, are dependent upon local rainfall-runoff within the Lower Zambezi catchment or unplanned (potentially

Received 8 December 2008. Accepted 4 January 2010.

ISSN 1571-5124 print/ISSN 1814-2060 online
DOI:10.1080/15715121003714837
http://www.informaworld.com

Figure 1 Map of the Lower Zambezi Valley, from Cahora Bassa reservoir to the Zambezi Delta on the Indian Ocean coast

catastrophic) water releases from the upstream dams. These hydrological changes are further exacerbated by the construction of dykes along the Lower Zambezi River that prevent even relatively large flooding events (up to 13,000 $m^3 s^{-1}$) from inundating the southern floodplains. The cumulative impact of these developments is a significant shift in the magnitude, timing, duration, and frequency of flooding events in the delta (Beilfuss 2001, Beilfuss and Bento in review).

Prior to regulation, Zambezi Delta floodwaters reached a peak in February/March and receded during an 8–9 month period, reaching a minimum in November. For the 28-year period (1930–1958) prior to Zambezi River regulation, the mean annual peak flood discharge in the delta region was approximately 9800 $m^3 s^{-1}$. The maximum duration of flooding above this level was 66 days. The annual flood pulse exceeded bankfull discharge (approximately 4500 $m^3 s^{-1}$) during every year of record. The mean date of occurrence of minimum flow was 14 November, with a low standard deviation of only 12 days. From mid-September through early December, the Zambezi River became a sluggish, braided system of rivulets and sandbars (average monthly discharges were 736 $m^3 s^{-1}$ in October and 620 $m^3 s^{-1}$ in November). Tidal influence occurred more than 80 km inland from the Indian Ocean coast (Beilfuss 2001, Beilfuss and Bento in review).

Today, with all five Cahora Bassa turbines in operation, the dam discharges a constant outflow throughout most years. Over the first 30 years of Cahora Bassa Dam operation, dry season Zambezi River discharge near the delta was approximately 2690 $m^3 s^{-1}$ in October (365% of pre-dam flows) and November (435%). There is no longer a clearly discernable period of high flows, as dam spillage is according to the Design Flood Rule Curve and has occurred in all calendar months, including October and November (Beilfuss in review). The mean annual maximum flood discharge was approximately 3800 $m^3 s^{-1}$ (39% of the pre-regulation maximum), and bankfull discharge occurred in only 43% of years (Beilfuss 2001, Beilfuss and Bento in review). Coastal sediment deposition has been reduced by perhaps 70% (Hall *et al.* 1977, Bolton 1984).

Numerous adverse biophysical changes have been associated with these shifts in flow characteristics, including a 1–2 m degradation of the mainstem channel, reduced water tables on the floodplain, invasion of woody savanna and thicket vegetation into open grassland and wetland, terrestrialization of abandoned alluvial channels, displacement of freshwater grassland species by salt-tolerant grassland species, and degradation of coastal shelf and mangrove communities (Tinley 1975, Beilfuss *et al.* 2000, Davies *et al.* 2000, Beilfuss 2001). Socio-economic impacts attributed to these deleterious hydrological changes include a reduction in floodplain and riverbank agriculture, inland fisheries, prawn fisheries, and safari hunting opportunity (through reduced carrying capacity for several trophy species) (SWECO 1983, Bolton 1986, Sushka and Napica 1986, Anderson *et al.* 1990, Gammelsrød 1992, Tha and Seager 2008). These adverse changes were exacerbated by the prolonged Mozambique civil war, during which thousands of people were killed or displaced, wildlife populations were decimated, and social and industrial infrastructure was destroyed in the region (Finnegan 1992).

Despite all, the delta remains vital for biodiversity conservation and the ecosystem services it provides to the local and national economy. The delta supports one of the largest breeding populations of Vulnerable Wattled Crane *Bugeranus carunculatus* and extensive nesting grounds for colonial waterbirds of conservation concern (Goodman 1992, Bento *et al.* 2007). Hundreds of thousands of rural villagers are dependent on the natural resources of the region. In 2003, the southbank of the Zambezi Delta (the 'Marromeu Complex') was designated Mozambique's first *Wetland of International Importance* under the Ramsar Convention, and the Government initiated planning for the restoration of the site.

Environmental flows are an essential element of the policy and management tool kit for restoring river-floodplain systems such as the Zambezi Delta (Arthington *et al.* 1992; Acreman 1996; Postel and Richter 2003, King and Brown 2006). They describe the quantity, timing, and quality of water flows required to sustain freshwater and estuarine ecosystems and the human livelihoods and well-being that depend on these ecosystems (Brisbane Declaration 2007). Environmental flow assessments can bring into relief the implications of water-resource developments, or management strategies, on ecosystems and communities hitherto excluded from decision-making (King and Brown 2006). For these to be constructive, however, information on the implications of changes to flow regimes should include considerations of the broader benefits and services offered by aquatic ecosystems. A key challenge is the communication of the science of environmental flows in a manner that makes it easy for non-specialists to absorb, process, and use information to facilitate meaningful trade-offs between different uses and users of water (Brown and Watson 2007).

Long-term dialogue about the sustainable management of Cahora Bassa Dam and the Lower Zambezi has emphasized the importance of implementing environmental flows (SWECO 1983, Davies 1998, Beilfuss and Davies 2000). However, water management authorities and others concerned about potential conflicts among water users and the impact on hydropower output have challenged the value of implementing environmental flows.

The main objectives of this project were to use available data and expert opinion for the following:

- identifying potential conflicts/trade-offs among users in the Zambezi Delta area with respect to flow requirements;
- assessing the impact of different environmental flow releases from Cahora Bassa Dam on firm power generation and total energy production;
- exploring the potential for the improvement in the condition of the Zambezi Delta through incorporation of environmental flow releases into Cahora Bassa Dam operational rules.

2 Methods

2.1 *The DRIFT modelling process*

A modification of a process called downstream response to imposed flow transformations (DRIFT; King *et al.* 2003) was used to evaluate different water management scenarios for the Zambezi Delta. DRIFT (Brown and Joubert 2003, King *et al.* 2003, Brown *et al.* 2005) is a structured process for combining data and knowledge from various disciplines to produce flow-related scenarios for water managers to consider. Its central rationale is that different parts of the flow regime elicit different responses from a river ecosystem. Thus, changes in one part of the flow regime will affect the ecosystem differently than changes in another part. Furthermore, the following assumptions have been made:

- it is possible to identify and isolate these different parts of the flow regime within a long-term hydrological data set of daily flows;
- it is possible to describe in isolation the probable biophysical consequences of changes in any one of these parts;
- the parts of the flow regime and their linked consequences can be re-combined in various ways, to describe the river condition of any flow regime of interest (the biophysical part of the scenario).

DRIFT is a scenario-based, holistic approach (e.g. Brown and Joubert 2003, King *et al.* 2003) among environmental flow assessment methodologies for regulated rivers (Postel and Richter 2003, Acreman and Dunbar 2004). It makes use of two multi-criteria approaches, namely multi-attribute value measurement (MAVT) and integer linear programming. The MAVT approach is used for the evaluation of the relative effects of changes in flow on a number of criteria. The scores (*integrity ratings*) in DRIFT are based on an interval scale, which covers percentage changes from present day associated with six points (0–5). The change from a score of 0–1 is regarded as being of the same importance as a change from a score of 4–5. The scores given to the flow changes according to each criterion are therefore all on a common scale of severity of impact – i.e. they are comparable and can be aggregated. Weights are not necessary, but the opportunity for weighting is given at each stage of aggregation (if justified).

The integer linear program is used after the evaluation to choose and combine different levels of change from each of the categories in order to create a flow regime that minimizes negative impacts on the stated criteria (i.e. minimizes the overall integrity rating) while achieving a particular target level of hydropower production. The ‘objective function’ (to be maximized) is thus the sum of integrity ratings and one of the constraints is the target hydropower production.

A number of MAVT approaches exist, including those with existing software such as DEFINITE (2006) and VISA (2008). While there would be advantages to using existing software, one of the great benefits of using MAVT in its basic form (e.g. SMART; Goodwin and Wright 1998) is that it simply and transparently can be implemented in a spreadsheet and can therefore be exactly tailored to the project for which it is required. Other popular approaches such as the analytic hierarchy process and the outranking methods (e.g. ELECTRE) were not considered appropriate for use in DRIFT as they tend to be more ‘black box’ in nature and both approaches would require prohibitive numbers of pairwise comparisons or parameters to be defined.

DRIFT has been applied, in various guises, in the Okavango River Basin (King and Brown 2009), Lesotho (King *et al.* 2000, Brown and Watson 2007, Brown *et al.* 2007), Zimbabwe (Mott Macdonald 2002, Brown 2007), Tanzania (Pangani Basin Water Office/IUCN Water and Nature Initiative 2007), and South Africa (Brown and King 2002; Brown *et al.* 2006, Van Der Berg *et al.* in press). In the Zambezi Delta, three key hydrological categories were selected for evaluation:

- dry season low flows;
- the ‘annual’ flood;
- 1:5 year return ‘extreme’ flood.

These categories were deemed to be those historically most affected by Cahora Bassa Dam, and for which changes to the operation of the dam were expected to result in significant consequences for the ecosystem/users of the delta (Beilfuss 2001, Beilfuss and Bento in review). More extreme flooding events (for example, 1:20 year return flood) were not selected as they are only controlled in part by Cahora Bassa Dam.

A range of *change levels* was evaluated for each of these categories, encompassing a mixture of changes in magnitude, duration, and timing (described below). Specialists in hydrology and floodplain hydraulics modelled downstream river condition associated with each change level and developed a Zambezi Delta mass transfer model to translate river stages into flooding depth and duration on the delta plains (Beilfuss and Brown 2006).

The 15 most important water uses or water-related concerns in the delta were identified for this study, based on priorities identified during extensive discussions with representatives from government agencies, NGOs, communities, and other stakeholders in the region (Table 1). For each use/concern, a user-identified specialist (referred to here as user-representatives) was engaged to provide expert opinion on the consequences for these uses/concerns of various measures aimed at restoring Zambezi flows towards pre-dam conditions. The user-representatives were nominated by their peers, and each had prior experience in the Zambezi River Basin.[1]

Each user-representative was responsible for selecting and analysing up to four sub-components for which a range of specific flow-related changes could be described (Table 1). For example, four species of freshwater fish (all important to local markets) were selected to represent freshwater fisheries, with each species strongly influenced by the flood regime but differing in ecological requirements and hence individual response to flow changes. For each of the chosen sub-components, the user-representatives described as quantitatively as possible (in terms of abundance, concentration, or extent) the following:

- status prior to river regulation;
- present-day status;
- the desired *target condition* (defined as the ‘natural’ or pre-impact state) for that sub-component.

The user-representatives then evaluated the consequences for each sub-component of the change levels associated with each of the hydrological flow categories (including a default change level reflecting no change in the present operating rules for Cahora Bassa Dam), to determine the following:

- whether the change will result in an increase or decrease in abundance/concentration/extent of the sub-component;
- whether the change represents a move towards or away from the target condition;
- the estimated *severity* of the predicted change, according to a six-point scale (Table 2).

The specialists presented their assessments at a workshop held in Maputo, Mozambique, attended by more than 100 stakeholders of the Lower Zambezi and other interested parties, during which their findings were critiqued and revised as necessary.

Table 1 Fifteen most important water uses/concerns identified for the study and the key sub-components corresponding to each user-representative for which flow-related changes were described[a]

Water use/concern	Sub-components analysed for flow-change analysis
Commercial agriculture	Irrigated commercial agriculture
Small-scale agriculture	Rainfed agriculture for food and cash crops Natural flooded rice
Estuarine ecology and coastal fisheries	Shallow-water shrimp fisheries Estuarine bottom fish Mangrove crab Primary productivity of coastal waters
Freshwater fisheries	Sharptooth catfish *Clarias gariepinus* Mozambique tilapia *Oreochromis mossambicus* Manyame labeo *Labeo altivelis* Tigerfish *Hydrocynus vittatus*
Livestock	Cattle
Large mammals	African buffalo *S. caffer* Waterbuck *K. ellipsiprymnus* Hippopotamus *H. amphibious* Plains zebra *Equus burchellii*
Waterbirds	Wattled crane *Grus carunculatus* Spurwinged goose *Plectropterus gambensis* Goliath heron *Ardea goliath* African skimmer *Rynchops flavirostris*
Floodplain vegetation	Mangroves Riparian forests Papyrus-dominated permanent swamps
Invasive species control	Palm and acacia savanna encroachment Alien aquatic plants
Natural resource availability	Mangrove forests Riparian trees Reeds and papyrus Palms
Water quality	Sediment Polluted effluent discharge Nutrient eutrophication of water bodies Salinity intrusion
Groundwater recharge	Recharge of floodplain soils and waterbodies
In-channel navigation	Mainstem Zambezi cargo transport
Human settlement patterns	Response to changes in flood vulnerability Response to flow-related economic opportunity
Public health	Water-borne disease Malaria

[a]A total of 13 uses/concerns were analysed using DRIFT. Specialist studies for public health and human settlement patterns were not completed in time for inclusion in the analysis.

Table 2 Severity ratings used to evaluate movement towards or away from target conditions for each sub-component in response to different change levels associated with each of the hydrological flow categories (from King *et al.* 2003)

Severity rating	Beneficial (+)	Detrimental (−)
0	No change	No change
1	0–19% move towards target	0–19% move away from target
2	20–39% move towards target	20–39% move away from target
3	40–59% move towards target	40–59% move away from target
4	60–79% move towards target	60–79% move away from target
5	80–100% move towards target	80–100% move away from target

The aim of the workshop was to fully educe the thought-process behind each specialist evaluation, and thus ensure that inputs prepared for the DRIFT model were not 'black box' and could be understood and replicated by others. The specialist reports and complete data sets are provided in Beilfuss and Brown (2006).

The information supplied by the user-representatives for each sub-component was then entered into a DRIFT database (Brown and Joubert 2003), which comprised a matrix of consequences, for a range of possible flow changes in the three flow categories. The database was used to evaluate the following:

- conflicting water users/concerns, i.e. potential trade-offs in the delta among different uses/concerns (aggregated) or their sub-components;
- a range of permutations to create new flow regime scenarios, together with their consequences for different users in the delta and the implications for hydropower generation.

The following assumptions were applied:

- the study focused on the Marromeu Complex of the Zambezi Delta (a management plan is in preparation for this area and includes strategies for implementation of environmental flow requirements based on the present study);
- present-day (2005) conditions were used as a starting point;
- a 30-year time horizon was used for predictions;
- each flow change was considered in isolation, i.e. it was assumed that the remainder of the flow regime was fixed at 2005 levels;
- the same magnitude of flows in the delta would result each year for the specified flood release from Cahora Bassa Dam. (This will not actually be the case, as the magnitude of flows at the delta will depend on downstream contributions, i.e. vary as a function of climate each year. User-representatives were requested to evaluate the importance of this variability to their specific sub-components).

Comparison of the ratings returned for the various flow changes by the user-representatives provides a clear indication of whether a particular flow change was perceived as beneficial, i.e. result in a positive move towards the target condition, or detrimental, i.e. result in a negative move away from the target condition for that user. In each case, a rating of zero denotes no expected change from present day condition. The documentation supporting the study provides the data, opinions and assumptions on which the inputs are based, and the limitations to which they are subjected (Beilfuss and Brown 2006).

The DRIFT software combines the scores returned by the user-representatives with the consequences for hydropower generation of supplying the various flow changes that were assessed (Brown and Joubert 2003). This allows for the creation of a range of permutations comprising 'new' flow regime scenarios, together with their consequences for different users in the delta and the implications for hydropower generation. These are created in the DRIFT SOLVER routine, using the Solver tool in Excel, which provides the necessary ('branch and bound') algorithm. An integer linear program (e.g. Winston 1994) optimizes the distribution of a given total volume of water among the different change levels of flow classes in a way that results in the lowest aggregate impact on the riverine ecosystem according to the integrity ratings. It does this by summing the ratings given for all the sub-components, taking into account all the negative or positive signs, to produce combinations of high and low flows that return the highest possible 'Percentage Move Towards Target' for that volume (Brown and Joubert 2003).

This information is then depicted using DRIFT-CATEGORY, the purpose of which is to display the relationship between the hydropower lost in the provision of the flows and the percentage move towards or away from the target conditions described by each of the users.

2.2 *Description of change levels considered*

For dry season low flows, three alternatives for magnitude, two alternatives for duration, and two alternatives for timing (i.e. month of year) were assessed, resulting in five change levels over and above pre-dam and present-day conditions (Table 3). The magnitude values represent a step-wise reduction in dam outflows corresponding to a successive reduction in the number of turbines in operation,[2] ranging from four turbines (changes levels 1 and 2) to two turbines (change level 5). The duration and timing correspond to the late dry-season months (October, November) when flows are at a natural (pre-dam) minimum (Beilfuss 2001).

Three alternatives for magnitude, three alternatives for duration, and two alternatives for timing were assessed for the

Table 3 Change levels analysed for DSLFs and wet season annual floods

Hydrological period	Change level	Cahora Bassa discharge (m^3 s^{-1})	Timing (month of year)	Duration	Downstream tributary inflow (m^3 s^{-1})	Estimated discharge in the delta (m^3 s^{-1})
Baseline	–	Not specified	Not specified	Not specified	Varies	Not specified
DSLF[a]	1	1800	November	1 Month	450	2250
	2	1800	October and November	2 Months	450	2250
	3	1350	November	1 Month	450	1800
	4	1350	October and November	2 Months	450	1800
	5	900	November	1 Month	350	1350
Wet season annual flows	1	3700	December	2 Weeks	800	4500
	2	3700	December	4 Weeks	800	4500
	3	2750	February	2 Weeks	1750	4500
	4	2750	February	4 Weeks	1750	4500
	5	3375	December and January	8 Weeks	1125	4500
	6	2825	February and March	8 Weeks	1675	4500
	7	6200	December	2 Weeks	800	7000
	8	6200	December	4 Weeks	800	7000
	9	5250	February	2 Weeks	1750	7000
	10	5250	February	4 Weeks	1750	7000
	11	5875	December and January	8 Weeks	1125	7000
	12	5325	February and March	8 Weeks	1675	7000
	13	9200	December	2 Weeks	800	10,000
	14	9200	December	4 Weeks	800	10,000
	15	8250	February	2 Weeks	1750	10,000
	16	8250	February	4 Weeks	1750	10,000
	17	8875	December and January	8 Weeks	1125	10,000
	18	8325	February and March	8 Weeks	1675	10,000

Notes: Each change level reflects a different combination of the magnitude, timing, and duration of discharges from Cahora Bassa dam. The estimated discharge in the delta for each level is the sum of Cahora Bassa outflows and the expected (mean) magnitude of downstream tributary contribution for the corresponding timing and duration.

[a]Further reductions in Zambezi dry season flow (by further reducing the number of turbines in operation) were determined to be politically unacceptable at present due to lost hydropower generation, as a consequence, pre-regulation dry season flow levels are not proposed as an attainable change level.

annual wet season flood, resulting in 18 change levels over and above pre-dam and present-day conditions. The range in magnitude values correspond to different flooding levels in the Zambezi Delta, including approximate bankfull discharge (4500 m^3 s^{-1}), annual mean monthly flood discharge (7000 m^3 s^{-1}), and annual mean maximum flood discharge (10,000 m^3/s). The duration and timing correspond to 2-, 4-, and 8-week flow releases during the early flood season (December–January) and peak flood season (February–March) under pre-dam conditions (Beilfuss 2001). One additional change level was used to evaluate a more ‘extreme’ flood event, a 1:5 year flood discharge in the Zambezi Delta.

A simulation model using the HEC-5 multi-purpose, multi-reservoir routing software (US Army Corps of Engineers 1998) was developed for the Zambezi River Basin to assess firm power generation and total energy production over the range of target outflows required from Cahora Bassa to create the different change levels. Model design and assumptions, data input, outflow scenarios, sensitivity testing, and results are described in detail elsewhere (Beilfuss in review) and only briefly outlined here. The model inflow series consists of a measured and reconstituted monthly flow record for the past century (1908–2004), representing the range of climatic variability that might be considered representative of expected future Zambezi flows.[3] Upper Zambezi runoff is routed through Kariba reservoir and power station and combined with regulated (Itezhitezhi and Kafue Gorge Dams on the Kafue River) and unregulated runoff from the Middle Zambezi to constitute the regulated inflow series to Cahora Bassa. Target outflows from Cahora Bassa are realized through a combination of turbine discharges and sluice gate spillage. The simulation modelling indicated that a range of environmental flow releases were possible from Cahora Bassa Dam within the constraints of existing demand for firm power and total energy production (Beilfuss in review).

Each change level for Zambezi Delta environmental flows corresponds to a regulated outflow from Cahora Bassa combined with inflows from Lower Zambezi River Basin (including the Luia, Luenha, Revuboe, and Shire River tributaries). Because Lower Zambezi flow data are available only for a shorter, interrupted period of record relative to the Cahora Bassa inflow series from the Upper and Middle Zambezi, these data could not be extended to derive a reliable 97-year flow series for use in the simulation model (Beilfuss 2001). Downstream flows in the

Zambezi Delta region therefore were approximated by adding the long-term mean monthly inflow from all downstream tributaries to the modelled target outflows from Cahora Bassa Dam for the corresponding time period (Table 3).

For the Cahora Bassa target outflows required to produce each change level, we modelled firm power output for each month, and calculated firm power reliability as the percentage of months out of the total that firm power requirements are met or exceeded. We calculated total power output as the mean of the annual total power generated for the inflow series. Target outflow reliability was calculated as the percentage of years in which outflows met or exceeded the specified flood release conditions, through a combination of turbine and sluice gate discharges. The percentage of years that these environmental flows would occur under baseline conditions (without target outflows) is also given for each change level.

3 Results

The ratings returned for each of the user-representatives for the five possible changes (all reductions) considered for the dry season low flows are provided in Figure 2. These show that the majority of user-representatives perceive reductions in the dry season low flows as neutral or negative (user integrity rating < 0), with notable exceptions for certain sub-components of floodplain vegetation (mangrove forests) and waterbirds (African Skimmer *Rhynchops flavirostris*).

Figure 3 provides the ratings returned for each of the user-representatives for the 18 possible changes considered for the annual flood. The results indicate that the majority of users perceive some form of reinstatement of the annual flood to be beneficial (user integrity rating > 0). The exceptions to this were those concerned about in-channel navigation and commercial agriculture, which could be negatively affected by higher magnitude annual floods.

Figure 4 provides the combined ratings for all users who expressed a preference of reinstatement of the annual flood, and indicates that, on average, the perceived (combined) beneficial effects of the floods increase with increased magnitude and

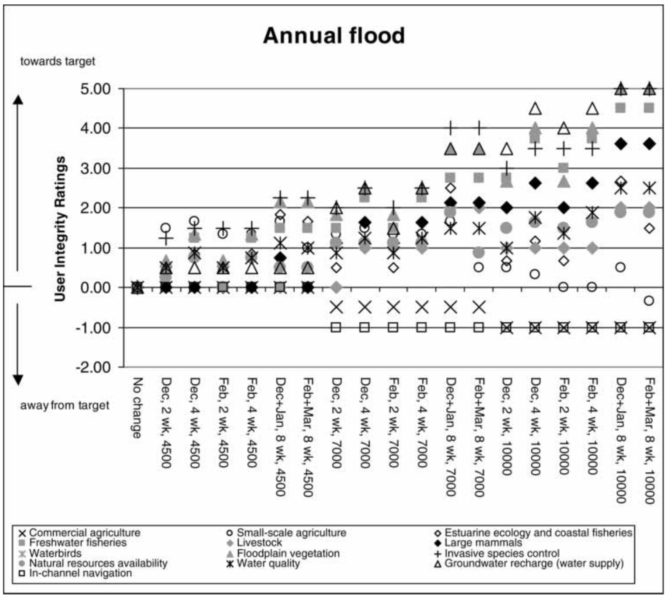

Figure 3 User integrity ratings returned for each of the water users/concerns for the 18 changes considered for the annual flood

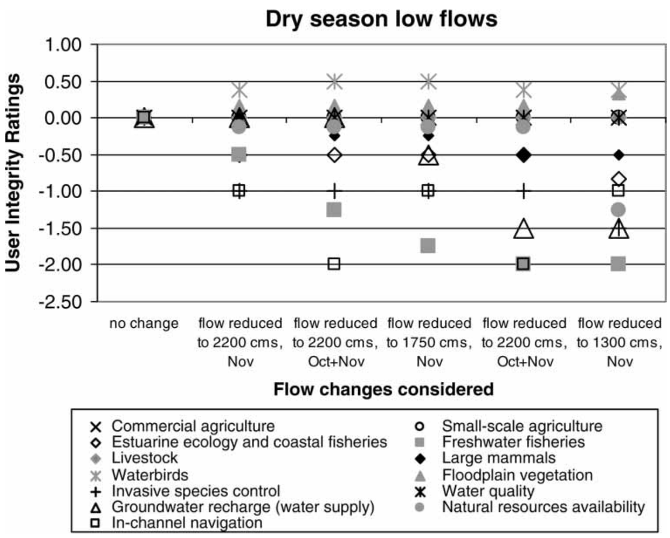

Figure 2 User integrity ratings returned for each of the water users/concerns for the five changes considered for the DSLFs. A larger positive score indicates stronger movement towards the target (ideal or natural) condition for that user/concern, whereas a larger negative score indicates strong movement away. Each water use/concern represents an average score for its specific sub-components, although individual sub-component responses may differ

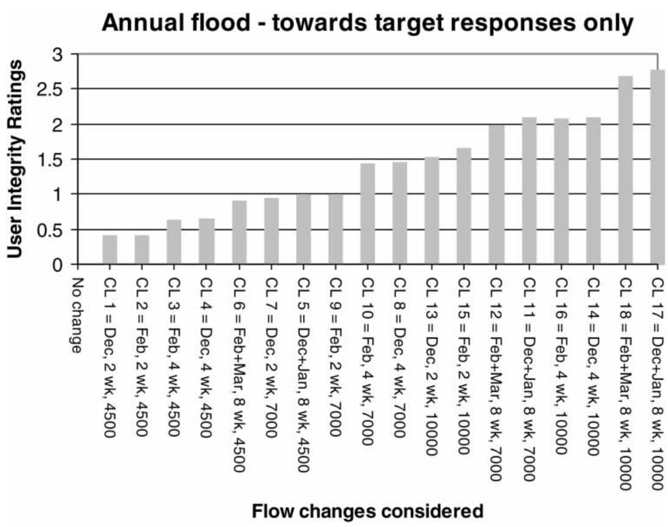

Figure 4 Combined ratings for users/concerns with a preference for reinstatement of the annual flood, including small-scale agriculture, estuarine ecology and coastal fisheries, freshwater fisheries, livestock, large mammals, waterbirds, floodplain vegetation, invasive species control, natural resource availability, water quality, and groundwater recharge, for the 18 change levels considered. (CL = change level; Table 3)

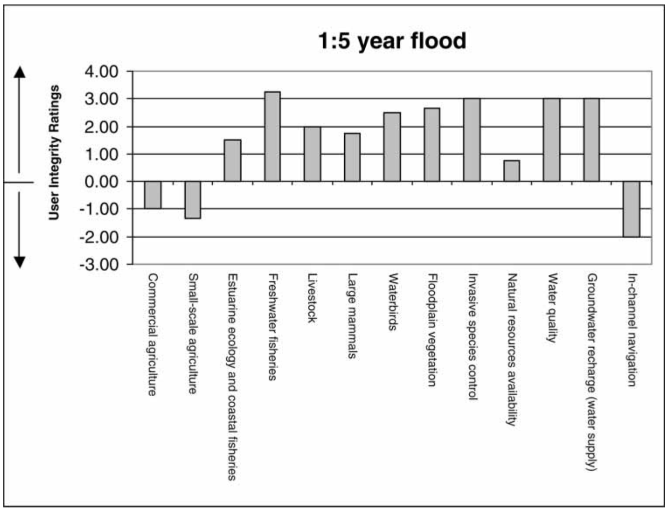

Figure 5 Ratings returned for each of the users for the reinstatement of the 'extreme' 1:5 year flood, on a periodic basis

increased duration. Users did not show a strong preference for the timing of the annual flood (e.g. February vs. December flood).

The ratings returned for each of the user-representatives for the reinstatement of the 1:5 year flood are given in Figure 5 and indicate that the majority of users perceive some form of reinstatement of the 1:5 year flood to be beneficial. As was the case for the annual flood, the exceptions to this are those users concerned with in-channel navigation and commercial agriculture, as high flood levels could negatively affect those activities.

The hydropower modelling indicates that immediate improvement in the Zambezi Delta flow regime could be made with almost no impact on hydropower production. Change Level 3 wet season annual outflows (2-week discharge of 2750 m^3 s^{-1} in February) could be achieved in 97.3% of all years, with a firm power reliability of 97.8%, and no reduction in annual power (GWH a^{-1}) generation (Table 4). These same outflows would occur in only 7.7% of all years under present management. With slight reductions in hydropower, many of the change levels (target outflows) could be achieved. Change level 7 (2-week discharge of 6200 m^3s^{-1} in December), for example, could be achieved in about 94.5% of years (but only 29.7% of all years under current management practices), with a firm power reliability of 96.2% and 1.4% reduction in total annual energy production. These outcomes may be realized even with the current level of regulated inflows to the dam (i.e. without conjunctive management of upstream Zambezi dams). Furthermore, higher target outflows could be attained with less effect on hydropower generation through the use of a minimum reservoir threshold for water releases, adoption of a new Flat Flood Rule Curve governing Cahora Bassa outflows, or other alternatives (Beilfuss in review).

The DRIFT-CATEGORY plot, which displays the relationship between the hydropower lost in the provision of the flows and the percentage move towards or away from the target conditions described by each user-representative, is shown in Figure 6. Figure 6 was created with the requirements of each user given equal importance. It depicts the combined ratings for all users at the level of the whole delta, relative to the current state of the system (DRIFT Integrity Score of zero on the *y*-axis), and the hydropower values provided are expressed

Table 4 Target outflow reliability, baseline outflow reliability, firm power reliability, total annual energy production, and energy production as a percentage of baseline production for different annual flood change levels, using simulated monthly inflows from the Zambezi River catchment over the period of 1907–2004

Change Level	Target outflow reliability (%)	Baseline outflow reliability (%)	Firm power reliability (%)	Energy production (GWH a^{-1})	Energy as % of baseline
Baseline	–	–	98.4	14,393	100.0
1	95.6	85.7	97.3	14,333	99.6
2	94.5	58.2	96.7	14,273	99.2
3	97.8	7.7	97.3	14,407	>100.0
4	97.8	7.7	97.1	14,357	99.7
5	92.3	42.9	94.2	14,083	97.8
6	95.6	2.2	95.1	14,355	99.7
7	94.5	29.7	96.2	14,186	98.6
8	89.0	2.2	92.9	13,722	95.3
9	94.5	3.3	95.8	14,064	97.7
10	91.2	3.3	92.5	13,637	94.7
11	72.5	4.4	89.7	13,112	91.1
12	78.0	1.1	83.9	12,963	90.1
13	89.0	5.5	93.3	13,801	95.9
14	78.0	0.0	90.9	13,067	90.8
15	90.1	2.2	92.2	13,612	94.6
16	83.5	1.1	90.0	12,993	90.3
17	24.2	0.0	87.0	12,575	87.4
18	25.3	0.0	68.0	12,018	83.5

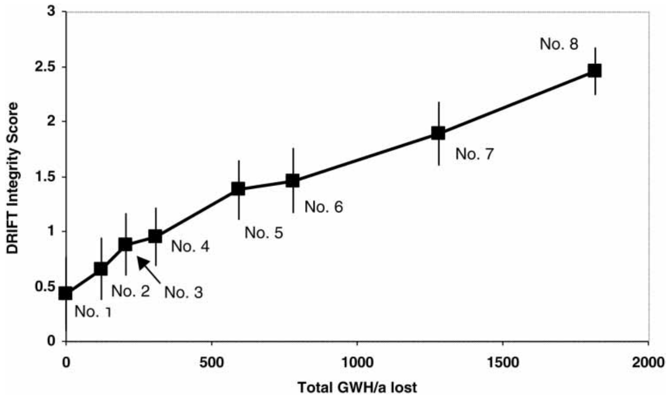

Figure 6 DRIFT CATEGORY plot for combined ratings of the 13 users/concerns assessed, showing the energy loss (in GWH a^{-1}) associated with each combined DRIFT Integrity Score for each optimized flow regime. Each point represents a complete scenario and each is numbered as per Table 3

as hydropower reduction (in GWH a^{-1}) linked to the provision of each scenario. The combined scores are expressed as DRIFT integrity ratings (Brown and Joubert 2003), and denote a move towards or away from the target state. Each of the data points in Figure 6 represents an optimized flow regime made up of a combination of the following:

- one of six levels of change in the dry season low flows (present day plus five changes);
- one of 19 levels of change in the annual flood (present day plus 18 changes);
- one of two levels of change in the 1:5 year flood (present day and one change);
- the remainder of the flow regime at present-day levels.

In every case, the optimization programme in DRIFT selected present day levels for dry season lowflows and for the 1:5 year flood, i.e. the only changes selected (and those deemed more important) were changes to the annual flood.

As noted above, the timing of the annual flood did not emerge as being as important as the magnitude and duration of the flood. This is illustrated by the change levels that were selected in order of most beneficial to least beneficial for the combined delta users (Table 5).

4 Discussion

4.1 *Potential conflicts/trade-offs among water users*

The study revealed minimal conflict (trade-offs) among different user-representatives with regard to reinstating environmental flows. The majority of user-representatives perceive reductions in the dry season lowflows as neutral or negative. The reasons for this are varied and include, for example, concerns about water supply for agriculture and navigation, salinity intrusion, and freshwater fish stocks and fisheries (Beilfuss and Brown 2006). The exceptions are the ratings from those user-representatives concerned with certain sub-components of biodiversity, as the reduced low flows would provide some much needed variability in the system. Of all the sub-components considered, the fate of the African Skimmer is probably most linked to reduced low flows in the delta, as extended low dry season flows are required for it to complete its breeding successfully (Coppinger *et al.* 1988). Inter-annual variability in low flows (e.g. a dry season flow reduction during particularly dry years every 3–5 years) would help in resolving this conflict by providing periodic breeding conditions for the species. Further hydraulic studies are needed to assess the impact of higher dry season low flows (DSLFs) on channel incision.

The majority of user-representatives perceive some form of reinstatement of the annual flood to be beneficial. Reasons cited include enhanced productivity of flood recession, riverbank, natural flood, and small-scale irrigation systems for the production of rice, maize, beans, and other important cash and food crops, estuarine and coastal ecology, freshwater fisheries, livestock and wildlife grazing grounds, and waterbird productivity, as well as floodplain water supply (groundwater recharge) (Beilfuss and Brown 2006). The exceptions to this were those user-representatives concerned with in-channel navigation and commercial agriculture. The DRIFT Integrity Scores provided by those two user-representatives suggest that although they would not necessarily benefit from annual flood releases, some releases (which could benefit other users) are not expected to negatively affect them.

The lack of preference for floods in February (the time of traditional peak flooding) over December was a surprising

Table 5 Annual flood change levels selected in order of most beneficial to least beneficial for the combined delta users

No.	% GWH a^{-1} lost (%)	DRIFT 'integrity score'	Loose translation of integrity score	Annual flood	Change level
1	0	0.43	*c.* 8% towards net target	December; 2 weeks; 4500 $m^3 s^{-1}$	1
2	2	0.65	*c.* 12% towards net target	February; 2 weeks; 4500 $m^3 s^{-1}$	3
3	3	0.80	*c.* 15% towards net target	December; 2 weeks; 7000 $m^3 s^{-1}$	7
4	5	0.95	*c.* 18% towards net target	December + January; 8 weeks; 4500 $m^3 s^{-1}$	5
5	10	1.22	*c.* 23% towards net target	December; 2 weeks; 10,000 $m^3 s^{-1}$	13
6	13	1.30	*c.* 25% towards net target	February; 2 weeks; 10,000 $m^3 s^{-1}$	15
7	21	1.82	*c.* 36% towards net target	December + January; 8 weeks; 7000 $m^3 s^{-1}$	11
8	30	2.30	*c.* 46% towards net target	December + January; 8 weeks; 10,000 $m^3 s^{-1}$	17

finding, and has significant management implications. The timing of the annual flood has particular relevance for hydropower generation at Cahora Bassa Dam. Flood releases during December are timed to coincide with the early stages of flood rise, and enable increased storage capacity in Cahora Bassa reservoir for the remaining flood season (Beilfuss and Brown 2006). Therefore, flood releases scheduled for December will serve to reduce the magnitude and frequency of major (emergency) flood discharges during subsequent peak flooding months. Flood releases during February, timed to the historical period of peak flooding, would have only a minor effect on the magnitude and frequency of emergency flood discharge, and may contribute in some years to extreme downstream flooding conditions. February releases may also significantly prejudice hydropower generation in dry years.

With respect to the 1:5 year flood, there was general agreement that these would be beneficial, especially for large-scale ecological processes. However, the negative social impacts of large floods were also acknowledged (including the potential danger to human life) as was the fact that many of the benefits of a 1:5 year flood would also be provided by a managed annual flood in December, which would have much lower negative social effects. Additionally, there was generally greater within-user conflict (i.e. trade-offs among specific sub-components) on the question of the reintroduction of the 1:5-year flood than there was for reinstating an annual flood.

Overall, reinstating the annual flood was singled out as the most valuable change that could be made to the delta flow regime. Under present day conditions, the occurrence of the annual flood is irregular and, when it does occur, its timing is erratic. While many users saw some benefit in the reinstatement of large flood events, such as the 1:5-year flood, and modest gains from the reduction of the dry season low flows, the benefits of these interventions were generally seen as lower than those for reinstating the annual flood, and in some cases the negative effects of large floods and reduced low flows were undeniable. Although different users may 'prefer' floods of somewhat different magnitude, duration or timing, the perceived benefits increase in the delta with an increase in magnitude and duration of the annual flood, provided it occurs sometime in December–February and is not catastrophic in magnitude or duration.

The DRIFT combined flow requirements reflect a situation where the requirements of each user were given equal importance. Some form of weighting may be desirable in the future to reflect stakeholder preferences or ecological thresholds for the delta.

4.2 *Potential conflicts/trade-offs between water users and hydropower generation*

While the benefits of annual flood releases to delta users may be clear, water releases nonetheless incur a cost in terms of lost hydropower generation (in terms of firm power guarantees and total annual energy production). In order for meaningful improvement in the delta to be achieved, some trade-off is necessary, and it seems likely that that trade-off will involve a reduction in hydropower generation.

Our hydrological and hydropower modelling indicates that the releases considered here are achievable. Of the 18 Annual Flood Change Levels considered, 7 can be generated with a firm power reliability $>95\%$ and hydropower reductions of $<2.3\%$ (Table 4). Sixteen of the 18 require $<10\%$ reduction in annual energy production, some of which could be offset by regional coordinated power production (Klaassen 2008, Southern African Power Pool 2008) or allowing a reduced frequency (i.e. lower target outflow reliability) for meeting environmental flow objectives during drought years (Beilfuss in review).

Whether or not these trade-offs are 'realistic' is a subjective assessment and cannot be made by the user-representatives involved in this study. While many may feel that the trade-offs required to improve the delta are both desirable and realistic, there may be compelling reasons for others why this is not so. The intention of the study is not to make decisions, but rather to provide objective information to facilitate communication and assist in decision-making.

In conclusion, the outcome provides a useful indication of the flow requirements for a range of Zambezi Delta uses and concerns. This study has illustrated that there is a strong and consistent requirement for water in the delta for most users, and a strong and consistent message that reinstating at least some of the historic flow patterns will result in significant improvement in many of the areas that have been shown to be of concern. Furthermore, the level of consensus between the user-representatives provides compelling substantiation of the views expressed by individuals and consensus between recognized experts has been shown elsewhere to have considerable legal influence in water allocation disputes. The analysis suggests that opportunities exist for socio-economic and ecological benefits in the delta that significantly outweigh their economic costs, with at least one scenario indicating the possibility of improvements with no reduction in power generation.

Acknowledgements

We are especially grateful to C. Bento of the University of Eduardo Mondlane-Mozambique and P. da Silva of the Gabinete do Plano de Desenvolvimento da Região do Zambeze for their long-term contribution to this work. We are indebted to D. Purkey, J. Timberlake, P. Funston, D. Tweddle, R. Silva, P. de Silva, E. Chonguica, R. Brito, A. Joubert, and J. King for their participation in this project. We thank the International Crane Foundation for their financial and administrative support for this project, and the Liz Claiborne and Art Ortenberg Foundation, World Wide Fund for Nature, and Gregory C. Carr Foundation for their funding support. Thanks also to B. Richter, T. Scudder, and three anonymous reviewers for their comments on earlier drafts.

Notes

1. We are aware that user-representatives, however knowledgeable and sensitive to realities on the ground, can never be a proxy for the voices of the people whose multiple experiences and daily lives shape their efforts to secure sustainable livelihoods. Our effort to capture these voices and bring them into the DRIFT modelling process via specialists included hundreds of hours of interviews with residents of the Lower Zambezi River Basin through a participatory rural appraisal process.
2. Based on turbine discharge at reservoir full supply level; actual turbine discharge will be lower as reservoir operating head declines during the dry season.
3. The impact of climate change on environmental flows was beyond the scope of the present study, but Beilfuss (in review) modelled the sensitivity of Cahora Bassa energy generation and target outflows to 10–20% reductions in Zambezi mean monthly flows.

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