Prescribed Flooding and Wetland Rehabilitation in the Zambezi Delta, Mozambique

R.D. Beilfuss[1] and B.R. Davies[2]
[1]International Crane Foundation,
P.O. Box 447, Baraboo, Wisconsin, USA.
[2]Freshwater Research Unit, Zoology Department,
University of Cape Town, South Africa.

1. The Impact of Dams on Zambezi Delta Wetlands

The mighty Zambezi, fourth largest river system in Africa, is the lifeline of southern Africa. From its headwaters in northwestern Zambia to its outlet 2,574 km downstream into the Indian Ocean, the Zambezi drains an area of 1,570,000 km^2 from eight countries and carries a mean annual flow of 2,400 $m^3 s^{-1}$ across the arid central African plateau (Balek 1977, Davies 1986). Some of the most important wetland areas in Africa, such as the Okavango Delta and Kafue Flats, are linked to the Zambezi system (Figure 1). Although few places evoke a sense of untamable African wilderness like the Zambezi, efforts to control the river and its tributaries behind large hydroelectric dams have greatly diminished the productivity and diversity of the river system. Nowhere have the consequences been more dire than in the great Zambezi Delta.

The Zambezi Delta in central Mozambique is a wetland system of profound conservation value. Of particular importance is the 5,000 km^2 Marromeu complex, located along the southern bank of the lower Zambezi River in the delta, which includes the protected Marromeu Buffalo Reserve and three managed hunting units (Figure 1). Prior to the development of the Zambezi River, the Delta supported a great diversity of wetland communities that were home to legendary

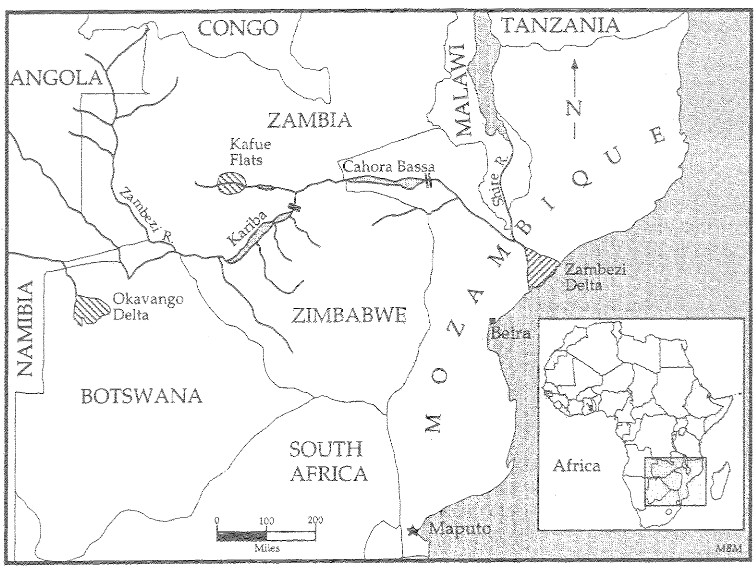

Figure 1. The Zambezi River system of Southern Africa.

W. Streever (ed.), An International Perspective on Wetland Rehabilitation, 143–158.

concentrations of African elephant (*Loxodonta africana*), cape buffalo (*Syncerus caffer*), and waterbuck (*Kobus ellipsipymnus*). The Delta provided spawning grounds for riverine and anadromous fishes and critical dry-season grazing lands for domesticated livestock and wildlife. Extensive coastal mangroves and estuaries supported a lucrative prawn fishery (Anderson et al. 1990, Gammelsrod 1996, Singini 1996).

Prior to the construction of Kariba Dam on the middle Zambezi River in 1959, peak floods inundated a mosaic of habitats in the 18,000 km^2 Zambezi Delta, flooding an area comparable in size to the Okavango Delta in Botswana (Tinley 1977, White 1993). Low-lying floodplains were saturated with sediment-rich Zambezi floodwaters for up to 9 months of the year. With the closing of Kariba Dam, approximately 50% of the total Zambezi runoff became regulated. The vast Lake Kariba, third largest reservoir in the world, now captures the transient early flood generated by local rainfall in the middle Zambezi catchment and effectively reduces and regulates the major annual flood from the upper Zambezi catchment area (Davies 1986). The reduction in downstream flooding desiccated the delta's rich alluvial soils, causing soil salinization and the invasion of upland, woody vegetation into the seasonal alluvial grasslands (Tinley 1975).

Despite these changes in the Zambezi's hydrological regime, river runoff below Kariba Dam was sufficient to seasonally inundate large expanses of the Delta until the construction of the massive Cahora Bassa Dam in 1975. With the closing of Cahora Bassa, the ancient floodcycles of the Zambezi River were lost and the hydrologic connection between the river and its floodplain was severed (Tinley 1975). The Shire River, the only significant tributary below Cahora Bassa dam, only contributes about 8% to lower Zambezi runoff. Most runoff is generated within the local catchment. The frequency, timing, magnitude, duration, and sediment load of Zambezi River floods now differ greatly from historic flooding conditions (Bolton 1983, Suschka and Napika 1990) (Figure 2). Beilfuss and Allan (1996) observed the lower Zambezi River more than 2 m below bankful discharge in the delta during the period when peak floods normally occurred. Inundation of the Zambezi Delta, when it occurs, is now dependent upon local rainfall-runoff within the lower Zambezi sub-catchment or unplanned (possibly catastrophic) water releases from upstream dams.

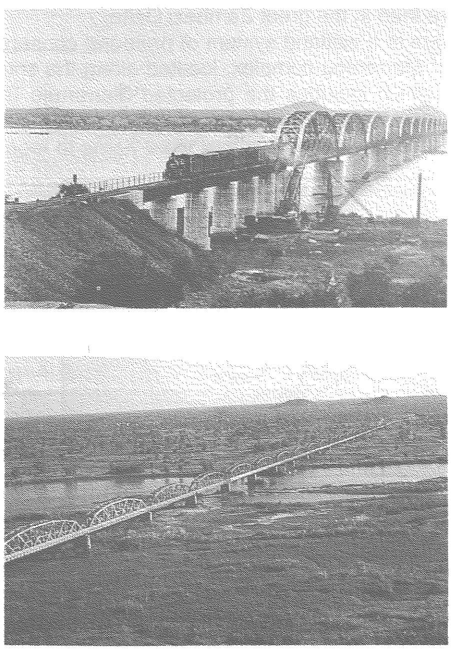

Figure 2. Peak flood discharge in the lower Zambezi River has been dramatically reduced and regularized by upstream dam construction. The top photograph shows the lower Zambezi River at flood stage in 1932, while the bottom photograph shows the same section at flood stage in 1996.

Hall and Davies (1974), Davies et al. (1975), and Tinley (1975) predicted severe consequences from these hydrological changes, including reduced artisanal fisheries and shrimp industry productivity, reduced silt deposition and nutrient availability, severe coastal erosion, saltwater intrusion, replacement of wetland vegetation by invasive upland species, reduction in coastal mangroves, failure of vegetation to recover from grazing, and disrupted or mistimed reproductive patterns for wildlife species. Recent research largely substantiates these predictions. The lack of natural, seasonal variation in flow has resulted in a precipitous decline in the delta prawn fishery (Gammeslrod

1996, Hoguane in press). Anderson et al. (1990) observed the delta as much drier at the end of the dry season than under natural conditions, with a reduction in wetland and open water areas, infestation of stagnant waterways with exotic vegetation, and intrusion of saltwater. Villagers attribute the failure of their grazing, fishing, and flood recession agriculture practices to the dam (T. Scudder, Personal Communication). There is widespread encroachment of woody savanna species onto the herbaceous floodplain. The desiccation of the floodplain has also opened the area to aggressive poaching of wildlife species, with a 95% or greater reduction in Cape buffalo, waterbuck, reedbuck (*Redunca arundinum*), zebra (*Equus burchellii*), and hippopotamus (*Hippopotamus amphibius*) between 1979 and 1995 (Tello and Dutton 1979, Anderson et al. 1990, Beilfuss and Allan 1996) (Figure 3). Grassland fires are widespread across the dry plains (Anderson et al. 1990). Although the Delta still supports major concentrations of waterbirds and one of the largest colonies of Eastern White Pelicans (*Pelecanus onocrotalus*) in southern Africa, there is no evidence of breeding success among several flood-dependent waterbird species of international concern, including the Wattled Crane (*Bugeranus carunculatus*) and African Skimmer (*Rhynchops flavirostris*) (Beilfuss and Bento in press) (Figure 4).

This case study documents the scientific and political process undertaken to begin rehabilitation of the Zambezi Delta as part of a comprehensive program for the integrated development and ecological restoration of the lower Zambezi basin. The overall program, an interdisciplinary collaboration among Mozambican, South African, and North American researchers and decision-makers, aims to conduct the fundamental hydrological, socio-economic, and ecological research necessary to test the hypothesis that artificial flood releases are an effective tool to restore and enhance key ecological processes and local production systems in the lower Zambezi system, and that incorporation of an annual controlled flood into the procedures for operating the Cahora Bassa Dam is the optimal use of Zambezi water. The program also aims to make policy recommendations as to how the dam should be operated in the future.

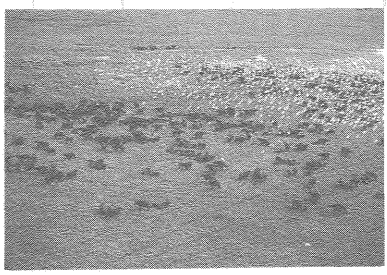

Figure 3. Cape buffalo feeding in the Marromeu Complex of the Zambezi Delta. Prior to dam construction, the Zambezi Delta supported the largest herd of Cape Buffalo in southern Africa.

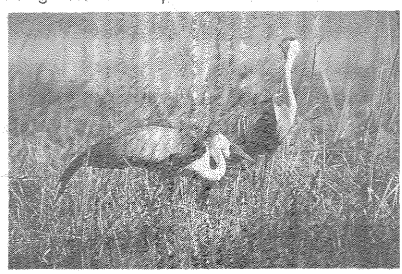

Figure 4. Wattled Cranes breed during peak flood conditions, feeding their chicks on the pulse of plant and insect life that follows receding floodwaters. Although present in large numbers, Wattled Cranes may no longer be breeding in the degraded floodplains below Cahora Bassa Dam.

The rehabilitation process for the Zambezi Delta involves 1) identifying the role of prescribed flooding as a strategy for restoring wetlands in the lower Zambezi system, 2) designing a prescribed flooding regime for the lower Zambezi system from available hydrologic and geomorphic data, subject to dam design limitations and changes in river hydrology, water quality, floodplain ecology, and land use and settlement patterns, 3) building institutional support to accept and implement the rehabilitation strategy, and 4) establishing a research program to model, monitor, and evaluate the effectiveness of prescribed flooding for rehabilitating the delta. These steps are described below.

2. Prescribed Flooding as a Strategy for Wetland Rehabilitation

The past 40 years of water resource development on the Zambezi River has overwhelmed all other human impacts on the Zambezi Delta. Although basin resources have been utilized for shifting cultivation, bee-keeping, logging, cash cropping, and intensive hunting activity for centuries (Tinley 1977), much of the delta remains undeveloped with only limited areas of agricultural and industrial activity. Any efforts to rehabilitate these floodplain wetlands must therefore begin with improving the hydrological regime of the river basin (see Bayley 1991, Petts 1996, Stanford et al. 1996). The management strategy that offers the best potential for fully restoring the natural ebb and flow of the Zambezi River and its hydrologic connection with the delta floodplains is removal of the upstream dams. Where dams are no longer serving a useful purpose or require expensive repairs, removal is increasingly advocated (Shuman 1995, Collier et al. 1996). However, this strategy is clearly not consistent with the current development aims of Mozambique and the lower Zambezi basin, which stipulate intensive hydroelectric power generation, transportation, and commercial irrigation (Posada and Woort 1996). Local initiatives, such as the removal of abandoned railroad dikes that prevent Zambezi distributary flows from reaching parts of the delta, may lead to some improvement in the water regime but do not operate at a broad enough scale to affect conditions across most of the delta (P. Dutton, Personal Communication). The best available option for river basin managers is therefore to simulate historic hydrologic conditions in the lower Zambezi system through scheduled flood releases from upstream dams.

The use of prescribed flooding for the benefit of downstream communities and ecosystems has gained worldwide attention in recent years. In the western United States, artificial flood releases from large dams are being tested to meet instream flow requirements for riverine habitats, salmon fisheries, and recreational demands (Stevens and Wegner 1995, Collier et al. 1996). In helping rebuild sandbars, beaches, and backwater areas along the Colorado River, for example, controlled flooding from Glen Canyon Dam is demonstrating that prescribed floods can have beneficial effects and that dam management strategies can be developed to allow for such periodic events (Stevens 1997, Vaselaar 1997).

In Africa, the role of artificial flood releases below large dams is gaining acceptance as a strategy for integrated rural development (Acreman 1994). In the Komadugu-Yobe basin of Nigeria, there is unanimous consensus among policy-makers, scientists, and river basin managers that artificial flooding should play a central role in the integrated development of the river basin. As a result, wet season floods were released from Tiga and Challawa Gorge Dams in 1994 (Polet and Thompson 1996). Controlled flood releases in the Pongolo River Basin in South Africa provide recession irrigation, grazing, and water supply to downstream users. Flood release schedules are dictated by the community, through Water Committees organized among fourteen wards that represent the views and needs of the 70,000 inhabitants of the Pongolo floodplain (Bruwer et al. 1996). Research downstream of Manantali Dam in the Senegal River basin has demonstrated that controlled flood releases could be combined with existing demands for hydropower output to benefit more than 500,000 floodplain farmers (Horowitz 1994). In Cameroon, the Waza Logone flood restoration study is exploring the role of artificial floods in restoring the natural and socio-economic value of the Logone floodplain downstream of Maga Dam. Researchers are assessing the effects of various water management options on floodplain inundation for fisheries, agriculture, and grazing (Wesseling et al. 1996). In South Africa, an inexpensive, site-specific workshop technique has been developed to assess ecologically sensible flood flows and low flows for specific rivers and specific water-development projects. The technique, Instream Flow Requirements (IFR), uses experts in a simple iterative process known as the "building block methodology" (King and Tharme 1994, Tharme 1996). A picture of the "minimum flow" requirements is rapidly built for the river under consideration and the seasonal variability necessary to maintain basic ecological functioning of the system is then built into the operational rules for the relevant water development project.

Such artificial flooding regimes also offer enormous potential for the rehabilitation of floodplain ecosystems such as the Zambezi Delta. Re-establishing the physical and biological connections between the main channel, backwaters, and floodplains is central to the rehabilitation of river systems (Gore and Shields 1995). Stanford et al. (1996) argue that the loss of biodiversity and habitat heterogeneity associated with dams can be ameliorated in part through restoring flood peaks and baseflows. Nutrient-rich flood pulses can stimulate primary productivity and enhance overall biological productivity across river-floodplain systems (Junk et al. 1989, Bayley 1995). The alternating wet and dry phases of natural flood cycles create and maintain the dynamic mosaic of channel and floodplain habitats that help support the diverse and productive flora and fauna of floodplains (Bayley 1991, Stanford et al. 1996). Re-establishing the hydrologic connectivity between river and floodplain through flooding events is also integral to the diversity and resiliency of riverine fisheries (Welcomme 1995).

The observed benefits of the few flood pulses that have been released from Cahora Bassa Dam over the past 25 years further suggest that prescribed flood releases may be an important tool for the rehabilitation of the Zambezi Delta. After emergency flood releases from the dam in 1977-78, floodplain conditions improved dramatically for local flora and fauna and were maintained for nearly 2 years afterwards (P. Dutton, Personal Communication). Marked increases in Cape buffalo and waterbuck were observed on the floodplain grasslands, and encroaching upland vegetation receded from the floodplain (Anderson et al. 1990, Chande and Dutton in press). Hydrological conditions in the delta also showed marked improvement when, after more than a decade of drought, emergency flood releases led to overbank flooding in 1997. Waterbird populations were more abundant and more widely dispersed (Beilfuss and Bento in press). The flushing of stagnant waterways in the floodplain led to perhaps 10-20% reduction in cover by invasive floating aquatic plants such as *Azolla filiculoides* and *Eichhornia crassipes*.

Rehabilitation efforts for the Zambezi Delta will thus aim to implement an artificial flooding regime that will re-establish, to the extent possible, historic hydrological conditions and variability in the lower Zambezi system. Some researchers challenge the assumption that "natural is best" when critical processes and linkages are fundamentally changed by dam construction (Stevens and Wegner 1995). They argue that if pre-dam ecological conditions cannot be accurately known (as is the case of the Zambezi system), it is very difficult to set standards for restoration success. Alternatively, in the face of highly altered river systems, where hydrological requirements vary among individual species and communities, an argument can be made that the first step should be to mimic historic flooding conditions, including intra-annual and inter-annual variability, and allow downstream communities to respond accordingly (Sparks et al. 1990, Bayley 1991). Different waterbird species in the Marromeu Complex of the Zambezi Delta, for example, utilize a variety of different habitats in response to heterogeneous hydrologic conditions that cannot be recreated without more natural flooding patterns (Beilfuss and Bento in press). Similarly, flood recession agriculture, livestock grazing, and other agricultural activities along the river margin of the delta require spatial and temporal variations in hydrologic conditions (Scudder 1989). Rather than optimizing water regimes for one or a few species or water users, a better approach is to approximate the natural flow regime that previously maintained the entire suite of species and uses (Sparks 1995). The goal is therefore to facilitate the natural re-expression of the lower Zambezi river system to its historic capacity (Stanford et al. 1996).

This is not to say that the aim of re-establishing historic hydrologic conditions in the lower Zambezi system is to re-establish a pristine, undeveloped Zambezi Delta. Few countries, especially Mozambique, could afford not to exploit the rich resources of this immense floodplain system. Rather, the goal is to re-establish a hydrologic regime that will restore the dynamic processes and local production systems that were once part of the delta ecosystem. The living standards of tens of thousands of deltaic and riverine households are intimately linked to the natural ebb and flow of the Zambezi River (T. Scudder, Personal Communication) and are integral to the rehabilitation of the lower Zambezi. Ultimately, the rehabilitation process must be iterative and adapt to knowledge gained from observing the downstream effects of carefully-planned water releases (Stanford et al. 1996).

3. Simulating the Historic Flood Regime of the Lower Zambezi: Opportunities and Constraints

Efforts to simulate the historic flood regime of the Zambezi Delta require extensive data on the hydrology and geomorphology of the Zambezi system. Hydrological data from 1930 to the present from several gauging stations are being used to characterize the flow regime of the Zambezi River and its tributaries (for example, timing, magnitude, and duration of annual extreme maximum and minimum flow conditions, as well as flood frequency distributions) prior to Kariba Dam, after Kariba but prior to Cahora Bassa Dam, and under current conditions (Balek 1977, Davies 1986, Suschka and Napika 1990). Runoff contributed to the central delta from the lower Zambezi basin below Cahora Bassa Dam is estimated as the difference between streamflow and baseflow data at the Marromeu gauging station and known discharges from the dam. Inter-annual variation in inflow from among the lower Zambezi tributaries (Revue, Luenha, and Shire Rivers) is modeled independently from stream gauging data. The depth of the Zambezi River for a given flood flow is estimated using stage-discharge rating curves computed from long-term data at Marromeu. Using these data and detailed topographic maps, the depth, duration, and extent of inundation in the delta will be modeled for given discharges from the dam.

As with the historic flooding regime of the lower Zambezi, the simulated flooding regime should be variable in the timing, magnitude, and duration of annual flood releases. Such variability should reflect, to the extent possible, annual fluctuations in climate and runoff in the Zambezi basin. This model predicts that the full range of natural intra-annual and inter-annual variation of hydrologic regimes is necessary to truly sustain the native biodiversity and evolutionary potential of floodplain ecosystems (Sparks 1992, Richter et al. 1996). Periodic larger floods, characteristic of the historic Zambezi system, may serve to reset parts of the floodplain by flushing accumulated organic matter and nutrients from peripheral swamps and dispersing seed propagules to the floodplain margin (for example, Bayley 1995, Bruwer et al. 1996).

Ideally, a water management program for the lower Zambezi system would consist of an integrated flood release strategy involving the coordinated management of both Kariba and Cahora Bassa Dams. Unfortunately, Kariba Dam was designed without any consideration for future water releases. Although Kariba's six sluice gates have a maximum discharge capacity of 9,515 $m^3 s^{-1}$ (roughly equivalent to the mean annual Zambezi flood peak prior to Kariba), the gates are installed near the crest of the dam and can only operate for emergency water releases when the reservoir is near capacity (Olivier 1977) (Figure 5, top).

Prescribed flood releases from Cahora Bassa Dam, however, are achievable. Cahora Bassa's eight sluice gates are located significantly lower on the dam wall (111 m below the crest) than at Kariba, and are below the average operating level of the reservoir (Figure 5, bottom). The discharge capacity of each of the eight sluice gates is approximately 1,650 m^3s^{-1} (Olivier 1977). When operated near maximum discharge capacity, the gates can create floods similar in magnitude to average pre-Kariba flooding events in the lower Zambezi (Suschka and Napica 1990). During a 5-day period in March 1978, 1.27 billion m^3 of water was released from Cahora Bassa to protect the dam from overtopping after water levels reached reservoir storage capacity. A maximum discharge rate of 14,753 $m^3 s^{-1}$ was achieved by opening the eight flood gates and emergency spillway simultaneously (Hughes and Hughes 1992). River flows in the lower Zambezi exceeded 20,000 $m^3 s^{-1}$ (Suschka and Napica 1990). In February 1997, two sluice gates discharged 2,088 m^3s^{-1} downstream during peak flooding in the Zambezi and combined with unusually heavy local runoff to inundate widespread areas of the delta (H. Silva, Personal Communication). It is thus physically possible to generate historic floods of varying magnitude and duration from Cahora Bassa Dam, depending on hydrologic conditions in the reservoir and local runoff conditions in the lower Zambezi sub-basin. Floods must be generated as step-wise releases building to peak discharge, rather than high volume pulse releases which often function more as flushing flows and fail to mimic the historic hydrograph (for example, Hollis 1996, Scudder and Acreman 1996, Stevens 1997).

The re-establishment of historic floodflows in the lower Zambezi system does not necessarily result in the re-establishment of historic flooding conditions, however (Scudder and Acreman 1996). The ecological integrity of river systems depends not only on the annual exchange of water with the floodplain, but also sediment, nutrients, organic and inorganic matter, and living organisms (Ward and Stanford 1995). Kariba and Cahora Bassa reservoirs capture most of the sediment load of the upper and middle Zambezi systems, releasing clear, hypolimnetic waters downstream (Bolton 1983, Suschka and Napica 1990). Although there are no data on erosion and sedimentation in the lower Zambezi, the widespread coastline erosion and mangrove dieback (perhaps 40%) in the delta may be resulting in part from the reduced sediment load (P. Dutton, Personal Communication). Physico-chemical changes in the lower Zambezi, including increased salinity, and changes in the composition and productivity of algal and plankton communities, are also associated with ecological change in the delta (Davies 1986, Suschka and Napica 1990).

Artificial flood releases from Cahora Bassa Dam will likely increase sediment transport in the lower Zambezi relative to current conditions. Flood discharges will result in considerable

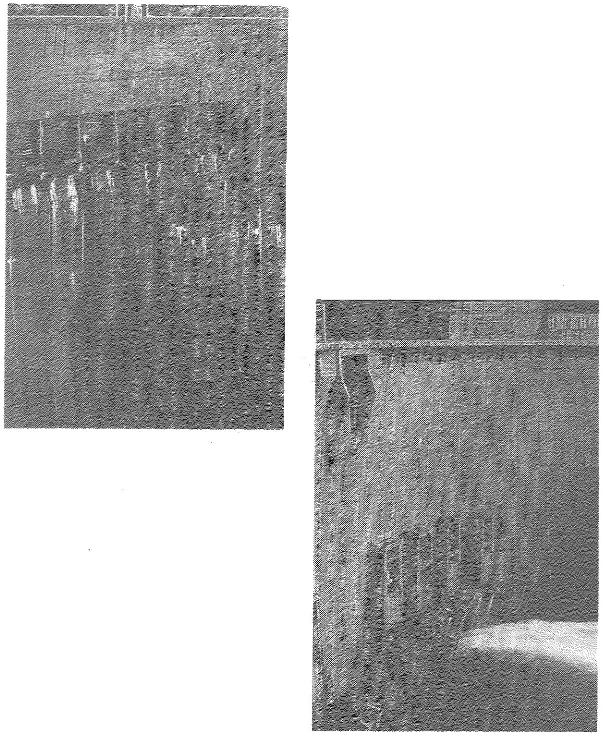

Figure 5. The six sluice gates at Kariba Dam (top) were installed too high to allow prescribed flood releases, but Cahora Bassa's (bottom) eight sluice gates can facilitate substantial flood releases.

channel degradation and sandbank scouring in the unstable alluvial stretches of the river along the 590 km course of the lower Zambezi to the coast (Suschka and Napica 1990). The magnitude and distribution of sediment transported to the delta under prescribed flooding conditions relative to historic flooding conditions, however, is unknown. Such processes are difficult to model, especially in combination with sediment inputs from lower Zambezi tributaries, and must be evaluated primarily from empirical data following flood releases.

The re-establishment of historic floodflows in the lower Zambezi system also does not imply that all of the ecological changes that have resulted from dam development can be reversed. Surface-floating water hyacinth (*Eichhornia crassipes),* salvinia (*Salvinia molesta*), and water fern (*Azolla filiculoides*) are now established in the delta waterways. Global efforts to eradicate these problem weeds, which effect flow patterns and community structure of floodplain waterways, have had limited success (Mitchell 1985). Rooted macrophytes from upland areas including barnyard grass (*Echinochloa crusgalli*) have also invaded abandoned anabranches in the delta, and a general shift towards less flood-tolerant species has been observed across the delta (Anderson et al. 1990). These effects are exacerbated by the dramatic decrease in grazing species utilizing the floodplain, including Cape buffalo, waterbuck, zebra, and especially hippopotamus, whose movements also help maintain open waterways (Tinley 1977, Chabwela and Ellenbrook 1990, Naiman and Rogers 1997).

Flood pulses that re-establish full hydrologic connection between the river and floodplain waterways should scour vegetation from many of these channels, as noted from observations of the 1997 floods. Depth and duration of flooding are the dominant edaphic controls on most floodplain vegetation (Denny 1993), and it is anticipated that flood releases that restore the historic patterns of floodplain inundation will tend to reverse the successional trend from wetland to upland vegetation. There is some evidence of this outcome from other prescribed flooding programs (for example, Bruwer et al. 1996), but most species-level and community-level responses to improved hydrologic conditions must again be ascertained from direct observations of prescribed flood releases. Relatively large flooding events may be necessary to remove upland trees that set seed and established in the floodplain in the absence of the annual flood.

In addition to recent geomorphic and ecological changes in the system, changes in land use and settlement patterns along the lower Zambezi system may also constrain prescribed flood design. Although there is little settlement in the Marromeu Complex interior, widespread encroachment is occurring in historically flood-prone areas of the lower Zambezi riverway (T. Scudder, Personal Communication). Most of the dwellings constructed, however, may be temporary structures erected for easier access to fishing areas (K. Wilson, Personal Communication). River terrace settlement was common and widespread along the lower

Zambezi prior to basin development to take advantage of overbank flooding events in the lower Zambezi (White 1993, Negrao 1995). Given the anticipated benefits of prescribed flooding for fisheries as well as flood recession agriculture, grazing, and groundwater access, temporary movement away from flood-prone areas may be acceptable during peak flood releases with an appropriate flood warning system and community-based rural development program in place. Further research and community-outreach will test these assumptions, but it is clear that the window of opportunity for implementing a prescribed flooding program will narrow with each passing year as villagers adjust their livelihoods in response to perceptions that the Zambezi River is permanently regulated.

4. Building Institutional Support for Zambezi Delta Rehabilitation

The management of Cahora Bassa Dam is integral to the economic development of Mozambique (Costa Braz in press). Management strategies for lower Zambezi waters must satisfy multi-sectoral demands for hydropower, transportation, and large-scale commercial irrigation, among others. Over the course of Zambezi basin development, water allocations to meet these demands have superseded the water-use needs of the subsistence communities and ecosystems of the lower Zambezi system. In fact, the vast social and ecological costs of Cahora Bassa Dam have never weighed into the economics of dam management (Bernacsek and Lopez 1984, Bolton 1986). Efforts to allocate waters for the rehabilitation of Zambezi floodplains must involve careful accounting of these costs and work towards building strong institutional support for water releases at local, regional, national, and international levels.

Rehabilitation efforts for the Zambezi Delta are thus approached as part of an integrated research program for the entire lower Zambezi basin, to assess the environmental, economic, and broader developmental advantages and disadvantages of different management strategies for Cahora Bassa Dam in terms of all the relevant stakeholders and ecosystem needs. Research elsewhere in Africa indicates that the best institutional strategy is one that balances the demands for hydropower, irrigation, and navigation, with the needs of subsistence communities and ecosystems that depend on historic flood cycles (Polet and Thompson 1996, Salem-Murdock 1996, T. Scudder, Personal Communication). Preliminary studies in Mozambique suggest similar findings for the lower Zambezi system. Research by Hoguane (in press) and Gammelsrod (1996), for example, implies that a slight reduction in hydropower output to accommodate increased flood flows and reduced dry season flows would result in a dramatic increase in shrimp production and harvest, netting millions of US dollars per annum in export sales. Anderson et al. (1990) and Chande and Dutton (in press) project a substantial economic return, in terms of trophy hunting and meat production, on restoring healthy populations of Cape buffalo and other game species that were decimated by illegal hunting following the desiccation of the floodplain grasslands below the dam. The economic impact of the Cahora Bassa Dam on flood recession agriculture, loss of crucial grazing at the end of the dry season, fisheries productivity, utilization of other natural resources involving both flora and fauna, groundwater access, and other activities, will also be quantified. These costs will be contrasted with the economic benefits of a water regime optimized solely for hydropower, commercial irrigation, or navigation (T. Scudder, Personal Communication).

To disseminate these findings to relevant policy makers and river basin managers, a series of workshops were slated. Most notably, the *Workshop on the Sustainable Use of the Cahora Bassa Dam and the Zambezi Valley* recently convened under the auspices of the Zambezi Valley Development Authority and the Arquivo do Patrimonio Cultural of Mozambique (Beilfuss 1997, Mavanga 1997). The workshop drew more than fifty scientists, managers, and decision-makers from Mozambique, southern Africa, and abroad, including the regional governor and two national ministers. Through invited papers, working groups, and discussions, participants educated themselves about the impacts of Cahora Bassa Dam on the hydrology of the Zambezi River and the consequences of these hydrological changes for the livelihood of human communities and for the flora and fauna of the Zambezi basin. Participants discussed the management of Cahora Bassa Dam to optimize use of Zambezi water for local development and conservation in addition to other national interests, and immediate actions to improve water management and build consensus among Zambezi users. Participants concluded that outflow from Cahora Bassa Dam must be managed such that simulation of the natural seasonal and inter-annual changes in water flow in the Zambezi River are re-established (Davies 1998).

Future meetings will challenge a widening circle of stakeholders and decision-makers until consensus is reached on an integrated management plan for the entire Zambezi basin, both upstream and downstream communities. This includes key international stakeholders concerned with hydropower sales from the dam, especially neighboring Zimbabwe and South Africa, and ultimately involves constituents of the proposed Southern Africa Power Pool (Paice 1995). Calls for the allocation of Zambezi waters to benefit Zambezi basin communities and ecosystems, in addition to other national and international development interests, are receiving increasing favor in the decentralized political system of Mozambique.

5. Assessing the Role of Prescribed Flooding in Wetland Rehabilitation: Research Needs

The rehabilitation of the Zambezi Delta is an adaptive management process. Researchers must model, monitor, evaluate, and adjust the prescribed flooding regime to meet wetland rehabilitation goals and success criteria. However, to date no quantitative research has been conducted on species-level, community-level, or ecosystem-level responses to flood releases in the Zambezi Delta or elsewhere in tropical Africa. Much of our knowledge must be gained empirically, from direct observation of short-term ecological responses to prescribed flooding events.

Prior to the release of an artificial flood, researchers are assessing the historic and present hydrological regime of the river-floodplain system, the state of the floodplain ecosystem under these different hydrologic regimes, and species-level, community-level, and ecosystem-level adaptations to different hydrologic conditions. From these data, the effects of different artificial flood discharges on the depth, duration, and timing of floodplain inundation will be modeled, and an attempt to predict both short-term (immediately measurable) and long-term responses of the floodplain ecosystem to these new hydrologic regimes will be made. Parallel research by project colleagues will model the social and economic benefits of Zambezi flooding.

The historic hydrological regime of the lower Zambezi system (prior to construction of Kariba) is best characterized by a suite of hydrologic parameters, including mean monthly magnitude of discharge, annual 1-day, 3-day, 7-day, 30-day, and 90-day maximum and minimum discharges, date of each annual 1-day maximum and minimum discharge, the number and mean duration of high and low flood pulses with each year, the means of all positive and negative differences between consecutive daily mean discharges, and the average number of rises and falls each year (for example, Richter et al. 1996). The historic frequency distribution of large floods, including the 2-year, 5-year, 10-year, 25-year, 50-year, and 100-year return period events, is approximated from the data series and supplemented by detailed historic accounts of great floods, as compiled by historians (G. Liesegang, Personal Communication). A similar hydrological analysis follows for the period 1959 to 1974 (Kariba Dam influence) and 1975 to present (Cahora Bassa and Kariba Dam influence), and is contrasted with the historic hydrologic parameters. These statistics both characterize the hydrologic alteration that has occurred in the system over the 40-year period of river basin development and provide target conditions for the lower Zambezi under prescribed flooding.

To assess historic changes in the Zambezi Delta ecosystem under different hydrological regimes, ecological parameters are analyzed at the species-level, community-level, and landscape-level. The distribution, deposition, and nutrient composition of silt in lower Zambezi floodwaters is compared to conditions that occurred prior to Cahora Bassa Dam (Hall et al. 1976, Jackson and Davies 1976). Research will quantify the release of organic and fine particulate matter from the dam and their effect on plankton and invertebrates at the base of the food chain (Hall et al. 1977, Davies 1986) and draw comparisons to other floodplain systems in tropical Africa. Research on historic changes in the diversity and productivity of lower Zambezi fisheries will draw from pre-impoundment research by Jackson (1986) and colleagues. Aerial and ground censuses of major game and non-game wildlife populations, conducted during the wet and dry seasons in accordance with the previous survey efforts, provide information on population dynamics and habitat utilization of key species and populations (Tinley and Sousa Dias 1970, Tello and Dutton 1979, Anderson et al. 1990, Beilfuss and Allan 1996). These surveys are supplemented by detailed field studies of the population structure and breeding ecology of key flood-dependent species, such as the Wattled Crane, that may provide insight on species-level response to restored flooding condition (Beilfuss and Bento in press).

Landscape changes in the major geomorphological features and vegetation communities of the Zambezi Delta are evaluated from successive 1:50,000 aerial photographs, 1:250,000 Landsat images, low-altitude aerial transect surveys, and ground reconnaissance photographs to cover the period since Kariba Dam was constructed (for example, Dunham 1989a, Anderson et al. 1990, Church 1995, Beilfuss and Allan 1996, Gurnell 1997). The number of major vegetation cover types and changes in the proportion of the floodplain occupied by each cover type over time will be determined. Several parameters related to habitat connectivity and the spatial arrangement of patches will be compared for each vegetation community, including frequency distribution of patch sizes, area-weighted mean patch size, and fractal dimension (O'Neill et al. 1988). The terrestrialization processes that have occurred, particularly the disconnection of braids (pleisiopotamon) and meander bends (paleopotamon) on the floodplain, will be assessed.

Possible causal relationships between changes in the historic flood regime of the lower Zambezi and changes in the biodiversity, biological productivity, and habitat heterogeneity of the delta will be estimated from related studies of the Zambezi system and other relevant tropical floodplains. Davies et al. (1975), Tinley (1975), Guy (1981), Davies (1986), Dunham (1989a), Dunham (1989b), Anderson et al. (1990), Suschka and Napika (1990), Massinga (1992), Dennis and Tarboton (1993), Beilfuss and Allan (1996), Masundire (1996), Beilfuss and Bento (in press), and others describe the qualitative changes in vegetation, geomorphology, or habitat heterogeneity that have occurred since dam development in the Zambezi system. Direct hydrological controls on the ecology or productivity of tropical floodplain vegetation are described by Junk (1970), Howard-Williams (1975), Gaudet (1977), Tinley (1977), Denny (1985), Howard-Williams (1985), Mitchell (1985), Thompson (1985), Payne (1986), Salo et al. (1986), Hughes (1988), Hughes (1990), Terborgh and Petren (1991), Patton and McKee (1995), Sutcliffe and Parks (1996), Thompson (1996), and others. Potential short-term responses (for example, metrics for breeding success of key species, water quality, propagule establishment) will be distinguished from long-term responses (for example, shifts in vegetation cover and geomorphological features) at different scales of data collection.

From these data, the effects of different artificial flood discharges on the depth, duration, and timing of floodplain inundation will be modeled, along with the short-term and long-term response of the floodplain ecosystem to these new hydrologic regimes (for example, Sutcliffe and Parks 1987, Hollis and Thompson 1993, Hollis 1996, Wesseling et al. 1996). To test these predictions, appropriate spatial and temporal scales of data collection before flood releases are established by researchers that will capture changes to the system following flooding events; this will allow correlation of certain short-term changes in the floodplain ecosystem with the hydrologic characteristics of prescribed flooding regimes (Amoros et al. 1987). The monitoring program, following from on-going research described above, addresses species-level and ecosystem-level response to prescribed flooding events. The ecological attributes of statistical sampling units (or habitat templates), defined by hydrology, geomorphology, and vegetation associations, are evaluated from remote sensing, aerial reconnaissance, and field studies (Bayley 1995). Long-term changes in the floodplain ecosystem must be assessed relative to the new prescribed flood regime (for example, changes in the mean annual magnitude, depth, and duration of flooding) because of uncertainties in linking most long-term (lagged) ecological shifts to individual flooding events.

Evaluation of success in rehabilitating the Zambezi Delta occurs at several spatial and temporal scales. At the broadest level, success is defined in terms of ecosystem processes, particularly the reintroduction of flooding in the lower Zambezi. How well the prescribed flooding regime mimics natural flooding in the lower Zambezi over a multi-year period will be examined. For example, to what degree does the mean and variance of the prescribed flood hydrograph (for example, magnitude, timing, and duration of river discharge) replicate the historic flood hydrograph? More detailed metrics are established at the landscape-level, community-level, and species-level to ascertain the degree to which prescribed flooding is achieving desired ecological responses. At the landscape level, for example, the degree to which vegetation cover types in the restored floodplain mimic historic vegetation patterns, as measured from pre-dam aerial photographs, will be assessed (for example, what is the percentage increase or decrease in open floodplain or swamp forest relative to historic conditions?). At the species level, success criteria are based on population parameters, and specific metrics can be compared among regional wetlands with differing hydrologic conditions (for example, how does the breeding success of the Wattled Crane population in the Zambezi Delta compare to that of other floodplain systems with relatively intact hydrology?).

The degree to which the prescribed flooding regime can be adjusted in response to ecological criteria depends in part on the effectiveness of the flooding in meeting socio-cultural and economic success criteria. Project scientists, decision-makers, and Zambezi basin stakeholders will assess the flood releases with respect to overall success criteria and evaluate whether rehabilitation efforts are meeting social, economic, and ecological needs in the lower Zambezi basin, and hence whether the project remains politically viable.

6. Conclusions: A View to the Future

Globally, researchers are examining whether large river floodplains can be "restored" to support viable communities and ecosystems (Gore and Shields 1995). The rehabilitation of river-floodplains must begin with an experimental approach in which hydrological restoration alternatives are evaluated in terms of clearly defined socio-economic and ecological parameters (Bayley 1995). African governments, managers, and scientists, with prescribed flooding programs underway in several nations and others under consideration, are leading this charge (Acreman 1994).

Implementation of a prescribed flooding program at the scale of the lower Zambezi basin is a long-term process demanding strong political will, community-outreach, and international scientific cooperation. Participants in the process must assess the role of prescribed flooding as a strategy for restoring wetlands and design an appropriate flooding regime for the lower Zambezi system, build strong institutional support to accept and implement the flooding strategy, and establish an adaptive management and research program to model, monitor, and evaluate the effectiveness of flood releases in restoring the diversity and productivity of the floodplain.

While great strides have been taken to bring this program to fruition, the dream of a rejuvenated Zambezi Delta is still a distant vision. The full realization of the ideas and recommendations of the Workshop on the Sustainable Use of Cahora Bassa Dam and the Zambezi Valley will require the on-going commitment of many individuals and institutions. Collectively, a fully inclusive master plan must be developed to guide the future of the Zambezi Basin. The alternative, a path of continued degradation and decline in the Zambezi Delta, would ultimately prove much more costly to the people and ecosystems of Mozambique.

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