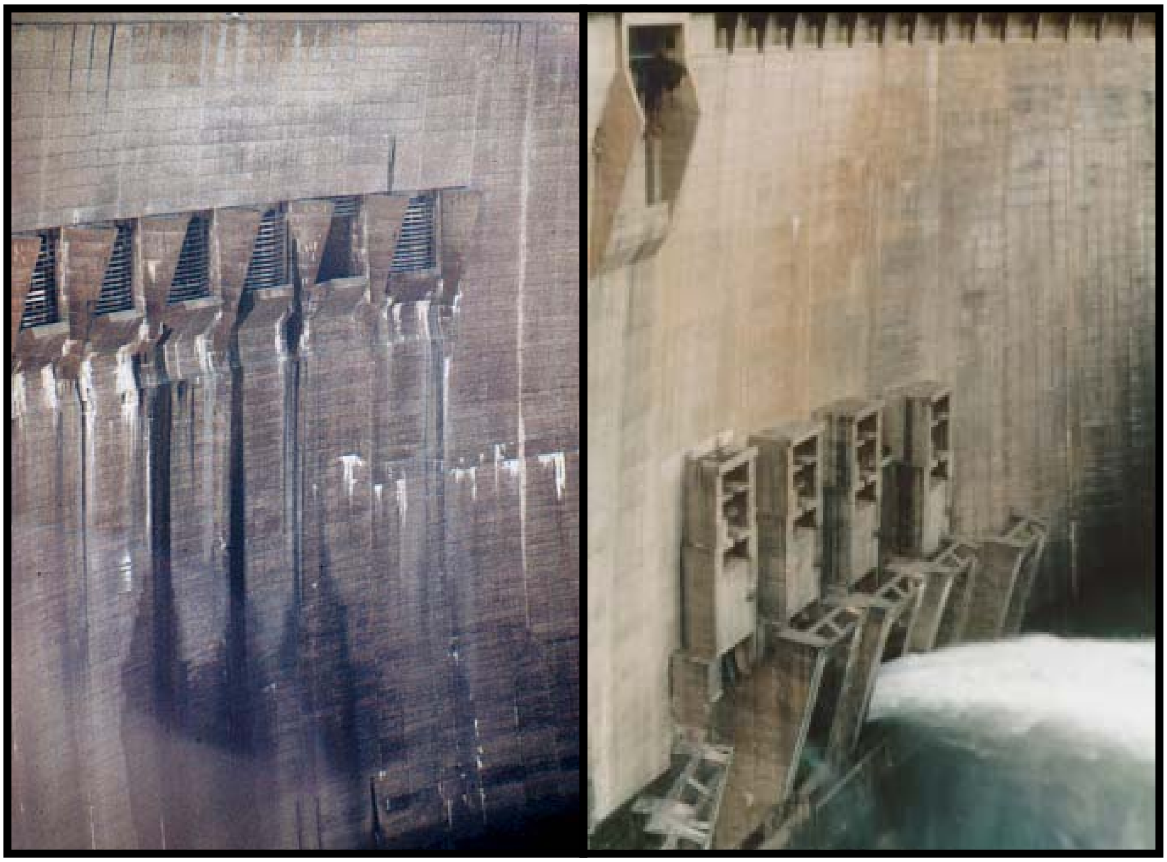
PRESCRIBED FLOODING AND RESTORATION POTENTIAL
IN THE ZAMBEZI DELTA, MOZAMBIQUE



WORKING PAPER #3
PROGRAM FOR THE SUSTAINABLE MANAGEMENT OF CAHORA BASSA DAM AND THE LOWER ZAMBEZI VALLEY

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WORKING PAPERS OF THE PROGRAM FOR THE SUSTAINABLE MANAGEMENT OF CAHORA BASSA DAM AND THE LOWER ZAMBEZI VALLEY

1. Wattled Cranes, waterbirds, and wetland conservation in the Zambezi Delta, Mozambique (Bento and Beilfuss 2000)
2. Patterns of hydrological change in the Zambezi Delta, Mozambique (Beilfuss and dos Santos 2001)
3. Patterns of vegetation change in the Zambezi Delta, Mozambique (Beilfuss, Moore, Dutton, and Bento 2001)
4. Prescribed flooding and restoration potential in the Zambezi Delta, Mozambique (Beilfuss 2001)
5. The status and prospects of Wattled Cranes in the Marromeu Complex of the Zambezi Delta (Bento, Beilfuss, and Hockey 2002)
6. The impact of hydrological changes on subsistence production systems and socio-cultural values in the lower Zambezi Valley (Beilfuss, Chilundo, Isaacman, and Mulwafu 2002)

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PRESCRIBED FLOODING AND RESTORATION POTENTIAL IN THE ZAMBEZI DELTA

INTRODUCTION

The past century of water resource development on the Zambezi River has resulted in significant adverse changes in the hydrological regime of the Zambezi Delta. The socio-economic and ecological consequences of these changes have been widespread and severe. The productivity of flood recession agriculture, fisheries, and grazing lands has declined. Widespread invasion of woody species into the delta grasslands, retrogression of coastal mangroves, displacement of wetland vegetation by less palatable upland bunchgrass species, and terrestrialization of abandoned waterways are evident. The process and patterns of change suggest that conditions will continue to deteriorate unless key indicators of hydrological change can be improved. Efforts to rehabilitate the delta floodplains must therefore begin with restoring the hydrological regime of the Zambezi system.

Prescribed flooding

Re-establishing the hydrological connection between the main channel, backwaters, and floodplain is fundamental to the rehabilitation of river systems (Gore and Shields 1995). Stanford *et al.* (1996) argue that the first step in ameliorating the loss of productivity and biodiversity associated with dams and embankments is to re-establish the natural pattern of flood peaks and baseflows. Nutrient-rich flood pulses stimulate primary productivity and food chain dynamics across river-floodplain systems (Junk *et al.* 1989, Bayley 1995). The alternating wet and dry phases of natural flood cycles create and maintain the mosaic of channel and floodplain habitats that help support the diverse and productive flora and fauna of floodplains (Bayley 1991, Stanford *et al.* 1996). The hydrological connection between river and floodplain is also integral to the diversity and resiliency of production systems (Scudder 1989), riverine fisheries (Welcomme 1995), and many wildlife species (*e.g.,* Sheppe and Osborne 1971, Bento *in press*).

In the Zambezi basin, there are relatively few alternatives available for restoring the natural rhythms of the river-floodplain system. Dam removal has gained worldwide attention as an important tool for restoring the hydrological regime of rivers (Shuman 1995, Maclin and Sicchio 1999), but the removal of Cahora Bassa Dam (despite its many problems) is not an option given the current development aims of Mozambique that encourage intensive hydroelectric power generation, transportation, and commercial irrigation in the lower Zambezi Valley (Posada and Woort 1996, Gabinete do Plano do Zambeze 2001). The once-annual discharge of surplus reservoir waters at the end of the dry season to increase storage capacity for the rainy season (*i.e.,* a variation on management practices currently in place) will produce mis-timed flooding patterns that will only worsen conditions for downstream people and wildlife. But the release of scheduled floods during the normal (historical) period of flooding offers enormous potential for benefiting farming systems and floodplain ecosystems while continuing to meet demands for hydropower, flood mitigation, and other economic development aims.

The use of prescribed flooding has gained worldwide attention in recent years as a tool for meeting Environmental Flow Requirements (*EFRs*) on regulated rivers (Michener and Haeuber 1998). 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, Adler 1996, Molles *et al.* 1998, 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 high volume, short duration flood discharges can have beneficial effects and that dam management strategies can be developed to allow for such periodic events (Stevens 1997, Vaselaar 1997).

In Africa, Scudder (1980) first suggested the importance of prescribed flood releases. Managed flood releases are gaining acceptance as a strategy for ameliorating the impacts of large dams and promoting integrated rural development (Acreman 1994). Although poorly understood from an ecological perspective, prescribed flooding has been shown to provide significant socio-economic benefits in several African basins.

In the Komadugu-Yobe basin of northeastern 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 have been released from Tiga and Challawa Gorge Dams (Polet and Thompson 1996). Barbier et al. (1997) demonstrated that the benefits of a unit of water for dam-induced large-scale commercial irrigation are less than for a unit of water released for the benefit of downstream floodplains and users.

Controlled flood releases in the Pongolo River Basin in South Africa provide recession irrigation, grazing, and water supply to downstream users. Initial efforts to restore the downstream floodplain through improved water management failed because flood releases were made at the inappropriate time of year and damaged floodplain crops (Bruwer 1997). Flood release schedules are now stipulated by the downstream 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).

Following a four year study in the Senegal River basin in the late 1980s, researchers from France, Senegal, and the United States convinced policy makers and planners in the Government of Senegal and the World Bank that controlled releases from the Manantali Dam could be combined with desired outputs of hydropower for the benefit of over 500,000 Senegalese residents (Horowitz and Salem-Murdock 1990). As in the Nigeria case, the study placed a dollar value on the various flood-related economic activities of local villagers for comparison with commercial irrigation. The comparison showed that the most economic strategy involved a slight reduction in waters allocated for hydropower generation and commercial irrigation in order to provide a controlled downstream flood (Horowitz 1991). Other studies are examining the value of prescribed floods for waterbird conservation in the Senegal Delta (Triplet and Yesou 2000).

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). Scholte *et al.* (2000) report on the potential benefits of floodplain rehabilitation for waterbirds at Waza National Park.

On the Tana River in Kenya, downstream flooding is vital to the livelihoods of thousands of people for subsistence agriculture, fishing, livestock rearing, and horticulture (Acreman *et al.* 2001). Tana River floodplains provide dry-season refuge for livestock and wildlife. But the Tana River is also important for meeting electricity demands throughout Kenya, and hydropower dams have been proposed. To meet these conflicting needs, engineers and planners are designing future dams to enable a wide range of prescribed flood releases as well as to generate hydropower (Japanese International Cooperation Agency 1997).

Within the Zambezi basin, prescribed flood releases were first considered in the Kafue River catchment. Itezhitezhi Dam was designed and constructed with the capacity to generate a prescribed flood of 300 m^3/s during a four week period in March for the maintenance of agricultural and biological productivity in the Kafue Flats (Scudder and Acreman 1996). Although the additional reservoir storage capacity increased project costs by 15%, the Ministry of Power, Transport, and Communication agreed to the plan because of the importance of the annual floods for aquifer recharge, alluvial deposition, flood recession agriculture, livestock grazing, and floodplain fisheries (Handlos and Williams 1985).

The role of prescribed flood releases to improve conditions in the lower Zambezi Valley was first proposed by SWECO (1983). SWECO proposed an environmental flow release (*freshet*) from Cahora Bassa to coincide with high flows from downstream tributaries. SWECO estimated that a release of $7 \times 10^9\ m^3$ during February, in excess of power generation needs, would create a desired flood peak of 9000 m^3/s in the Zambezi Delta region. While noting that the volume of water released in a freshet was less than the volume of a naturally occurring flood (and therefore different in effect from a natural flood), they predicted that flood releases would benefit natural vegetation, agricultural productivity, and the carrying capacity of grasslands by reducing soil salinization. They also predicted that the short-duration releases would reduce the growth of invasive aquatic macrophytes in river channels. SWECO noted that the benefits of freshets would be most pronounced during dry years, especially during periods of consecutive dry years. Despite the enormous potential of prescribed flood releases, the SWECO recommendations were ignored by Hidroeléctrica de Cahora Bassa (the Portuguese corporation charged with the management of the dam) and the Ministry of Public Works and Transport (the Mozambique government body charged with the management of water resources) even though the power station required negligible amounts of water between 1981-98 because the transmission lines were destroyed and the station was maintained on a 'care and maintenance basis only' (Li-EDF-KP Joint Venture consultants 2001).

These and other case studies from around the world demonstrate that, regardless of whether releases are targeted towards promoting rural development or biodiversity conservation, program managers must work closely with decision-makers and local communities to achieve an effective prescribed flooding program. Acreman *et al*. (2001) proposed a series of critical steps to successfully implement a prescribed flooding program in this context. Similar steps are now underway to establish a flood release program in the lower Zambezi catchment. These steps include:

- *establishing the links between floods and the floodplain ecosystem;*
- *defining objectives for flood releases;*
- *determining the structural feasibility of flood releases;*
- *defining flood release options;*
- *assessing impacts of different flood release options;*
- *determining the financial feasibility of flood releases;*
- *developing stakeholder participation and institutional support for releases;*
- *selecting the best available flooding option;*
- *establishing a monitoring program to evaluate flood releases;*
- *generating pilot flood releases; and*
- *providing feedback for the adaptive management of future flood releases.*

In this working paper, I examine the hypothesis that an effective prescribed flooding program can be implemented for the lower Zambezi Valley through these steps, with particular emphasis on modeling different flood release options from Cahora Bassa Reservoir. This paper builds on the findings of Working Papers #2 and #3, in which I assessed some of the key links between flooding and the delta ecosystem, towards elucidating the relationship between the productivity and diversity of the delta and the magnitude, timing, duration, and frequency of flooding events.

OBJECTIVES FOR FLOOD RELEASES

An effective prescribed flooding program must be based on clear and realistic objectives for flood releases. Objectives may be defined in terms of economic, social, or ecological criteria. These objectives should be defined in terms of desired benefits that are equitably distributed among stakeholders and contribute to fostering sustainable livelihoods on and around the floodplain (Acreman *et al.* 2001).

One of the most important national economic objectives for flood management in the Zambezi system, for example, is to increase productivity of the coastal prawn industry relative to current conditions (Hoguane 1997). But floodplain communities in the Zambezi basin will not support prescribed flooding efforts unless they also gain measurable social and economic benefits from flooding. Their objectives may include higher productivity of flood recession agriculture, improved catch-per-unit-effort in floodplain fisheries, and increased carrying capacity for animal husbandry. Objectives may also identify less tangible benefits related to the aspirations of dam-affected people (Acreman *et al.* 2001), such as improvements in food security, access to groundwater, health, or general well-being.

Ecological objectives are perhaps the most difficult to quantify, given the limitations of our knowledge about the response of many species of plants and animals to flooding patterns. There is no precedent for assessing the effects of managed flows on floodplain ecosystems, especially vegetation communities. Although we can probably never define exactly how much water the delta ecosystem and all its component parts need, we can identify specific ecological objectives and strive towards understanding how much water is needed to meet these targets. Economic objectives should be carefully selected to capture ecological responses that may not be directly measurable. For example, a sustained improvement in catch-per-unit-effort for floodplain fisheries may reflect improved fish feeding conditions on the inundated floodplains, more natural breeding behavior of riverine fish, and improved survival of young fish on the floodplains and in the river. Objectives to maintain delta biodiversity may be established at a species-specific level (*e.g.,* improve the breeding success of endangered Wattled Cranes or Cape Buffalo relative to current conditions). Objectives may also be established at a landscape level, such as targets for restoring certain characteristics of the natural vegetation community—especially as related to improving the palatability/carrying capacity of floodplain grasslands for large mammals. Objectives might target a reduction in the cover or rooted frequency of woody invasive species, bunchgrass species, or salt-tolerant species in areas of former freshwater stoloniferous grassland, relative to current conditions. The historical base maps and database described in Working Paper #3 were developed to provide a guide for establishing specific targets for vegetation restoration. Ecological objectives may also include altering the current patterns of other disturbance processes in the delta, such as a reduction in extent of dry season fires or shift in wildlife grazing patterns.

STRUCTURAL FEASIBILITY OF FLOOD RELEASES

The most fundamental consideration in assessing the feasibility of prescribed flood releases is whether the dam has been constructed to allow for flood releases (Scudder and Acreman 1996). The structural feasibility of flood releases includes adequate outlet capacity and reservoir storage volume to enable desired flood releases, and intakes designed to pass sediments downstream.

Ideally, a water management program for the lower Zambezi system would consist of an integrated flood release strategy involving the coordinated management of Kariba and Cahora Bassa Dams. Unfortunately, Kariba Dam was designed without any consideration for prescribed flood releases. Although Kariba's six sluice gates have a maximum discharge capacity of 9515 m^3/s (roughly equivalent to the mean annual Zambezi flood peak prior to Kariba), the gates are installed near the crest of the dam and are only operated for emergency water releases when the reservoir is near capacity (Olivier 1977). Thus, Kariba did not release any floodwaters in excess of minimum turbine requirements over a twenty-year period between 1981 and 2001 as reservoir levels remained below capacity.

Prescribed flood releases from Cahora Bassa Dam, however, are achievable. Cahora Bassa's eight sluice gates are located 111 meters below the crest, significantly lower on the dam wall than at Kariba, and are below the average operating level of the reservoir. The discharge capacity of each of the eight sluice gates is approximately 1650 m^3/s (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. During a five-day period in March 1978, 1.3×10^9 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 was generated by opening the eight floodgates and emergency spillway simultaneously (RPT 1979). Under normal operating conditions, the sluice gates may be operated independently, with partial openings, to generate step-wise releases building to a peak discharge, rather than single high volume pulse releases that do not reflect natural flooding conditions (*e.g.,* Scudder and Acreman 1996, Hollis 1996, Stevens 1997).

Mean annual inflows to Cahora Bassa are approximately 77.1×10^9 m^3 (see Working Paper #2). Total live storage capacity at the normal maximum operating level is 51.7×10^9 m^3, giving a capacity to inflow (*turnover*) ratio of 0.67 (Kariba, in comparison, has a turnover ratio of 1.6). Average annual turbine discharge is about 50×10^9 m^3 per annum, with the remaining inflows (more than 27×10^9 m^3 per annum) released as spillage through the sluice gates—waters that could be managed to generate prescribed flooding events. Because Cahora Bassa has inadequate capacity to store the 1:10,000 year design flood, operators must discharge reservoir waters downstream prior to the normal flooding season to create adequate storage capacity. Construction of additional emergency spillway capacity of about 5000 m^3/s at Cahora Bassa would enable the use of a Flat Rule Curve, allowing for greater flexibility in water release patterns and improved hydropower generation (see discussion below).

Cahora Bassa does not have an outlet structure designed to pass sediment downstream. This is probably the most serious limitation to the effectiveness of prescribed flood releases for the lower Zambezi. 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 1995a). Sediment inflows to Cahora Bassa are captured in part by Kariba and Kafue Gorge Dams[1], but the Luangwa River transports a heavy sediment load to the Middle Zambezi, much of which was deposited in the lower Zambezi Valley prior to Cahora Bassa (Hidrotécnica Portuguesa 1965b, Hall, Valente, and Burholt 1977, Bolton 1984b). Cahora Bassa Reservoir now captures most of the sediment load of the Middle Zambezi system, releasing silt free waters downstream (Suschka and Napica 1986). Several studies suggest a reduction in the supply of coarse sands to the delta during floods (SWECO 1983, Davies *et al.* 2001). Prescribed flood releases from Cahora Bassa Dam would likely increase sediment transport in the lower Zambezi relative to current conditions. High volume flood discharges will result in considerable 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 1986). The magnitude and distribution of sediment transported to the delta under prescribed flooding conditions relative to historic flooding conditions, however, is unknown. The construction of the proposed Mepanda Uncua Dam downstream of Cahora Bassa would further reduce sediment transport in the lower Zambezi.

MODELING FLOOD RELEASE OPTIONS

To examine the availability of water for prescribed flood releases from Cahora Bassa Dam, I adapted the HEC-5 model, *Simulation of flood control and conservation systems*, to model the Zambezi River system. The HEC-5 computer model was developed in its original form at the Hydrological Engineering Center of the U.S. Army Corps of Engineering in 1973, and has since been expanded to include operation for hydropower and required downstream flows. The current version of the program, HEC-5 Version 9, released in October 1998 (U.S. Army Corps of Engineers 1998), was used for the Zambezi simulations.

Model design and assumptions

HEC-5 is a multi-purpose, multi-reservoir routing program that enables the modeling of complex river-reservoir systems in considerable detail, using a simple water balance approach. The simulation includes diversions from the system for downstream water users, evaporation and rainfall on reservoirs, releases from reservoirs to meet hydropower demand or downstream flood requirements, and inflows to reservoirs either as they occur naturally or as modified by upstream system components. The system configuration is defined by routing reaches and specified downstream locations. Model data are defined starting at the upstream boundaries of the system, and data for each location are entered sequentially downstream. The most upstream location on each tributary must be a reservoir, with physical data to describe inflows, storage (volume-area-elevation relationships), outlet capacity, and operation locations. Hydropower reservoirs include specifications for installed capacity, overload ratio, tailwater elevation, power efficiency, and firm energy requirements. Downstream flow constraints and water use demands are specified at non-reservoir locations called control points. All locations, including reservoirs, require control point data that include routing criteria to the next downstream location. The entire reservoir system, based on reservoir and control point data, is defined in an ASCII data file, followed by the inflow data for the simulation.

Reservoir operation criteria are defined with respect to an index level for each reservoir storage zone. Level 1 is the top of the inactive (dead storage) pool, and no reservoir releases are possible below this level. Level 2 is the top of the buffer pool. When the reservoir level drops below the buffer pool level, a drought condition is indicated and only essential demands (designated as *required flows*) are met. Above the buffer pool, all water demands are met (*desired flows*). Level 3 marks the top of the conservation pool, the zone of normal reservoir operation for hydropower, diversions, and desired downstream flows. Level 4 is the top of the flood control pool. The zone between the conservation pool and the flood control pool is the active flood storage zone, where water is stored when it cannot be safely passed through the downstream channel system. Above the flood control pool is the zone of surcharge storage where the reservoir accommodates water above the emergency spillway level up to level 5, the dam crest.

For hydropower simulations, the HEC-5 program computes the energy requirements for each time period of operation. Either monthly energy requirements or period-by-period energy requirements can be used. The program cycles through the simulation one interval at a time, starting with an estimated average storage level using the end of the previous periods storage initially (S_1) and then the average of computed and end-of-period storage. Gross head is computed by subtracting tailwater elevation (based on a tailwater rating curve) from reservoir elevation (corresponding to estimated average storage). Reservoir releases (Q_o) are then computed as a function of gross head, firm energy requirements, and plant efficiency. Evaporation (E) is computed from reservoir area, based on average reservoir storage. Ending storage (S_2) is determined from reservoir inflows (Q_I) using the continuity equation, where $S_2 = S_1 - E + (Q_i – Q_o)$.

At the end of the first cycle, the program uses the new S_2 to compute the average storage level. On subsequent cycles, the new computed power release is compared to the computed power release computed for the previous cycle. If the difference is more than 0.0001, the program cycles again (up to five times). If the difference is less, the program proceeds to check the maximum energy that could be produced during the time interval using the overload factor and installed capacity, and checks that discharges are within the limit of maximum penstock capacity. The program also checks to determine if there is sufficient water storage to make the power release. If there is not sufficient water in storage, the program reduces the hydropower release to just arrive at the minimum pool level. If water storage is sufficient, the power release for the reservoir establishes the minimum flow for the site. The program then proceeds to the next time step.

Figure 4-1 provides a schematic of the reservoir routing system modeled for the Zambezi River using HEC-5. Water availability for potential prescribed flood releases from Cahora Bassa Dam is affected by Upper Zambezi and Gwembe Valley runoff routed through Kariba reservoir, Kafue runoff routed through Itezhitezhi and Kafue Gorge reservoirs, and unregulated Middle Zambezi runoff[2]. I used a one-month time step to model system inflows and outflows. Daily water levels are available to model the system only during 1975-98, a period characterized by the prolonged southern Africa drought from 1980-95. While this period clearly reflects recent hydrological conditions, it is not representative of water conditions over most of the past century nor of likely weather patterns during the next 25 years (Gasse 2001). The use of monthly data enables a long-term simulation covering the period 1907-98 that includes the full range of climatic conditions in the Zambezi basin.

Evaporation losses are computed from monthly averages for Kariba and Cahora Bassa Reservoirs, but monthly net means are used for the three Kafue River reservoirs. The model assumes continuous power generation through any month at each power station, and does not incorporate peaking operation. Turbine efficiency is modeled from the characteristic curves for turbines at Cahora Bassa, but a constant efficiency is assumed for Kariba and Kafue Gorge power stations which have a very small range of water level fluctuation. Similarly, friction head losses are assumed constant at all stations, because of the relatively low range of allowable water levels between dead storage and full storage. Maximum power output is equal to the installed capacity at each power station. Outflows are computed as turbine releases and spillage, including releases for downstream water requirements.

The criterion chosen for firm energy estimates for each hydropower station depends on the reliability level, the choice between total annual generation or monthly-based analysis, and the selection of an event-based (number of months during which the target firm output could not be met) or quantity-based (number of megawatts short of target) criteria. Firm power estimates for this study, following from the discussions in Shawinigan-Lavalin and Hidrotécnica Portuguesa (1990b) modeling studies, use event-based, monthly generation criteria. A firm power reliability of 95% (*e.g.*, failure to meet firm power demand no more than once in 20 months on average) is considered to be the minimum acceptable standard for power generation, although higher firm power levels are also investigated (Shawinigan-Lavalin and Hidrotécnica Portuguesa 1990b). Total power generation was estimated as average annual energy output.

Runoff from the Upper Zambezi and Gwembe Valley catchments is based on the times series data, 1907-98. The annual time series of monthly inflows routed through Kariba Reservoir is given in Figure 4-2. Kariba characteristics are based on the original design studies with recent revisions from the Zambezi River Authority (Table 4-1). Kariba Dam outflows are governed by hydropower generation requirements and the Design Flood Rule Curve (DFRC) which specifies how reservoir water levels are drawn down prior to each rainy season to provide additional capacity for safely storing and passing the design flood. Mean monthly evaporation is modeled using long-term data collected at Kariba meteorological station. The Kariba generating head depends on the relative water levels in the reservoir and tailrace sections.

Kariba Reservoir levels are based on fixed elevation-storage-area-outlet capacity relationships. Tailrace levels are based on specific stage-discharge relations. The total installed capacity of the two Kariba Power Stations is 1350 MW. Firm power is estimated as 730 MW continuous, based on a 95% reliability criterion determined in the Shawinigan-Lavalin and Hidrotécnica Portuguesa (1990b) and Batoka Joint Venture Consultants (1993b) studies. Minimum water releases for social or environmental purposes are not stipulated for Kariba Dam, as per current operating policy. Water diversions by riparian communities are considered to be insignificant relative to total Zambezi flows, and are not modeled explicitly.

Runoff from the Kafue catchment is routed through Itezhitezhi Reservoir, the Kafue Flats, and Kafue Gorge Reservoir. Inflows are based on the time series data for inflows to Itezhitezhi Reservoir, 1907-98. The annual time series of monthly inflows routed through Itezhitezhi Reservoir is given in Figure 4-3. Itezhitezhi operates to store floodwaters and release water for hydropower generation at Kafue Gorge downstream. Itezhitezhi Reservoir characteristics are based on the original design studies (Table 4-2). Evaporation from Itezhitezhi is calculated from Class A pan data. The outlet capacity is not critical because the gated spillways, bottom outlets, and power plant intake can be adjusted to release the desired amount of water during any month whenever there is water above the minimum operating level (Shawinigan-Lavalin and Hidrotécnica Portuguesa 1990a). The minimum operating level, or Lower Supply Level, is 1006.0 m amsl. The Full Supply Level is set at 1029.5 m. These two operating limits provide a live storage of 4.925 x 10^9 m^3. Releases from Itezhitezhi must maintain a continuous minimum flow of 25 m^3/s in all months except March, when a release of 300 m^3/s is stipulated to inundate the Kafue Flats.

The Kafue Flats is modeled as a natural (passive) reservoir to account for time lags in the movement of water releases from Itezhitezhi to Kafue Gorge (a distance of 400 km) and allow for evapotranspirative water losses from the floodplain (Table 4-3). As noted by Shawinigan-Lavalin and Hidrotécnica Portuguesa (1990a), estimates of tributary inflow between Itezhitezhi Dam and the Kafue Flats are not reliable because of the insufficient number of flow observations made on the tributaries of the Kafue River in this reach, and the high rates of evaporation in the flats. A simplified approach is used in which inflows to the Kafue Flats are modeled as a fixed proportion (20%) of inflows to Itezhitezhi. Shawinigan-Lavalin and Hidrotécnica Portuguesa (1990a) derived this proportion from rainfall-runoff modeling for the local Kafue Flats catchment. Outflows from the Kafue Flats are governed by a fixed stage-discharge relationship, based on rating curves for the Nyimba and Namwala gauging stations. Evapotranspiration from the Kafue Flats and Kafue Gorge Reservoirs are based on Class A pan data and meteorological data using the Penman (1948) formula.

Kafue Gorge is modeled as a run-of-river reservoir, with a Lower Supply Level of 972.0 m and a fully supply level of 976.6 m (Table 4-4). Live storage is 0.785 x 10^9 m^3. Because of the high head on the Kafue Gorge Dam, tailrace water level variations do not have a significant influence on turbine flows. A mean tailrace level of 581 m is used, with a net head of 395 m at fully supply level. The installed capacity at Kafue Gorge Dam is 900 MW. Firm power is estimated as 590 MW continuous, based on a 95% reliability criterion from Shawinigan-Lavalin and Hidrotécnica Portuguesa (1990a) studies. Existing water rights specify that 15 m^3/s must be released between Kafue Flats and Kafue Gorge Dam for non-power purposes.

Cahora Bassa Reservoir operates to store floodwaters and release water for hydropower generation. Cahora Bassa Reservoir characteristics are based on the design studies by Hidrotécnica Portuguesa (1965c) with recent revisions provided by Hidroeléctrica de Cahora Bassa (Table 4-5). Inflows are based on the time series data for the Middle Zambezi catchment, 1907-98, including runoff from the Luangwa River and other ungauged catchments. The annual time series of incremental monthly inflows from the Middle Zambezi catchment is given in Figure 4-4. These flows are combined with Kariba and Kafue Gorge Reservoir outflows to create the Cahora Bassa Reservoir inflow series. The minimum operating level, or Lower Supply Level, is 295.0 m amsl. The Full Supply Level is set at 326.0 m amsl. These two operating limits provide a live storage of 51.7 x 10^9 m^3. Evaporation from Cahora Bassa is based on Class A pan data.

The total installed capacity of the Cahora Bassa Power Station is 2075 MW. The generating head depends on the relative water levels in the reservoir and tailrace sections. Reservoir levels are based on fixed elevation-storage-area-outlet capacity relationships. Tailrace levels are based on specific stage-discharge relations. Firm power is estimated as 1370 MW continuous, based on a 95% reliability criterion used in the estimating Cahora Bassa outflows for the Mepanda Uncua Dam design studies (Li-EDF-KP Joint Venture Consultants 2000).

Cahora Bassa outflows are governed by these hydropower generation requirements and a flood rule curve, whereby the reservoir water levels are drawn down prior to each rainy season to provide additional capacity for safely storing and passing the design flood. Spillway discharges are based on all eight gates fully opened, with the crest gate operating for reservoir elevations above 327.0 m. Minimum water releases for social or environmental purposes are not stipulated for the baseline Cahora Bassa Dam model, but are modeled explicitly as different prescribed flooding scenarios. Water diversions by riparian communities are considered to be insignificant relative to total Zambezi flows, and are not modeled explicitly.

Hydropower reservoirs in the Zambezi system are assumed to operate independently. In theory, conjunctive operation of Zambezi reservoirs could significantly reduce water availability for prescribed flood releases by offsetting reservoir release patterns to optimize hydropower generation throughout the year. However, the strong regional influence of the ITCZ on climatic patterns in the Zambezi catchment, particularly between the Upper Zambezi and Kafue catchments, limits the opportunity for increased output through conjunctive operation. Shawinigan-Lavalin and Hidrotécnica Portuguesa (1990b), Batoka Joint Venture Consultants (1993b), and Li-EDF-KP Joint Venture Consultants (2000) compared conjunctive and independent operation of Zambezi hydropower dams and found only a slight increase in total system firm power output. Given this, and the long-standing lack of cooperation between Zimbabwe, Zambia, and Mozambique on interbasin development issues, conjunctive operation is deemed to be highly unlikely in the foreseeable future.

Hydropower stations proposed for future development in the Zambezi system were also not modeled. Upstream of Cahora Bassa, these include the Kafue Gorge Stage 3 (450 MW) and Itezhitezhi Dam Power Plant (80 MW) on the Kafue River, and Batoka Gorge Power Plant (1600 MW), Mupata Gorge Power Plant (1085 MW), Devil's Gorge Power Plant (1000 MW), Katombora Reservoir and Victoria Falls South Bank development (390 MW), Kariba upgrade (an additional 300 MW at the North Bank Station Power and 84 MW at the South Bank Station power plant) (Shawinigan-Lavalin and Hidrotécnica Portuguesa 1990b). Any of these dams could reduce the opportunity for prescribed flooding releases by further stabilizing the Zambezi flood regime, but their development requires international cooperation and co-financing between Zambia and Zimbabwe and is unlikely in the current political climate.

The proposed Cahora Bassa North Bank (up to 1600 MW) and downstream Mepanda Uncua (up to 2400 MW) hydropower developments could have a very significant effect on the opportunity for prescribed flooding. Mepanda Uncua will generate approximately 1348 MW at a Full Supply Level of 205-207 m amsl (Li-EDF-KP Joint Venture Consultants 2000). Mepanda Uncua will be a run-of-the-river structure designed to pass flood releases (prescribed or emergency) from Cahora Bassa, but will be operated for peaking power in tandem with Cahora Bassa, and therefore will affect the overall

management of the Zambezi flow regime. The Cahora Bassa North Bank project would increase power production at Cahora Bassa by 882 MW (Li-EDF-KP Joint Venture Consultants 2000). Operation of Cahora Bassa North Bank would require a higher average daily turbine outflow, increasing the need for flood storage during the wet season to meet dry season turbine requirements. Cahora Bassa North Bank has also been proposed for peaking operation. The effects of these dams on water availability for prescribed flood releases will be investigated further when design parameters are established.

Sensitivity testing

After establishing the baseline parameters for modeling the Zambezi system using HEC-5, I generated preliminary output to define a reliable inflow series for Cahora Bassa Reservoir. Inflows were routed through Kariba and Kafue Gorge Dams, with output compared to observed operational levels and results from previous system hydropower studies (Shawinigan-Lavalin and Hidrotécnica Portuguesa 1990b, Batoka Joint Venture Consultants 1993b). Physical model parameters were adjusted until they closely replicated patterns of turbine outflows, reservoir storage levels, firm power output, and total power output from existing dams.

Outflows from Kariba and Kafue Gorge Dams and incremental inflows from the Middle Zambezi catchment were then routed through Cahora Bassa Reservoir to generate baseline levels for firm power level and reliability and total power output, based on default settings including the current Design Flood Rule Curve for reservoir operation[3]. Each parameter was varied to test for the sensitivity of model output to the input data. The parameters include friction head loss, reservoir evaporation, and flood rule curve operation at Cahora Bassa, and firm power generation at Kariba and Kafue Gorge hydropower stations (Table 4-6). Each parameter was increased to the maximum probable level within the expected range of operating conditions.

Use of the Flat Rule Curve (FRC), with a fixed end-of-month water level of 326 m amsl[4], depends on the construction of an additional spillway to fully pass the 1:10,000 year design flood. Other parameters including turbine efficiency and net operating head, based on recent rating curve data, are considered to be reliable and unlikely to undergo significant revision (Batoka Joint Venture Consultants 1993b). Upstream water diversions were deemed to be very unlikely to increase to a level that would significantly alter Cahora Bassa inflow patterns in the near future, although Botswana, Namibia, and especially South Africa have long sought to divert Zambezi waters to meet regional water needs (Scudder 1993, Basson 1995).

Table 4-6. Parameters tested for sensitivity to Zambezi system model output. The baseline case (A-0) uses the default setting for each parameter tested. Other model parameters were deemed to have negligible influence on model output, and were not tested for sensitivity.

Case	Parameter	Default setting	Sensitivity test
A-1	Friction head loss	1.5 m	3.0 m (increased by 100%)
A-2	Net evaporation	Monthly mean values	Monthly means increased by 20%
A-3	Flood rule curve	Design Flood Rule Curve, with specified end-of-month levels	Flat Rule Curve, with fixed 326 m amsl maximum level for all months
A-4	Kariba firm power	730 MW (current output level)	810 MW (increased ~10%)
A-5	Kafue Gorge firm power	590 MW (current output level)	648 MW (increased ~10%)

The sensitivity of Cahora Bassa hydropower generation to changes in various input parameters is given in Table 4-7. Large increases in friction head loss (Case A-1) and net evaporation (A-2) result in a negligible reduction in firm power reliability and total power output. Increases in Kariba firm power output (A-4) generate higher turbine outflows and reduce the frequency of spillage, hence reducing the variability of inflows to Cahora Bassa Reservoir and slightly increasing annual power production. The reduced reliability of Kariba output at this higher generation level, however, results in more frequent turbine shutdown at Cahora Bassa with a decrease in firm power reliability. The effect of changes in Kafue Gorge firm power output (A-5), which controls a much smaller proportion of the total Zambezi catchment, is negligible. Given the relatively low sensitivity of hydropower output to these four input parameters, even with the large increases tested, the default settings are considered to be sufficient for modeling system hydropower generation.

Table 4-7. Results from tests of parameter sensitivity on firm power reliability and annual power production.

Case	Test	Target power (MW)	Reliability (%)	Total annual power (GW)	Power as % of default settings
A-0	Default	1370	98.4	14392	100.0
A-1	Friction head loss	1370	98.3	14338	99.6
A-2	Net Evaporation	1370	98.3	14317	99.5
A-3	Flood rule curve	1370	99.2	14912	103.6
A-4	Kariba firm power	1370	97.3	14462	100.5
A-5	Kafue Gorge firm power	1370	98.4	14375	99.9

The choice of flood rule curve, however, has a very significant effect on power generation at Cahora Bassa Dam. The FRC, with a constant end-of-month water level of 326 m amsl, resulted in significantly higher levels of firm power reliability and total power generation than the current DFRC. This relationship holds across the range of possible firm power target levels (Figure 4-5). Furthermore, the adoption of a FRC for Cahora Bassa management may be fairly likely in the near future. Li-EDF-KP Joint Venture Consultants (2000) recently proposed that construction of additional spillway capacity at Cahora Bassa should coincide with the construction of any future downstream run-of-river dams such as Mepanda Uncua. Based on these findings, each of the prescribed flooding model scenarios were run under two conditions, one using the current DFRC and one using the FRC. These scenarios are described below.

Prescribed flooding scenarios

I modeled 22 prescribed flood scenarios as case studies (Table 4-8), with Case A outflows as the default settings (*i.e.*, with no specified outflows). For each scenario, I generated firm power output for each month, and calculated firm power reliability as the percentage of months out of the total (1092 months) that firm power requirements are met or exceeded. I calculated total power output as the annual mean of the total power generated over the 91-year inflow series. Target outflow reliability is 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. For example, with a firm target of 1370 MW under current operating conditions, a January release of 5000 m^3/s is possible in 84 years out of the 91-year time series (a 92.3% reliability). The percentage of years that these outflow levels occur under baseline conditions (with no target outflows) is also given for each case study.

The first four scenarios involve prescribed outflows designed to mimic historical mean monthly flooding patterns. Case B outflows are based on setting monthly continuous release targets to replicate the monthly means for the four peak flooding months (January-April) based on unregulated inflows from the 1907-98 time series data. Case C and D outflows are based on the monthly means from first three (January-March) and second three (February-April) peak flooding months, respectively, and Case E outflows are based on the monthly means from the two peak flooding months of February and March.

The remaining case studies examine the potential to generate short-duration, high volume flood

Table 4-8. Prescribed flood release scenarios modeled.

Scenario	Target outflows	JAN	FEB	MAR	APR
Outflows to maintain current flow patterns					
Case A	Outflows not specified				
Outflows to mimic historical monthly flow patterns					
Case B	Outflows based on unregulated 4-month mean inflows	3100	5000	5200	4500
Case C	Outflows based on unregulated 3-month mean inflows	3100	5000	5200	
Case D	Outflows based on unregulated 3-month mean inflows		5000	5200	4500
Case E	Outflows based on unregulated 2-month mean inflows		5000	5200	
Outflows to generate short-duration, high volume flood releases					
Case F	Outflows for January freshet-1	3000			
Case G	Outflows for January freshet-2	4000			
Case H	Outflows for January freshet-3	5000			
Case I	Outflows for February freshet-1		3000		
Case J	Outflows for February freshet-2		4000		
Case K	Outflows for February freshet-3		5000		
Case L	Outflows for February freshet-4		6000		
Case M	Outflows for February freshet-5		7000		
Case N	Outflows for February freshet-6		8000		
Case O	Outflows for March freshet-1			3000	
Case P	Outflows for March freshet-2			4000	
Case Q	Outflows for March freshet-3			5000	
Case R	Outflows for March freshet-4			6000	
Case S	Outflows for March freshet-5			7000	
Case T	Outflows for March freshet-6			8000	
Case U	Outflows for January freshet when minimum reservoir level > 316 m amsl at end of December	5000			
Case V	Outflows for February freshet when minimum reservoir level > 316 m amsl at end of January		5300		
Case W	Outflows for March freshet when minimum reservoir level > 316 m amsl at end of February			5000	

releases on a monthly or semi-monthly basis. These floods do not attempt to mimic historical flow patterns, but rather to generate a volume of flood water during the historical period of overbank flooding that may benefit downstream production systems and ecological functions. Outflows of 3000 m^3/s, 4000 m^3/s and 5000 m^3/s were modeled for January. For February and March, outflows of 3000 m^3/s, 4000 m^3/s, 5000 m^3/s, 6000 m^3/s, 7000 m^3/s, and 8000 m^3/s were modeled.

Each of these short-duration prescribed floods can be considered as continuous monthly outflows, or as average monthly outflows for variable daily or weekly discharge patterns. A mean monthly flow of 5000 m^3/s in January, for example, would provide a prescribed flood release of about 8000 m^3/s for 14-days with minimal (turbine only) releases during the remainder of the month to generate firm power output. The exact volume of water available for prescribed flooding releases above the amount required for power output depends on the firm power target and the net operating head at the power station. At the Full Supply Level of 326 m amsl, turbine releases required to meet a firm power output of 1370 MW are about 1200 m^3/s. At 316 m amsl, firm power output requires a release of slightly less than 1300 m^3/s, and as reservoir levels approach the minimum supply level required turbine outflows are more than 1500 m^3/s. To generate 1450 MW firm power, turbine outflows range from about 1280 m^3/s at Full Supply Level to nearly 1600 m^3/s at the Lower Supply Level. Mean monthly flow requirements during February are slightly higher than those during the longer months of January and March, so a mean discharge of about 5300 m^3/s is required during February to generate a 14-day prescribed flood event of approximately 8000 m^3/s. A 7-day prescribed flood of about 8000 m^3/s in February would require a mean monthly discharge of about 3000 m^3/s. A flow of 4000 m^3/s would enable a 7-day prescribed flood approaching 12,000 m^3/s.

In each of these case studies, prescribed flood releases are created by the combination of turbine outflows and sluice gate spillage. I specified prescribed flood releases as *required outflows*, to be generated as long as reservoir water levels remain above the lower supply (dead storage) level. Hydropower releases are also generated as long as reservoir levels remains above the Lower Supply Level. To allow for reduced flood releases when reservoir levels reach a critical lower threshold, I modeled three additional scenarios as Cases U, V, and W. These releases are modeled as *desired outflows*, with releases curtailed when reservoir levels fall below the reservoir buffer level (designated in the model as 316 m amsl, or 10 m below the Full Supply Level). Hydropower releases remained as required outflows.

I modeled each scenario twice, once using the DFRC and once using the FRC configuration, for a total of 44 runs. The construction of additional spillway capacity at Cahora Bassa must be justified in part by offering increased levels of firm power output and total energy generation, therefore firm power output levels for each decision rule curve are set independently, based on the maximum firm power that can be generated at 98% reliability for each configuration. The DFRC scenarios are thus configured for 1370 MW output (the current generating level), and the FRC scenarios are configured for 1450 MW output (Figure 4-5).

I modeled the special case of generating a 14-day prescribed flood of approximately 8000 m^3/s during January, February, or March for different firm power target levels to assess the relationship between power generation and outflow reliability for the optimal FRC configuration (Table 4-9). Six runs are made for each case study. No minimum water level threshold is specified for these scenarios.

Table 4-9. Prescribed flood release scenarios modeled for a range of firm power target levels.

Scenario	Target outflows	JAN	FEB	MAR	APR
Case X	Outflows for 14-day freshet of approximately 8000 m^3/s in January (same configuration as Case H)	5000			
Case Y	Outflows for 14-day freshet of approximately 8000 m^3/s in February		5300		
Case Z	Outflows for 14-day freshet of approximately 8000 m^3/s in March (same configuration as Case Q)			5000	

Finally, I conducted three additional sensitivity tests to assess how changes in friction head loss, reservoir evaporation, and firm power generation at Kariba and Kafue Gorge hydropower stations affect the availability of water for prescribed flood releases. Each parameter was reset to the level used to test the firm power sensitivity of (default) Case A, described above. Case V, with outflows from Cahora Bassa designated to generate a flood release of 5300 m^3/s in February when reservoir levels exceed the buffer level of 316 m amsl using the FRC, was selected for sensitivity testing. The baseline parameters were also tested for the DFRC configuration.

Prescribed flooding options

Efforts to mimic historical average flooding patterns below Cahora Bassa Gorge are significantly constrained by the operation of upstream dams. The hydrograph of mean monthly inflows to Cahora Bassa over the period 1907-98 is shown in Figure 4-6 for unregulated inflows (modeled with no upstream dams over the period of record) and regulated inflows (modeled with Kariba and Itezhitezhi/Kafue Gorge Dams in operation over the entire period). Upstream power stations have increased dry season inflows during July to November, increased wet season flows during December and January, and reduced peak flood discharges during February-May. Increased evaporation losses from upstream reservoirs relative to unregulated conditions has also reduced the total volume of water available at Cahora Bassa reservoir by an average of 8% per annum. The time series of regulated and unregulated monthly inflows to Cahora Bassa from 1907-98 (Figure 4-7) reveals that monthly inflows most closely resemble natural low-flow conditions towards the end of periods of prolonged drought, such as during the 1920s and 1990s, when upstream reservoir levels fall near the minimum supply level and turbine discharges are curtailed. Such drought periods, however, also result in the near elimination of spillage during the normal time of peak flooding inflows. As discussed in Working Paper #2, Kariba Dam released only turbine outflows during the prolonged drought period from 1981 to 2001 while reservoir levels remained below the Full Supply Level. Overall, maximum monthly discharges follow an erratic pattern, substantially higher than natural inflows during some years (*e.g.*, 1947/48, 1971/72), and substantially less during many other years (Figure 4-8). These erratic release patterns are due in part to the use of a DFRC at Kariba. Although Kariba Reservoir has greater storage volume than Cahora Bassa, and thus greater capacity to store extreme flooding events, managers must follow a flood rule curve to ensure sufficient capacity to pass the design flood.

Cahora Bassa Reservoir and Power Station operate to further alter inflow patterns. The degree that Zambezi flows are modified is highly dependent on the decision curve used for reservoir management. The hydrograph of regulated mean monthly inflows to Cahora Bassa over the period 1907-98 is given in Figure 4-9, with outflows generated by following the DFRC and FRC.

Outflow patterns with the DFRC differ substantially from inflow patterns. Regular reservoir drawdowns prior to the peak flooding season generate outflows greatly in excess of inflows, including large end-of-dry season flow volumes during November and December. As a result, reservoir water levels fluctuate by more than 5 m each year under normal operating conditions, and by more than 8 m during wet years (Figure 4-10). End-of-flood-season drawdowns after very wet years result in a second spike in outflows, typically during June or July. Minimum outflows often occur during February-March, the period of peak flows prior to Zambezi regulation. Outflow patterns resemble inflow patterns only during the mid-dry season, August-October, when reservoir levels fall well below the DFRC levels. Turbine outflows to meet firm energy requirements at Kariba Dam range from about 830 m^3/s at Full Supply Level to more than 950 m^3/s at the minimum operating level. Turbine outflows from Kafue Gorge Dam are about 170 m^3/s. Together, these sources provide a steady inflow that meets 75-85% of turbine outflow requirements at Cahora Bassa, and the magnitude of minimum flows are relatively unchanged as they pass through Cahora Bassa. Figures 4-11 and 4-12 show the time series and correlation of regulated inflows and outflows, respectively, using the DFRC and showing that inflow patterns are very weakly correlated to outflow patterns (r^2=0.293).

Outflow patterns following the FRC, however, closely approximate regulated inflow patterns throughout the hydrological cycle. With the FRC, Cahora Bassa stores floodwaters up to the 326 m amsl Full Supply Level to meet hydropower requirements, and then passes additional inflows downstream. Reservoir levels remain close to the Full Storage Level except during critical dry periods (Figure 4-13). Water levels spike above the 326 m threshold only when inflows exceed the total outlet capacity, as occurred in the 1958 simulation. Inflows are stored during the wet season to meet dry season turbine discharge requirements, but the reservoir turnover ratio is less than one and a high proportion of flood season inflows are passed through the reservoir during year of average to above average inflows. The FRC therefore provides less flood season attenuation than the DFRC (Table 4-10), and more closely approximates patterns of peak inflows. The maximum monthly regulated inflow to Cahora Bassa was 13,698 m^3/s in February 1958. Operation according to the DFRC reduced the maximum discharge by 24.5% to 10,341 m^3/s. Maximum discharge following the FRC was reduced by 7.0% to 12,803 m^3/s. The maximum monthly unregulated discharge was 16,635. Figures 4-14 and 4-15 show the time series and correlation of regulated inflows and outflows, respectively, using the FRC and showing that flow patterns are highly correlated (r^2=0.954) except during very dry years.

Table 4-10. Percentage of months during which simulated Zambezi flows exceeded a given threshold. Under unregulated conditions, mean monthly flows exceeded 12,000 m^3/s every 8-10 years on average.

Exceedance threshold	Unregulated inflows	Regulated Inflows	Outflows using DFRC	Outflows using FRC
>12,000 m^3/s	0.5	0.1	0.0	0.1
>10,000 m^3/s	0.9	0.1	0.1	0.1
>9000 m^3/s	1.6	0.4	0.2	0.5
>8000 m^3/s	2.6	1.0	0.4	0.8
>7000 m^3/s	4.4	1.7	1.0	1.7
>6000 m^3/s	6.9	3.8	2.1	3.3
>5000 m^3/s	11.9	7.0	5.1	6.0
>4000 m^3/s	19.1	11.4	12.6	10.7
>3000 m^3/s	31.0	20.8	24.2	18.4
>2000 m^3/s	45.5	38.2	32.9	31.9

Because outflows patterns using either the DFRC and the FRC do not resemble unregulated inflow patterns, the first prescribed flooding scenarios were designed to test whether regulated outflows from Cahora Bassa could mimic unregulated flow patterns while maintaining firm power output requirements. The results of these case studies with respect to firm power reliability, total power output, and target outflow reliability are given in Table 4-11.

Table 4-11. Firm power reliability, total annual power, and target outflow reliability for different prescribed flood release scenarios. Cases study parameters are described in Table 4-8.

Scenario	Rule curve	Firm power (MW)	Reliability (%)	Energy production (GWh/yr)	Energy as % of baseline	Target outflow reliability (%)	Baseline outflow reliability (%)
Case A-0	DFRC	1370	98.4	14,392	100.0	--	--
Case A-6	FRC	1450	98.3	15,038	100.0	--	--
Case B-1	DFRC	1370	65.1	12,703	88.3	39.6	1.1
Case B-2	FRC	1450	61.0	12,909	85.8	39.6	4.4
Case C-1	DFRC	1370	80.8	13,014	90.4	68.1	1.1
Case C-2	FRC	1450	76.0	13,303	88.5	59.3	7.7
Case D-1	DFRC	1370	68.0	12,556	87.2	48.4	1.1
Case D-2	FRC	1450	65.4	12,861	85.5	48.4	4.4
Case E-1	DFRC	1370	85.5	13,074	90.8	81.3	1.1
Case E-2	FRC	1450	83.5	13,508	89.8	79.1	9.9

Prescribed flood releases designed to maintain historical mean annual flows over a four-month period (Case B) result in an unacceptable reduction in firm power reliability, and a 11.7-14.2% reduction in annual power output (depending on the flood rule curve used). Required outflows are satisfied in less than 40% of all years, and average peak monthly discharges during February, March, and April are 15-20% less than under unregulated conditions (Figure 4-16). Firm power failures occur throughout the hydrological record, although during the prolonged wet period from 1947-66 both target firm power and target outflow levels are satisfied. In this and other historical flow pattern test cases, outflow patterns resulting from use of the DFRC and FRC are similar, although power generation with the FRC is consistently higher. Under the FRC baseline case A-6 (with no specified outflows) these same historical mean annual flow patterns occur in only 4 of 91 years (4.4%), while under DFRC baseline case A-0 in 1 of 91 years (1.1%).

Prescribed release scenarios that attempt to mimic unregulated inflows over a three-month period (Cases C and D) are similarly problematic. Case C, with January-March releases, offered significantly higher firm power reliability and outflow reliability, but remained well below acceptable limits. As with Case B, the mean monthly hydrograph for Case C reasonably mimics the natural flood rise in December-January, and more closely approximates peak flood levels in February-March, but declines rapidly in April to near-minimum annual outflow levels (Figure 4-17). The hydrograph for Case D more closely mimics the historical rise and fall of Zambezi flows, although mean monthly discharges in all flood season months fall well below unregulated levels (Figure 4-18). Case D power output is only slightly higher than Case B, suggesting that water availability is particularly limiting for April flood releases. Given this, and because April generally marks the beginning of the period of flood recession following peak discharges in February and March under unregulated conditions, the remaining flood release scenarios are designed for the period from January-March despite the historical occurrence of higher average flow conditions in April than January.

Case E tests the availability of inflows to mimic unregulated mean monthly flows during the peak flooding period of February-March. Firm power reliability is unacceptably low, but total power generation is reduced by only about 10% and outflow reliability is about 80%. This prescribed release pattern closely mimics the typical hydrograph rise from December to February, with a slight decrease in March outflows followed by a very steep drop in April to the annual minima (Figure 4-19). When no outflow levels are specified, these historic mean monthly flow patterns occur in less than 10% of all years with the FRC, and only 1% of all years with the DFRC.

The next series of tests, case studies F-T, are used to assess the availability of inflows to produce a range of different target high volume, short duration releases during the historical period of peak flooding. Case studies F-H test water availability for prescribed flooding in January. Using the existing DFRC, an outflow of 4000 m^3/s can be generated in more than 93% of all years, with a firm power output of 1370 MW at 95.8% reliability. Total energy production is reduced by about 2.2%. Under baseline conditions with the DFRC, this outflow level occurs in about 40% of all years. With the FRC, an outflow of 4000 m^3/s can be generated in 94.5% of all years with 1450 MW firm power output at better than 96% reliability (Table 4-12). At this outflow, the total reduction in energy production relative to baseline conditions is only 1.3%. Without target outflow levels, this outflow level is generated in 41.8% of all years using the FRC. An outflow of 3000 m^3/s can be satisfied using both the DFRC and FRC management options with less than 1% reduction in annual hydropower output, and less than 2% reduction in firm power reliability. Target outflows of 5000 m^3/s reduce firm power reliability below the 95% threshold, requiring the use of slightly lower firm power target levels. Total energy production is reduced by only 3-4%, however. All firm power failures occurred towards the end of the prolonged drought period that lasted from 1983-97.

Case studies I-N are used to assess the availability of inflows to generate a range of mean monthly outflow levels in February. Mean monthly outflows of 4000 m^3/s (Case J) can be achieved in nearly 95% of all years using both the DFRC and FRC while maintaining greater than 95.6% firm power reliability levels (Table 4-13). In sharp contrast, this outflow level occurs in only 3.3% of all years under baseline conditions using the DFRC. Monthly outflows up to 8000 m^3/s can be reliably generated in most years with less than 10% reduction in total energy production. Such outflows levels are very rare under baseline regulated inflows using the DFRC and FRC, but occur with a frequency of about 1 in 3 years under unregulated conditions (Table 4-10). Firm power failures occur during the 1983-97 drought period. Higher outflow levels are also affected by the 1915-25 drought period.

Case studies O-T assess the availability of inflows to generate a range of mean monthly outflow levels in March. As is the case in February, mean monthly outflows of 4000 m^3/s (Case P) can be achieved in more than 95% of all years using both the DFRC and FRC while maintaining at least 95% firm power reliability levels (Table 4-14). This outflow level occurs in only 2% of all years under baseline conditions

Table 4-12. January prescribed flood releases. Cases that meet the minimum firm power reliability criterion (95%) are shaded. Cases study parameters are described in Table 4-8.

Scenario	Rule curve	Firm power (MW)	Reliability (%)	Total energy production (GWh/yr)	Energy as % of baseline	Target outflow reliability (%)	Baseline outflow reliability (%)
Case F-2	DFRC	1370	96.7	14,260	99.1	94.5	50.5
Case F-1	FRC	1450	96.8	14,957	99.5	95.6	48.4
Case G-2	DFRC	1370	95.8	14,075	97.8	93.4	39.6
Case G-1	FRC	1450	96.1	14,840	98.7	94.5	41.8
Case H-2	DFRC	1370	94.5	13,851	96.2	92.3	27.5
Case H-1	FRC	1450	93.2	14,588	97.0	92.3	30.8

Table 4-13. February prescribed flood releases. Cases that meet the minimum firm power reliability criterion (95%) are shaded. Cases study parameters are described in Table 4-8.

Scenario	Rule curve	Firm power (MW)	Reliability (%)	Total energy production (GWh/yr)	Energy as % of baseline	Target outflow reliability (%)	Baseline outflow reliability (%)
Case I-2	DFRC	1370	96.7	14,285	99.3	97.8	6.6
Case I-1	FRC	1450	96.6	14,940	99.3	97.8	63.7
Case J-2	DFRC	1370	95.6	14,021	97.4	94.5	3.3
Case J-1	FRC	1450	95.8	14,808	98.5	94.5	37.4
Case K-2	DFRC	1370	94.2	13,745	95.5	92.3	3.3
Case K-1	FRC	1450	93.4	14,531	96.6	92.3	18.7
Case L-2	DFRC	1370	90.8	13,440	93.4	85.7	2.2
Case L-1	FRC	1450	90.4	14,237	94.7	89.0	6.6
Case M-2	DFRC	1370	90.0	13,213	91.8	83.5	1.1
Case M-1	FRC	1450	89.4	13,957	92.8	84.6	3.3
Case N-2	DFRC	1370	90.0	13,047	90.7	83.5	1.1
Case N-1	FRC	1450	88.7	13,659	90.8	84.6	3.3

using the DFRC, and about a quarter of all years using the baseline FRC. Monthly outflows up to 8000 m^3/s can be reliably generated in most years with less than 10% reduction in annual power production. Such outflows levels are very rare under baseline regulated inflows using the DFRC and FRC, but occur with a frequency of about 1 in 3 years under unregulated conditions (Table 4-10). March outflows greater than 6000 m^3/s do not occur without target outflow levels using the DFRC, but occur every 1.2 years on average with unregulated inflows. Firm power failures occur during the 1983-97 drought period, with higher outflow levels affected also by the 1915-25 drought period.

For each of the above case studies, the target mean monthly discharge of 5000-5300 m^3/s (the minimum discharge necessary to release a 14-day flood pulse of about 8000 m^3/s) reduces firm power generation below the minimum 95% reliability criterion. Three options are available to reach this target discharge level and meet firm power reliability requirements. One alternative is to reduce target outflow reliability, by allowing for flood releases only when reservoir levels exceed a certain threshold level. Another option is to reduce firm power requirements to a level such that target releases can be met at or above the 95% reliability threshold. A third alternative is to use minimum threshold levels in combination with small reductions in firm power.

The first alternative, the improvement in firm power reliability when target outflows are limited to periods when the reservoir elevation is above 316 m amsl[5] is given in Table 4-15. By constraining

Table 4-14. March prescribed flood releases. Cases that meet the minimum firm power reliability criterion (95%) are shaded. Cases study parameters are described in Table 4-8.

Scenario	Rule curve	Firm power (MW)	Reliability (%)	Total energy production (GWh/yr)	Energy as % of baseline	Target outflow reliability (%)	Baseline outflow reliability (%)
Case O-2	DFRC	1370	96.7	14319	99.5	96.7	2.2
Case O-1	FRC	1450	96.4	14865	98.8	97.8	57.1
Case P-2	DFRC	1370	95.1	14,032	97.5	95.6	2.2
Case P-1	FRC	1450	95.0	14,580	97.0	95.6	26.4
Case Q-2	DFRC	1370	91.7	13,674	95.0	91.2	1.1
Case Q-1	FRC	1450	90.8	14,198	94.4	90.1	13.2
Case R-2	DFRC	1370	88.9	13,376	92.9	86.8	0.0
Case R-1	FRC	1450	88.4	13,881	92.3	86.8	4.4
Case S-2	DFRC	1370	88.3	13,152	91.4	85.7	0.0
Case S-1	FRC	1450	87.3	13,575	90.3	85.7	2.2
Case T-2	DFRC	1370	87.5	12,873	89.4	80.2	0.0
Case T-1	FRC	1450	84.6	13,210	87.8	84.6	2.2

releases to this threshold, target outflows of 5000 m^3/s in January (Case U) and March (Case W) and 5300 m^3/s in February (case V) can be realized with a minimal reduction in target outflow reliability (relative to the unconstrained case) for both DFRC and FRC operations. Total energy production remains high in all cases.

Table 4-15. Firm power reliability, total annual power, and outflow reliability for prescribed outflows of 5000 m^3/s in January, 5300 m^3/s in February, and 5000 m^3/s in March when the reservoir elevation is above 316 m amsl, using the DFRC and FRC.

Scenario	Rule curve	Firm power (MW)	Reliability (%)	Total energy production (GWh/yr)	Energy as % of baseline	Target outflow reliability (%)	Unconstrained outflow reliability (%)
Case U-1	DFRC	1370	97.2	13,993	97.2	85.7	6.6
Case U-2	FRC	1450	96.2	14,704	97.8	87.9	4.4
Case V-1	DFRC	1370	97.0	13,811	96.0	86.8	5.5
Case V-2	FRC	1450	95.8	14,588	97.0	87.9	4.4
Case W-1	DFRC	1370	96.9	13,869	96.4	86.8	4.4
Case W-2	FRC	1450	95.9	14,400	95.8	87.9	2.2

The hydrographs of regulated mean monthly outflows using the DFRC and FRC with a January target outflow of 5000 m^3/s when reservoir levels are above 316 m amsl are shown in Figure 4-20. Regulated outflow patterns do not closely resemble unregulated conditions, but provide for an early flood season discharge that may serve to complement early peak discharges from lower Zambezi Valley tributaries. The hydrographs of regulated mean monthly outflows using the DFRC and FRC with a February target outflow of 5300 m^3/s above the 316 m threshold are given in Figure 4-21. The FRC closely resembles the rising limb of the unregulated hydrograph, drops sharply during March, and recedes slowly until September. The hydrographs of regulated mean monthly outflows using the DFRC and FRC with a March target outflow of 5000 m^3/s above the 316 m threshold are shown in Figure 4-22. The FRC follows the rising limb of the unregulated hydrograph in December and January, then plateaus in February at about 74% of the historical monthly discharge, before rising again to the March flood peak. The DFRC hydrograph is sharply bimodal, with peaks in January and March and a lesser peak in July resulting from occasional dry season reservoir drawdown.

The choice of minimum reservoir elevation threshold for constraining flood releases depends on the acceptable trade-offs between firm power reliability, total energy production, and target outflow reliability. The 95% reliability criterion could be met with a threshold elevation as low as 313 m and enable target flood releases in nearly 9 years out of 10 on average (Case U-2F, Table 4-16). Target outflows could also be satisfied in about 2 out of 5 years simply by redistributing outflows without any reduction in firm power or total energy production, a 10% improvement relative to baseline outflows (Case U-2A). With a 1% reduction in firm power reliability and 1.7% reduction in total energy production, however, target outflows can be satisfied in about 87% of all years (Case U-2B).

Table 4-16. Sensitivity of firm power reliability, annual power production, and target outflow reliability to reservoir elevation threshold for flood releases. Tested for a January flood release of 5000 m^3/s using FRC.

Scenario	Minimum reservoir Level (m amsl)	Firm power (MW)	Reliability (%)	Total energy production (GWh/yr)	Energy as % of baseline	Target outflow reliability (%)	Outflow reduction (%)
Case U-2A	325	1450	98.3	15,038	100.0	40.7	51.6
Case U-2B	320	1450	97.3	14,777	98.3	86.8	5.5
Case U-2C	316	1450	96.2	14,704	97.8	87.9	4.4
Case U-2D	315	1450	95.8	14,688	97.7	87.9	4.4
Case U-2E	314	1450	95.3	14,679	97.6	89.0	3.3
Case U-2F	313	1450	95.1	14,673	97.6	89.0	3.3

The second alternative for meeting target outflows without reducing the probability of meeting firm power demand is to accept a reduced level of firm power output. The social, economic, and ecological benefits of improving flow conditions in the lower Zambezi may be offset the lost revenue from a marginal reduction in hydropower output (see discussion below). Case studies X, Y, and Z re-examine target discharges of 5000 m^3/s in January, 5300 m^3/s in February, and 5000 m^3/s in March, respectively, over a range of firm power levels using the FRC. Table 4-17 shows the firm power reliability, total power output, and target outflow reliability as a function of firm power for a target outflow of 5000 m^3/s in January using the FRC. The relationship between firm power output and reliability is plotted in Figure 4-23. With a 5.5% reduction in firm power, target outflows can be generated with almost 95% reliability and firm power demand can be met with greater than 96% reliability (Case X-4). To generate firm power at the 98% reliability level, a 17.2% reduction in firm power output would be required (Case X-1). Such a configuration would result in only 4.5% reduction in total power output, however.

Table 4-18 shows firm power reliability, total power output, and target outflow reliability as a function of firm power for a target outflow of 5300 m^3/s in February using the FRC. The relationship between firm power output and reliability for this target outflow is plotted in Figure 4-24. To generate firm power at the 98% reliability level, target firm power must again be reduced to 1200 MW. At the 1370 MW firm power level, equivalent to current firm power output using the DFRC without additional spillway capacity, firm power can be generated at greater than 95% reliability, target outflows can be met with 93.4% reliability. Average annual power output is about 95.5% of the total generation potential.

Table 4-19 shows firm power reliability, total power output, and target outflow reliability as a function of firm power for a target outflow of 5000 m^3/s in March using the FRC. The relationship between firm power output and reliability for this target outflow is plotted in Figure 4-25. Prescribed flooding target

Table 4-17. Range of firm power reliability, annual power output, and target outflow reliability for different firm power output limits. Data are based on a target outflow of 5000 m^3/s during January using the FRC. Firm power reduction is calculated relative to the baseline case (A-6) of 1450 MW firm power.

Scenario	Firm power (MW)	Firm power reduction (%)	Reliability (%)	Total energy production (GWh/yr)	Energy as % of baseline	Target outflow reliability (%)
Case X-1	1200	17.2	98.2	14,367	95.5	95.6
Case X-2	1230	15.2	97.8	14,379	95.6	95.6
Case X-3	1300	10.3	96.9	14,455	96.1	94.5
Case X-4	1370	5.5	96.1	14,512	96.5	94.5
Case X-5	1400	3.4	95.1	14,542	96.7	93.4

Table 4-18. Range of firm power reliability, annual power output, and target outflow reliability for different firm power output limits. Data are based on a target outflow of 5300 m^3/s during February using the FRC.

Scenario	Firm power (MW)	Firm power reduction (%)	Reliability (%)	Total energy production (GWh/yr)	Energy as % of baseline	Target outflow reliability (%)
Case Y-1	1200	17.2	98.1	14,172	94.2	95.6
Case Y-2	1250	15.2	97.2	14,220	94.6	93.4
Case Y-3	1300	10.3	96.8	14,294	95.1	93.4
Case Y-4	1350	6.9	95.9	14,342	95.4	94.5
Case Y-5	1370	5.5	95.4	14,360	95.5	93.4
Case Y-6	1400	3.4	94.1	14,387	95.7	93.4

levels are more difficult to attain during March than in January and February. To generate firm power at the 98% reliability level, target firm power must be reduced by more than 24% to 1100 MW, and annual power production reduced by 8.8%. At the 1370 MW firm power level, equivalent to current firm power output using the DFRC without additional spillway capacity, firm power reliability falls below 95%.

Table 4-19. Range of firm power reliability, annual power output, and target outflow reliability for different firm power output limits. Data are based on a target outflow of 5000 m^3/s during March using the FRC.

Scenario	Firm power (MW)	Firm power reduction (%)	Reliability (%)	Total energy production (GWh/yr)	Energy as % of baseline	Target outflow reliability (%)
Case Z-1	1100	24.1	98.0	13,715	91.2	95.6
Case Z-2	1200	17.2	96.1	13,880	92.3	94.5
Case Z-3	1250	15.2	95.7	13,939	92.7	94.5
Case Z-4	1300	10.3	94.7	14,021	93.2	94.5
Case Z-5	1370	5.5	94.1	14,162	94.2	92.3
Case Z-6	1400	3.4	92.2	14,357	95.5	90.1

A third alternative is to combine small reductions in firm power output with a minimum threshold for target outflows. This option offers a wide range of alternatives for optimizing the benefits of improved flooding patterns with hydropower generation. Management of Cahora Bassa to release a prescribed flood of 5300 m^3/s in February when reservoir water levels exceed 316 m amsl (Case V), for example, will generate 1370 MW firm power at nearly 98% reliability with less than a 4% reduction in annual power production relative to baseline conditions (Table 4-20). This configuration will produce the desired flood discharge in 9 years out of 10. While such management options are very sensitive to inflow patterns, with both power and outflow failures occurring during periods of prolonged drought, they are not highly sensitive to increases in evaporation or changes in upstream power generation. A substantial increase in reservoir evaporation (20% as in Case A-2 above) has only a negligible effect on power generation, and did not reduce outflow reliability. Increased firm power generation at Kariba and Kafue Gorge power stations result in slightly higher outflow reliability. The results of the sensitivity tests for these parameters are summarized in Table 4-20.

Table 4-20. Sensitivity of power generation and outflow reliability to changes in water availability, for a firm power target of 1370 MW and prescribed flood release of 5300 m^3/s during February when reservoir water levels exceed 316 m amsl using the FRC. Changes in net evaporation, Kariba firm power, and Kafue Gorge power output are the same as those described in Table 4-6.

Scenario	Test	Target power (MW)	Reliability (%)	Total energy production (GWh/yr)	Energy as % of baseline	Outflow reliability (%)
V-3	Default	1370	97.6	14,453	96.1	90.1
V-4	Net Evaporation increased 20%	1370	97.5	14,335	95.3	90.1
V-5	Kariba firm power increased 10%	1370	96.3	14,620	97.2	92.3
V-6	Kafue Gorge firm power increased 10%	1370	97.6	14,533	96.6	91.2

Summary

The preceding analysis provides several important insights about the potential for flood releases. First, the design flood rule curve results in a highly erratic flow pattern in the lower Zambezi, including rising flood stages during the end of the dry season and flood recession during the historic time of peak flooding. Substantial improvement in downstream flooding patterns and hydropower output can be achieved by increasing the outflow capacity at Cahora Bassa Dam and adopting a FRC.

Second, efforts to recreate the historical flood hydrograph for the lower Zambezi system by designing flood releases to match historical mean monthly flows over a 4-month, 3-month, or even 2-month period are not possible without substantial reductions in hydropower output. Flood releases designed to mimic historical unregulated mean monthly flows during the peak flooding period of February-March, provide 1370 MW at 85.5% reliability with the DFRC and 1450 MW with 83.5% reliability with the FRC (Table 4-11). Total power generation is reduced by about 10%. Target outflow reliability is about 80%.

Third, a variety of options are available for generating short-duration, high volume flood pulses during the normal flood season months of January, February, or March. A reservoir release capable of generating a January prescribed flood of over 8000 m^3/s for 14-days in 92.3% of all years, for example, is possible with a 3.8% reduction in total power generation providing 94.5% firm power reliability at 1370 MW using the DFRC (Case H-2, Table 4-12). Alternatively, with the FRC a reservoir release capable of generating the same January prescribed flood is possible in 94.5% of all years with a 3.5% reduction in total power generation providing 96.1% firm power reliability at 1370 MW (Case X-4, Table 4-17). These options include stepped-release patterns with gradually increased and decreased discharges. The optimal magnitude and duration of flood release depends on the desired depth and duration of floodplain inundation, but may be constrained by the allowable rate of rise of water levels on the floodplain or the maximum allowable velocity in the mainstem Zambezi.

Fourth, firm power reliability and total energy generation for a given prescribed flood target can be substantially improved by establishing minimum reservoir elevation thresholds for releasing water. If water releases for prescribed flooding are curtailed when reservoir levels fall below 316 m amsl, for example, firm power reliability for the January prescribed flood described above increases to 97.2%, and total power generation increases by 1%. Target outflows are met in 85.7% of all years, a 6.6% reduction relative to no minimum threshold.

And fifth, future development of Cahora Bassa North Bank or downstream Mepanda Uncua Dam may affect the availability of water for prescribed flood releases from Cahora Bassa Dam. The impact of these structures must be further investigated once final design criteria are approved. Regardless of future river development, however, Cahora Bassa will remain the most important structure for managing flood patterns in the lower Zambezi system.

DOWNSTREAM EFFECTS OF DIFFERENT FLOOD RELEASE OPTIONS

The impact of different flood release options on floodplain farming communities and ecosystems depends on both the capacity to generate floods of specified magnitude, timing, duration, and frequency in the downstream floodplain, and the degree to which floodplain processes and production systems respond to improved flooding patterns.

Generating target floods

Downstream flooding patterns depend not only on characteristics of the prescribed flood release, but on runoff from tributaries in the downstream catchment, patterns of floodplain inundation, and local sources of inflows and outflows (the floodplain water balance). The main sources of runoff in the lower Zambezi catchment are from the Luia, Revuboe, and Luenha tributaries draining the plateau region and the Shire River Valley (see Working Paper # 2). Lower Zambezi runoff may significantly affect the timing and duration of flooding and the maximum depth and rate of rise of water on the floodplain. Depending on stakeholder interests in the lower Zambezi catchment, flow releases might be timed to occur simultaneously with peak flooding downstream, or timed to occur before or after downstream runoff has peaked. RPT (1980) called this latter flood release strategy “virtual storage.” Floods from the Moravia-Angonia and Manica Plateau tributaries tend to rise quickly, however, with each event having a time to peak of about 30 hours and duration of about 80 hours. Flood warning times are therefore minimal, ranging from zero to a maximum of 25 hours for rainfall events high in catchment, making efforts to synchronize flood releases with downstream flows difficult. Nonetheless, the range of probable inflows from the plateau tributaries during the period when prescribed floods are scheduled for release is fairly well known.

Tributary flooding events may occur anytime between late December and early March (Figures 2-33, 2-37, 2-40). Peak flooding typically occurs in January-February in the Luenha catchment, and February-March in the Luia and Revuboe catchments, and the combined annual peak flood may occur anytime between mid-January and late-March. Average daily runoff during this period is about 800-1000 m^3/s (Figure 4-26). The combined mean annual peak flood from all tributaries is about 1600 m^3/s. The combined five-year RI flood is about 4000 m^3/s, and the 20-year RI flood is about 6000 m^3/s (Figure 2-40). These discharges may contribute substantially to a short-duration prescribed flood release from Cahora Bassa Dam. A 14-day flood discharge of 8000 m^3/s would be expected to generate peak floods of about 8800-9600 m^3/s on average at Muturara, exceeding 12,000 m^3/s during wet years. Historically, average peak floods of about 8000-11,000 m^3/s occurred at Muturara during February or March.

Peak runoff from the Shire catchment, attenuated by the Elephant and Ndindi floodplains, typically occurs in March, although peaks may occur as early as January during years when heavy rainfall in the Milange Mountains generates large flooding events in the Ruo River catchment (Figure 2-46). The duration of high flood flows is more prolonged in the Shire catchment, with better warning times possible from upstream stations. Average daily runoff from the Shire over the period January-April is about 750 m^3/s. Average maximum daily flow is about 1350 m^3/s. The five-year RI flood is about 1500 m^3/s, and the 20-year RI flood is about 1800 m^3/s (Figure 2-46).

The lower Zambezi catchment thus contributes about 1500-3000 m^3/s on average to flood releases from Cahora Bassa Dam. Significantly higher flows are possible during years when catchment runoff is closely synchronized. During extreme wet years cumulative inflows may exceed 7000 m^3/s, possibly doubling the magnitude of flooding produced by a prescribed flood release.

The patterns of floodplain inundation also strongly affect the degree to which prescribed flooding objectives may be met. As described in Working Paper #2, overbank flooding on the north bank occurs along the Cuacua distributary at flows exceeding 5000 m^3/s (Figure 2-57), and extensive areas are flooded at flows of 7000-9000 m^3/s (Figure 2-58). Traditional flood recession practices were adapted to floods of this magnitude (Liesegang and Chidiamassamba 1977). The southern half of the delta, including the Marromeu complex, can be only inundated by exceptional floods, however, because the Zambezi River's floodways between the riparian villages of Chupanga and Marromeu are blocked by dikes for road and rail causeways (Figure 2-56).

Efforts are currently underway to improve the movement of floodwater into the south bank floodplains through the dike between Marromeu and Chupanga and through the present route of the Inhamitanga-Marromeu railway line. A hydrographic survey is being conducted to indicate where adequate elevation structures should be constructed in the levee to allow free access of floodwater to the delta. This process will be undertaken in conjunction with prescribed flood releases. Tinley (1994) cautioned that floodplain managers must first monitor how effectively the delta south bank is inundated under present conditions by flood releases from Cahora Bassa before any management action is taken to make wide gaps in the dikes where they cross the floodways. Otherwise, efforts may lead to the catastrophic development of a major river course through the middle of the Marromeu reserve.

Responding to target floods

The effectiveness of different flood release options also depends on the degree to which floodplain processes and production systems respond to improved flooding patterns. *Subsistence farmers and fishers* in the lower Zambezi have adjusted their livelihoods for two generations to cope with failed or erratic flooding patterns. To realize the potential benefits of flood releases for flood recession cropping and floodplain fisheries, affected people must be willing to adjust their livelihoods again. This requires building trust between rural peoples and dam managers through workshops and other community outreach, and – most importantly – establishing consistent management practices that reflect a commitment to that trust. Floodplain farming practices in the lower Zambezi are generally opportunistic and may readily adjust to improved flooding conditions (Scudder 1980). The reversibility of long-term changes in fishing practices are more uncertain. Many young men who have only fished the mainstem Zambezi since the collapse of the floodplain fishery state that they are unwilling to fish the floodplains in the future because of the threat of hippos and crocodiles, even when village elder fishers expound on the tremendous productivity of the floodplain fishery in past times (Mr. Baldeau Chande *pers. comm.*). After the extensive floods of 2001, however, numerous fishing camps were spontaneously established to harvest the abundance of fish that resulted from the first significant floods in 24 years.

Changing patterns of settlement may also constrain the options available for managed floods in the lower Zambezi basin. Historically, the annual spread of floodwaters restricted settlements to terraces above the active channel shelf (Hidrotécnica Portuguesa 1965a, White 1993). After peak flooding, farmers moved on to the floodplain to cultivate the fertile alluvial soils (Negrão 1995). Over the past forty years, however, floodplain farmers have adjusted to reduced flooding by encroaching into historically flood-prone areas close to the Zambezi River. The main river channel between Chupanga and Luabo, once scoured by floods on an annual basis, now supports small houses and agricultural plots on stabilized sandbars. Widespread shelters have been erected for easier access to fishing areas. Although these structures are periodically wiped-out by large floods, farmers have few choices but to rebuild close to their resource base.

Although these settlement patterns currently limit the magnitude of flood releases possible, rural residents may be willing to move away from flood-prone areas if managed floods support historical patterns of fisheries, flood recession agriculture, grazing, and groundwater access[6]. Effective educational workshops will be critical to cultivate local support for flood releases, especially given the negative attitudes about flooding among younger farmers who associate flooding with the chaotic release patterns from Cahora Bassa (Beilfuss *et al.* 1999).

Equally important is an adequate flood warning system. Although communication between the dam managers and lower Zambezi residents has been extremely poor in the past, the effective system during the Zambezi floods of 2001 suggests that flood warning is now a serious government priority (Hanlon 2001). The window of opportunity for implementing a prescribed flooding program will narrow with each passing year as villagers further adjust their livelihoods in response to the current hydrological regime of the Zambezi River.

The response of *floodplain flora* to changes in the flooding regime depends on the water requirements and flood-tolerance of individual species (Nilsson 1996). The invasion and retreat of woody species in the delta, for example, is a strongly hysteretic process. The hydrological conditions that enable young woody saplings to invade and survive on the floodplain grasslands are different from the conditions necessary to remove established adult trees (Kozlowski 1984). Although seed dispersal is rarely limiting to the spread of woody species into the floodplain (Tinley 1977), most tree species will not germinate underwater and are excluded from lowlying swamp areas (Middleton 1999). Those seedlings that establish on appropriate substrates in the higher floodplain experience very high mortality following flooding events (Kozlowski 1984). During the 2001 Zambezi floods, nearly all *Hyphaene* palms saplings less than 2 years old were eliminated along the western edge of the Zambezi Delta. As plants mature, their tolerance to depth and duration of flooding increases. Saplings are more flexible than seedlings in their tolerance of flooding (*e.g.*, Whitlow and Harris 1979), and most adult trees have a range of flood tolerance depending on their anatomical, morphological, or metabolic adaptations to flooding (Hook 1984, Jackson and Drew 1984). Middleton (1999) provides comprehensive tables of seedling, sapling, and adult survivorship of woody floodplain species, although data from Africa are limited.

Even highly tolerant species eventually die-out under prolonged inundation. Record flooding on the Missouri River during the mid-1990s removed many adult trees that had established on the low-level terrace after decades of reduced flooding (Galat *et al.* 1998). The probability that individual flooding events will reduce woody cover likely decreases with time, however. The 2001 Zambezi floods appear to have had little effect in reducing the extent of adult *Hyphaene, Borassus,* and *Acacia* savanna cover.

The conditions that foster the displacement of stoloniferous grassland by upland bunch grass species, and the displacement of freshwater herbaceous species by salt-tolerant species are similarly related to factors affecting seedling recruitment and adult survival (Kozlowski 1984). The inherent ability of adult plants to survive various water regimes varies widely among woody species and is a major determinant of the vegetation composition in wetlands (Middleton 1999). The majority of floodplain species have higher rates of production under less flooded conditions, and many bunch grass species on the African floodplains experience aggressive, vigorous growth when the duration of flooding is limited (Thompson 1985). Because the depth and duration of flooding are the dominant edaphic controls on most floodplain vegetation (Denny 1993), over time a properly designed flooding regime should tend to reverse the successional trend from wetland to upland vegetation and, by flushing accumulated salts, the trend from freshwater to salt-tolerant vegetation.

The establishment of aggressive floating aquatic plants such as water hyacinth (*Eichhornia crassipes),* salvinia (*Salvinia molesta*), and water fern (*Azolla filiculoides*) in the delta waterways may be an irreversible process, however. Global efforts to eradicate these problem weeds, which effect flow patterns and community structure of floodplain waterways, have had very limited success (Mitchell 1985). Flood pulses may help reduce the cover of these species, however, by scouring vegetation from waterways as noted during after the 1997 and 2001 floods.

Floodplain mammals are mobile and opportunistic in their response to changes in the hydrological regime and food supply (Dunham 1994, Rees 1978, Sheppe and Osborne 1971). Individual adaptations to even decades of failed flooding are likely to be reversible if floodplain conditions improve. *Floodplain waterbirds* such as Wattled Cranes also show a particularly strong response to improved hydrological conditions. Wattled Crane pairs are stimulated to breed by flooding conditions and raise their chicks as floodwaters recede. They respond immediately to flooding conditions, with many pairs attempting to breed during years of adequate flooding and few breeding attempts during years when floods fail. The critical food source for Wattled Cranes, underground tubers of the spike rush *Eleocharis acutangula,* are only produced after the floodplain undergoes a cycle of flooding and drawdown (Bento *in press,* Beilfuss 2000).

Regardless of the flood release option selected, periodic extreme floods characteristic of the historic Zambezi system will continue to affect the productivity and diversity of the Zambezi Delta (see Working Paper #2). The storage capacity of Cahora Bassa Reservoir is inadequate to control major flooding events from the Zambezi headwaters region and Middle Zambezi catchment, and although maximum flood peaks may be attenuated to some extent very significant downstream flows are still possible. The likelihood of these floods every 20 years or so reinforces the need for a sensible policy linking management floods with floodplain settlement. The 1978 flood wave alone killed 45 people, displaced more than 200,000, and destroyed nearly 60,000 ha of crops (RPT 1979). Emergency rescue operations prevented more deaths during the floods of 1997 and 2001.

These periodic large floods may be important for certain floodplain processes that cannot be sustained by high volume, short-duration prescribed floods, however. Large floods serve to reset parts of the floodplain by flushing accumulated organic matter and nutrients from peripheral swamps, dispersing seed propagules to the floodplain margin, and depositing silt on the floodplain (*e.g.*, Bayley 1995, Bruwer *et al.* 1996, Middleton 1999). After the 1978 floods, floodplain conditions improved substantially for local flora and fauna (Tello and Dutton 1979). Marked increases in Cape buffalo and waterbuck were observed on the floodplain grasslands, and encroaching upland vegetation receded from the floodplain (Chande and Dutton 1997).

FINANCIAL FEASIBILITY OF FLOOD RELEASES

The management of Cahora Bassa Dam is integral to the economic development of Mozambique. As discussed in the previous section, managed flood releases are highly constrained by inter-basin demands for hydropower. For any flood release program to be sustainable in the long-term it must fall within the range of water available after current firm power demands are met for the system. If insufficient water is available to satisfy flood release objectives at the current energy production levels, managers must demonstrate that an incremental reduction in firm power output or total energy production would be offset by the economic gains to downstream users.

Over the course of Zambezi basin development, water allocation to meet hydropower demands has superseded the water-use needs of the subsistence communities and ecosystems of the lower Zambezi system. In fact, the social and ecological costs of Cahora Bassa Dam have never weighed into the economics of dam management (Bernacsek and Lopez 1984, Bolton 1984a). Efforts to allocate waters for the prescribed flood releases must therefore involve careful accounting of the benefits resulting from improved hydrological conditions in the basin.

Research elsewhere in Africa indicates that flood releases are financially feasible when they balance the demands for hydropower, irrigation, and navigation with the needs of subsistence communities and ecosystems that depend on historic flood cycles (Salem-Murdock and Niasse 1993, Polet and Thompson 1996). Preliminary studies in Mozambique suggest a similar situation in the lower Zambezi system. Research by Hoguane (1997) 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 substantial increase (about 20% or 1500 tonnes per annum) in prawn production and harvest. Based on current market rates for prawns, the annual benefit from improving river flows is potentially about $US 10 million (Li-EDF-KP Joint Venture Consultants 2001). Anderson *et al.* (1990), Goodman (1992), and Chande and Dutton (1997) 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. They estimated the capital value of the current standing crop of major herbivore species in the Marromeu Complex at more than $US 13 million. A very conservative estimate of the value of restored flooding in the Zambezi Delta would be in the order of $US 20 million per annum, and this does not include the economic benefits of the improved flooding conditions for flood recession agriculture, floodplain grazing at the end of the dry season, fisheries productivity, use of various natural resources, groundwater access and water supply, and other activities.

These benefits must be contrasted with the economic benefits of a water regime optimized solely for hydropower[7]. Hydropower sales from Cahora Bassa are currently valued at about $US 200 million/annum (Dr. Simao Muhai *pers. comm.*). The direct economic benefits of prescribed flood releases would therefore potentially outweigh the cost of a 10% reduction in hydropower output, valued at $US 20 million/annum[8].

Based on these preliminary estimates, prescribed flood releases appear to be financially as well as structurally feasible in the lower Zambezi Valley. But of course, the economic benefits and costs are not evenly distributed among stakeholders. Ultimately, the implementation of an effective prescribed flooding program in the lower Zambezi Valley depends on the political will of stakeholders to do so.

STAKEHOLDER SUPPORT FOR FLOOD RELEASES

To realize the full potential of prescribed flood releases in the lower Zambezi Valley, managers must engage the various basin stakeholders and authorities throughout the planning process. Ideally, this process would enable everyone's voices to be heard and considered (Acreman *et al.* 2001). Full identification of all stakeholders requires a lengthy participatory process, however (*e.g.*, Horowitz 1991, Bruwer *et al.* 1996). Different stakeholders must be identified at local, regional, national, and even international levels where relevant. Stakeholders may also vary according to ethnicity, gender, age, or social status.

In large floodplain systems such as the lower Zambezi catchment, the total number of stakeholders is much too high to enable direct representation of all individuals in the planning process. Institutions and organizations must be identified to represent bodies of stakeholders. Broad groups of local stakeholders in the Zambezi Delta include the farmers, fishers, livestock herders, palm wine makers, artisans, and others who use the floodplain resources at different times of the year; traditional chiefs and administrative district leaders who govern resource use patterns; hunting concession operators; and the Sena Sugar industry, coastal prawn industry, and other industries with a stake in future navigation and irrigation development schemes. Regional stakeholder groups in the lower Zambezi Valley include the communities and industries surrounding Cahora Bassa Reservoir, downstream water users from the dam to the delta, and provincial governors and relevant administrative offices. At a national scale, key stakeholders include the Zambezi Valley Development Authority (GPZ), Ministry of Public Works and Transportation, Ministry of Energy, Agriculture and Natural Resources, Ministry of Tourism, Ministry of Culture, and the University of Eduardo Mondlane. International stakeholders include Hidroeléctrica de Cahora Bassa, the managers of upstream dams (especially the Zambezi River Authority and Zambia Electric Supply Company), those concerned with hydropower sales from the dam, especially neighboring Zimbabwe and South Africa, and ultimately the constituents of the proposed Southern Africa Power Pool (Paice 1995). International economic development interests, especially the Southern Africa Development Community (SADC), also have a strong stake in the process.

Groups of stakeholders have been involved in the Zambezi planning process through a series of workshops. Most notably, the *Workshop on the Sustainable Use of the Cahora Bassa Dam and the Zambezi Valley* convened in 1997 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, stakeholders, and decision-makers from Mozambique, southern Africa, and abroad, including two regional governors and three national ministers. Through invited papers, working groups, and discussions, participants educated themselves about the effects 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. Staff of Hidroeléctrica de Cahora Bassa explained their current management objectives and practices for the dam (Costa Bras 1997). Participants discussed the future management of Cahora Bassa Dam to optimize use of Zambezi water for local development and conservation in addition to other national interests, and the actions needed 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 through managed flood releases (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. 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.

SELECTING THE BEST FLOOD RELEASE OPTION

The "best" flood management option for the lower Zambezi Valley and Delta is derived from the established objectives for flood releases, various stakeholder interests, financial feasibility of flood releases (especially the acceptable levels of hydropower reduction), potential flood release options (based on modeling results), and impacts of different flood release options on downstream production systems and ecological processes. The flooding regime must ultimately be defined in terms of the desired timing, duration, depth, and frequency of flooding, and rates of rise and fall of water, on the floodplain. Flows may also be constrained by maximum permissible velocities in the river channel to avoid excessive channel erosion, and water temperature and quality considerations may also be important at certain times of the year[9].

Several methods are available to help define these optimal prescribed flooding patterns for downstream stakeholders. Flow requirements may be identified through the process of Participatory Rural Appraisal and stakeholder workshops. *Participatory Rural Appraisal* techniques were successfully used to identify desired flooding patterns in the Waza-Logone floodplain in Cameroon (Acreman *et al.* 2001). In the Lower Zambezi basin, local *stakeholder workshops* will build from the *Workshop on the Sustainable Use of the Cahora Bassa Dam and the Zambezi Valley* convened in 1997. Oral histories are being collected in selected villages along the entire length of the lower Zambezi to understand the traditional uses of the Zambezi River prior to construction of Cahora Bassa Dam, and to understand how local communities have adapted their livelihoods to the current erratic flooding regime (Beilfuss *et al.* 1999).

Methods to identify flow requirements to meet ecological objectives in the Lower Zambezi Valley and Delta are limited. King *et al.* (1999), in a comprehensive review of flow assessment methodologies, note that inadequate emphasis has been place worldwide on research into ecological flows for wildlife and wetland systems, and there are no existing methodologies or guidelines for assessing these environmental flow requirements. Available methodologies that may be adapted to assess ecological flow requirements include hydrological indices, desktop analyses, multi-disciplinary expert panels, and biological response modeling (e.g., Acreman *et al.* 2001). Ecological objectives may include the maintenance or rehabilitation of natural resources used by people downstream of the dam, or the conservation of certain wildlife species or vegetation communities.

Natural hydrological indices (historic flow methods) are the most commonly applied methods of setting flow requirements (Jowett 1997). These methods are typically based on providing a percentage of the mean annual or monthly flow, or a minimum low flow during critical dry periods. This method is well suited to highly altered river systems such as the Zambezi. Where critical processes and linkages have fundamentally changed and pre-impact ecological conditions are poorly known, specific downstream water requirements are difficult to determine. Hydrological indices may also be appropriate where hydrological requirements vary among water users as well as individual species, as any flood release strategy requires trade-offs among different stakeholders (*e.g.,* Bishop *et al.* 1990). The water requirements for flood recession agriculture, fisheries, and other agricultural activities vary along the length of the river margin, for example (*e.g.,* Bruwer *et al.* 1996). And different mammal and waterbird species in the delta use a variety of different habitats in response to heterogeneous hydrologic conditions (Tinley 1994, Beilfuss and Bento 1997).

The ideal flood release strategy may therefore be to initially approximate the natural flow regime that previously maintained the entire suite of species and human activities (Sparks 1995). This involves mimicking to the degree possible the intra- and inter-annual variability of the system, and allowing downstream communities to respond accordingly (*e.g.,* Sparks *et al.* 1990, Bayley 1991). Such a regime may offer the best opportunity to restore the dynamic processes and local production systems that were once integral to the delta ecosystem. However, efforts to mimic natural hydrological conditions are highly constrained by the availability and pattern of inflows. The management of Kariba Dam, for example, has fundamentally changed the hydrological regime of the Zambezi River to such an extent that the historical mean annual flow pattern cannot be recreated below Cahora Bassa Dam without very significant and unacceptable reductions in hydropower generation.

Desktop studies involve a review of available data from literature related to river flows and water requirements for particular species or communities (Acreman *et al.* 2001). This method may represent an improvement over hydrological indices where specific ecological objectives have been established, because desk-top studies offer quantitative information about the ecological requirements or response thresholds of certain key species of interest (Jowett 1997). Hydraulic data requirements include water depth or velocity thresholds for different species of fish or invertebrates, for example, or water quality constraints. However, data from desktop studies often must be extrapolated from distant study sites to the target floodplain, and results may not be comparable. Data on vegetation distribution and dynamics from other African floodplain systems provide important insights into the links between flooding and vegetation response in the Zambezi Delta, but are not directly transferable because of differences in species composition, hydrology, soils, and especially salinity.

To overcome the limitations of extrapolating data from other sites, flood release options for specific ecological targets may be also assessed through *multi-disciplinary panels of experts.* In South Africa, a 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*s), 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 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. The workshops may involve field visits to affected areas to test assumptions and fill data gaps. A similar approach has been adopted in Australia (Swales and Harris 1995). The expert-panel method is ideally suited for estimating specific flow requirements for the Zambezi basin, and local and regional experts in aquatic ecology, hydrology, geomorphology, wetland botany, wildlife management, anthropology, and other disciplines are actively participating in this process.

More complex *biological response models* (habitat methods) may be appropriate in the rare instances where detailed knowledge is available about the specific hydrological requirements of target species (*e.g.,* Tennant 1976). Habitat methods include the Physical Habitat Simulation System or PHABSIM (Milhous *et al.* 1984) and Instream Flow Incremental Methodology or IFIM (Bovee 1982, Estes and Orsborn 1986). The models are sophisticated, requiring considerable training, operational expenses, and data input, and can be easily misused (Orth 1987, Jowett 1997). Application of the PHABSIM model to river systems with large variations in macrophyte density, for example, may lead to significantly distorted results (Hearne and Johnson 1994). For these reasons, river ecologists in southern Africa have generally rejected this approach in favor of the expert panel method (Davies 1998).

Regardless of the method chosen for selecting the best flood release alternative, trade-offs are inevitable among different water use sectors, target species, and desired floodplain processes. At worst, the water requirements of local communities and key floodplain species may be incompatible. Certain high volume, short-duration flood releases may meet objectives for improving recession agriculture or fisheries, for example, but might not be sufficient to reduce the cover of invasive tree species or trigger seasonal migrational movements among herbivores to reduce grazing pressure. These trade-offs must be clearly defined in the flood release objectives and through a transparent process of stakeholder participation.

MONITORING, EVALUATING, AND ADAPTING THE RELEASE PROGRAM

Prescribed flooding must be an adaptive management process. River managers must monitor flood releases and evaluate the degree to which flooding patterns meet clearly stated objectives. Subsequent flood releases must then be modified according to these findings (Stevens and Wegner 1995). The institutions responsible for prescribed flooding releases must have the technical capacity to assess the appropriate timing, magnitude, and duration of flooding that is required and to monitor the effects of flood releases though the collection and analysis of data on agriculture, fisheries, vegetation, wildlife, hydropower, and other water use sectors (Scudder and Acreman 1996).

To evaluate the effectiveness of flood releases on downstream conditions, monitoring data must be collected prior to the release of managed floods and must continue well after a flood release program is implemented**.** Data should be collected to test certain clearly-defined social, economic, or ecological objectives. Ideally, objective criteria can be evaluated relative to an historical reference state (assessing system improvement over time), and in reference to other systems (assessing system status relative to comparable areas). Assessment criteria should be quantifiable with replicable methods, and strongly linked to measurable hydrological conditions. The criteria also must be carefully considered in the context of local climatic conditions, downstream tributary runoff patterns, and other uncontrolled variables. For example, a year of exceptional rainfall in the Mozambique plateau region might contribute to overbank flooding patterns and improvements in the floodplain fisheries that otherwise would not be met by prescribed floods during a more average rainfall year.

The monitoring program should be sufficiently robust to capture changes in downstream conditions over a range of temporal and spatial scales. Data are needed to evaluate short-term responses after only one or two flood releases (for immediate feedback to dam managers and other decision-makers), and medium- to long-term responses resulting from several consecutive years of flood releases. Objectives related to short-term responses are typically evaluated at a site-specific or species-specific scale. Multi-year observations may be necessary before proposing changes in the prescribed flood regime, to more clearly control for natural fluctuations in ambient conditions. Criteria might include measurable improvements in flood recession crop yield, fisheries productivity or catch-per-unit-effort, or reproductive success of certain target species. For example, *how many Wattled Crane chicks were produced in the Marromeu Complex in the year(s) immediately before and after managed flood releases?* And also, *how does the breeding success of the Wattled Crane population in the Marromeu Complex before and after managed flood releases compare to the breeding success of Wattled Cranes in the Okavango Delta or another comparable floodplain system*?

Long-term monitoring is needed to assess many changes at a landscape scale, especially to distinguish short-term cyclical fluctuations in vegetation composition (*e.g.*, variability around the mean) from long-term directional patterns of change (*e.g.*, shift in mean conditions). Van der Valk (1981) and Finlayson (1991), for example, demonstrated cycles of wetland vegetation change that lasted for more than 10 years, and multi-year cycles are reported from papyrus swamps (Gaudet 1977) and shallow lakes (Howard-Williams 1975) in Africa. Ecological conditions may have a lagged response to changes in hydrological conditions, or may be linked to threshold conditions (*e.g.*, a minimum magnitude or duration of peak floods) that depend on downstream flow contributions and are not met in all years (Fuchs and Statzner 1990). Long-term objectives might include a 20% reduction in the cover of woody vegetation on the floodplain, a 10% reduction in the cover of emergent and floating aquatic vegetation on certain floodplain waterways, or a 5% increase in the cover of inland coastal mangrove over a 5-year period. Data may also relate to habitat connectivity and the spatial arrangement of vegetation patches, such as changes in the frequency distribution of patch sizes, area-weighted mean patch size, and fractal dimension (Turner and Gardner 1991). Hydrogeomorphic changes, such as increased silt deposition or reduced soil salinity, may require even longer monitoring time frames.

Ongoing monitoring efforts towards establishing restoration objectives for the delta include coastal prawn fishery research (Hoguane 1997), Wattled Crane research (Bento *in press*), large mammal censusing (Chande and Dutton 1997), and mangrove ecology (Doddema and Manjate 2000). An historical vegetation basemap of the delta was generated from archival aerial photographs and satellite imagery (Working Paper #3) to provide restoration success targets based on the degree to which conditions that occurred prior to construction of Kariba Dam are re-established. A comparable 2000 vegetation basemap derived from satellite imagery, aerial reconnaissance, and sampling transects, provides a current reference for evaluating changes over time associated with prescribed flood releases.

CONCLUSIONS

Globally, river managers are assessing whether large river floodplains can be “restored” to support viable communities and ecosystems. The rehabilitation of river-floodplains must begin with an inclusive and adaptive approach in which hydrological restoration alternatives are evaluated in terms of clearly defined socio-economic and ecological parameters. African governments, managers, and scientists, with prescribed flooding programs underway in several nations and others under consideration, are leading this charge.

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. The past seven years of research have contributed to understanding the link between hydrological degradation and ecological change, and the potential for ameliorating negative changes through managed flood releases. Significant areas of floodplain and wetland downstream would benefit from the re-establishment of more natural flooding patterns. Adequate inflows to Cahora Bassa Dam are available to make substantial flood releases. And the downstream benefits accruing from modest flood releases – in terms of coastal prawn fisheries, flood recession cropping, floodplain fisheries, and wildlife productivity – may significantly exceed the lost opportunity costs of using stored water for hydropower.

The degree to which managed floods can reverse deleterious changes in farming/fishing systems downstream of the dam and the productivity and diversity of the Zambezi Delta ecosystem now remains to be tested. Participants in the process must continue to define clear objectives for managed flood releases, further elucidate the financial feasibility of such releases, build strong stakeholder support to develop and implement a flooding strategy, and establish an adaptive management program to model, monitor, and evaluate the effectiveness of flood releases for meeting restoration objectives. 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 1997 *Workshop on the Sustainable Use of Cahora Bassa Dam and the Zambezi Valley* will require the on-going commitment of many individuals and institutions. The alternative, a path of continued degradation of the Zambezi Delta, would ultimately prove much more costly to the people and wildlife of Mozambique.

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REFERENCES

Acreman, M. 1994. The role of artificial flooding in the integrated development of river basins in Africa. Pages 35-44 in C. Kirby and W. R. White, eds. *Integrated river basin development.* Chichester: John Wiley & Sons.

Acreman, M.C. Farquharson, F.A.K., McCartney, M.P., Sullivan, C., Campbell, K., Hodgson, N., Morton, J., Smith, D., Birley, M., Knott, D., Lazenby, J., Wingfield, R., and E.B. Barbier. 2001. *Managed flood releases from reservoirs: issues and guidance. Report to DFID and the World Commission on Dams.* Wallingford, U.K.: Centre for Ecology and Hydrology.

Adler, T. 1996. Healing waters: flooding rivers to repent for the damage done by dams. *Science News* 150: 188-189.

Anderson, J., P. Dutton, P. Goodman, and B. Souto. 1990. *Evaluation of the wildlife resource in the Marromeau complex with recommendations for it's further use*. Maputo: LOMACO.

Barbier, E.B., M.C. Acreman, and D. Knowler. 1997. *Economic valuation of wetlands: a guide for policy makers and planners.* Gland: Ramsar Convention.

Basson, M.S. 1995. South Africa water transfer schemes and their impact on the Southern Africa region. Pages 41-48 in T. Matiza, S. Crafter, and P. Dale., eds. *Water resources use in the Zambezi Basin. Proceedings of a workshop held at Kasane, Botswana , April 28-May 2 1993.* Gland: IUCN.

Batoka Joint Venture Consultants.1993b. *Batoka Gorge Hydro Electric Scheme Feasibility Study. Section 13. Reservoir operation studies. Final Report.* Harare: Zambezi River Authority.

Bayley, P.B. 1991. The flood pulse advantage and the restoration of river-floodplain systems. *Regulated Rivers* 6: 75-86.

———. 1995. Understanding large river-floodplain ecosystems. *Bioscience* 45: 153-58.

Beilfuss, R.D. 1997. Restoring the flood: a vision for the Zambezi. *The ICF Bugle* 23(4): 1-2.

———. 2000. Piecing together the story of an African floodplain: water, wetlands, and Wattled Cranes. *The ICF Bugle* 26(1): 1-3.

Beilfuss, R.D., and C.M. Bento. 1997. Impacts of hydrological changes on the Marromeu complex of the Zambezi Delta, with special attention to the avifauna. *Paper presented at the workshop on the sustainable use of Cahora Bassa Dam and the Zambezi Valley, 29 September to 2 October, 1997, Songo, Mozambique.*

Beilfuss, R.D, T. Scudder, A. Isaacmen, and A. Chilundo. 1999. *Sustainable development and habitat restoration in the lower Zambezi Valley, Mozambique. A proposal to the John D. and Catherine T. MacArthur Foundation.* Chicago, Illinois.

Bento, C.M. In press. *The status and ecology of Wattled Cranes in the Zambezi Delta, Mozambique.* M.Sc. Thesis. University of Cape Town.

Bernacsek, G.M., and S. Lopez. 1984. *Investigations into fisheries and limnology of Cahora Bassa Reservoir seven years after dam closure. FAO/GCP/MOZ006/SWE Field doc. 9*. Rome: U.N. Food and Agriculture Organization.

Bishop, A.B., T.B. Hardy, and B.D. Glabou. 1990. Analyzing instream flow trade-offs for small hydropower development. *Rivers* 1(3): 173-182.

Bolton, P. 1983. *The regulation of the Zambezi in Mozambique: a study of the origins and impact of the Cahora Bassa Project.* Ph.D. Thesis. University of Edinburgh, Scotland.

Bolton, P. 1984a. Mozambique's Cahora Bassa project: an environmental assessment. Pages 156-167 in E. Goldsmith and N. Hildyard, eds. *The social and environmental effects of large dams a report to the European Ecological Action Group (ECOROPA). Vol. 2.* Camelford, Cornwall, UK: Wadebridge Ecological Centre.

———. 1984b. Sediment deposition in major reservoirs in the Zambezi Basin. Pages 559-567 in D.E. Walling, P. Wurzel, and S.S.D Foster, eds. *Challenges in African hydrology and water resources. Proceedings of the Harare Symposium, July 1984, convened and organized by the Ministry of Water Resources and Development and the Department of Civil Engineering, University of Zimbabwe. IAHS Publication 144.* Wallingford, Oxfordshire: International Association of Hydrological Sciences.

Bovee, K.D. 1982. *A guide to stream habitat analysis using the instream flow incremental methodology. U.S. Fish and Wildlife Service Biological Services Program FWS/OBS-82/26.*Washington D.C.

Bruwer, C. 1997. Lessons learned from the community-based management of the Phongolo floodplain, South Africa. *Paper presented at the workshop on the sustainable use of Cahora Bassa Dam and the Zambezi Valley, 29 September to 2 October, 1997, Songo, Mozambique.*

Bruwer, C., C. Poultney, and Z. Nyathi. 1996. Community-based hydrological management of the Phongolo floodplain. Pages 199-212 in M. C Acreman and G.E Hollis, eds. *Water management and wetlands in sub-Saharan Africa.* Gland: IUCN.

Chande, B., and P. Dutton. 1997. Impacts of hydrological changes on the Marromeu complex of the Zambezi Delta, with special attention to the mammal fauna. *Paper presented at the workshop on the sustainable use of Cahora Bassa Dam and the Zambezi Valley, 29 September to 2 October, 1997.* Songo, Mozambique.

Collier, M., R.H. Webb, and J.C. Schmidt. 1996. *Dams and rivers a primer on the downstream effects of dams. U.S. Geological Survey Circular.* Denver: U.S. Dept. of the Interior, U.S. Geological Survey.

Costa Bras, M. 1997. The management of Cahora Bassa Reservoir: the owner's perspective. *Paper presented at the workshop on the sustainable use of Cahora Bassa Dam and the Zambezi Valley, 29 September to 2 October, 1997, Songo, Mozambique.*

Davies, B.R., ed. 1998. *Sustainable Use of the Cahora Bassa Dam and the Zambezi Valley. Final report.* Maputo: Arquivo do Patrimonio Cultural and Ford Foundation.

Davies, B.R., R.D. Beilfuss, and M.C. Thoms. 2001. Cahora Bassa retrospective, 1974-1997: effects of flow regulation on the Lower Zambezi River. *Verh. Internat. Verein. Limnol.* 27: 1-9.

Denny, P. 1993. Wetlands of Africa: Introduction. Pages 1-128 in D.F. Whigham, D. Dykjova, and S. Hejn, eds. *Wetlands of the world: inventory, ecology, and management*. Dordrecht: Kluwer Academic Publishers.

Doddema, M., and J. Manjate. 2000. Valuation of the mangrove areas in the coastal districts of Dondo, Marromeu, and the northern part of Beira city, Province of Sofala. Pages 1-27 in M. Doddema, compilor. *Baseline data and evaluation procedures for the formulation of Mangrove Resources Management Plan in the northern part of Sofala Province. Volume 1.* Maputo: Direcçao Nacional de Florestas e Fauna Bravia.

Dos Santos, J.F. 1968. Aproveeitamento hidroelectrico de Cabora Bassa: dimensionamento hidrologico do orgaois de descarga. *Electricidade, Lisbon* 55: 236-47.

Dunham, K.M. 1994. The effect of drought on the large mammal populations of Zambezi River in the woodlands. *Journal of Zoology* 234: 489-526.

Estes, C.C., and J.F. Orsborn. 1986. Review and analysis of methods for quantifying instream flow requirements. *Water Resources Bulletin* 22: 389-397.

Finlayson, C.M. 1991. Plant ecology and management of an internationally important wetland in monsoonal Australia. Pages 90-98 in J.A. Kusler and S. Daly, eds. *Proceedings of an International Symposium on Wetlands and River Corridor Management. July 5-9, 1989, Charleston, South Carolina.* Berne, New York: Association of State Wetland Managers.

Fuchs, U., and B. Statzner. 1990. Time scales for the recovery potential of river communities after restoration: lessons to be learned from smaller streams. *Regulated Rivers* 5: 77-87.

Gabinete do Plano do Zambeze. 2001. *Informational brochure for private investment.* Maputo.

Galat, D.L., L.H. Fredrickson, D.D. Humburg, K.J. Bataille, J.R. Bodie, J. Dohrenwend, G.T. Gelwicks, J.E. Havel, D.L. Helmers, J.B. Hooker, J.R. Jones, M.F. Knowlton, J. Kubisiak, J. Mazourek, A.C. McColpin, R.B. Renken, and R.D. Semlitsch. 1998. Flooding to restore connectivity of regulated, large-river wetlands: natural and controlled flooding as complementary processes along the lower Missouri River. *Bioscience* 48(9): 721-734.

Gammelsrod, T. 1996. Effect of Zambezi River management on the prawn fishery of the Sofala Bank. Pages 119-124 in M. C Acreman and G. E Hollis, eds. *Water management and wetlands in sub-Saharan Africa.* Gland: IUCN.

Gasse, F. 2001. Hydrological changes in Africa. *Science* 292(5525): 2259.

Gaudet, J.J. 1977. Natural drawdown on Lake Naivasha, Kenya, and the formation of papyrus swamps. *Aquatic Botany* 3: 1-47.

Goodman, P.S. 1992. Zambeze Delta - an opportunity for sustainable utilisation of wildlife. *International Waterfowl and Wetlands Research Bureau Bulletin* 8: 12.

Gore, J.A., and F.D. Shields. 1995. Can large rivers be restored? *Bioscience* 45(3): 142-152.

Hall, A., I., M.C.B. Valente, and M.S. Burholt. 1977. The Zambezi River in Mozambique: the suspended solids regime and composition of the middle and lower Zambezi prior to the closure of Cahora Bassa Dam. Portugal: Departmento da Quimica, Univ. Aveiro.

Hall, A., I. Valente, and B.R. Davies. 1977. The Zambezi River in Mocambique: the physico-chemical status of the middle and lower Zambezi prior to the closure of the Cabora Bassa Dam. Freshwater Biology 7: 187-206.

Hanlon, J. 2001. Floods displace thousands in Mozambique. *The Guardian.* March 28.

Haws, E.T., N. Reilly, and D. Plinston. 1982. Lower Zambezi floods and warning system: reassessment of Cahora Bassa design flood and operations. *Commission Internationale des Grands Barrages*: 345-57.

Hearne, J., and I. Johnson. 1994. Determination of ecologically acceptable flows in rivers with seasonal changes in the density of macrophyte. *Regulated Rivers* 9: 177-84.

Hidrotécnica Portuguesa (HP). 1965a. *Anexos ao Plano Geral de Fomento e Ocupacao do Vale do Zambeze. Elementos de estudo. Ocupacao de terras cadastro.* Maputo: Missão de Fomento e Povoamento do Zambeze.

———. 1965b. *Anexos ao Plano Geral de Fomento e Ocupacao do Vale do Zambeze. Elementos de estudo. Sedimentologia e reconhecimento de fundacoes.* Maputo: Missão de Fomento e Povoamento do Zambeze.

———. 1965c. *Anexos ao Plano Geral de Fomento e Ocupacao do Vale do Zambeze. Estudos base. Empreendimentos prioritarios. Aproveitamento de Cabora-Bassa.* Maputo: Missão de Fomento e Povoamento do Zambeze.

———. 1973. *Navigabilidade do Rio Zambezi: disponibilidade de caudais*. Lisbon, Portugal: GPZ.

Hoguane, A. 1997. Shrimp abundance and river runoff in Sofala Bank - the role of the Zambezi. *Paper presented at the workshop on the sustainable use of Cahora Bassa Dam and the Zambezi Valley, 29 September to 2 October, 1997, Songo, Mozambique.*

Hollis, G.E. 1996. Hydrological inputs to management policy for the Senegal River and its floodplain. Pages 155-184 in M.C. Acreman and G.E Hollis, eds. *Water management and wetlands in sub-Saharan Africa.* Gland: IUCN.

Hook, D.D. 1984. Adaptations to flooding with fresh water. Pages 265-124 in T.T. Kozlowski, ed. *Flooding and plant growth.* New York: Academic Press.

Horowitz, M.M., and M. Salem-Murdock. 1990. *The Senegal River Basin monitoring activity. Phase one synthesis*. Binghamton, New York: Institute for Development Anthropology.

Horowitz, M.M. 1991. *The Senegal River Basin Monitoring Activity. Phase one final report*. Binghamton, New York: Institute for Development Anthropology.

Howard-Williams, C. 1975. Vegetation changes in a shallow African lake: response of the vegetation to a recent dry period. *Hydrobiologia* 47(3&4): 381-398.

Jackson, M.B., and M.C. Drew. 1984. Effects of flooding on growth and metabolism of herbaceous plants. Pages 47-128 in T.T. Kozlowski, ed. *Flooding and plant growth.* New York: Academic Press.

Japanese International Cooperation Agency (JICA). 1997. *Feasibility study on Mutonga/Grand Falls Hydropower Project. Report to the Republic of Kenya Ministry of Energy.* Nairobi, Kenya.

Jowett, I.G. 1997. Instream flow methods: a comparison of approaches. *Regulated Rivers* 13: 115-127.

Junk, W.J., P.B. Bayley, and R. Sparks. 1989. The flood pulse concept in river-floodplain systems. In ed D. P. Dodge, ed. *Proceedings of the International Large River Symposium (LARS), Honey Harbour, Ontario, Canada, September 14-21, 1986. Canadian Special Publication of Fisheries and Aquatic Sciences 106.* Ottawa: Dept. of Fisheries and Oceans.

King, J.M., and R. Tharme. 1994. *Assessment of the instream flow incremental methodology and initial development of alternative instream flow methodologies for South Africa. Contract report 295/1/94 to the South African Water Research Commission.* Pretoria.

King, J.M., R. Tharme, and C. Brown. 1999. *Definition and Implementation of Instream Flows. WCD Thematic Report, Environmental Issues II.1.* World Commission on Dams, South Africa.

Kozlowki, T.T. 1984. Response of woody plants to flooding. Pages 129-164 in T.T. Kozlowski, ed. *Flooding and plant growth.* New York: Academic Press.

Kranendonk, L. 1980. *Escoamentos mensais criticos da albuferiras de Kariba e Cahora Bassa e curvas guia superior de Cahora Bassa.* Maputo: Direcçao Nacional de Aguas.

Li-EDF-KP Joint Venture Consultants (Lahmeyer-Knight Peisold-Electricite' de France). 2000. *Mepanda Uncua and Cahora Bassa North Project. Simulation of Reservoir Operation and Energy Generation on Zambezi River.* Maputo: Unidade Tecnica de Implentacao de Projectos Hidroelectricos.

_____. 2001. *Mepanda Uncua and Cahora Bassa North Project. Environmental Flow releases.* Maputo: Unidade Tecnica de Implentacao de Projectos Hidroelectricos.

Liesegang, G., and M. Chidiamassamba. 1997. Alternativas e tecnicas adaptadas as cheias usadas pelas comunidades ao longo do Vale de Zambeze. *Paper presented at the workshop on the sustainable use of Cahora Bassa Dam and the Zambezi Valley, 29 September to 2 October, 1997, Songo, Mozambique.*

Maclin, E. and M. Sicchio. 1999. *Dam removal success stories: restoring rivers through selective removal of dams that don't make sense. Final report.* San Francisco: American Rivers, Friends of the Earth, and Trout Unlimited.

Mavanga, B. 1997. Energia da HCB chega a' RAS ate' final do ano. *Noticias*. 30 September.

Michener, W.K., and R. A. Haeuber. 1998. Flooding: natural and managed disturbances. *Bioscience* 48(9): 677-680.

Middleton, B. 1999. *Wetland restoration: flood pulsing and disturbance dynamics.* New York: John Wiley & Sons.

Milhous, R.T., Wegner, D.L., and T. Waddle. 1984. *User's guide to the physical habitat simulation programs. U.S. Fish and Wildlife Service Biological Services Program FWS/OBS-81/43.* Washington D.C.

Mitchell, D.S. 1985. Surface-floating aquatic macrophytes. Pages 109-124 in P. Denny, ed. The ecology and management of African wetland vegetation: a botanical account of African swamps and shallow waterbodies. Dordrecht: Dr. W. Junk Publishers.

Molles, M.C., C.S. Crawford, L.M. Ellis, H.M Vallett, and C.N. Danm. 1998. Managed flooding for riparian ecosystem restoration. *Bioscience* 48(9): 677-680.

Negrão, J. 1995. *One hundred years of African rural family economy the Zambezi delta in retrospective analysis*. Lund, Sweden: University of Lund.

Nilsson, C. 1996. Remediating river margin vegetation along fragmented and regulated rivers in the north: what is possible? *Regulated Rivers* 12: 415-431.

Olivier, H. 1977. *Great dams in southern Africa*. Cape Town: Purnell.

Orth, D.J. 1987. Ecological considerations in the development and application of instream flow-habitat models. *Regulated Rivers* 1: 171-181.

Paice, D. 1995. Power hungry: an electricity grid for sub-equatorial Africa? *Africa - Environment and Wildlife* 3(2): 65-66, 68.

Penman, H.L. 1948. Natural evaporation from open water, bare soil, and grass. *Proceedings of the Royal Society of London* A193: 120-145.

Polet, G., and J.R. Thompson. 1996. Maintaining the floods - hydrological and institutional aspects of managing the Komadugu-Yobe River basin and its floodplain wetlands. Pages 73-90 in M.A. Acreman and G.E. Hollis, eds. *Water management and wetlands in sub-Saharan Africa.* Gland: IUCN.

Posada, A., and M. ter Woort. 1996. *Cahora Bassa North Bank and Mepanda Uncua Hydroelectric Projects: information memorandum*. Washington, D.C.: The Energy and Infrastructure Division, Southern Africa Department, Africa Regional Office, The World Bank.

Rees, W.A. 1978. Ecology of the Kafue lechwe: soils, water levels, and vegetation. *J. Applied Ecology* 15: 163-76.

Rendel, Palmer, and Tritton Consulting and Designing Engineers. (RPT) 1979. *Review of the hydrological network, and study of the design of a flood warning system for the Zambezi River. Consultancy Report.* London: Institute of Hydrology.

———. 1980. *Review of the hydrological network, and study of the design of a flood warning system for the Zambezi River. Supplementary report.* London: Institute of Hydrology.

Salem-Murdock, M., and M. Niasse. 1993. *Senegal River Basin monitoring activity II. Executive summary.* Binghamton, New York: Institute for Development Anthropology.

Scholte, P., S. de Kort, and M. van Weerd. 2000. Floodplain rehabilitation in far northern Cameroon: expected impact on bird life. *Ostrich* 71(1&2): 112-117.

Scudder, T. 1980. River basin development and local initiatives in savannah environments. In D.R. Harris, ed. *Human ecology of savannah environments.* New York: Academic Press.

——. 1989. River basin projects in Africa. *Environment* 31(2): 4-32.

——. 1993. Pipe dreams: can the Zambezi River supply the region's water needs? *Cultural Survival Quarterly* 17(2): 45-47.

Scudder, T., and M.C. Acreman. 1996. Water management for the conservation of the Kafue wetlands, Zambia and the practicalities of artificial flood releases. Pages 101-106 in M.A. Acreman and G.E. Hollis, eds. *Water management and wetlands in sub-Saharan Africa.* Gland: IUCN.

Shawinigan-Lavalin and Hidrotécnica Portuguesa. 1990a. *Simulation of Kafue Gorge Power Plant operation: Hydroelectric Hydrological Assistance Project - Phase 1*.SADCC 3.0.4.

———. 1990b. *Simulation of the joint operation of major power plants in the Zambezi Basin: Hydroelectric Hydrological Assistance Project - Phase 1*.SADCC 3.0.4.

Sheppe, W., and T Osborne. 1971. Patterns of use of a floodplain by Zambian mammals. *Ecological Monographs* 41(3): 179-205.

Schuman, J.R. 1995. Environmental considerations for assessing dam removal alternatives for river restoration. *Regulated Rivers* 11: 249-261.

Sparks, R.E. 1995. Need for ecosystem management of large rivers and their floodplains. *Bioscience* 45(3): 168-182.

Sparks, R.E., P.B. Bayley, S.L. Kohler, and L.L.Osborne. 1990. Disturbance and recovery of large floodplain rivers. *Environmental management* 14: 699-709.

Stanford, J.A., J.V. Ward, W.J. Liss, C.A. Frissell, R.N. Williams, R.N. A. Lichatowich, and C.C. Coutant. 1996. A general protocol for restoration of regulated rivers. *Regulated Rivers* 12: 391-413.

Stevens, L.E., and D.L. Wegner. 1995. Changes on the Colorado River: operating Glen Canyon Dam for environmental criteria. Pages 65-74 in J.L. Traub, ed. *Proceedings of a national symposium on using ecological restoration to meet Clean Water Act goals*. Chicago: EPA.

Stevens, W.K. 1997. A dam open: Grand Canyon roars again. *New York Times,* sec. B, pp. 7, 12. February 25.

Suschka, J., and P. Napica. 1986. Ten years after completion of Cahora Bassa Dam. Pages 171-203 in *The impact of large water projects on the environment: proceedings of an international symposium*. Paris: UNEP/UNESCO.

Swales, S., and J.H. Harris. 1995. The Expert Panel Assessment Method (EPAM): a new tool for determining environmental flows in regulated rivers. Pages 125-134 in D.M. Harper and A.D.J. Ferguson, eds. *The ecological basis for river management.* London: John Wiley & Sons.

SWECO/SWED POWER. 1982. *Cahora Bassa hydroelectric power scheme - State II, Pre-investment report, Part 1: Hydrology and Water Management*. Stockholm, Sweden.

———. 1983. *Cahora Bassa hydroelectric power scheme - State II, Pre-investment report, Part 5: Ecology*. Stockholm, Sweden.

Tello, L.P., and P. Dutton. 1979. *Programa de Operação Bufalo.* Maputo: Direção Naçional de Florestas e Fauna Bravia.

Tennant, D.L. 1976. Instream flow regimens for fish, wildlife, recreation, and related environmental resources. Pages 359-373 in J.F. Orsborn and C.H. Allman, eds. *Proceedings of the Symposium and Specialty Conference on Instream Flow Needs II.* Bethesda, Maryland: American Fisheries Society.

Tharme, R. 1996. *Review of international methodologies for the quantification of the instream flow requirements of rivers. Report to the South African Department of Water Affairs & Forestry*. Pretoria.

Thompson, K. 1985. Emergent plants of permanent and seasonally-flooded wetlands. Pages 43-108 in P. Denny, ed. *The ecology and management of African wetland vegetation: a botanical account of African swamps and shallow waterbodies.* Dordrecht: Dr. W. Junk Publishers.

Tinley, K. 1977. *Framework of the Gorongosa ecosystem, Mozambique.* Ph.D. Dissertation. University of Pretoria. South Africa.

_____. 1994. *Description of Gorongosa-Marromeu Natural Resource Management Area. Section2: ecological profile of the region (form, content, process).* Harare: IUCN Regional Office for Souther Africa.

Triplet, P., and P. Yésou. 2000. Controlling the flood in the Senegal Delta: do waterfowl populations adapt to their new environment? *Ostrich* 71, no. 1&2: 106-11.

Turner, M.G., and R.H. Gardner. 1991. *Quantitative methods in landscape ecology. The analysis and interpretation of landscape heterogeneity*. New York: Springer-Verlag.

U.S. Army Corps of Engineers (U.S. ACOE). 1998. *HEC-5 Simulation of flood control and conservation systems. Version 8.0 User's Manual*. Davis, California: U.S. ACOE Hydrological Engineering Center,.

Van der Valk, A.G. 1981. Succession in wetlands: a Gleasonian approach. *Ecology* 62: 688-696.

Vaselaar, R. T. 1997. Opening the flood gates: the 1996 Glen Canyon Dam experiment. *Restoration and Management Notes* 15: 119-25.

Ward, J.V., and J.A. Stanford. 1995a. The serial discontinuity concept: extending the model to floodplain rivers. *Regulated Rivers* 10: 159-168.

Welcomme, R.L. 1995. Relationships between fisheries and the integrity of river systems. *Regulated Rivers* 11: 121-36.

Wesseling, J.W., E. Naah, C.A. Drijver, and D. Ngantou. 1996. Rehabilitation of Logone floodplain, Cameroon, through hydrological management. Pages 185-198 in M.A. Acreman and G.E. Hollis, eds. *Water management and wetlands in sub-Saharan Africa.* Gland: IUCN.

White, L. 1993. *Bridging the Zambesi a colonial folly*. Houndmills, Basingstoke, Hampshire: Macmillan.

Whitlow, T.H., and R.W. Harris. 1979. *Flood tolerance in plants: a state-of-the-art review. Technical report E-79-2.* U.S. Army Corps of Engineers, Vicksburg, Mississippi.

ENDNOTES

[1] Even before the construction of Kariba, Itezhitezhi, and Kafue Gorge reservoirs, much of the sediment load from the Zambezi and Kafue headwaters regions was captured by large floodplains such as the Barotse Plain, Chobe Swamp, Lukanga Swamp, and Kafue Flats (Bolton 1984b).

[2] Other hydropower stations in the Zambezi system that do not significantly affect Zambezi runoff patterns were not modeled. These include the Victoria Falls run-of-river hydropower plant (108 MW) on the mainstem Zambezi, and the Nkula Falls 'A' (24 MW), Nkula Falls 'B' (80 MW), and Tedzani Falls (40 MW) run-of-river hydropower dams on the Shire River.

[3] The adoption of an appropriate Design Flood Rule Curve for the operation of Cahora Bassa Dam has been the subject of considerable debate over the years (Bolton 1983). Dos Santos (1968) was the first to calculate a DFRC for Cahora Bassa, later revised by Hidrotécnica Portuguesa (1973), using generated time series data to determine the 1:10,000 year design flood. These curves assumed that non-turbine discharges would not be made until the end-of-month level of the flood rule curve was reached, after which the gates would be fully opened.

After severe flooding resulted from emergency flood releases from Cahora Bassa in 1978, RPT (1979) was commissioned to re-evaluate the DFRC and related flood management practices. RPT calculated a new set of input data to simulate the operation of the Cahora Bassa. RPT proposed that discharges should be made up to a chosen "threshold" in order to reduce the need for higher discharges at a later date. The thresholds were chosen to provide the maximum discharge that could be made without causing serious flooding downstream. The study demonstrated that appreciable flood alleviation could be achieved by adopting the proposed policy of threshold discharges. RPT later reassessed their work and proposed a slightly revised DFRC (Haws *et al.*1982).

Following the release of the RPT study, engineers of the Direcção Naçional de Aguas (DNA) in Maputo undertook an independent study of the DFRC (Kranendonk 1980). The study was based on a reassessment of the data used by Dos Santos (1968) and the application of revised techniques for estimating the magnitude of extreme floods. Two alternative methods of analysis were proposed for estimating the DFRC.

SWECO (1982), as part of their assessment of the proposed North Bank Power Station at Cahora Bassa, re-evaluated the DFRC again. SWECO suggested that if the maximum discharge capacity of the dam were increased by about 25% (3600 m^3/s) by constructing an additional spillway, it would be possible to replace the DFRC with a single normal maximum operating level for the reservoir. Increased spillway capacity would increase the peak flood discharge downstream of the dam and thereby increase the flood risk in the floodplain, but SWECO demonstrated that the peaks could be partially attenuated during flood months by reserving storage capacity in Cahora Bassa Reservoir to curtail releases from the dam when the downstream tributaries were in flood.

The DFRC used in the HEC-5 modeling studies was provided by HCB (see diagram below). The DFRC is similar to the DNA model (Kranendonk 1980). Review of the inflow and outflow data for Cahora Bassa Reservoir suggest that the DFRC is not applied consistently in all years, however, so the true operating rules for Cahora Bassa remain somewhat of a mystery.

Design Flood Rule Curve used by HCB.

[4] The maximum permissible water level for the Flat Rule Curve is 326 m amsl. Water levels above this threshold result in the surface area of Cahora Bassa Reservoir extending beyond Mozambique territorial boundaries into Zambia and Zimbabwe. By convention, reservoir elevations may temporarily exceed this threshold for short-duration, extreme flooding events, but may not exceed this level during regular reservoir operations. A Flat Rule Curve target level below 326 m amsl would reduce the gross head available for hydropower generation, and is therefore unlikely to be adopted.

[5] The fixed 316 m amsl reservoir threshold also serves to better stabilize reservoir water levels by minimizing releases during drought periods that otherwise tend to accelerate reservoir drawdown towards the Lower Supply Level. The extreme range of allowable reservoir water levels under normal operating

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conditions (there is a 31 m difference between lower supply and Full Supply Levels) is a major constraint to agriculture, navigation, and economic development in the Cahora Bassa reservoir (Davies 1998).

[6] The Mozambique Government recently enacted new floodplain zoning legislation designed to relocate people from floodprone areas in the Zambezi basin and elsewhere, towards reducing the vulnerability of the population to future flooding disasters as occurred in 2000 and 2001.

[7] Currently, Cahora Bassa Dam is also being managed for navigation at the river ferry crossing on the National Road at Caia. The 2001 Zambezi floods altered the Zambezi channel and banks at Caia, and a minimum Zambezi discharge of 2000 m^3/s (up from 1400 m^3/s in 2000) is now required to maintain the ferry crossing. Cahora Bassa is now releasing water through sluice gates in addition to turbine releases. Operators at Hidroeléctrica de Cahora Bassa are concerned that this navigational flow requirements will cause excessive dry season reservoir draw down and potentially affect power generation (Dr. Henrique Silva *pers. comm.*). However, plans are underway for a bridge crossing at Caia, to be completed within the next five years, and river navigation is unlikely to be a major constraint on water management in the long-term.

[8] Preliminary studies by Li-EDF-KP Joint Venture Consultants (2001) suggest that the construction of the proposed Mepanda Uncua or Cahora Bassa North Bank projects may further increase the economic cost of prescribed flood releases if further reductions in power output are needed to meet target flood levels. These costs must also be considered in the overall benefit-cost analysis for flood releases.

[9] Outflows from Cahora Bassa are from the nutrient-rich hypolimnion, and may reduce water quality in the upper reaches below the dam relative to historical conditions (Hall, Valente, and Davies 1977)

Table 4-1. Modeling parameters for Kariba Reservoir and Power Station

Reservoir elevation-area-volume-outflow data

Elevation (m amsl)	475.5	476	477.0	478	479.0	480.0	481.0	482	483.0	484.0	485.0	486.0	487.0	488.5	489.5
Area (km^2)	4354	4405	4507	4608	4709	4811	4901	4991	5081	5171	5261	5350	5440	5577	5671
Volume ($x10^9 m^3$)	54	2272	6706	11,278	15,911	20,613	25,962	30,408	35,427	40,568	45,778	51,088	56,507	64,798	76,854
Spillway (m^3/s)	--	--	--	--	7528	7751	7973	8168	8381	8584	8786	8974	9161	9445	9515

Source: Li-EDF-KP Joint Venture Consultants (1999) (compiled from ZRA records). Spillway discharges are for six gates fully open.

Design Flood Rule Curve (end-of-month levels)

Month	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep
Level	486.5	486.0	485.5	484.0	485.4	487.75	488.5	488.5	488.5	488.0	487.5	487.0

Source: Li-EDF-KP Joint Venture Consultants (1999) (compiled from ZRA records)

Reservoir Full Supply Level	488.5 m amsl	**Friction head loss**	0.70 m
Reservoir Minimum Operating Level	475.5 m amsl	**Turbine efficiency**	0.88 assumed for overall average
Installed hydroelectric capacity	1350 MW	**Penstock capacity**	not specified

Tailwater rating curve

Level	379.95	383.7	384.86	386.19	387.67	388.48	391.96	399.87	402.55	404.55
Discharge	0	479	719	959	1319	1518	3000	9000	12000	15000

Source: Li-EDF-KP Joint Venture Consultants (1999).

Monthly net reservoir evaporation (mm)

Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep
181	117	-23	-38	-41	23	96	118	107	112	130	162

Source: Batoka Joint Venture Consultants (1993)

Inflow time series

See Appendix.

Reservoir withdrawals

Reservoir withdrawals contained within historical inflow series; no significant increase in future withdrawals anticipated.

Table 4-2. Modeling parameters for Itezhitezhi Reservoir

Reservoir elevation-area-volume-outflow data

Elevation (m amsl)	1006	1008	1010	1012	1014	1016	1018	1020	1022	1024	1026	1028	1029	1029.5	1035
Area (km^2)	90	105	120	138	158	177	203	224	253	284	314	346	364	374	446
Volume ($x10^9$ m^3)	0.699	0.894	1.119	1.377	1.673	2.008	2.387	2.814	3.291	3.551	4.118	4.746	5.439	5.624	7.049
Spillway (m^3/s)	300	300	300	300	300	300	300	402	690	1125	1674	2355	2700	2910	4450

Source: Li-EDF-KP Joint Venture Consultants (1999) (compiled from Shawinigan-Lavalin and HP 1990 report). Outflow consists of regulating gate and spillway discharges combined. Spillway outflows are for 3 gates; maximum discharge of low level regulating gate is 300 m3/s.

Design Flood Rule Curve:	None used
Reservoir Full Supply Level	1029.5 m amsl
Reservoir Minimum Operating Level	1006.0 m amsl

Monthly net reservoir evaporation (mm)

Oct	**Nov**	**Dec**	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**
190	50	-60	-90	-80	20	110	120	90	120	140	170

Source: Shawinigan-Lavalin and HP (1990) study.

Inflow time series

See Appendix.

Reservoir withdrawals

Reservoir withdrawals contained within historical inflow series; no significant increase in future withdrawals anticipated.

Downstream flow requirements

Minimum discharge of 300 m^3/s required for March; for all other months, minimum discharge of 25 m^3/s.

Table 4-3. Modeling parameters for Kafue Flats (Natural) Reservoir

Reservoir elevation-area-volume-outflow data

Elevation (m amsl)	976.0	977.0	978.0	979.0	980.0	981.0	982.0	983.0	983.5	984.0	984.25
Area (km^2)	30	114	405	950	1340	1586	1745	1865	1915	1955	1975
Volume ($x\ 10^9\ m^3$)	0.015	0.077	0.303	0.989	2.143	3.616	5.285	7.094	8.039	9.006	9.498
Spillway (m^3/s)	30	60	125	200	310	420	750	2000	2480	2960	3200

Data source: Batoka Joint Venture Consultants (1993) study.

Monthly net reservoir evaporation (mm)

Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep
232	78	-32	-66	-60	48	136	144	108	144	168	204

Data source: Shawinigan-Lavalin and HP (1990) study.

Inflow time series

Outflows from Itezhitezhi reservoir plus 20% of Itezhitezhi inflows (mean = 55.3 m3/s, 1907/07 - 1997/98).

Reservoir withdrawals

Reservoir withdrawals contained within historical inflow series; no significant increase in future withdrawals anticipated.

Table 4-4. Modeling parameters for Kafue Gorge Reservoir and Power Station

Reservoir elevation-area-volume-outflow data

Elevation (m amsl)	972.3	973.0	974.0	975.0	976.0	976.6	977.0	978.0
Area (km^2)	20	35	70	142	430	805	1175	2160
Volume (x 10^9 m^3)	0	20	69	170	423	785	1178	2845
Spillway (m^3/s)	780	1076	1420	1804	2220	2496	2668	3132

Source: Shawinigan-Lavalin and HP (1990) study

Design Flood Rule Curve	None used	**Friction head loss**	1.0 m
Reservoir Full Supply Level	976.6 m amsl	**Turbine efficiency**	0.88 assumed overall average
Reservoir Minimum Operating Level	972.0 m amsl	**Tailwater**	Mean tailwater level 581.9 m amsl used
Installed hydroelectric capacity	900 MW	**Penstock capacity**	not specified

Monthly net reservoir evaporation (mm)

Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep
232	78	-32	-66	-60	48	136	144	108	144	168	204

Source: Shawinigan-Lavalin and HP (1990) study

Inflow time series

Outflows from Kafue Flats (natural) reservoir.

Reservoir withdrawals

15 m3/s continuous abstraction in each month for in-basin demands between Kafue Flats and Kafue Gorge.

Table 4-5. Modeling parameters for Cahora Bassa Reservoir and Power Station

Reservoir elevation-area-volume-outflow data

Elevation (m amsl)	295	300	305	310	315	320	326	330	331
Area (km^2)	838	1065	1317	1597	1902	2233	2665	2974	3054
Volume (x 10^9 m^3)	0	4745	10689	17963	26699	37026	51704	62977	65991
Spillway (m^3/s)	6760	7990	9060	10020	10890	11700	12600	14173	15683

Source: Li-EDF-KP Joint Venture Consultants (1999)

Design Flood Rule Curve (end-of-month levels)

Month	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep
Level	326.0	323.0	320.8	321.4	324.7	328.4	329.0	329.0	328.0	326.0	326.0	326.0

Source: Hidroelectrica de Cabora Bassa

Reservoir Full Supply Level	326.0 m amsl	**Friction head loss**	1.5 m
Reservoir Minimum Operating Level	295.0 m amsl	**Penstock capacity**	2260 m3/s.
Installed hydroelectric capacity	2075 MW		

Turbine efficiency

Net head	90	95	100	105	110	115	120	125	130
Efficiency	89.3	92.7	95.8	95.6	95.9	95.6	95.2	94.2	92.9

Source: Turbine manufacturer rating curves (from HP 1965)

Tailwater rating curve

Level	193.98	198.89	201.08	204.29	206.86	211.05	216.05	221.5	226.14	232
Discharge	0	500	1000	2000	3000	5000	8000	10500	15000	22000

Source: Li-EDF-KP Joint Venture Consultants (1999).

Monthly net reservoir evaporation (mm)

Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep
113	43	-30	-7	19	93	159	192	208	249	193	139

Source: Hidroelectrica de Cabora Bassa

Inflow time series

See Appendix.

Reservoir withdrawals

Reservoir withdrawals contained within historical inflow series.

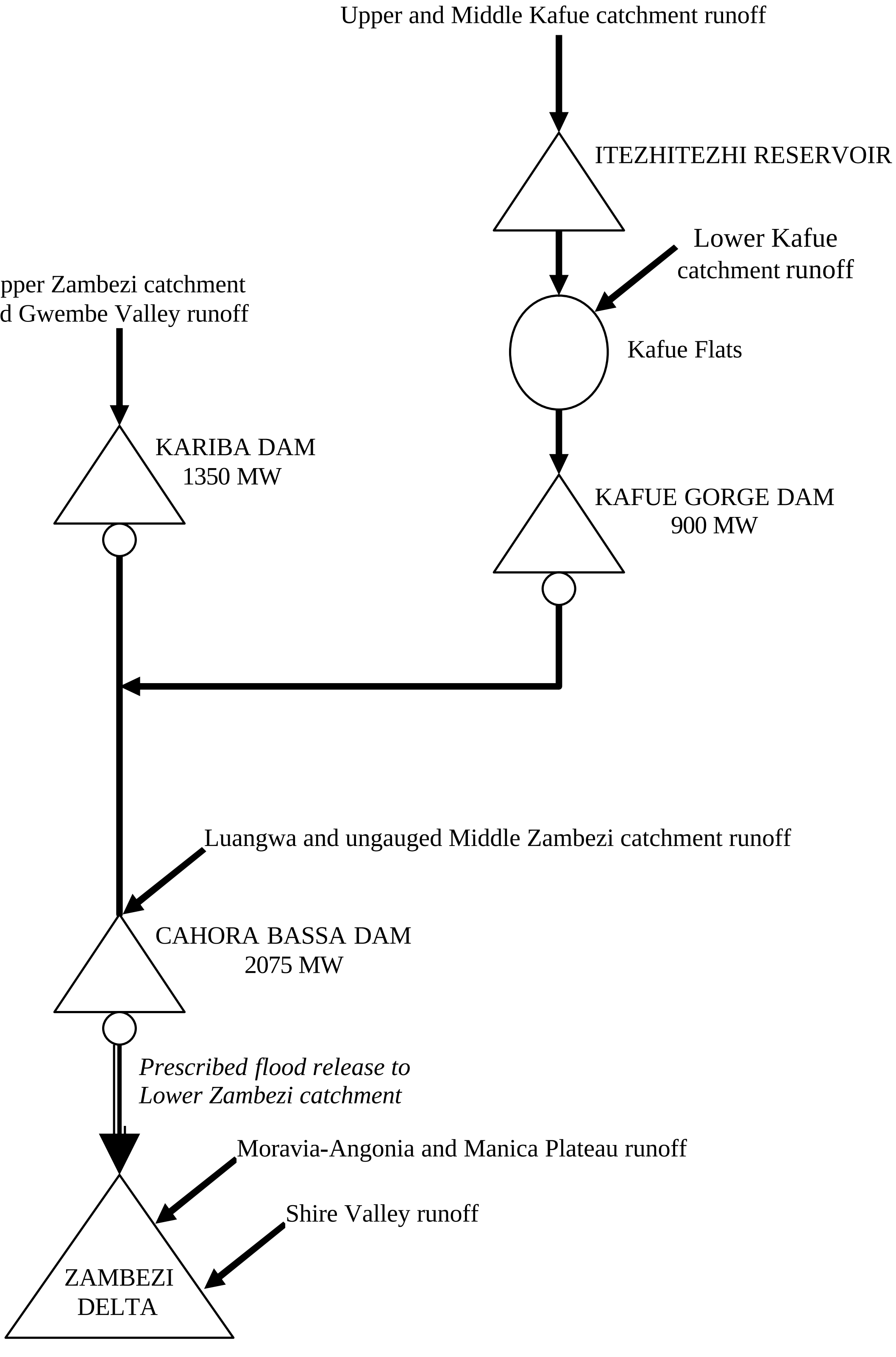

Figure 4-1. Schematic diagram of the Zambezi system prescribed flooding model.

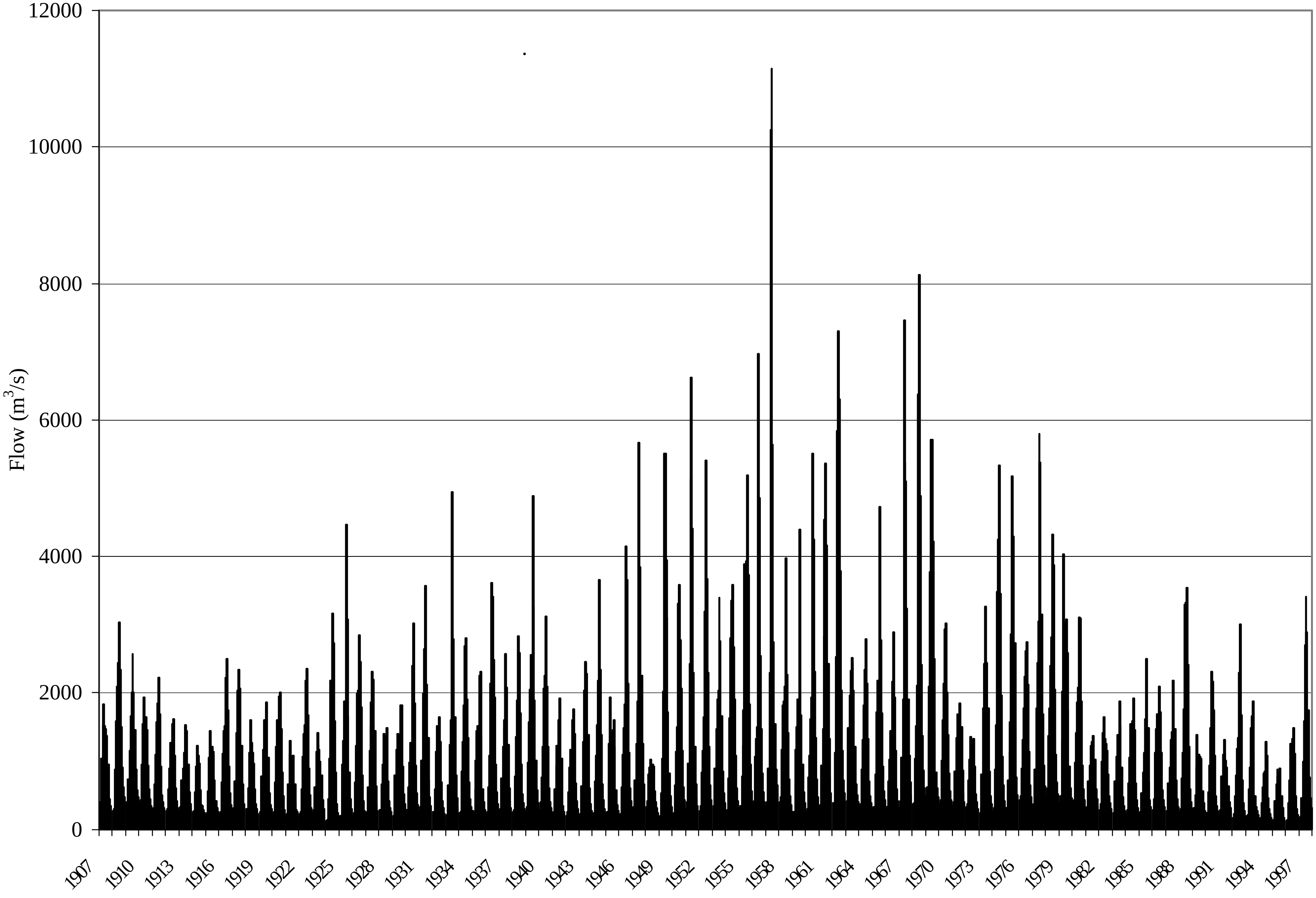

Figure 4-2. Time series of monthly inflows to Kariba Reservoir.

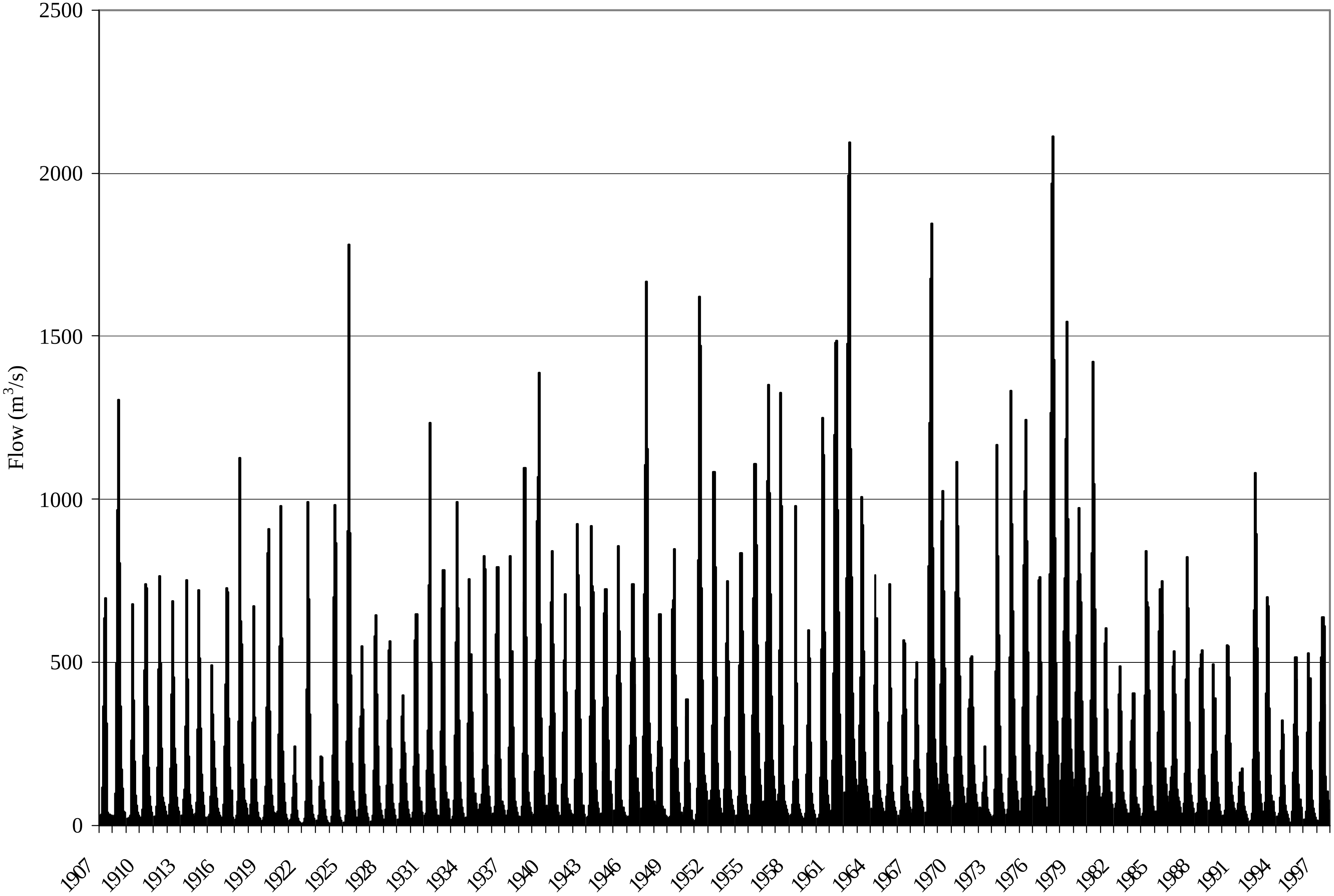

Figure 4-3. Time series of monthly inflows to Itezhitezhi Reservoir.

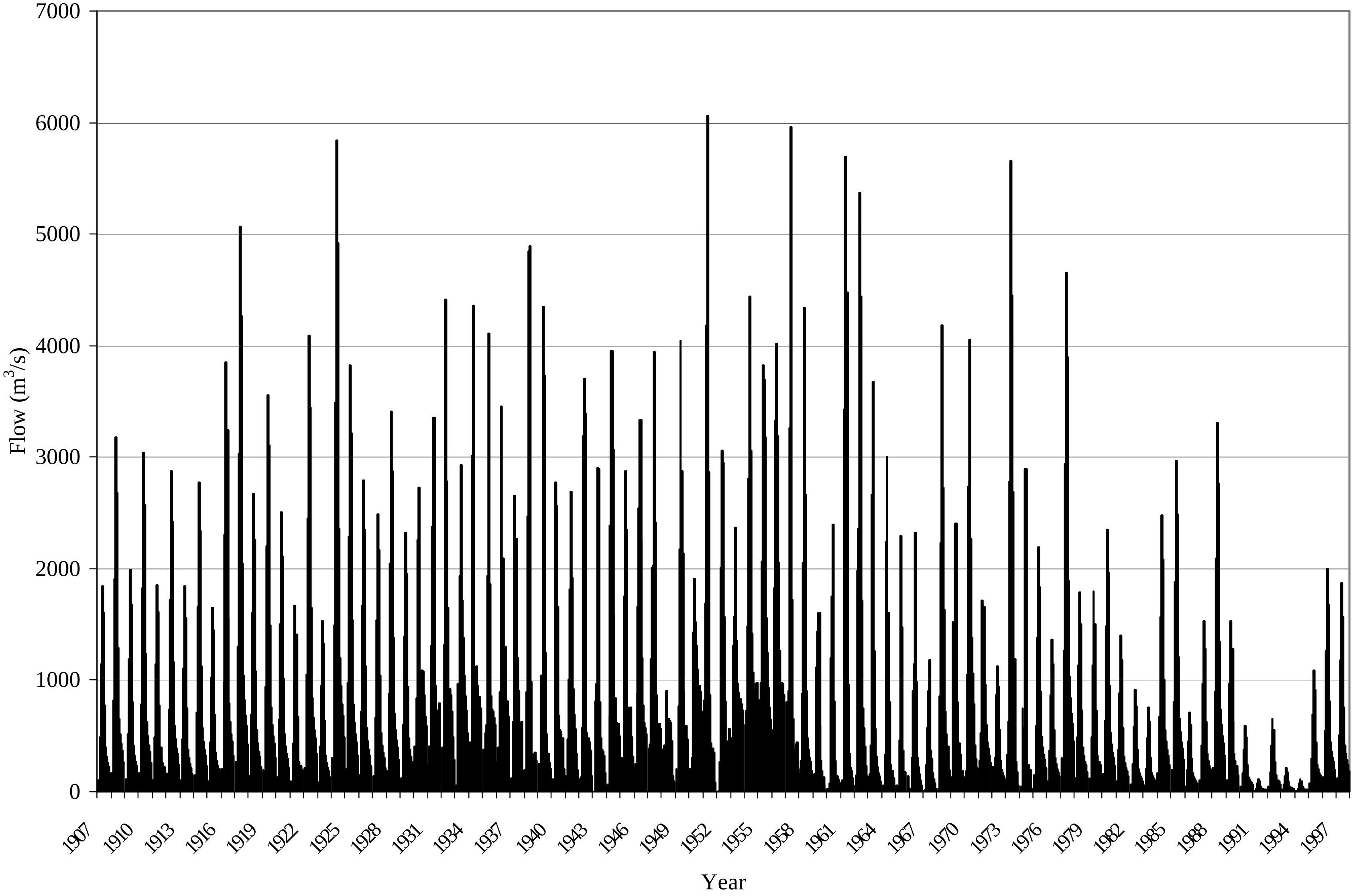

Figure 4-4. Correlation between time series of simulated unregulated and regulated mean monthly inflows to Cahora Bassa Gorge.

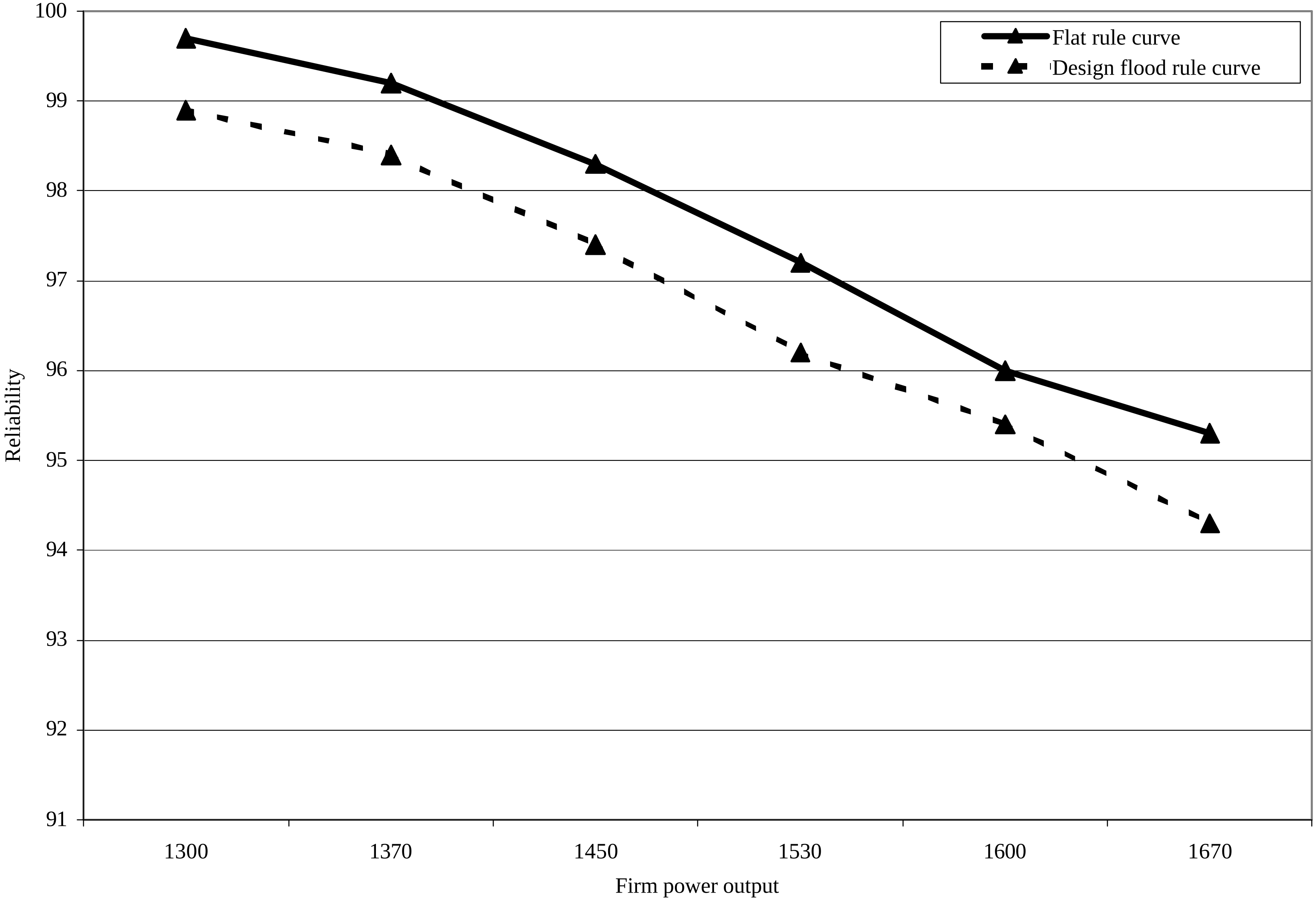

Figure 4-5. Relationship between firm power output and firm power reliability for simulated output from Cahora Bassa Dam with the Design Flood Rule Curve and Flat Rule Curve, using 1907-98 time series data.

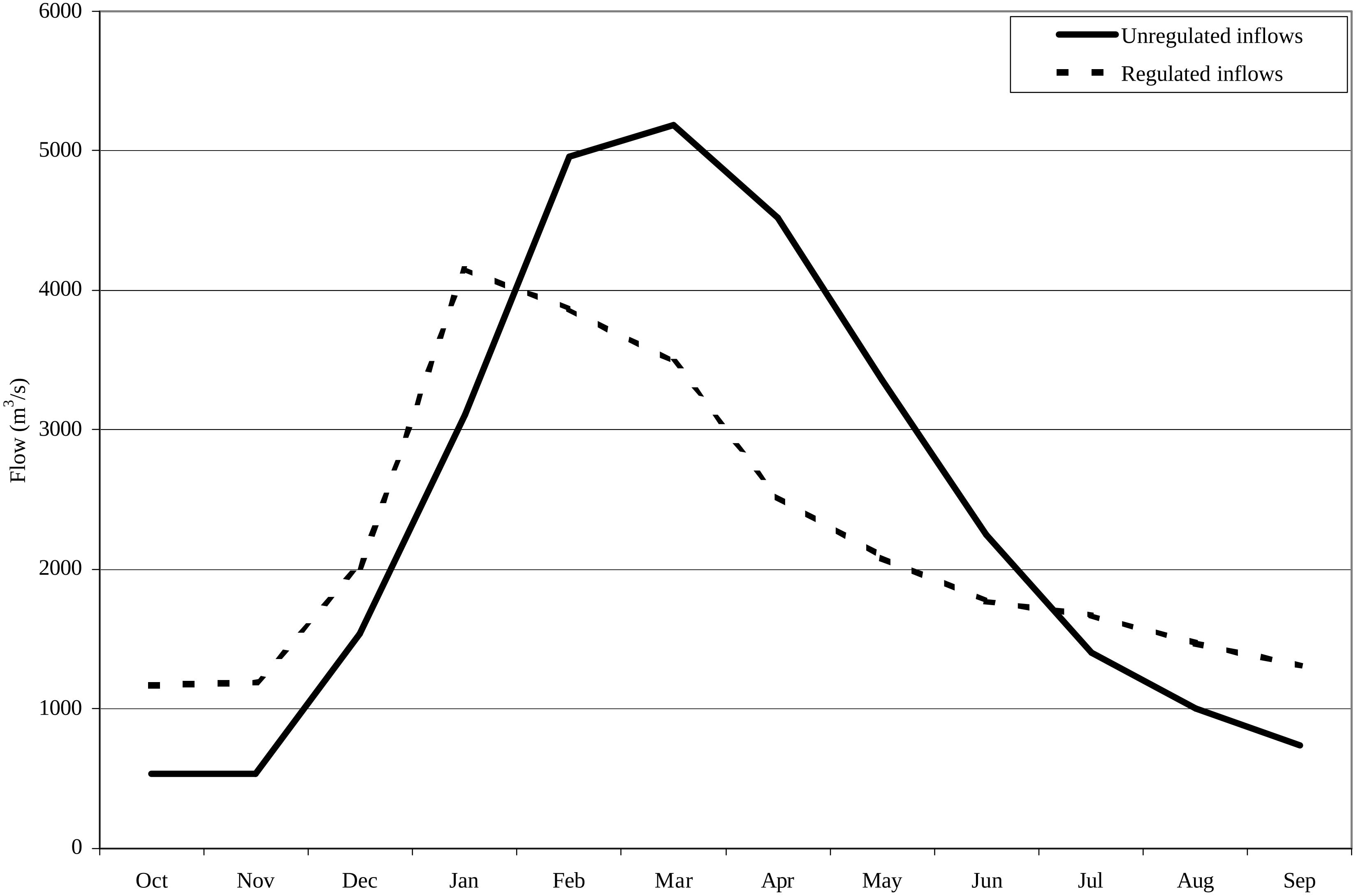

Figure 4-6. A comparison of hydrographs of simulated unregulated and regulated mean monthly inflows to Cahora Bassa Gorge, using 1907-98 time series data.

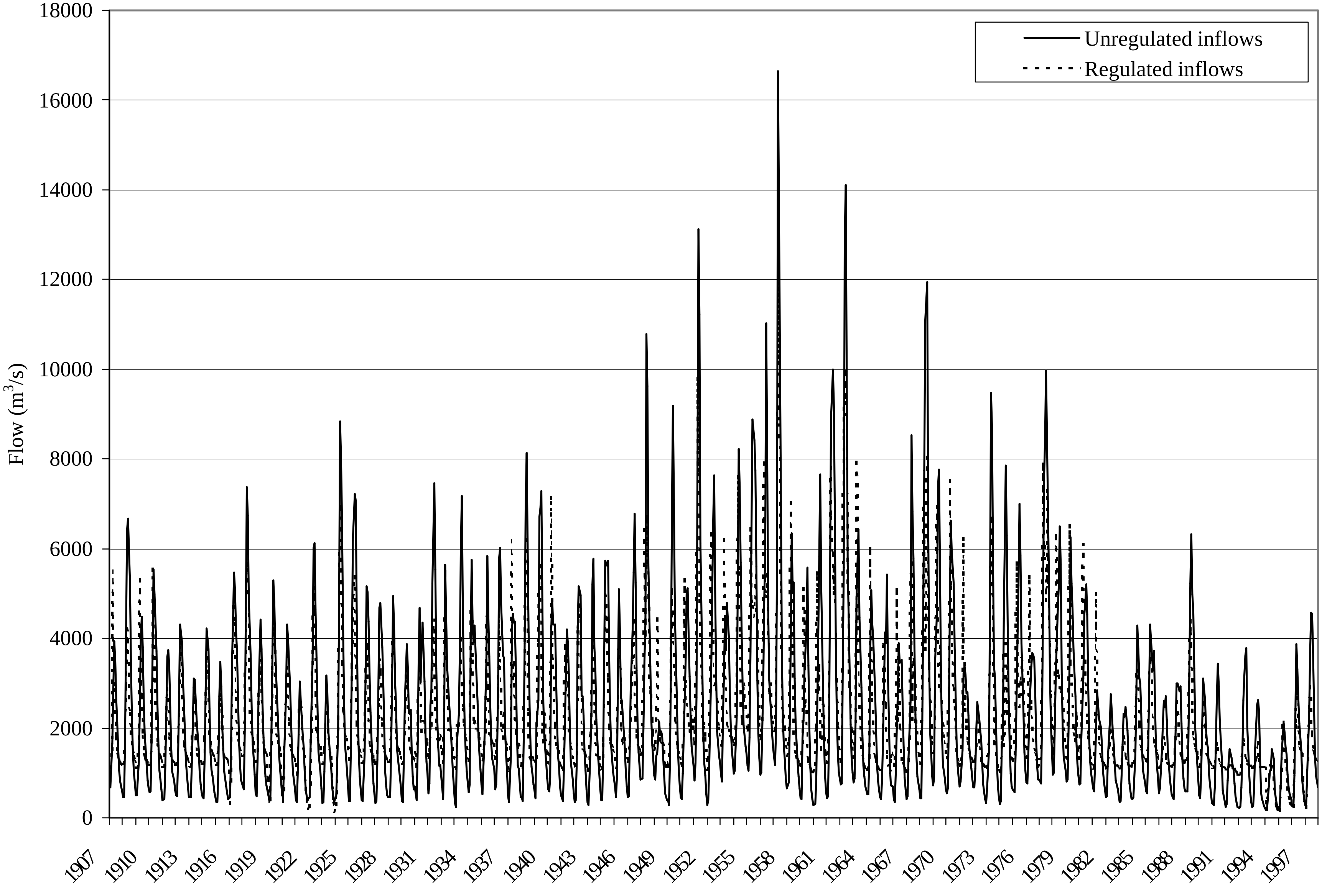

Figure 4-7. A comparison of time series of simulated unregulated and regulated mean monthly inflows to Cahora Bassa Gorge.

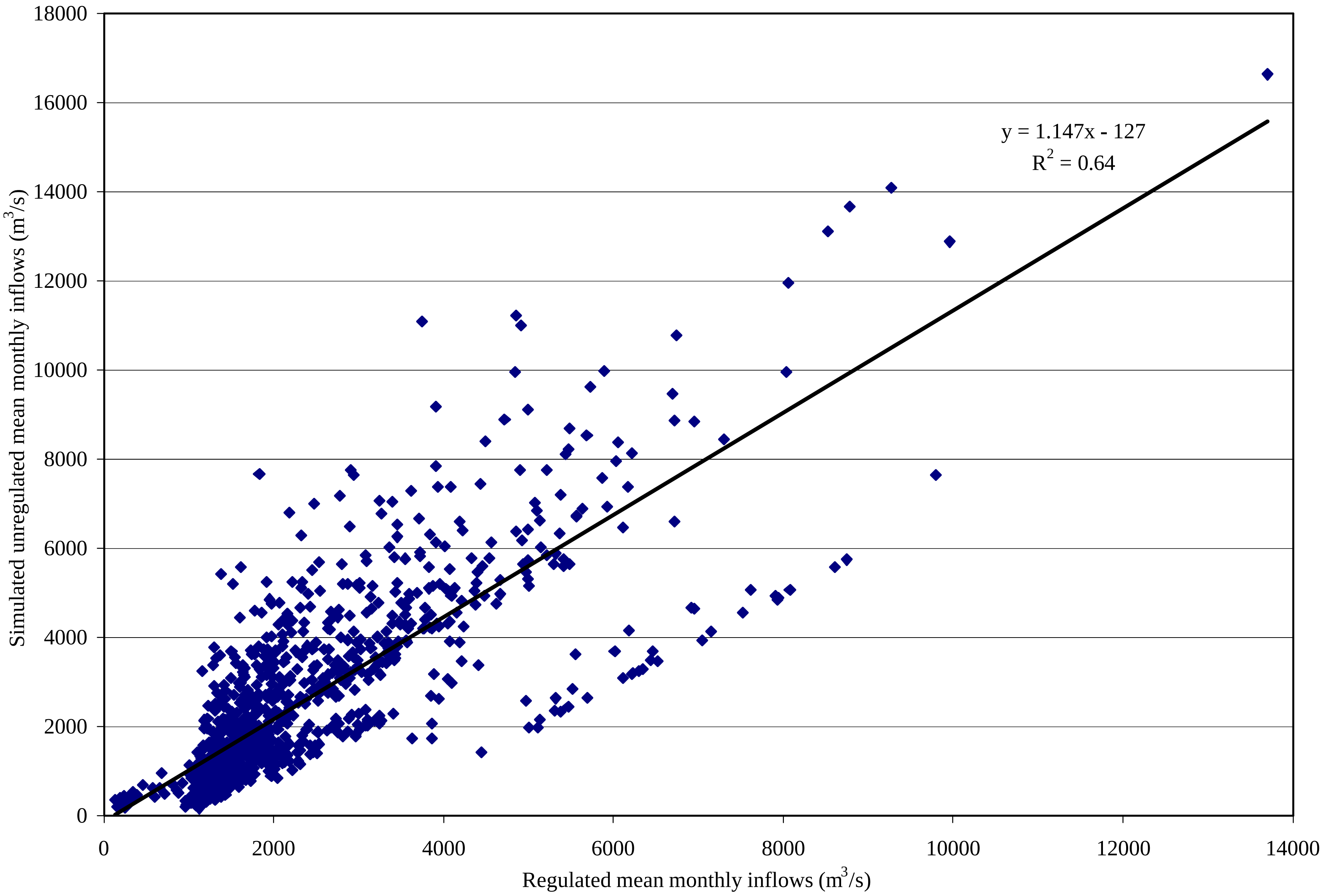

Figure 4-8. Correlation between time series of simulated unregulated and regulated mean monthly inflows to Cahora Bassa Gorge.

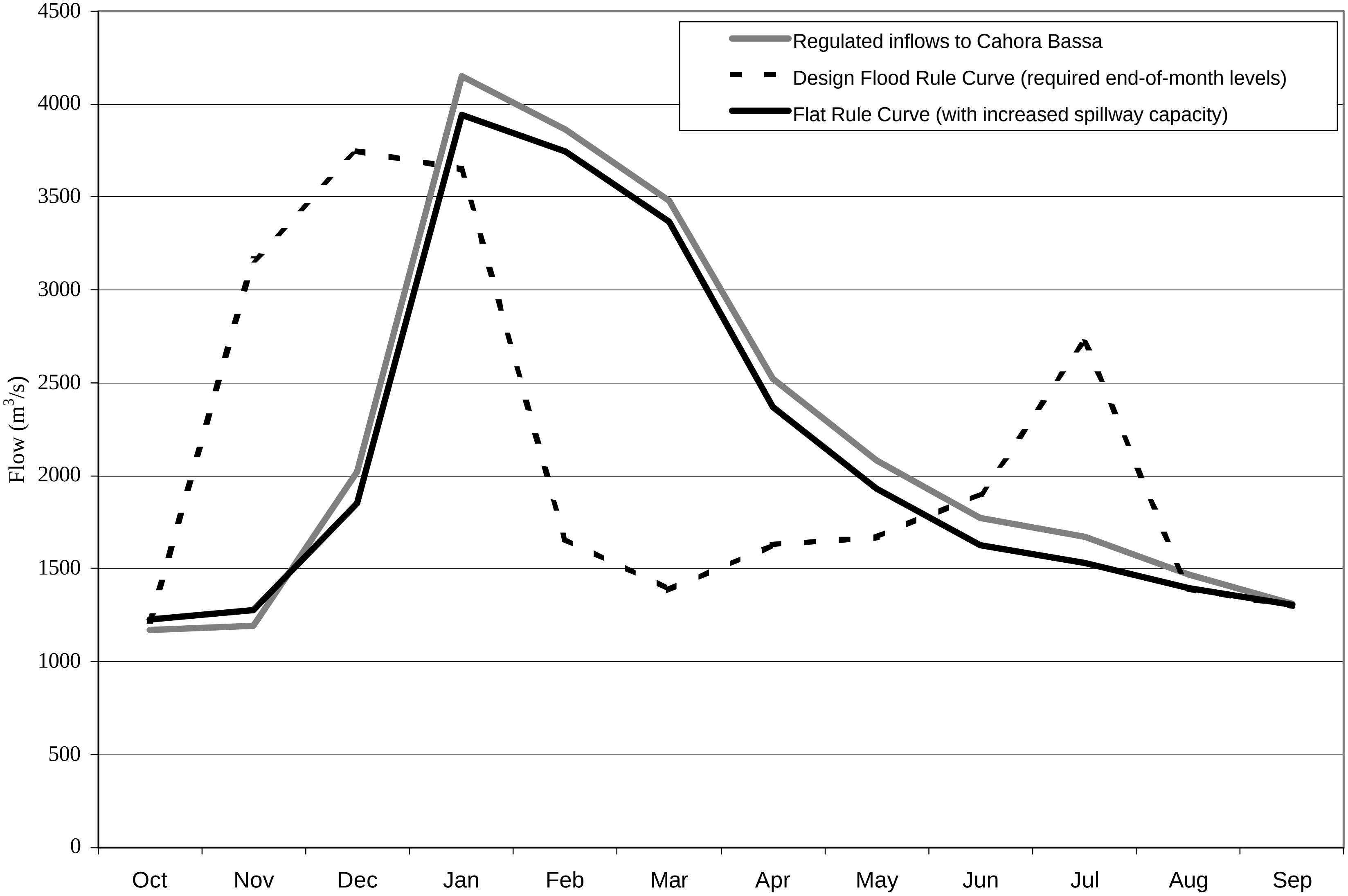

Figure 4-9. A comparison of hydrographs of simulated regulated mean monthly inflows to Cahora Bassa Gorge and regulated reservoir outflows with the Design Flood Rule Curve and Flat Rule Curve, using 1907-98 time series data.

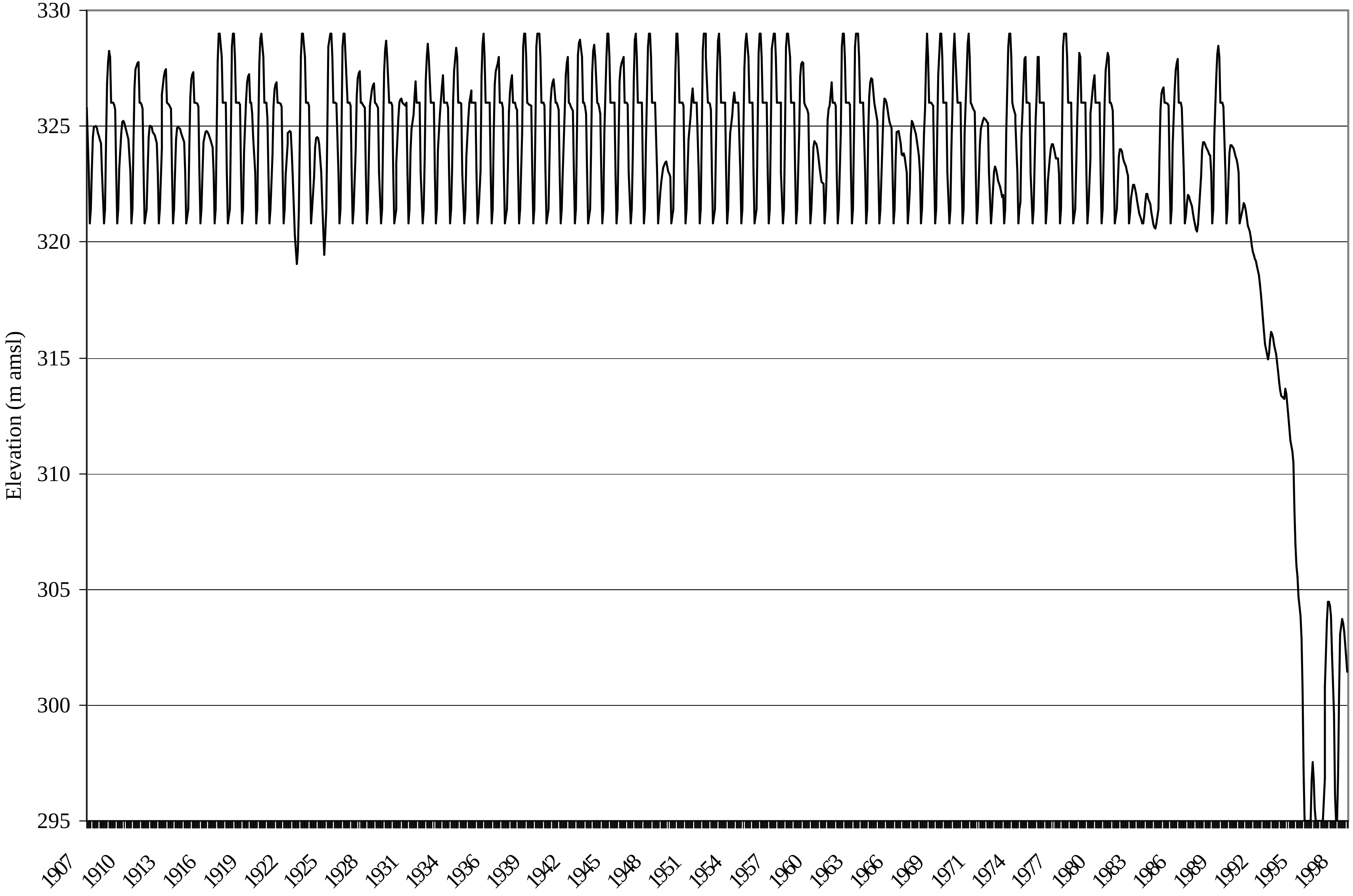

Figure 4-10. Cahora Bassa Reservoir simulated storage with Design Flood Rule Curve and 1370 MW firm power output.

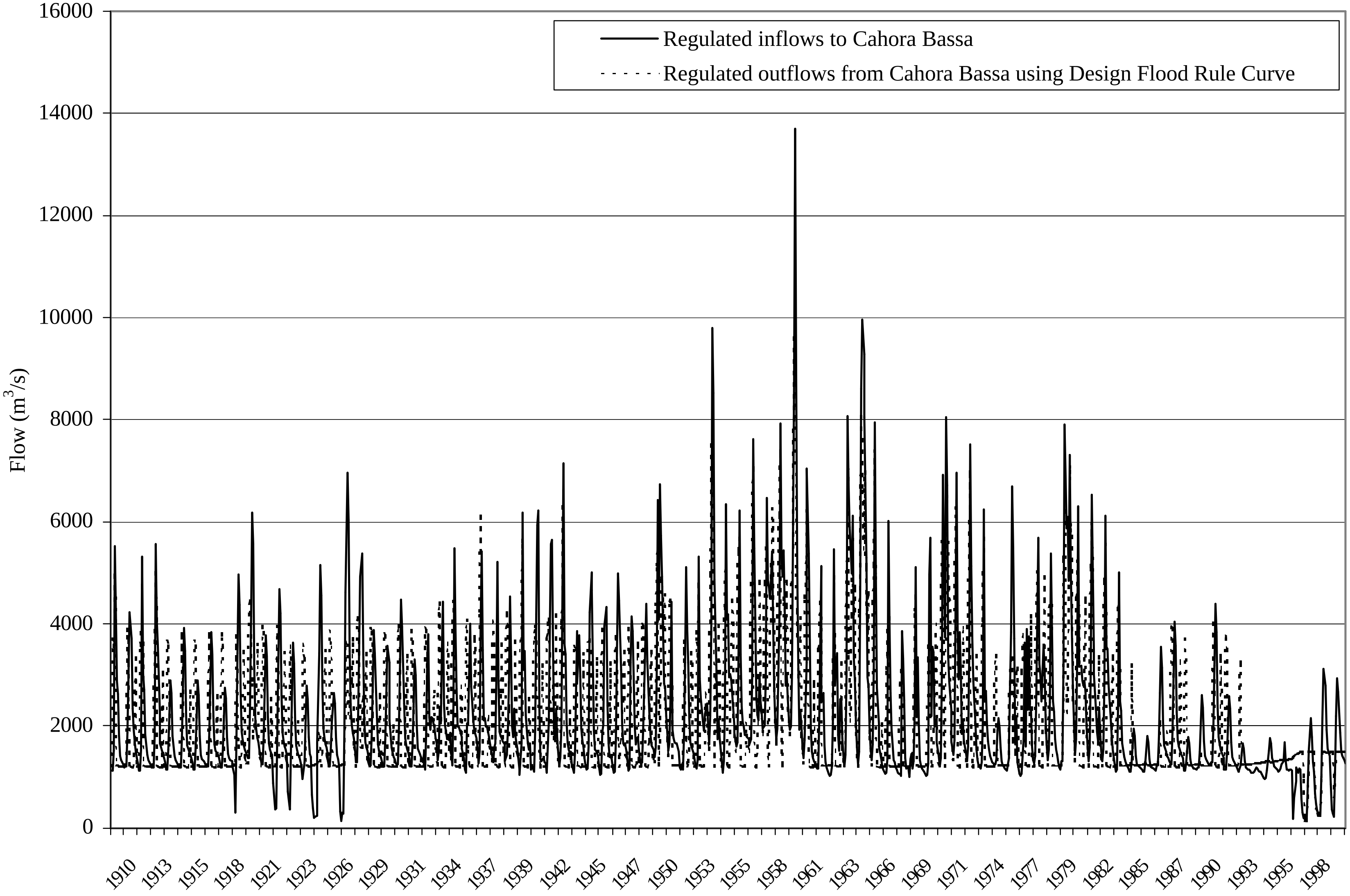

Figure 4-11. A comparison of time series of simulated regulated inflows to Cahora Bassa Reservoir and reservoir outflows using the Design Flood Rule Curve.

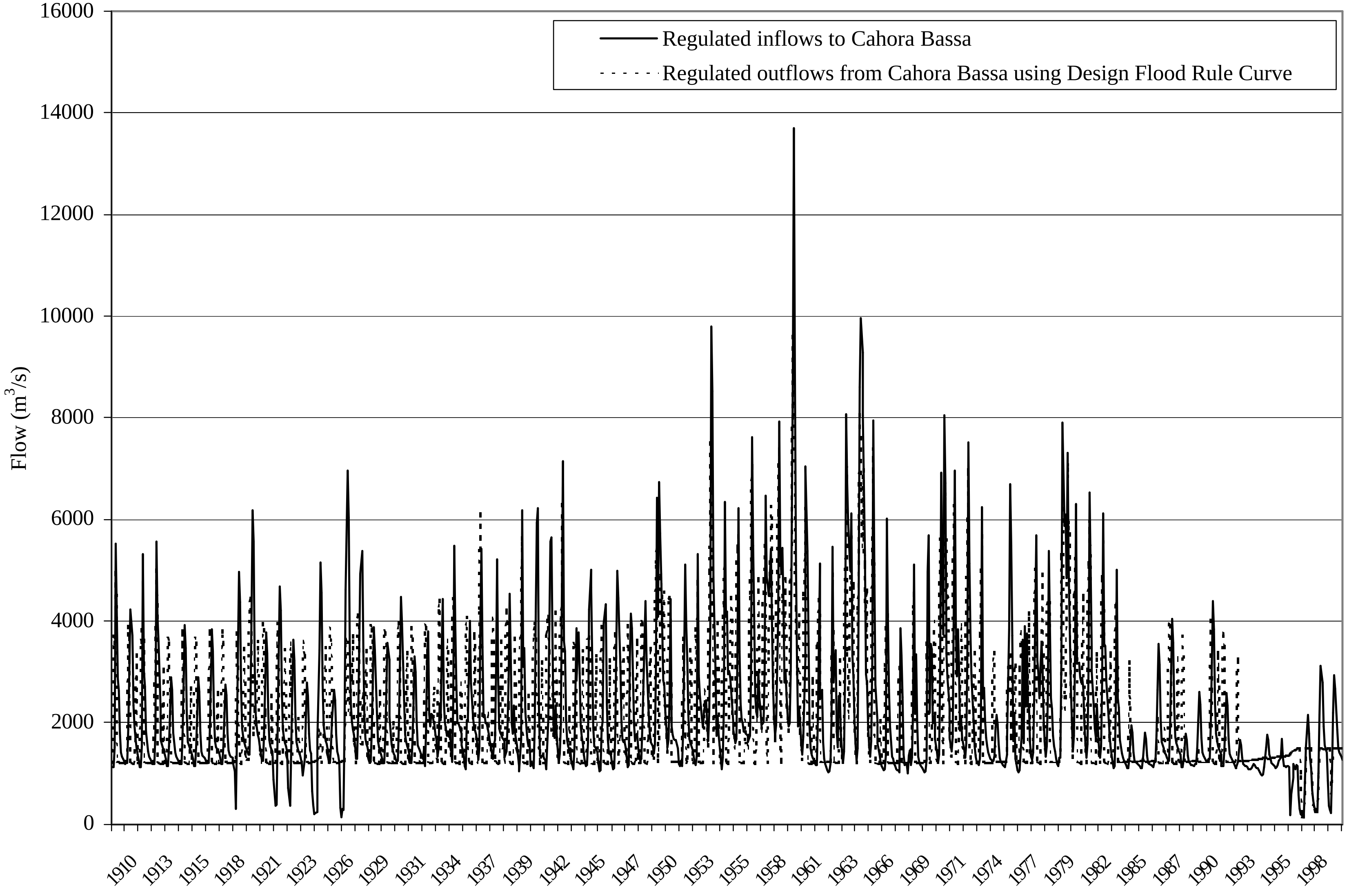

Figure 4-12. Correlation between time series of simulated regulated inflows to Cahora Bassa Reservoir and reservoir outflows using the Design Flood Rule Curve.

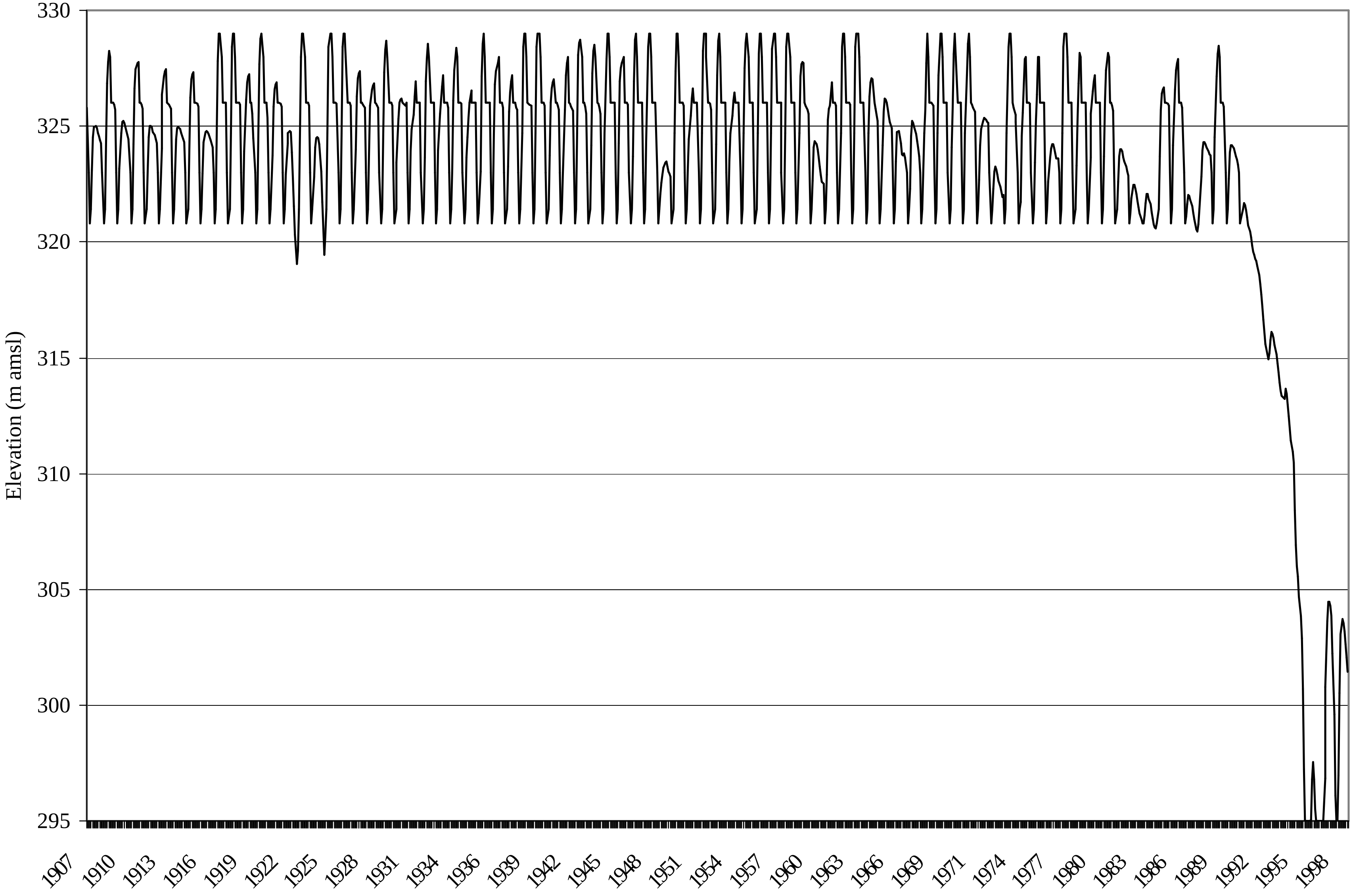

Figure 4-13. Cahora Bassa Reservoir simulated storage with Flat Rule Curve at 326 m amsl and 1450 MW firm power output.

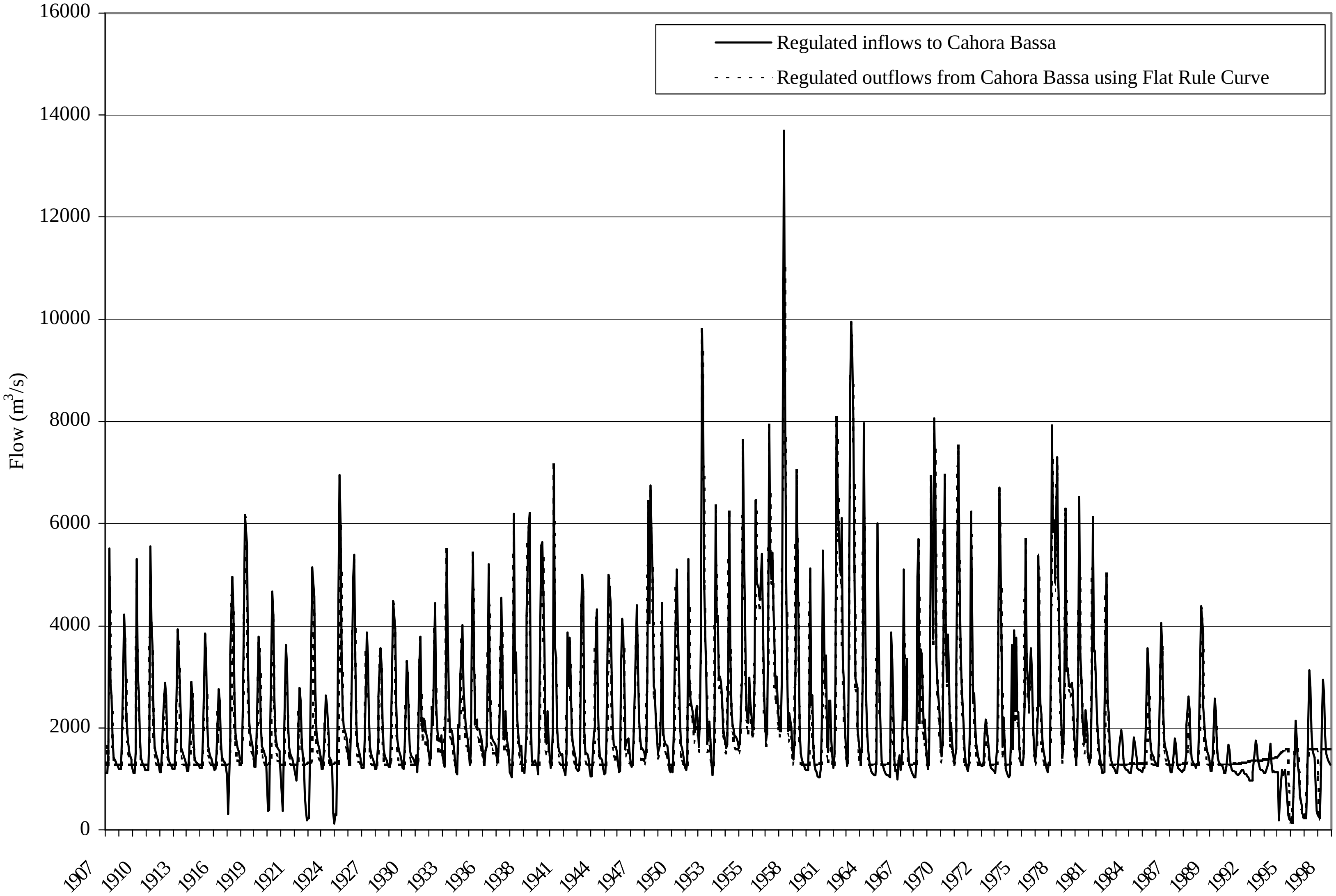

Figure 4-14. A comparison of time series of simulated regulated inflows to Cahora Bassa Reservoir and reservoir outflows using the Flat Rule Curve.

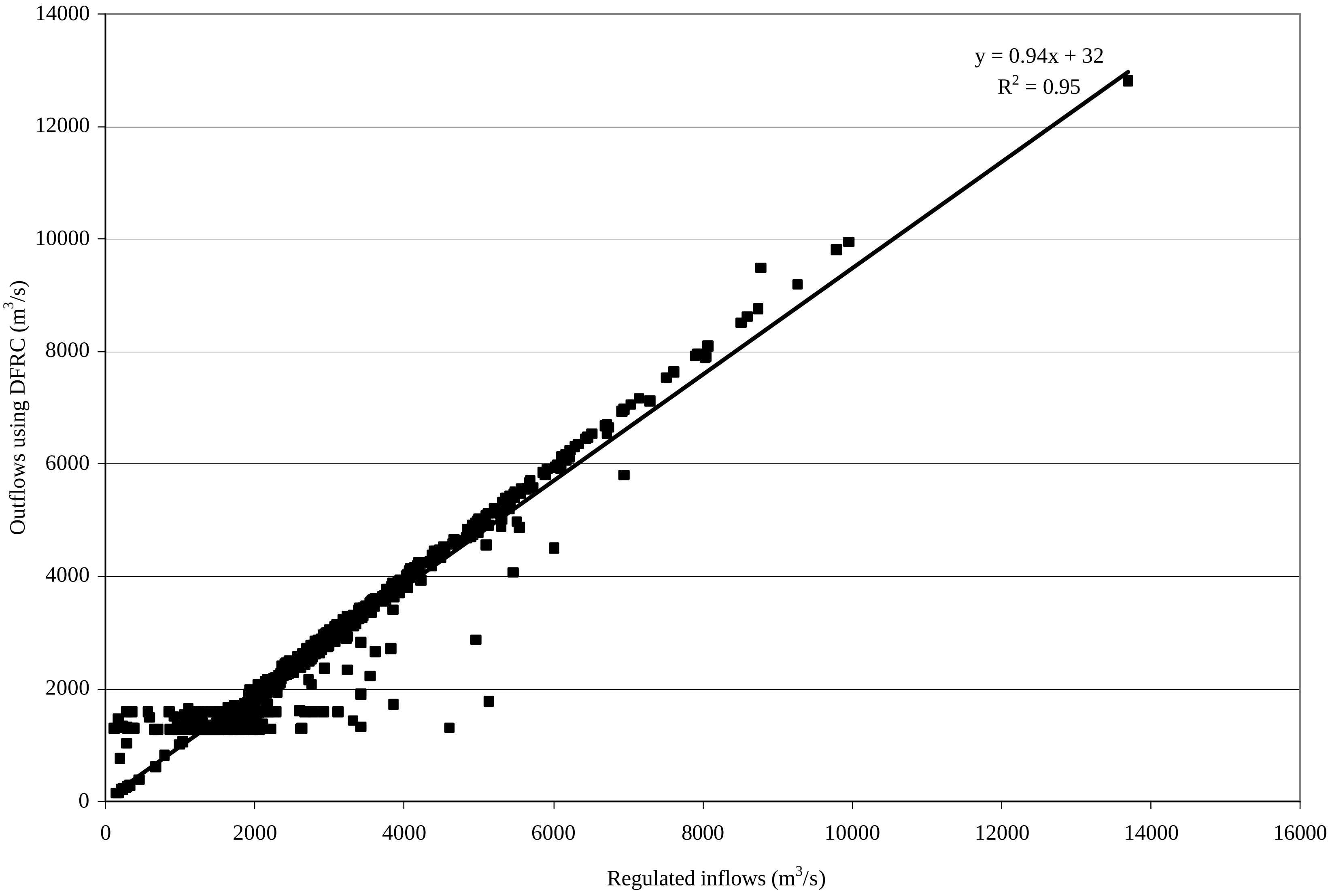

Figure 4-15. Correlation between simulated regulated inflows to Cahora Bassa Reservoir and reservoir outflows using the Flat Flood Rule Curve.

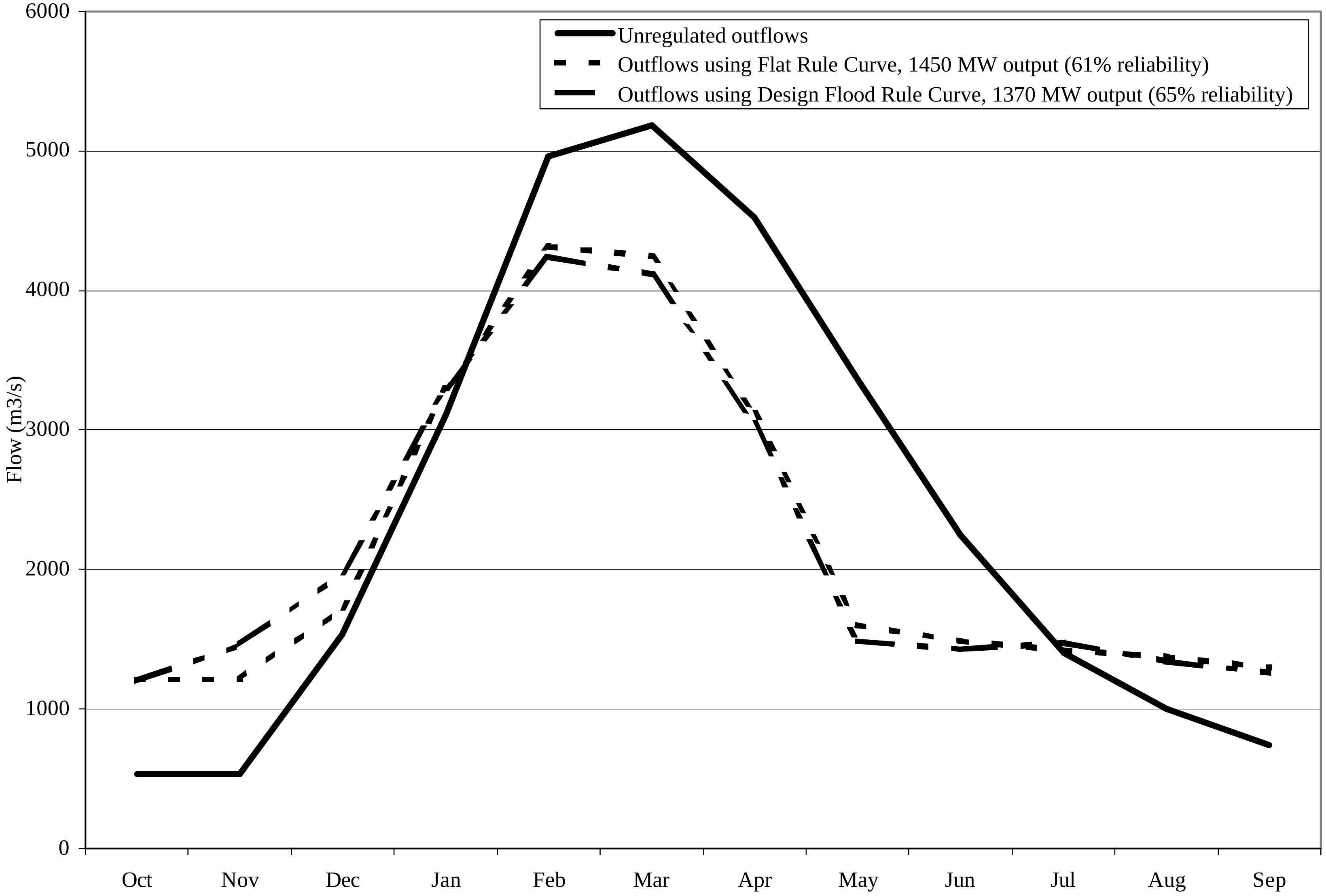

Figure 4-16. Mean hydrographs for simulated Cahora Bassa outflows, 1907-98 time series data, to release prescribed flood to mimic natural outflows of 3100 m^3/s during January, 5000 m^3/s during February, 5200 m^3/s during March, and 4500 m^3/s during April.

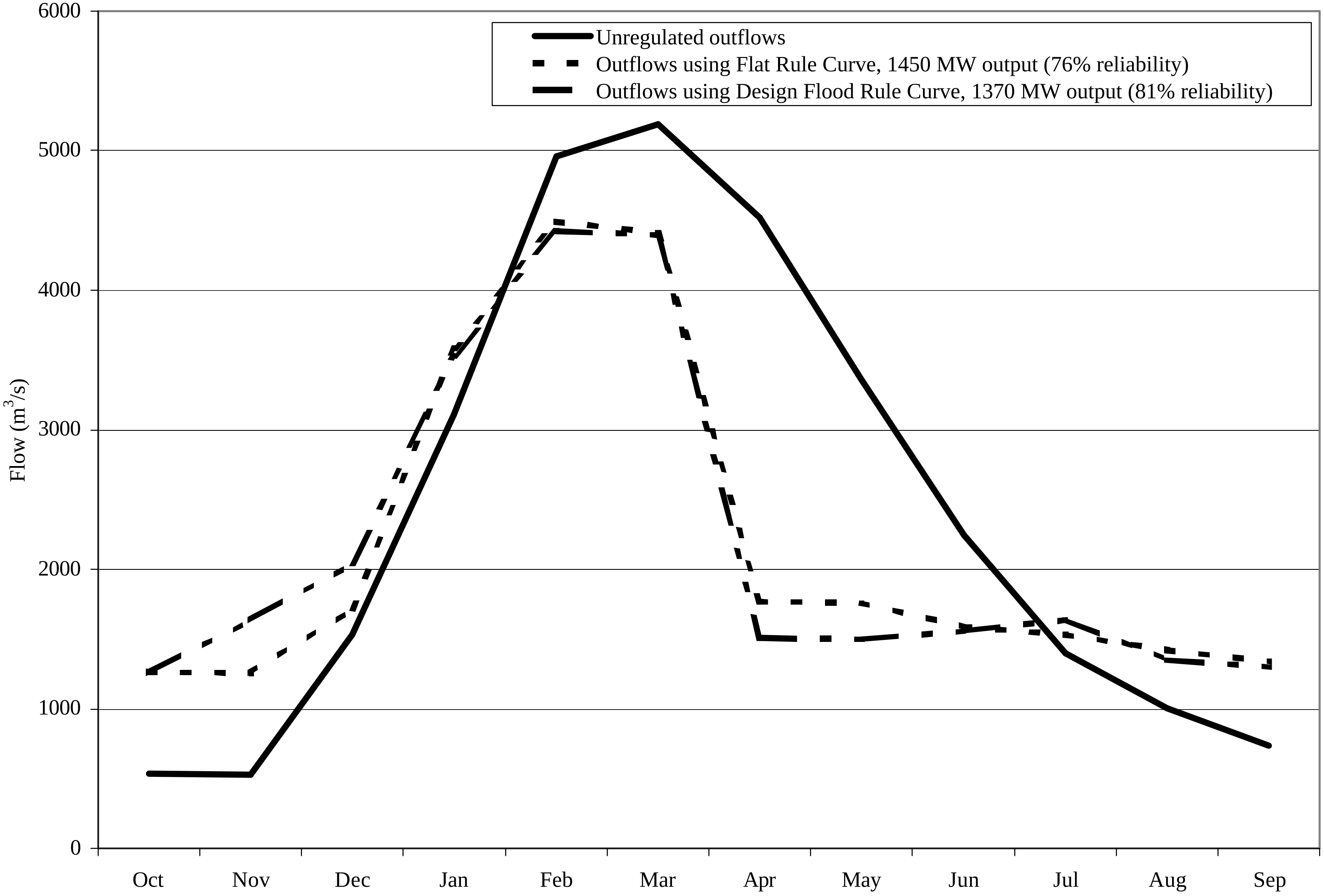

Figure 4-17. Mean monthly hydrographs for simulated Cahora Bassa outflows, 1907-98 time series data, to release prescribed flood of approximately 5000 m^3/s during January when reservoir water levels exceed 316 m amsl.

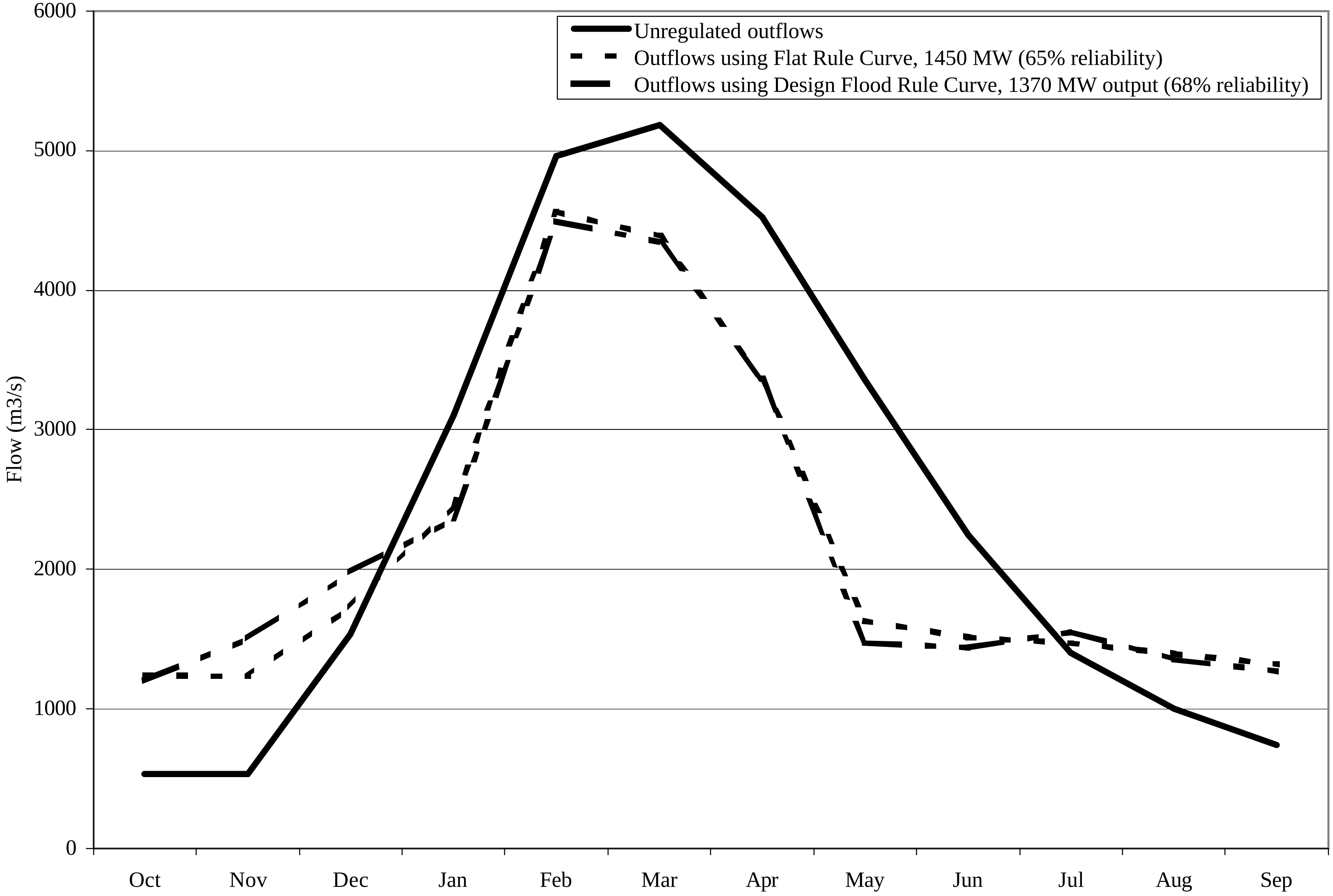

Figure 4-18. Mean hydrographs for simulated Cahora Bassa outflows, 1907-98 time series data, to release prescribed flood of 5000 m^3/s during February, 5200 m^3/s during March, and 4500 m^3/s during April.

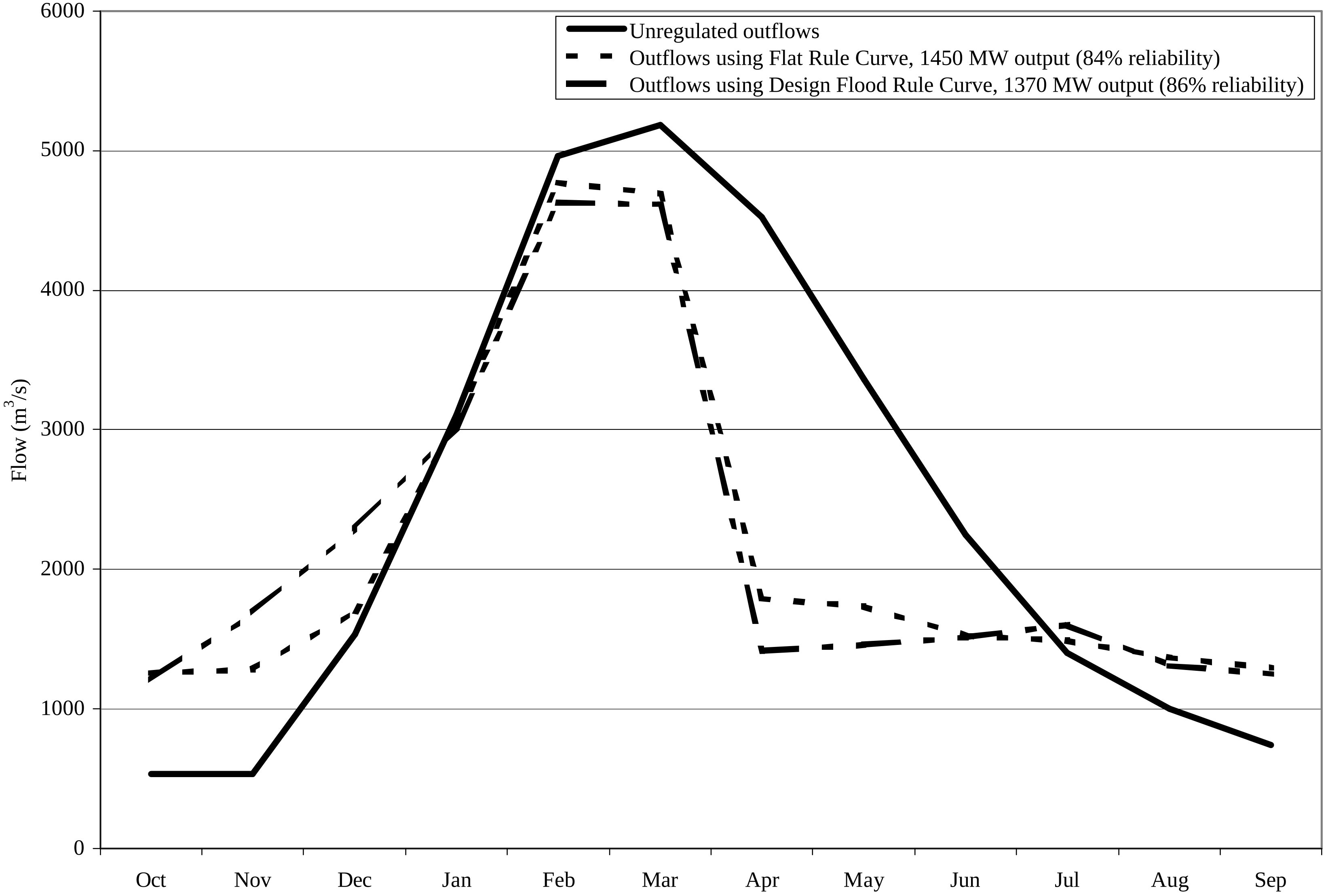

Figure 4-19. Mean hydrographs for simulated Cahora Bassa outflows, 1907-98 time series data, to release prescribed flood of 5000 m^3/s during February and 5200 m^3/s during March.

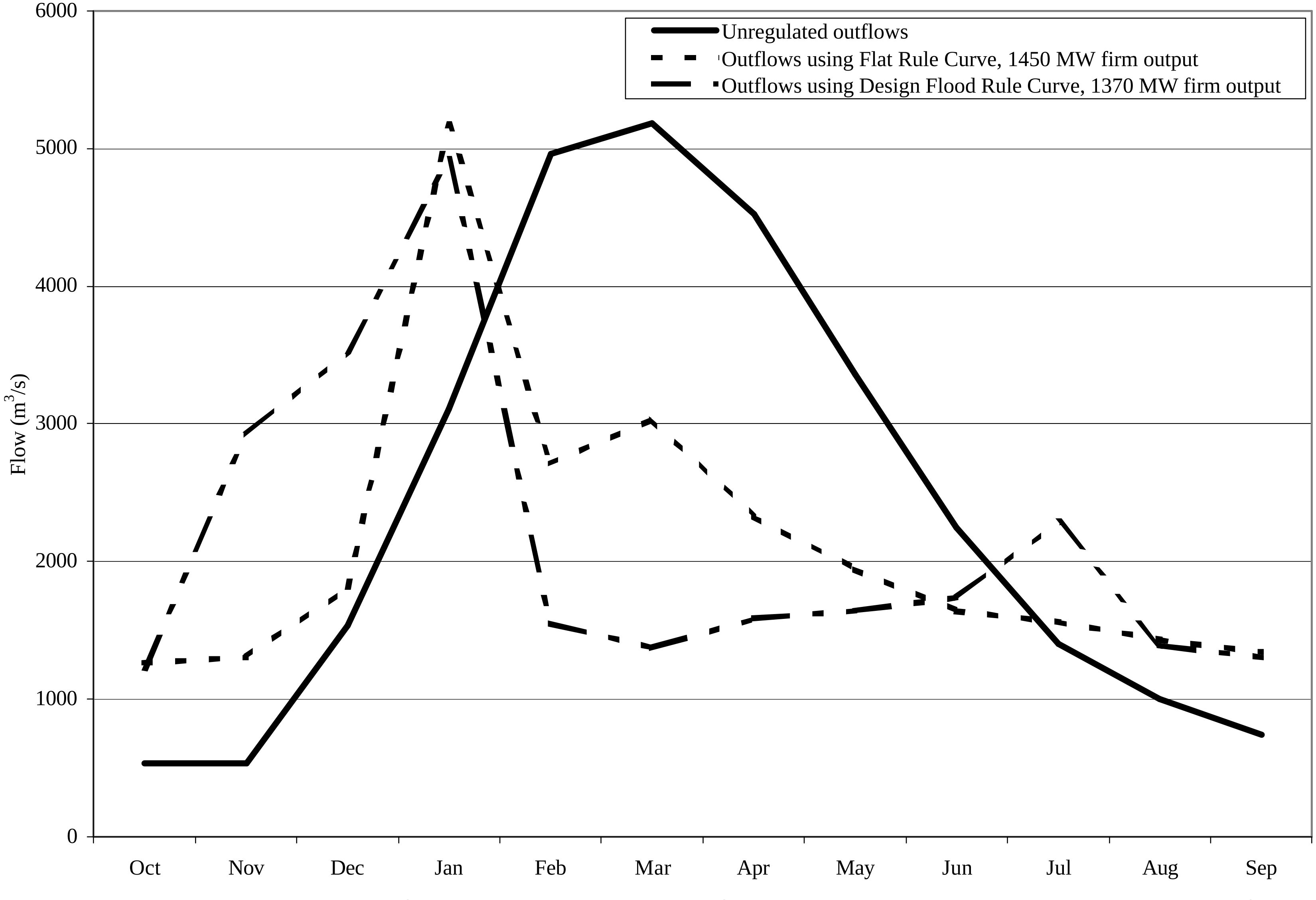

Figure 4-20. Mean monthly hydrographs for simulated Cahora Bassa outflows, 1907-98 time series data, to release prescribed flood of approximately 5000 m^3/s during January when reservoir water levels exceed 316 m amsl.

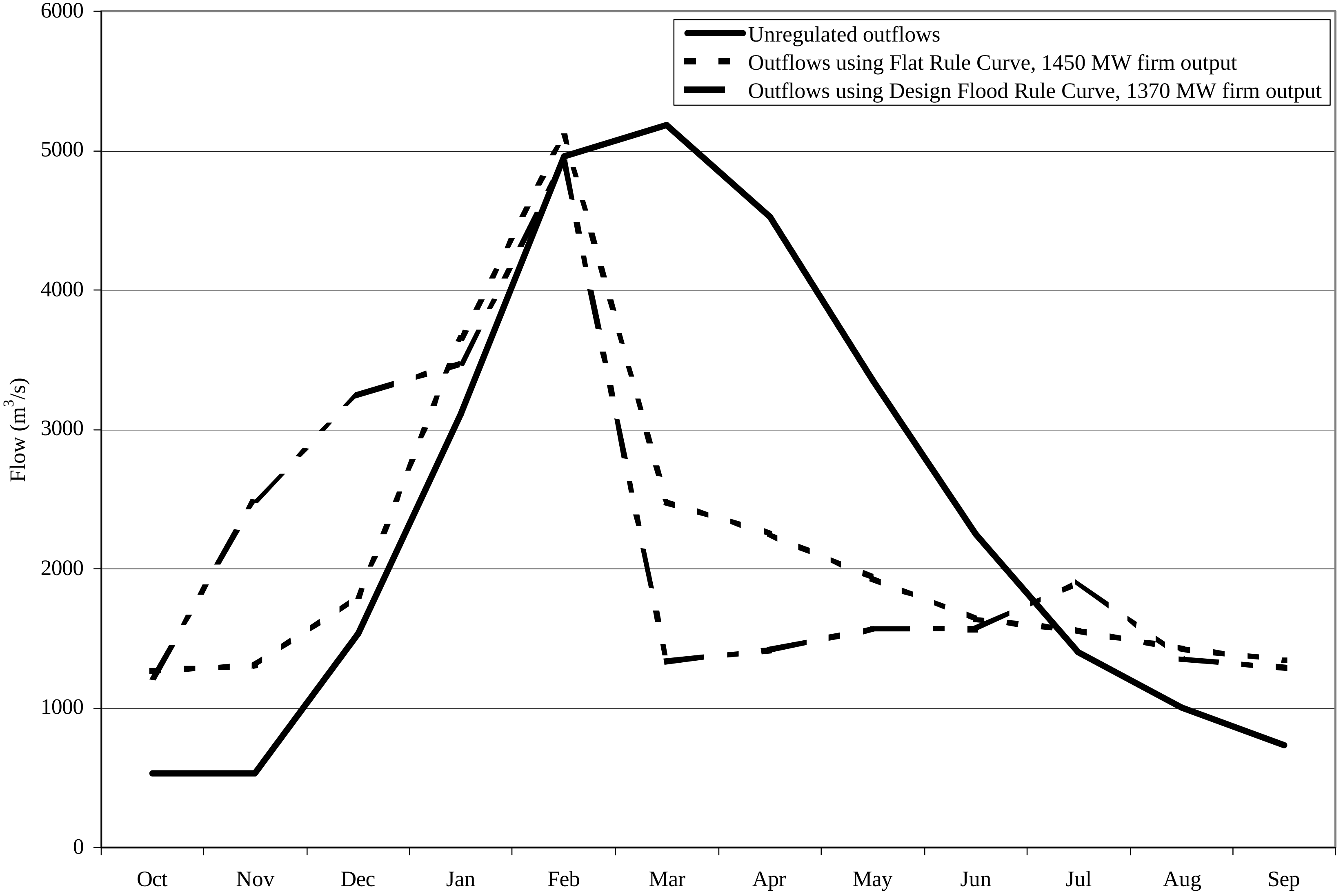

Figure 4-21. Mean monthly hydrographs for simulated Cahora Bassa outflows, 1907-98 time series data, to release prescribed flood of 5300 m^3/s during February when reservoir water levels exceed 316 m amsl.

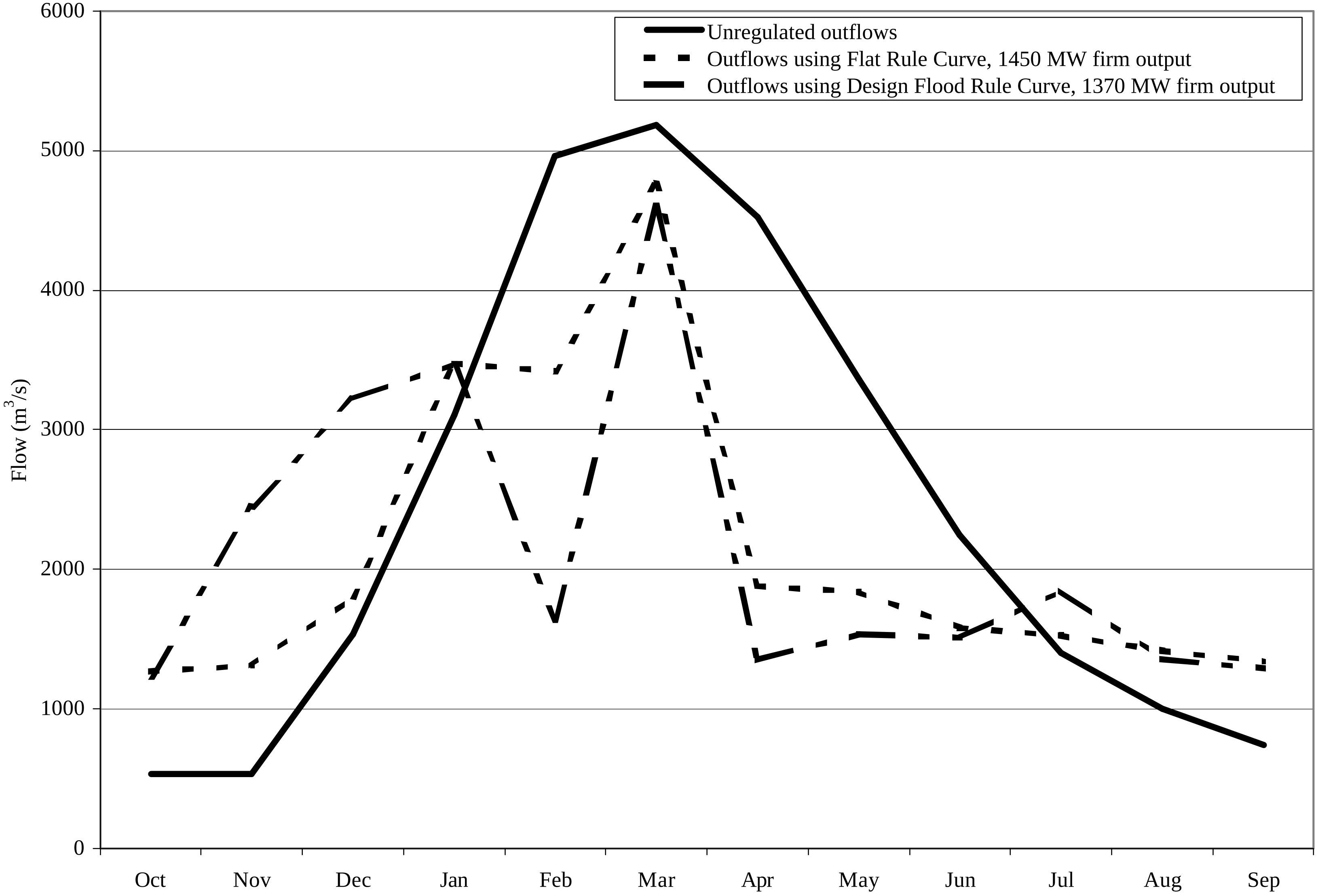

Figure 4-22. Mean monthly hydrographs for simulated Cahora Bassa outflows, 1907-98 time series data, to release prescribed flood of approximately 5000 m^3/s during March when reservoir water levels exceed 316 m amsl.

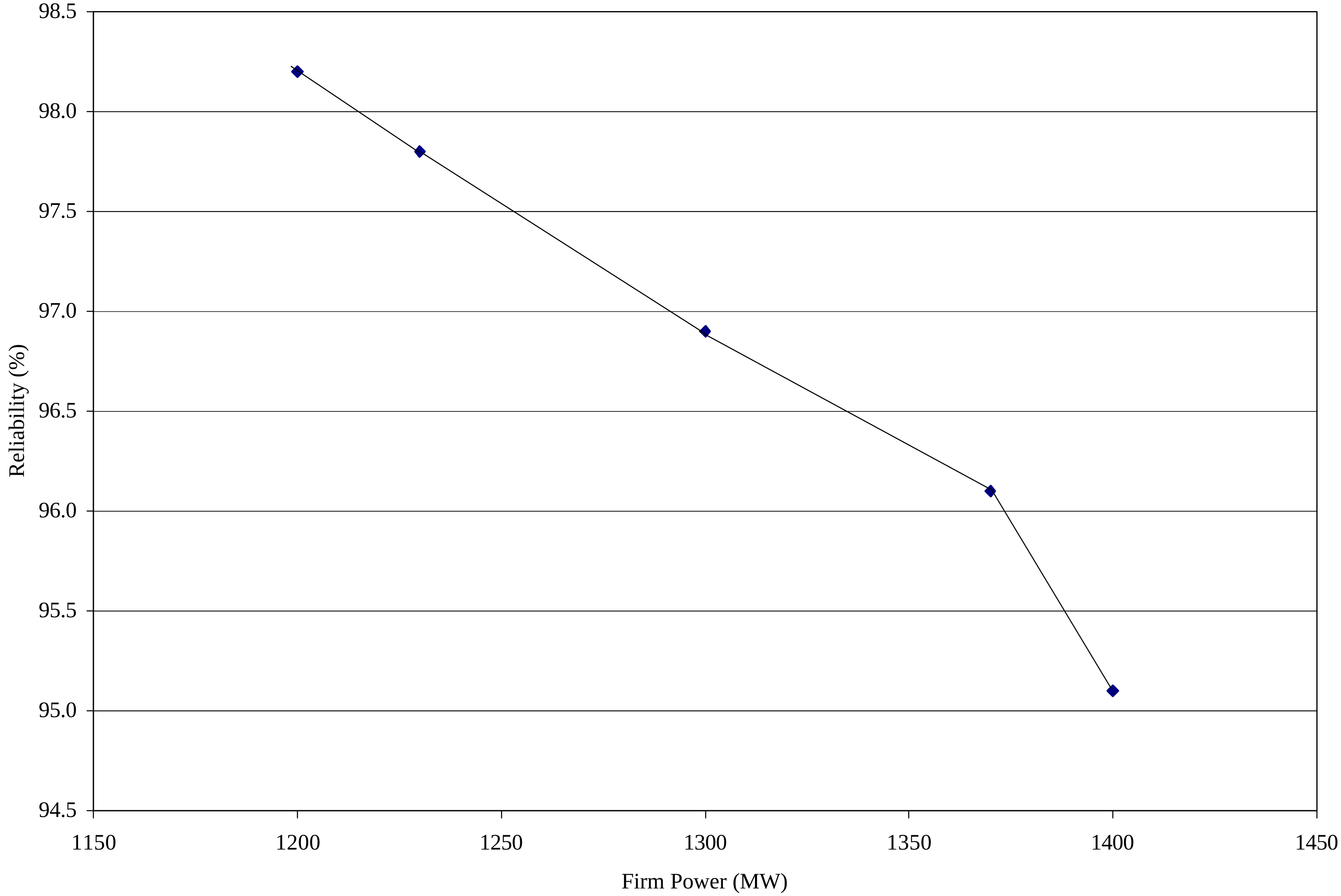

Figure 4-23. Firm power output vs. reliability for January prescribed flood release of 5000 m^3/s (approximately 8000 m^3/s for 14-days) from Cahora Bassa Dam.

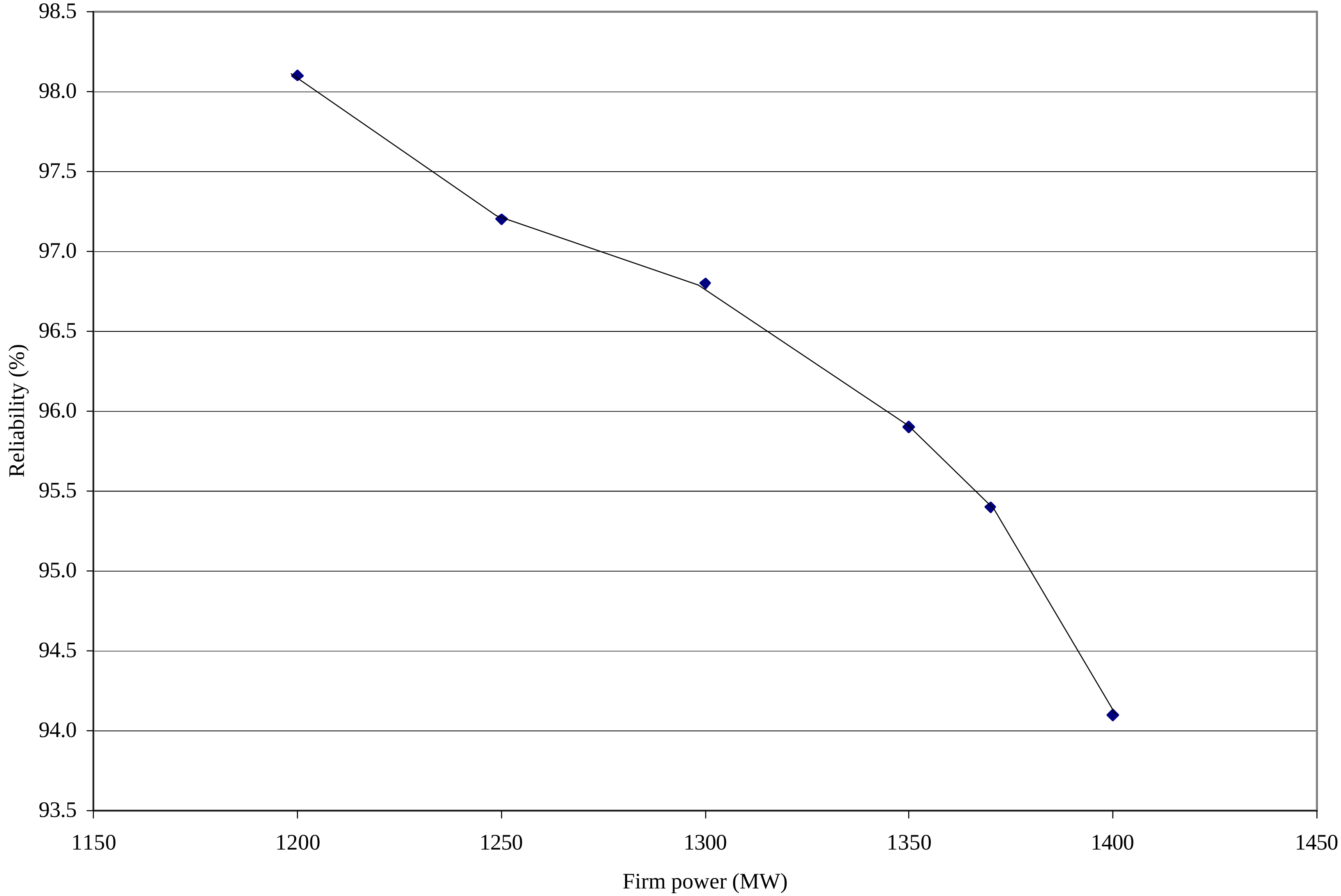

Figure 4-24. Firm power output vs. reliability for February prescribed flood release of 5300 m^3/s (approximately 8000 m^3/s for 14-days) from Cahora Bassa Dam.

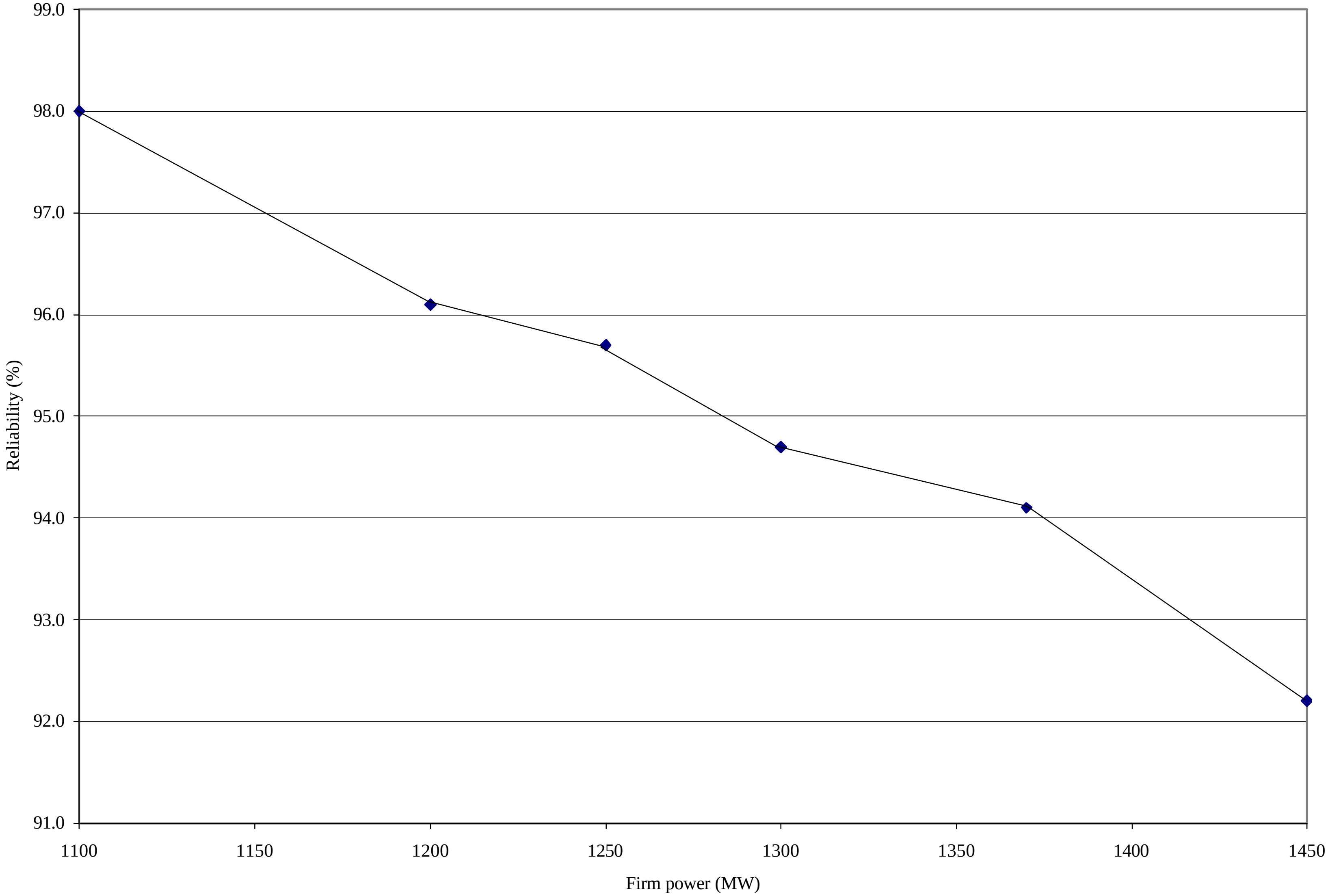

Figure 4-25. Firm power output vs. reliability for March prescribed flood release of 5000 m^3/s (approximately 8000 m^3/s for 14-days) from Cahora Bassa Dam.

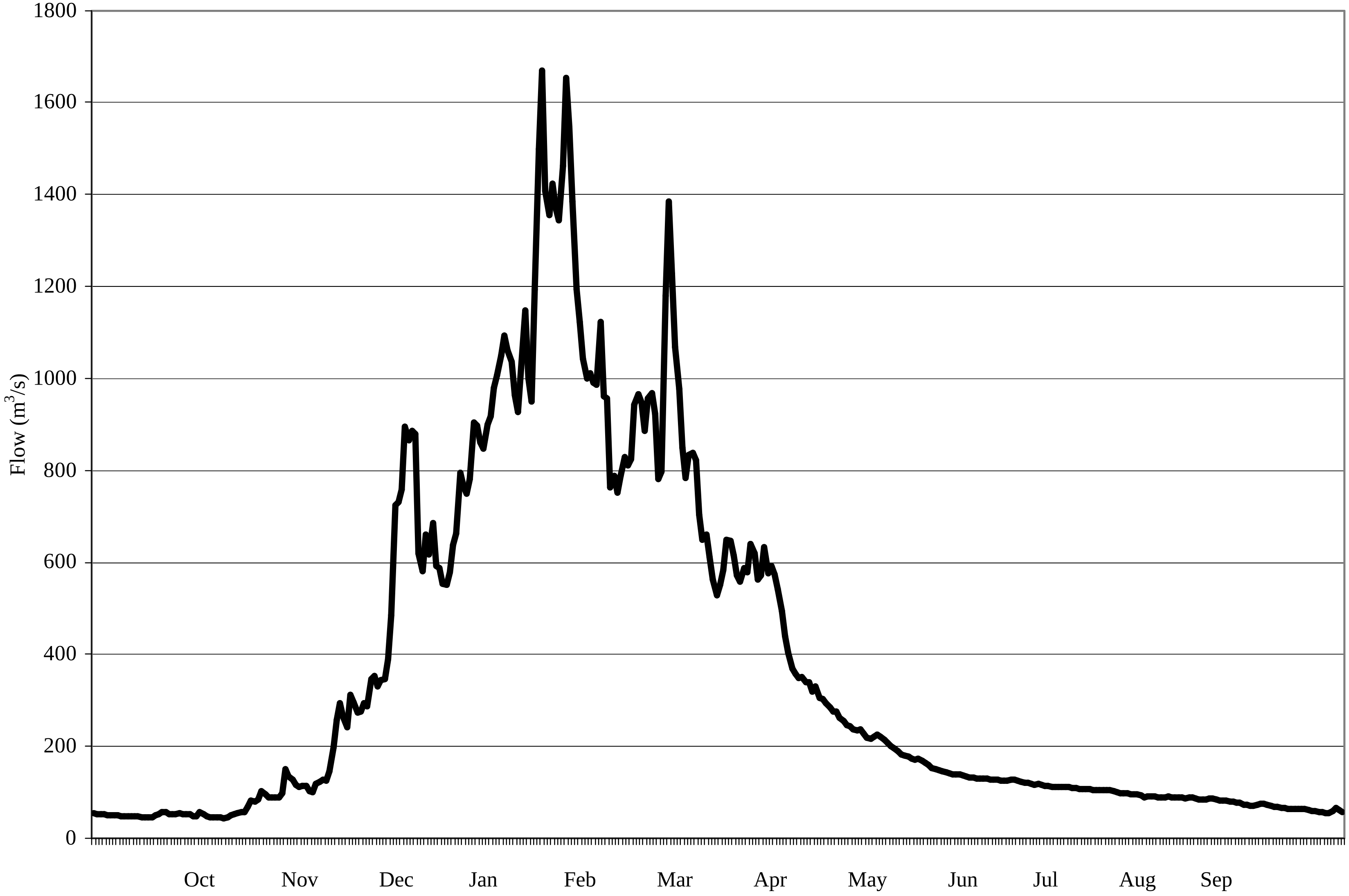

Figure 4-26. Hydrograph of estimated cumulative mean daily runoff from the Moravia-Angonia and Chimoio Plateau tributaries, 1976-00.