INDICATORS OF HYDROLOGICAL CHANGE IN THE LOWER ZAMBEZI RIVER

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Introduction

Hydrology is the most important determinant of wetland functions and values worldwide (*e.g.,* Finlayson and Moser 1991, National Research Council 1995, Mitsch and Gosselink 1993). In large floodplains such as the Zambezi Delta, the composition, structure, and function of the system—from the basic biological processes of primary production, decomposition, and consumption to the complex reproductive adaptations of plants and animals—depend on the hydrological connection between river and floodplain (*e.g.,* Welcomme 1979, Poff and Ward 1990, Sparks 1992, Bayley 1995, Heiler *et al.* 1995). The *Flood Pulse Concept* was postulated by Junk *et al.* (1989) to describe this connection in terms of the lateral exchange of nutrient and sediment-rich floodwaters between a river and its floodplain.

A fundamental principle of the flood pulse concept is that the natural (unregulated) flood regime of large rivers is *predictably unpredictable* (*e.g.*, Davies *et al.* 1995). The characteristics of any given flood event are uncertain and depend on the regional climatic conditions and other factors, but the magnitude, timing, duration, and frequency of hydrological conditions fall within a predictable range and pattern over time. This predictability is derived in part from the *persistence* of natural flow patterns in large river systems. As the annual flood builds up over the rainy season the characteristics of the flood hydrograph - the magnitude, extent, duration, and timing of peak flooding conditions - are increasingly revealed. As small floods build up during years of low rainfall in the catchment, for example, they do not suddenly transform into large, extensive floods.

The floodplain biota has evolved under, and is adapted to this “predictable” flood regime. Decomposition rates are typically highest at the onset of the flooding season, as floodwaters distribute detritus to consumers across the floodplain and stimulate high rates of primary production (Middleton *et al.*1992). Macroinvertebrates are morphologically, behaviorally, and physiologically adapted to the flooding regime of rivers through its influence on floodplain substrate, temperature, and water chemistry (e.g., Brooker 1981). Floods maintain the diversity and productivity of emergent macrophyte communities by modifying the microclimate and fluxes of sediment and organic matter (Finlayson *et al.* 1989, Gregory *et al.*1991, Brookes 1995). The annual flood cycle is critical to the life cycle completion of many woody and herbaceous species, with hydrochorous seeds and spores dispersing during high water and germinating as water levels recede (Middleton 1999). And the breeding and feeding behaviors of fish are very closely linked to the seasonal ebb and flow of floodwaters (Welcomme 1979, Bayley 1991).

In Africa, the breeding cycles of many species of waterbirds, including threatened species such as the Pel’s Fishing Owl (*Scotopelia peli*), Wattled Crane (*Grus carunculatus*), and African Skimmer (*Rhynchops flavirostris*), are triggered by the annual inundation and drawdown of floodwaters (*e.g.,* Hancock and Kushlan 1984, Hancock *et al.* 1992, Dennis and Tarboton 1993). Breeding is often timed to coincide with receding water conditions, so that young chicks can feed on the explosion of fish and invertebrate life across the floodplain (*e.g.,* Douthwaite 1974). African floodplain mammals migrate seasonally to take advantage of the luxuriant growth of palatable grasses on the inundated plains (*e.g.,* Sheppe and Osborne 1971, Tinley 1977, Rees 1978e, Dunham 1994).

The “predictable” hydrological regime of rivers also maintains the floodplain agriculture systems, fisheries, pasture, and forests that constitute the organizing element of community livelihood and culture

(World Commission on Dams 2000). This is especially true in the large floodplain systems of Africa. During the rainy season, the fertile alluvium adjacent to the river channel are planted with crops of cereals, legumes, and gourds that are harvested just prior to the river's expected annual flood. Farmers plant a second alluvial crop after the floodwaters begin to recede, sowing seeds just behind the retreating water line and harvesting at the end of the dry season (*e.g.,* Scudder 1972). Domestic animals are pastured on the lush vegetation growth that follows the flood recession during the dry season (*e.g.,* Bingham 1982, Grove 1985). The catch-per-unit-effort of fisheries increases as fish are stranded on the floodplain and concentrate in shallow pools during drawdown (*e.g.,* Welcomme 1979). The annual floods also maintain non-timber forest products and fuelwood resources on the floodplain, and recharge the local aquifers that provide an essential source of groundwater during the dry season (*e.g.,* Acreman *et al.* 2000). The general relationship between flooding conditions and patterns of fish behavior, vegetation growth, wildlife grazing, and cultivation on the floodplain over the annual hydrological cycle is given in Figure 2-1.

When the flooding regime is disrupted due to dams, embankments, or diversions, the hydrological connection between river and floodplain is altered or severed (*e.g.*, Sparks *et al.* 1990, Johnson *et al.* 1995, Ward and Stanford 1995a, 1995b). Numerous studies have documented the adverse effects of reduced and regularized flood flows worldwide, including reduced silt deposition and nutrient availability, channel degradation, loss of shallow wetland and open water areas, altered foodchain dynamics, reduced habitat heterogeneity and fragmentation, intrusion of saltwater, displacement of wetland vegetation by upland species, disrupted reproductive patterns for fish and wildlife species, and loss of coastal mangroves (*e.g.*, Baxter 1977, Brooker 1981, Petts 1984, Amoros 1991, Nilsson and Dynesius 1994, Ligon *et al.* 1995, Church 1995, Ward and Stanford 1995b, Nilsson and Jansson 1995, Welcomme 1995, McCully 1996, Colonnello and Medina 1998, others). Social and economic impacts may include failed flood recession agriculture, loss of grazing lands at end of dry season, reduced fishery and shellfishery harvest, reduced availability of various natural resources on the floodplain, and decreased access to groundwater (*e.g.*, Welcomme 1979, Scudder 1989, Barbier *et al.* 1997, Adams 1992, others). A wealth of studies in the Zambezi catchment associated with Kariba Dam, Itezhitezhi Dam, and Cahora Bassa Dam mirror these findings (*e.g.,* Attwell 1970, Scudder 1972, Begg 1973, Tinley 1975, Balon 1978, Rees 1978a&b, Chipungu 1981, Bolton 1984a, Handlos and Williams 1985, Suschka and Napica 1986, Anderson *et al.* 1990, Chabwela and Ellenbroek 1990, Machena 1992, Subramanium 1992, Masundire 1996, Beilfuss and Bento 1997, Hoguane 1997, Jackson 1997, Li-EDF-KP Joint Venture Consultants 1999, Beilfuss *et al.* 2000, Davies *et al.*2001, others).

Efforts to ameliorate adverse hydrological changes in the flooding regime must begin with an understanding of how hydrological processes have diverged over time from their historical, "predictable" character, and the possible causal links between hydrological changes and the social and ecological integrity of the floodplain. This is particularly true for the Zambezi system, which has undergone profound social and ecological changes over the past century but for which limited pre-impact studies are available.

Richter *et al.* (1996, 1997) proposed a useful framework for assessing hydrological alteration in ecosystems. The Richter *et al.* method, referred to as the Range of Variability Approach or RVA, defines key hydrological parameters that are important to the ecological functioning of floodplains systems. Sixty-four parameters are used to evaluate changes in the magnitude, duration, timing, frequency, and rate of change of flooding conditions before and after a carefully defined pre-impact and post-impact period.

The basic ecological underpinnings of the RVA are supported by recent ecological research that suggests that hydrological indicators should encompass the full range of inter-annual and seasonal hydrological variation in the historical flooding regime that sustained native biodiversity and productivity (Stanford *et al.* 1996, Petts 1996, Sparks 1995, National Research Council 1992). This approach is also backed by social research demonstrating that the activities of floodplain farmers and fishers are closely tied to the natural range of hydrological conditions, adapting their productivity to medium-sized floods and coping with drought and extreme flood events that sustained production systems in the long-term (Scudder 1972, Drijver and Marchand 1985, Grove 1985, Acreman *et al.* 2001).

In this paper, I apply the RVA to Zambezi River flows to evaluate the socio-economic and ecological implications of hydrological change on the Zambezi Delta. Using time series data, I estimate the means and coefficients of variation for the following indicators of hydrological alteration:

- monthly magnitude of flows;
- magnitude and duration of annual extreme flows;
- timing of annual extreme flows;
- frequency and duration of high and low flood pulses; and
- rate and frequency of change in flooding conditions.

Methods

I applied the Range of Variability Analysis to two sets of time series data for the Zambezi River. First, I assessed temporal changes in the hydrological regime of the Zambezi River at Muturara (near the apex of the Zambezi Delta) for two 28-year time periods, corresponding to the periods before and after significant river regulation The 1930-58 flow series covers the period prior to construction of Kariba Dam, during which Zambezi flows may be considered unregulated. The 1976-2004 flow series covers the period during which both Cahora Bassa and Kariba Dams have been in operation and more than 80% of mean annual runoff has been regulated. Second, I assessed spatial changes in the hydrological regime of the Zambezi River by comparing daily inflows to, and outflows from, Cahora Bassa Reservoir over the period 1976-2004. This analysis enabled the specific evaluation of Cahora Bassa Dam operation on Zambezi River flows, independent of any differences in mean annual rainfall in the Zambezi catchment between unregulated and regulated time period, and independent of the influence of Kariba Dam operation.

For each period, I calculated the means and coefficients of variation for the monthly magnitude of flows (12 parameters), the magnitude and duration of annual extreme flows (10 parameters), the timing of annual extreme flows (two parameters), the frequency and duration of high and low flood pulses (four parameters), and the rate and frequency of change in flooding conditions (four parameters). I also calculated the magnitude of deviation of each parameter between the two periods, and the percentage change.

For both the Muturara and Cahora Bassa comparisons, I plotted annual time series data for selected parameters to demonstrate patterns of variation within each period of evaluation. Each graph includes bars showing the long-term mean and one standard deviation above and below the mean.

Because flow data are not available from the Muturara gauge for most of the 1976-2004 period, I generated a twenty-eight year daily runoff time series for the Moravia-Angonia and Manica Plateau catchments using data from the mainstem Zambezi gaging station at Tete, the long-term gauging station at Revuboe, and rainfall-runoff relationships for the Luia and Luenha catchments. I added these inflows to Cahora Bassa outflows to extend the time series for Muturara to 1976-2004.

Examples of potential ecological and socio-economic consequences of changes in the magnitude, timing, duration, and frequency of flood pulses are drawn from extensive interviews with local communities in the Zambezi basin (Chilundo et al. 2002), personal observations, and published literature.

Results and discussion

The mean values for key hydrological indicators describing temporal changes in Zambezi flow patterns at Muturara between 1930-58 and 1976-2004 are given in Table 1. The mean values for hydrological indicators describing spatial changes in Zambezi flow patterns above and below Cahora Bassa Dam are given in Table 2 for the period 1976-2004. For each parameter, the magnitude and percentage of deviation between the two periods of evaluation are given. The tables also show a comparison of the coefficients of variation for each parameter and the magnitude and percentage of deviation between the periods of evaluation. A description of each parameter and an example of the socio-economic and ecological implications of changes in the parameter are given below.

Magnitude of mean monthly flows

One important set of indicators of hydrological change in the Zambezi Delta is the magnitude and variation in mean monthly flows. The monthly mean of the daily flows describes the “normal” daily conditions for the month, providing a measure of the degree to which the characteristic flood pulse, and associated habitat availability or suitability, has changed over time. Beilfuss (2001) used mean monthly flows to describe changes in runoff patterns at various points throughout the Zambezi catchment. The coefficients of variation, reflecting inter-annual variation in the monthly means, provide a measure of the predictability of the annual pattern of monthly flows (*i.e.*, the degree to which people and wildlife may anticipate and adapt to the annual flood regime).

The hydrograph of mean monthly flows at Muturara is shown for the period 1930-58 and 1976-2004 in Figure 1. Seasonal variability in the flow regime has significantly decreased while inter-annual variability has significantly increased. From 1930-58, the mean monthly maximum flow in March (7436 m^3/s) was more than an order of magnitude greater than the mean monthly minimum flow in November (617 m^3/s). Since 1976, the similarity of monthly means in the delta reflects a state of hydrological constancy. Mean maximum monthly flows are barely twice the mean minimum monthly flows. The mean monthly maximum flow in March is now 2868 m^3/s, a 61% decrease relative to pre-impact conditions, and mean minimum flow in November is 2115 m^3/s, a 243% increase. The mean monthly flow has decreased significantly during seven months (January to July), and increased significantly during four months (September to December). The coefficients of variation have increased significantly during seven months (March to August and November). Variation has increased by more than 200% in May and June.

Changes in the magnitude of mean monthly flows at Muturara can be partly explained by changing climatic patterns. There has been a 32% reduction in the mean annual flow between 1930-59 and 1976-2004. Part of this reduction may be due to evaporative water loss in Kariba, Kafue Gorge, and Cahora Bassa Reservoirs, but most is due to the extended drought period from the early 1980s to mid-1990s.

A comparison of the inflow-outflow hydrograph for Cahora Bassa Reservoir (Figure 2), however, reveals that the dam has clearly operated to significantly reduce mean monthly flood peaks and increase mean monthly dry season flows relative to inflows in addition to hydrological changes wrought by the operation of Kariba and Kafue Gorge Dams. Since closure of the Cahora Bassa, there is almost no characteristic flow pattern below the dam. The highest mean monthly discharges occur in December (several months before the historical peak flood) and July (mid-dry season). Downstream flow contribution from the unregulated plateau tributaries and Shire River help to offset these effects and result in higher variation in mean monthly flows at Muturara during the rainy season.

One possible consequence of the reduction in the seasonal variability of mean monthly flows is the crash of the floodplain fishery and coastal shellfishery in the delta. The yield and production of riverine fisheries is highly dependent on the magnitude of flood season flows (*e.g.,* Bayley 1991). The annual spread of floodwaters creates nearly optimal conditions for fish breeding and feeding activity (Welcome 1979). Flooding stimulates the production of food sources (including insects, worms, and mollusks) and the growth of emergent vegetation that provides both food and shelter. Many fish species “anticipate” these conditions by migrating laterally from the river channel to the floodplain to spawn just before or during the rise of floodwaters (Jackson 1986). During the floods, feeding is most intense and most fish reach peak condition. The number of surviving fry is directly proportional to the extent of inundation, as is the survival and growth of adult fish (Welcome 1979). When floods fail, fish are confined to the river channel (which offers minimal vegetation cover and fewer food sources) or are stranded in the floodplain before they can reach sufficient size to avoid predation (Bayley 1995).

Fish are the most important source of protein for the delta population, especially during times of food shortage. Historically, fishers concentrated in large numbers on the Zambezi floodplains, with seasonal fishing camps spread throughout the area between the main Zambezi channel and Mungari River distributary (Mr. Paul Dutton *pers. comm*). The annual months of low flows enabled a high catch of fish per-unit-effort because fishers were able to wade into the river using simple gill nets and baskets. SWECO (1983) estimated a total floodplain harvest of about 10,000 tons per annum under historical flooding conditions. Over the past three decades, riverine and near-shore coastal fisheries have replaced the floodplain fishery in the delta. The catch-per-unit-effort in the mainstem Zambezi is low due to high dry season flows, and most of the fishing camps are now found in the coastal waters of Chinde district. The change in volume and value of catches in unknown, but recently DNFFB (1998) and Turpie *et al.* (1998) estimated the total catch at one of main fishing camps (Chinde) at only 645 tons per annum. Similar declines are reported for the subsistence fishery of the Kafue Flats following river regulation (Hayward 1984, Subramanium 1992). After the extensive delta flooding of 2001, however, fishing camps were re-established on the floodplains for the first time since 1978 and fish harvests were the highest (total catch and biomass) in twenty years, with local markets at Marromeu and regional markets reported from as far as Malawi (Mr. Simoes Fombe *pers. comm.*).

The reproductive success of prawns is also closely linked to the patterns of mean monthly flows (Garcia and Le Reste 1981). Studies have shown there is a high degree of correlation between Zambezi runoff patterns and the abundance of shrimp at the Zambezi mouth (Da Silva 1986, Gammelsrod 1996, Hoguane 1997). Almost half of the shrimp species caught are of the species *Penaeus indicus*, which has a life cycle of one year. Spawning takes place at sea, but the larvae and juveniles require brackish water as nursery areas and must migrate against the current to reach the protected mangrove swamps. Because shrimp are inefficient swimmers, low dry season flows enable them to migrate inshore on tidal currents. High flood season flows, in turn, lower the salinity in the mangrove swamps, and trigger juveniles to move from the mangrove zone to the ocean to reproduce. Floodflows also spread nutrient-rich river water along the coastal bank to stimulate prawn recruitment.

The prawn fishery off the delta coast, which began in 1965, is one of the most important sources of foreign currency in Mozambique. The catch rate of the shrimp is reported to be decreasing at an alarming rate since the early 1980s (Gammelsrod 1992b). Hoguane (1997) estimated that the regulation of the Zambezi River is leading to a loss of $US 10-20 million per annum and Gammelsrod (1992a) predicted that catch rates would increase by 20% with increased flood flows and decreased dry season flows.

Magnitude and duration of annual extreme flows

A second important set of indicators of hydrological change is the magnitudes of extreme (maximum and minimum) annual flows of various durations. For any given year, the 1-day maximum (or minimum) is represented by the highest (or lowest) single daily flow occurring during the year. The mean magnitude of 1-day maximum and minimum flows defines the amplitude of the annual flood pulse. These extreme flows are a measure both of environmental stress in the system, and of the opportunity for large-scale regenerative processes (Richter *et al.* 1996). The inter-annual variation (*e.g.*, coefficient of variations) in the magnitude of these extreme flows further characterizes the probability of different extreme flood events.

A comparison of the annual series of maximum 1-day discharge values for the Zambezi River at Mutarara is given in Figure 3. During the period 1930-58, the mean maximum discharge at Muturara was 11,519 m^3/s, with a standard deviation of 4377 m^3/s. Since 1976, the mean maximum discharge has been 5912 m^3/s, with a standard deviation of 3370 m^3/s. This represents a substantial reduction (49%) in the mean maximum discharge, and substantial increase (50%) in the variability of the annual maximum. Only two floods since 1976 (the 1978 and 2001 floods) have exceeded the value of the mean maximum flow for the period 1930-58. Conversely, only one flood during the period 1930-58 failed to exceed the value of the mean maximum discharge for the 1976-2004 period. The 3-, 7-, 30-, and 90-day mean maximum flows follow a similar pattern (Table 1).

The effect of Cahora Bassa regulation on maximum 1-day flows is revealed in Figure 4. Large flooding events such as the 1978 flood are only partially attenuated by the dam and still result in high maximum flows. Medium-sized flood peaks (flows within the range of 3500-14,000 m^3/s), however, are significantly attenuated by Cahora Bassa.

The near elimination of medium-sized flooding events has contributed to the social and economic severity of large flooding events in the delta. Floodplain farmers have resettled close to the mainstem Zambezi to cultivate crops in the narrow band of alluvium that is inundated each year. Many farmers are emboldened by the perception that Cahora Bassa Dam can control large floods. This leads to a significant increase in flood risk and flood damage when large floods occur, such as the 1978 (RPT 1979) and 2001 floods (Hanlon 2001). Even floods that are moderate by historical standards such as the 1989 and 1997 floods (about 10,000 m^3/s at Muturara) resulted in extensive flood damage (Vaz 1989, De Vries *et al.*1997, Beilfuss 2001)[1].

The reduction in annual peak flooding has also affected patterns of wildlife grazing and threatened the long-term carrying capacity of the vast delta floodplains. Tinley (1977) described the migratory and local movements of wild ungulates in the delta as an opportunistic response to the availability of suitable food resources and water. The close proximity of different vegetation communities with different soil moisture conditions allows ungulate species to meet their year-round life requirements through a rotation grazing patterns in response to natural flood cycles. When floods fail to appear, the system is disrupted. Woody vegetation and thickets invade grasslands, and drought resistant grassland species replace wetland species

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[1]Several studies by the DNA have examined the role of Cahora Bassa management in lower Zambezi flooding. Novela (1989) reviewed the management of Cahora Bassa Dam during the flood of 1978, and demonstrated that different patterns of water release could have been made to reduce downstream flooding. Vaz (1989) assessed the management of Cahora Bassa dam and the contribution of downstream tributaries during the 1989 flood. Using 6-hour increment gauge data over this period, she routed inflows through the dam under different management scenarios, contrasting actual management during this time period (with up to 5 sluice gates opened) to a strategy of opening only 2 or 3 sluice gates to curtail flooding. DeVries *et al.* (1997) examined the floods of 1997 and concluded that they were the result of near-record rainfall in the Lower Zambezi Valley above Tete.

of higher nutrient content (Beilfuss 2001). The elimination of large floods facilitates year-round grazing on the open plains, and the stressed vegetation is further displaced by less palatable upland species. Similar patterns have been shown for the Kafue Flats (Rees 1978c&e) and middle Zambezi floodplains (Attwell 1970, Dunham 1994, Nilsson and Dynesius 1994) following river regulation. Cape buffalo are highly susceptible to starvation and high mortality when their pastures dry out early in the dry season, especially when uncontrolled fires sweep across the delta (Tinley 1977). Hippo (the only truly aquatic mammal species in the delta) and waterbuck are also vulnerable to poor forage conditions in the wet floodplains.

A comparison of the annual series of minimum 1-day discharge values for the Zambezi River at Mutarara is given in Figure 5. During the period 1930-58, the mean maximum discharge at Muturara was 501 m^3/s, with a standard deviation of 205 m^3/s. An increase in dry season low flows began with Kariba operation in 1959. Kariba increased the minimum low flows from 300-600 m^3/s to 600-900 m^3/s. Between 1930-58 and 1976-00, the mean maximum discharge has increased by 44% to 721 m^3/s[2].

Several species of wading birds, including the Openbilled Storks (*Anastomus lamelligerus*), depend on the annual minimum flows for feeding. Openbilled Storks concentrate in large numbers to feed on freshwater snails and mussels on the exposed shifting, sandbars of the lower Zambezi during the dry season (Beilfuss and Bento 1997). The further stabilization of the Zambezi flow regime will greatly diminish the availability of sandbar habitats and threaten one of the largest populations of Openbilled Storks reported in Africa.

Timing of annual maximum and minimum flows

A third important set of indicators of hydrological change is the dates of the 1-day annual maximum and minimum flows. The dates of occurrence of maximum and minimum flows are defined relative to the annual hydrological cycle, with October 1st set equal to day 1 of the hydrological cycle and September 30th equal to day 365. The inter-annual variation (*e.g.*, coefficient of variation) in the timing of flood flows provides a critical measure of the predictability with which annual flooding events will occur (Richter *et al.* 1996).

The effect of Cahora Bassa regulation on the timing of the annual 1-day maximum flows is shown in Figure 6. Maximum inflows generally occur between early February to late March. The mean date of maximum inflows is March 5, with a coefficient of variation of 0.16. Maximum outflows from Cahora Bassa, however, may occur during any month of the hydrological cycle depending on reservoir drawdown releases. The mean date of maximum outflows is January 26, but more than half of the annual maximum releases occurred during the dry season. The coefficient of variation of maximum outflows is 0.78. Annual minimum flows may also occur during any time of year depending on flow regulation by Kariba and Cahora Bassa Dams. The coefficient of variation of Cahora Bassa outflows is 0.57 (a 256% increase relative to inflows).

At Muturara, some of the effects of mis-timed water releases from Cahora Bassa are masked by tributary inflows during the flood season (Figure 7). Prior to Zambezi regulation, the mean annual maximum flood typically occurred during a very narrow window from mid-February to mid-March. The mean date of

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[2]This increase, although significant, is less than would have occurred if hydropower turbines were in full operation. Only one hydropower turbine was in (partial) operation at Cahora Bassa Dam from 1983-1997, and outflows were occasionally reduced to a trickle when the intakes were closed for servicing. A single sluice gate was periodically operated to discharge about 1200-1600 m^3/s. Future dry season outflows from Cahora Bassa Dam, with four turbines in operation, will rarely fall below 1600 m^3/s (Olivier 1977).

maximum flow was March 1, with a coefficient of variation of 0.14. Under the current regulated regime, peaks flows generally still occur during the rainy season, but variability in the timing of the floods has increased by 112%. Annual low flows, which occurred with remarkable consistency prior to Zambezi regulation (Figure 8), may now occur during almost any month of the year. In 1980 and 1998, the annual minimum flow occurred during the time of historical *peak* flooding in March.

The timing of the annual flood is critical for floodplain agricultural practices in the lower Zambezi system (Negrão 1995). Planting occurs on the heavy alluvial soils as floodwaters recede and crops are harvested prior to the next flooding cycle. Scudder (1972) observed that the extreme irregularity in Middle Zambezi flows below Kariba Dam has had terrible consequences for floodplain agriculture, with crops alternatively flooded out and desiccated. In the delta region, flood recession agriculture is similarly constrained by the timing of water releases from Cahora Bassa Dam. Occasional out-of-season drawdown releases from Cahora Bassa have wiped out crops along the length of the mainstem Zambezi River and along the Catarina, Chinde, and Mucelo distributaries. Turpie *et al.* (1998) estimated the total value of subsistence agriculture in the delta at US$5.3 million per annum, and chronic food insecurity is high (Schmidt 1997).

Key life cycle phases of many floodplain wildlife species are also intimately linked to the timing of annual floods. The fate of the Wattled Crane, a Globally Endangered resident of the Zambezi Delta, is closely linked to the timing of annual flood flows. In undisturbed floodplain systems elsewhere in Africa, Wattled Crane pairs are “triggered” to nest after peak flooding. Wattled Cranes nest in deep, open water after the major flood peak, to ensure that nests are protected from predators and wildfires but not drowned by further rising floodwaters. As floodwaters slowly recede, Wattled Cranes raise their single chick on the pulse of exposed plant and insect life (Konrad 1981). If flooding patterns are erratic or mis-timed, Wattled Crane pairs may not be induced to initiate nesting. If nesting is attempted, unanticipated water level rises can drown nests and food sources. Rapid water level drawdown in the floodplains may expose nests to wildfires and predators and limit food availability. On the Kafue Flats, Douthwaite (1974) observed that whereas 40% of Wattled Crane pairs attempt to breed in a year of normal flooding conditions, only 3% of all pairs breed in a year of negligible flooding conditions due to drought. Recent research in the Zambezi Delta suggests that Wattled Cranes have abandoned most of the floodplain now subject to erratic flooding patterns. Breeding occurs only in the floodplains adjacent to the Cheringoma escarpment, which still receives unregulated floodwaters (Beilfuss 2000, Bento *in press*). Based on these and other observations, hydrological changes in the delta may be contributing to a significant decline in the breeding success of the Wattled Crane.

Frequency and duration of high and low flood pulses

A fourth important set of indicators of hydrological change includes the number of annual occurrences during which the magnitude of flows exceeds an upper threshold or remains below a lower threshold, respectively, and the annual duration of high and low pulses (Richter *et al.* 1996). Hydrological pulses here are defined for Cahora Bassa Dam as the those periods within a year in which the daily mean inflow or outflow either rises above the 75th percentile of inflows (corresponding to a flow of 2044 m^3/s) or drops below the 25th percentile of inflows (908 m^3/s). High flood pulses for Muturara are defined for the threshold of overbank flooding in the delta region (approximately 4500 m^3/s). This flow corresponds to about the 75th percentile of long-term flows at Muturara. The low flood pulse is 1100 m^3/s, corresponding to the 25th percentile of Muturara flows.

A comparison of the annual series of the number of flood pulses above 4500 m^3/s for the Zambezi River at Muturara is given in Figure 9. During the period 1930-58, river flows typically pulsed above 4500 m^3/s twice per year: an early peak generated by the lower Zambezi Valley tributaries in January, and a later peak generated by peak runoff from the upper and middle Zambezi catchment during February and

March. At least one flood pulse above 4500 m^3/s occurred in all years of record. After 1976, flows at Mutarara failed to reach the minimum flooding threshold of 4500 m^3/s in 10 of 23 years. During years when flooding occurred, flood levels spiked above 4500 m^3/s up to six times in a single year due in part to dry-season drawdown discharges from Cahora Bassa Dam.

A comparison of the annual series for the duration of flood pulses about 4500 m^3/s is given in Figure 10. Prior to Zambezi regulation, the average duration of each flood pulse was 56 days with considerable year-to-year variability (the coefficient of variation was 0.49) (Table 1). Flood flows surpassed 11,000 m^3/s (approximately the mean maximum flow) in 14 of 28 years, for an average of 9 days per year (Table 2-27). Since 1976, the average duration of the annual flood pulse is only 9.7 days. Flooding remained above 4500 m^3/s for 165 days during the 1978 floods, but has not exceeded 46 days in any year since that time. Flood flows did not reach the historical mean maximum flow of 11,000 m^3/s in any year between 1978 and 2001.

The historical dry season flow regime was characterized by a long period of recession. There was exactly one low pulse per year, for an average duration of 89 days until the onset of the next flood season (Table 1). Since 1976, there are 1.4 low pulses on average during the dry season—often several (coefficient of variation is 1.3)—for an average duration of 59 days. There is no longer a clearly defined period of flood recession during the dry season.

The frequency and duration characteristics of the annual flood pulse have a critical influence on fisheries, wildlife, and agriculture, and are especially important for flushing accumulated salts from the delta floodplains. The balance between tidal saltwater and riverine freshwater is maintained by Zambezi flow and by local rainfall-runoff in the delta, with saline groundwater underlying the coastal floodplain. The hydromorphic vertisols covering all but the deepest depressions on the Quaternary Deltoid Plain are saline below 60 cm, but were generally non-saline in the upper 30 cm (Loxton, Hunting and Associates *et al.* 1975c). In recent years, the pattern of short-duration flooding is not sufficient to flush out salts from the delta substrate, and is facilitating the salinization of the upper soil layers. Tinley (1975) observed that as flooding decreased due to Kariba regulation the low-lying areas in the delta were becoming more saline, and during the initial filling of Cahora Bassa Reservoir saltwater intrusion occurred up to 70 km inland from the coast. SWECO (1983) considered salinization to be the gravest threat to the delta floodplains. Substrates once highly productive throughout the year are now productive only during the rainy season, and many soils have become alkaline or saline. Saline soils occur progressively closer to the main river channels over time, and eventually only soils in the immediate vicinity of the rivers remain productive. Large floods, such as those that occurred in 1978 and 2001, serve to flush some of the accumulated salts from the system but are unlikely to remove the full extent of salts accumulated since Cahora Bassa construction.

The frequency and duration of annual flooding also determines the composition and vigor of vegetation communities on the floodplain, especially the grasslands and papyrus swamps. Floodplain species occur along a moisture gradient, from species adapted to frequent floods of long duration to species adapted only to rare floods of short duration. Reduced flooding might result in areas of *Cyperus papyrus* being displaced by perennial swamp grassland species, or *Vetiveria-Ischaemum* being seasonally flooded bunch grassland invaded by *Hyphaene* palm savanna. Each of these changes has important implications for the wildlife of the delta. Similar changes were observed in Mana Pools floodplain in the middle Zambezi after the construction of Kariba Dam (Dunham 1989a, 1989b). The impact of hydrological change on the vegetation of the Zambezi Delta is discussed in depth in Beilfuss 2001.

Rate and frequency of change in hydrograph

The final set of indicators of hydrological change includes the number and mean rate of positive and negative changes in flows from one day to the next. The rate and frequency of change in flows describes the abruptness of changes in the floodplain hydroperiod and provides a measure of the rate and frequency of intra-annual environmental changes (Richter *et al.* 1996).

A comparison of the average annual rates of hydrograph rise for the Zambezi River at Mutarara is given in Figure 11. The historical flow regime was characterized by a relatively brief period of steadily increasing discharge, rising to one or more peaks during the flooding season, followed by a prolonged dry-season recession. The mean number of daily rises was 85, with an average increase of 244 m^3/s per day (Table 1). The mean number of daily falls was 209, with an average decrease of 97 m^3/s per day. Coefficients of variation are low.

Since 1976, the flow regime shows increasing flashiness, characterized by a large number of small, abrupt day-to-day changes. The average number of rises has nearly to doubled to 153 per day, and the average rate of daily increase is about 152 m^3/s. These changes are directly related to discharges from Cahora Bassa Dam (Figure 2-12). By regulating inflows for hydropower generation, Cahora Bassa significantly dampens Zambezi flows. The average annual rate of increase for inflows is 373 m^3/s, but is only 118 m^3/s for outflows. There is little difference between the mean annual number of increases (157) and decreases (174) in Cahora Bassa discharge (Table 2). Variation in the magnitude of daily fluctuations has not changed significantly.

Abrupt changes in the water regime are especially detrimental to species of birds, amphibians, and reptiles that nest on sandbars and floodplain waterbodies (*e.g.,* Nilsson and Dynesius 1994). Survival of the African Skimmer, now extinct in South Africa and restricted to a few river basins in southern Africa, depends in large part on the gradual rise and fall of water levels in large rivers such as the Zambezi (Coppinger *et al.* 1988). African Skimmers nest and roost on exposed, open sandbars in the mainstem Zambezi channel during the dry season. In the middle Zambezi, abrupt water releases from Kariba Reservoir during the dry season cause meter high wave surges downstream, sweeping away nests of any birds using the low islands (Coppinger *et al.* 1988). These affects are exacerbated by increased dry season flows that permanently inundate many sandbars, and the geomorphic changes in the main Zambezi channel leading to the stabilization and colonization of many coastal sandbars. As a result, many former nesting sites on the Zambezi have been abandoned (Dennis and Tarboton 1993).

Conclusion

The Zambezi Delta has undergone profound hydrological changes over the past century. The combined effects of Kariba and Cahora Bassa Dams and high embankments along the mainstem Zambezi have transformed the delta from a dynamic flood pulse system—maintained by runoff from a catchment extending over eight southern Africa nations—to an isolated system dependent on local rainfall-runoff. The magnitude, timing, duration, and frequency of flooding have changed significantly, with severe implications for the socio-economic and ecological health of the delta.

Studies linking hydrological parameters with socio-economic, cultural, and ecological processes in the delta are ultimately the window into understanding long-term change in the delta. Further research is needed to quantify the sensitivity of agricultural systems, fisheries, productivity, and biodiversity to changes in the hydrological regime of the Zambezi. Ongoing studies of the decline in coastal prawn productivity, failure of floodplain agriculture, die-off of coastal mangrove, and decline of endangered species such as the Wattled Crane, among others, provide a radically different perspective on the history of hydrological management of the Zambezi system than engineering reports and power sales.

Table 1. Five groups of hydrological indicators for the Zambezi River at Muturara, comparing parameters for the periods 1930-58 and 1976-2004. The magnitude and percent of deviation are given for the means and coefficients of variation for each parameter.

Indicator	1930-58 Mean	1976-04 Mean	Dev Mag	%	1930-58 CV	1976-04 CV	Dev Mag	%
Group 1: Monthly magnitude								
Oct	736	1717	981	133	0.45	0.53	0.09	19
Nov	617	2115	1498	243	0.47	0.63	0.17	36
Dec	1440	2490	1050	73	0.85	0.62	-0.23	-27
Jan	3886	2940	-946	-24	0.58	0.51	-0.07	-13
Feb	6496	3369	-3127	-48	0.54	0.55	0.01	2
Mar	7436	2868	-4569	-61	0.49	0.90	0.41	85
Apr	5859	2314	-3545	-61	0.37	0.94	0.57	157
May	4509	1945	-2564	-57	0.27	0.86	0.59	216
Jun	3418	1886	-1532	-45	0.28	0.85	0.57	203
Jul	2372	1937	-435	-18	0.29	0.76	0.46	157
Aug	1623	1586	-37	-2	0.32	0.47	0.15	48
Sep	1125	1582	457	41	0.38	0.47	0.09	22
Mean	3293	2229	-1064	14	0.44	0.67	0.23	75
Group 2: Magnitude and duration of annual extremes								
1-day max	11519	5912	-5606	-49	0.38	0.57	0.19	50
3-day max	11231	5618	-5613	-50	0.37	0.59	0.22	60
7-day max	10687	5335	-5352	-50	0.37	0.62	0.25	69
30-day max	8661	4563	-4098	-47	0.39	0.63	0.24	63
90-day max	6888	3552	-3336	-48	0.34	0.57	0.23	67
1-day min	501	721	220	44	0.41	0.50	0.08	20
3-day min	512	763	251	49	0.41	0.48	0.07	18
7-day min	516	923	407	79	0.41	0.40	-0.01	-3
30-day min	559	1373	815	146	0.40	0.37	-0.02	-6
90-day min	738	1458	720	97	0.40	0.41	0.02	4
Group 3: Timing of annual extremes (based on annual hydrological cycle beginning October 1)								
Date of annual max	150	132	-18	-12	0.14	0.30	0.16	112
Date of annual min	318	183	-135	-42	0.04	0.72	0.68	1755
Group 4: Frequency and duration of high pulses (4500 m^3/s) and low pulses (1100 m^3/s)								
High pulse count	2.3	1.7	-1	-27	0.49	1.13	0.64	130
High pulse avg. duration	56.1	9.7	-46	-83	0.82	1.98	1.16	141
Low pulse count	1.0	1.4	0	39	0.00	1.30	1.30	0
Low pulse avg. duration	89.0	58.7	-30	-34	0.41	1.36	0.95	229
Group 5: Rate and frequency of flow changes								
No. of rises	85	153	68	80	0.14	0.18	0.04	29
No. of falls	209	200	-9	-4	0.16	0.13	-0.03	-18
Means of + diffs btw daily	244	152	-91	-37	0.42	0.47	0.05	13
Means of – diffs btw daily	97	119	22	23	0.36	0.53	0.17	49

Table 2. Five groups of hydrological indicators for Cahora Bassa Reservoir, comparing inflows and outflows for the period 1976-2004. The magnitude and percent of deviation are given for the means and coefficients of variation for each parameter.

Indicator	Inflows Mean	Outflows Mean	Dev Mag	%	Inflows CV	Outflows CV	Dev Mag	%
Group 1: Monthly magnitude								
Oct	948	1669	721	76	0.41	0.55	0.14	34
Nov	1030	2057	1026	100	0.40	0.65	0.25	63
Dec	1419	2194	774	55	0.57	0.67	0.10	18
Jan	2503	2185	-318	-13	0.55	0.64	0.09	15
Feb	3771	2223	-1548	-41	0.68	0.67	-0.01	-2
Mar	3440	2033	-1407	-41	0.81	1.09	0.28	34
Apr	2343	1835	-509	-22	0.89	1.13	0.24	27
May	1743	1733	-10	-1	0.90	0.94	0.04	5
Jun	1509	1759	249	17	0.78	0.91	0.12	16
Jul	1380	1837	457	33	0.77	0.80	0.03	4
Aug	1147	1504	357	31	0.49	0.50	0.01	2
Sep	1032	1520	488	47	0.39	0.49	0.10	25
Mean	1855	1879	23	20	0.64	0.75	0.12	20
Group 2: Magnitude and duration of annual extremes								
1-day max	7175	4474	-2701	-38	0.54	0.72	0.18	34
3-day max	6645	4374	-2270	-34	0.55	0.74	0.19	35
7-day max	6126	4295	-1831	-30	0.56	0.74	0.19	34
30-day max	4533	3679	-854	-19	0.58	0.72	0.14	23
90-day max	3438	2915	-523	-15	0.60	0.63	0.03	5
1-day min	352	565	213	60	0.67	0.66	-0.02	-2
3-day min	556	688	133	24	0.43	0.50	0.07	16
7-day min	712	795	83	12	0.33	0.37	0.05	14
30-day min	821	944	123	15	1.00	0.36	-0.64	-64
90-day min	941	1147	206	22	0.27	0.42	0.16	59
Group 3: Timing of annual extremes (based on annual hydrological cycle beginning October 1)								
Date of annual max	145	118	-27	-19	0.16	0.78	0.62	384
Date of annual min	358	265	-93	-26	0.16	0.57	0.41	256
Group 4: Frequency and duration of high pulses (2044 m^3/s) and low pulses (908 m^3/s)								
High pulse count	13.4	5.1	-8	-62	0.64	1.23	0.59	92
High pulse avg. duration	6.7	15.9	9	136	0.81	1.32	0.51	62
Low pulse count	24.7	4.3	-20	-83	0.68	0.96	0.27	40
Low pulse avg. duration	2.1	27.4	25	1205	0.95	1.89	0.94	99
Group 5: Rate and frequency of flow changes								
No. of rises	181	157	-24	-14	0.08	0.18	0.10	118
No. of falls	171	174	3	1	0.12	0.18	0.06	53
Means of + diffs btw daily	373	118	-256	-68	0.65	0.59	-0.06	-9
Means of – diffs btw daily	376	104	-272	-72	0.56	0.58	0.02	3

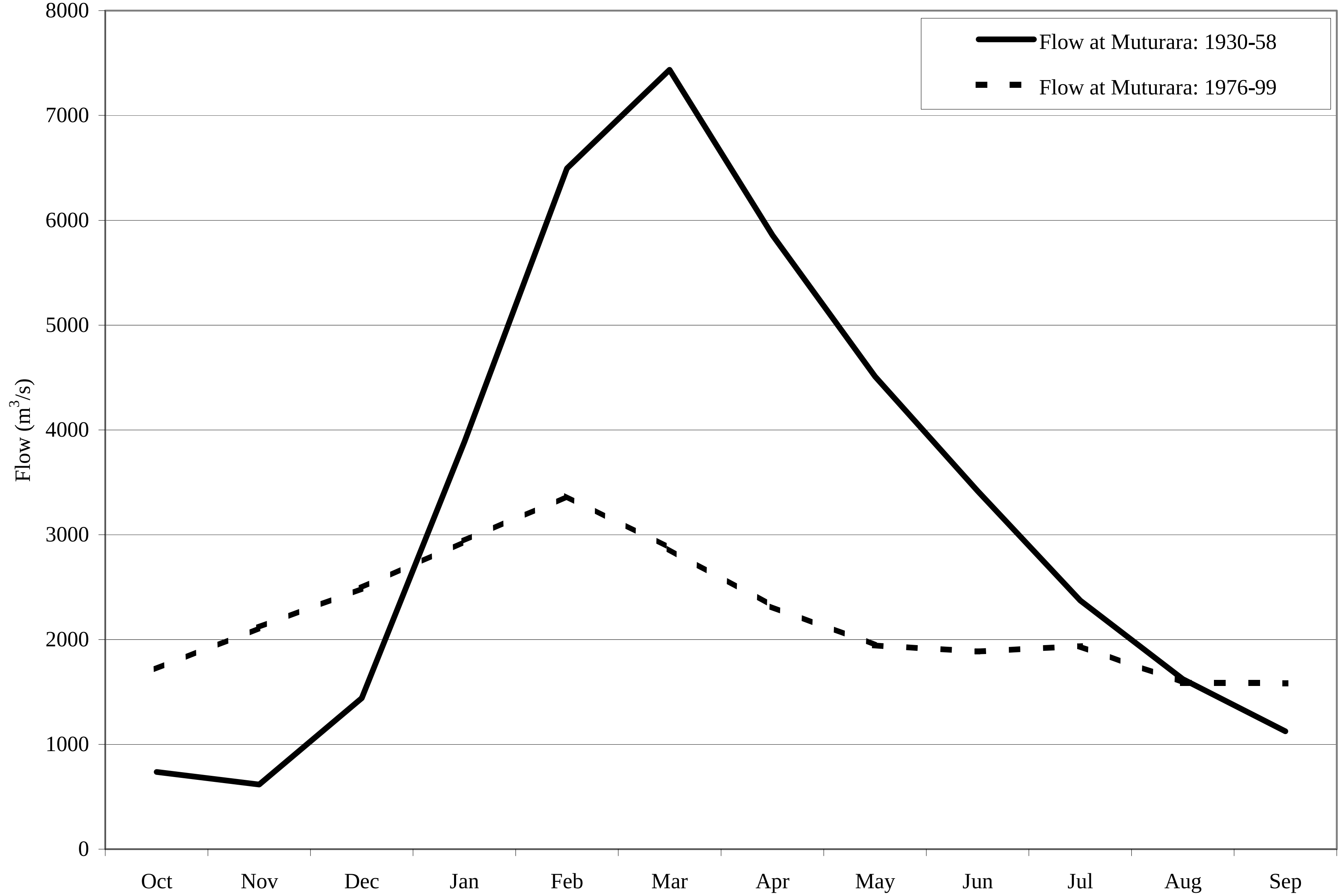

Figure 1. A comparison of mean monthly flow values for Zambezi River at Muturara, before construction of Kariba Reservoir (1930-58) and after construction of Cahora Bassa Reservoir (1976-99).

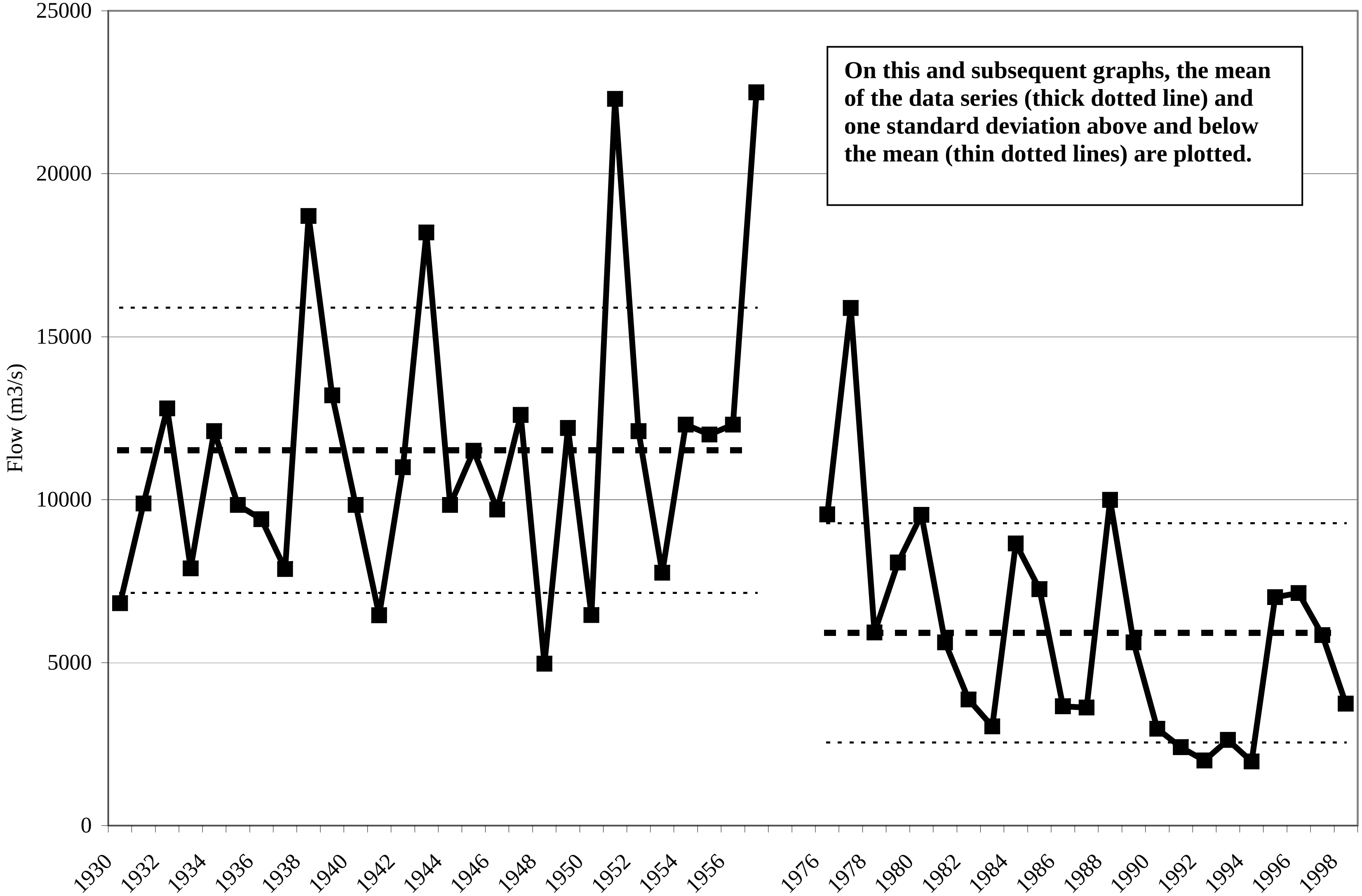

Figure 2. A comparison of maximum 1-day discharge values for the Zambezi River at Mutarara, before construction of Kariba Reservoir (1930-58) and after construction of Cahora Bassa Reservoir (1976-99).

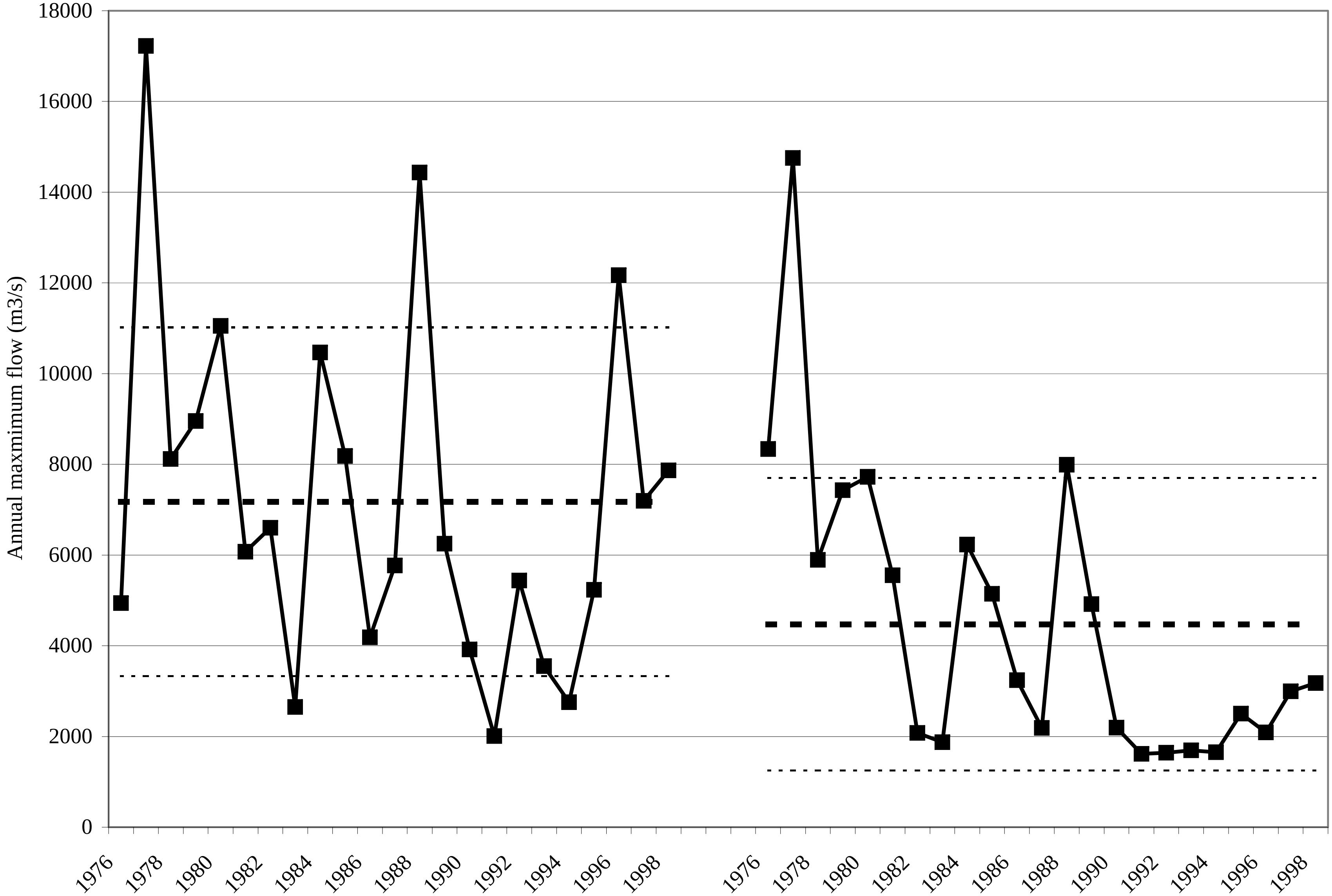

Figure 3. A comparison of annual series of maximum 1-day values for inflows and outflows at Cahora Bassa Reservoir.

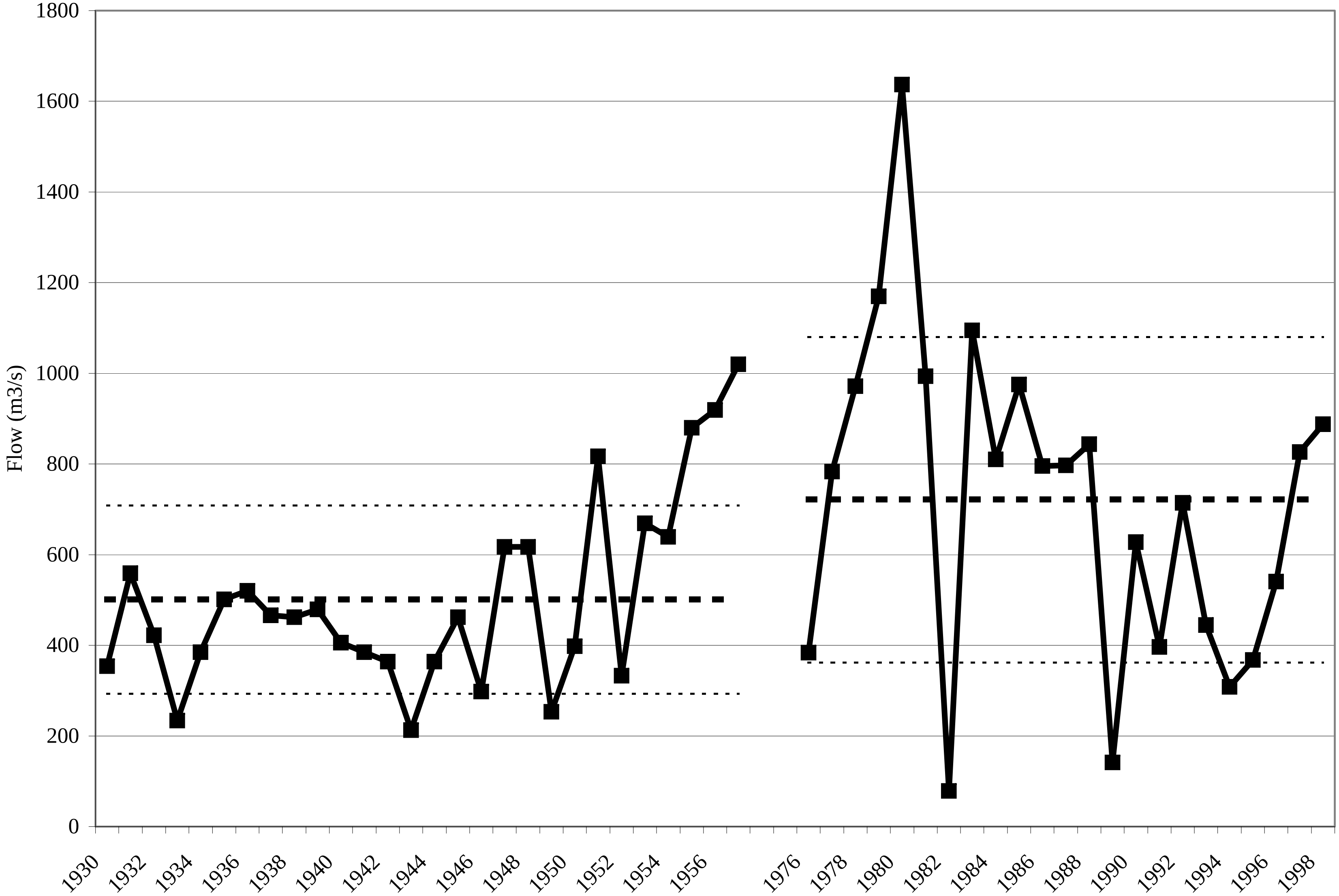

Figure 4. A comparison of minimum 1-day discharge values for the Zambezi River at Muturara, before construction of Kariba Reservoir (1930-58) and after construction of Cahora Bassa Reservoir (1976-99).

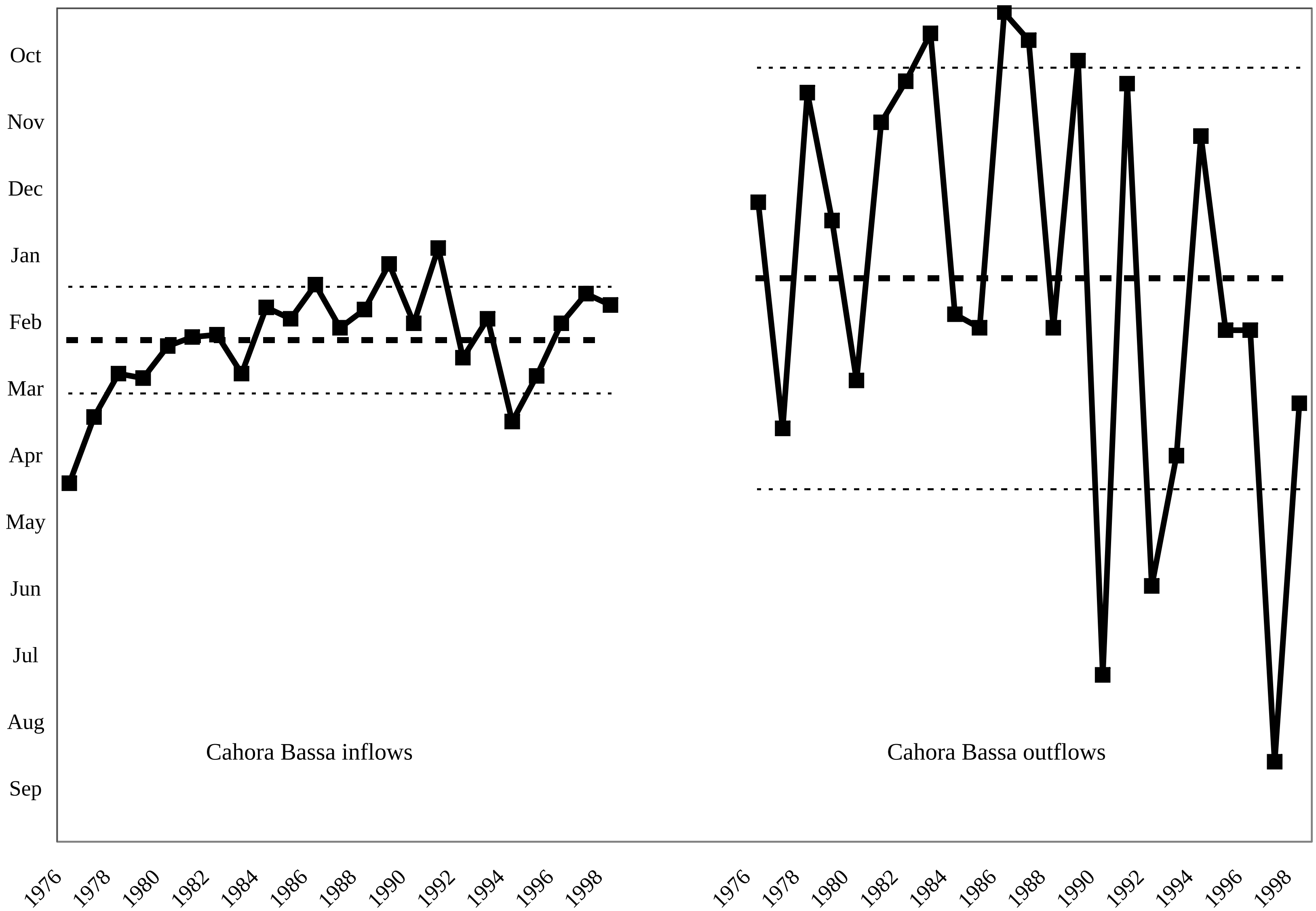

Figure 5. A comparison of the annual series of values for the timing of annual maximum 1-day inflows and outflows at Cahora Bassa Reservoir.

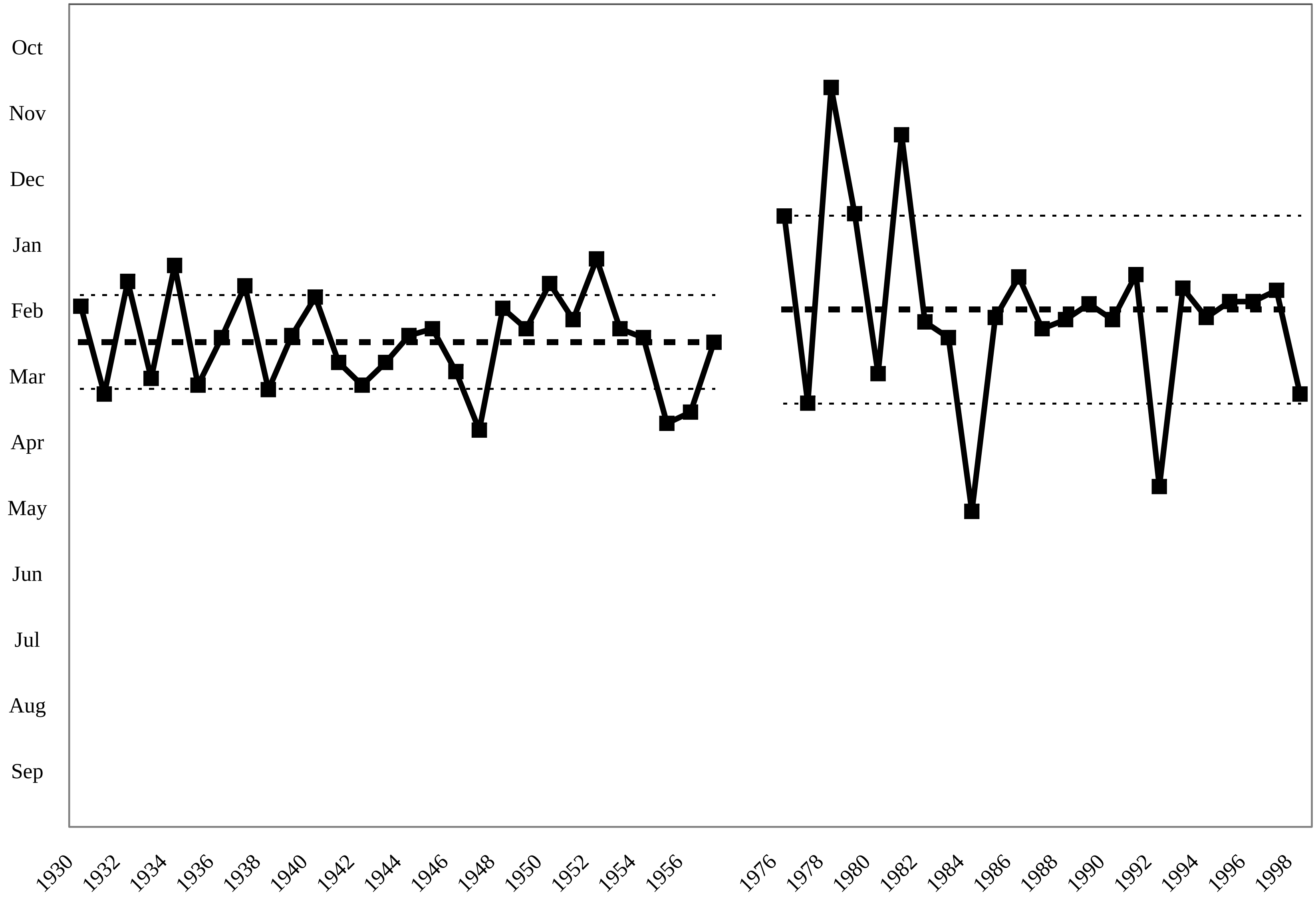

Figure 6. A comparison of the annual series of values for the timing of annual maximum 1-day Zambezi River flow at Muturara, before construction of Kariba Reservoir (1930-58) and after construction of Cahora Bassa Reservoir (1976-99).

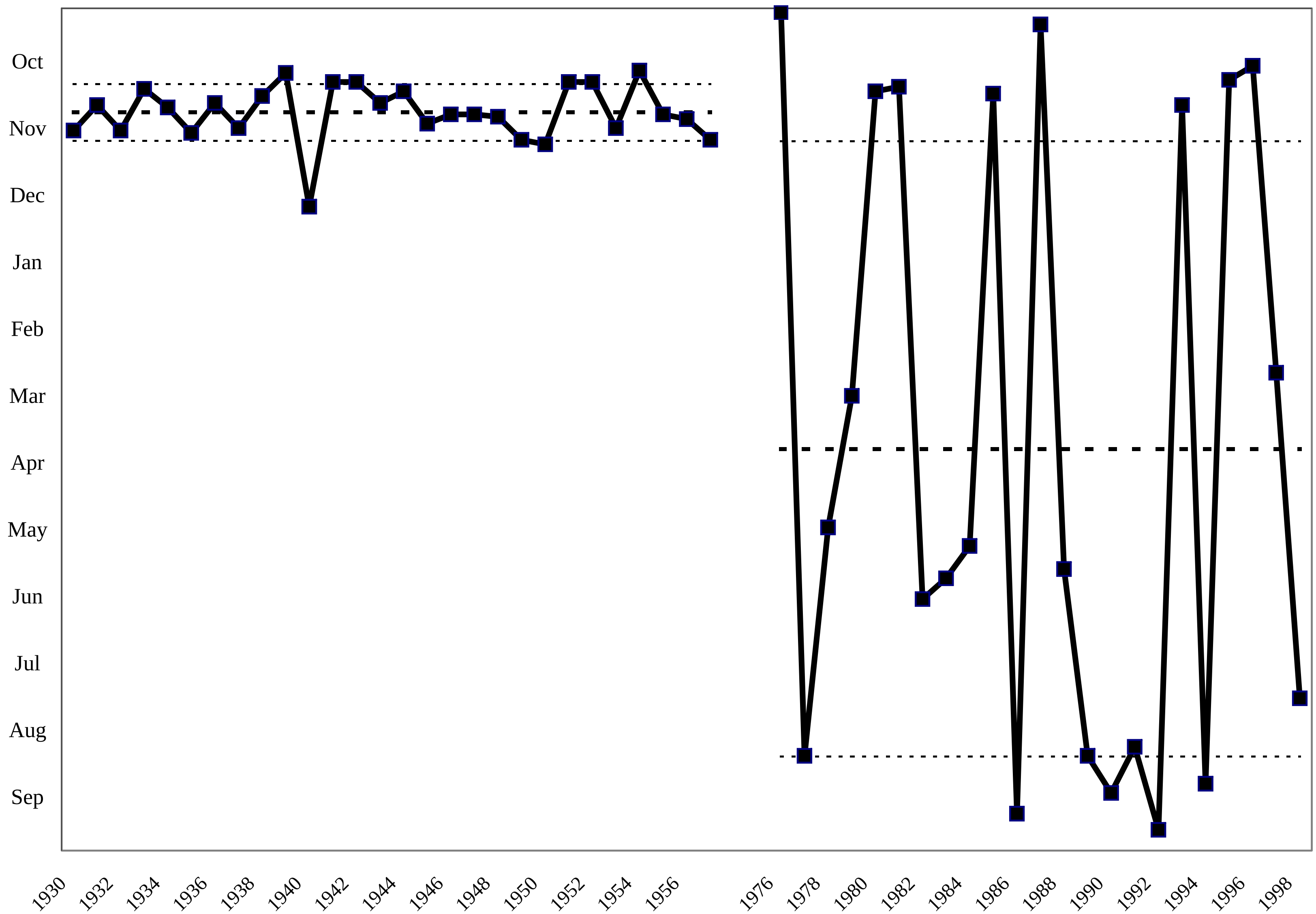

Figure 7. A comparison of the annual series of values for the timing of annual minimum 1-day Zambezi River flows at Muturara, before construction of Kariba Reservoir (1930-58) and after construction of Cahora Bassa Reservoir (1976-99).

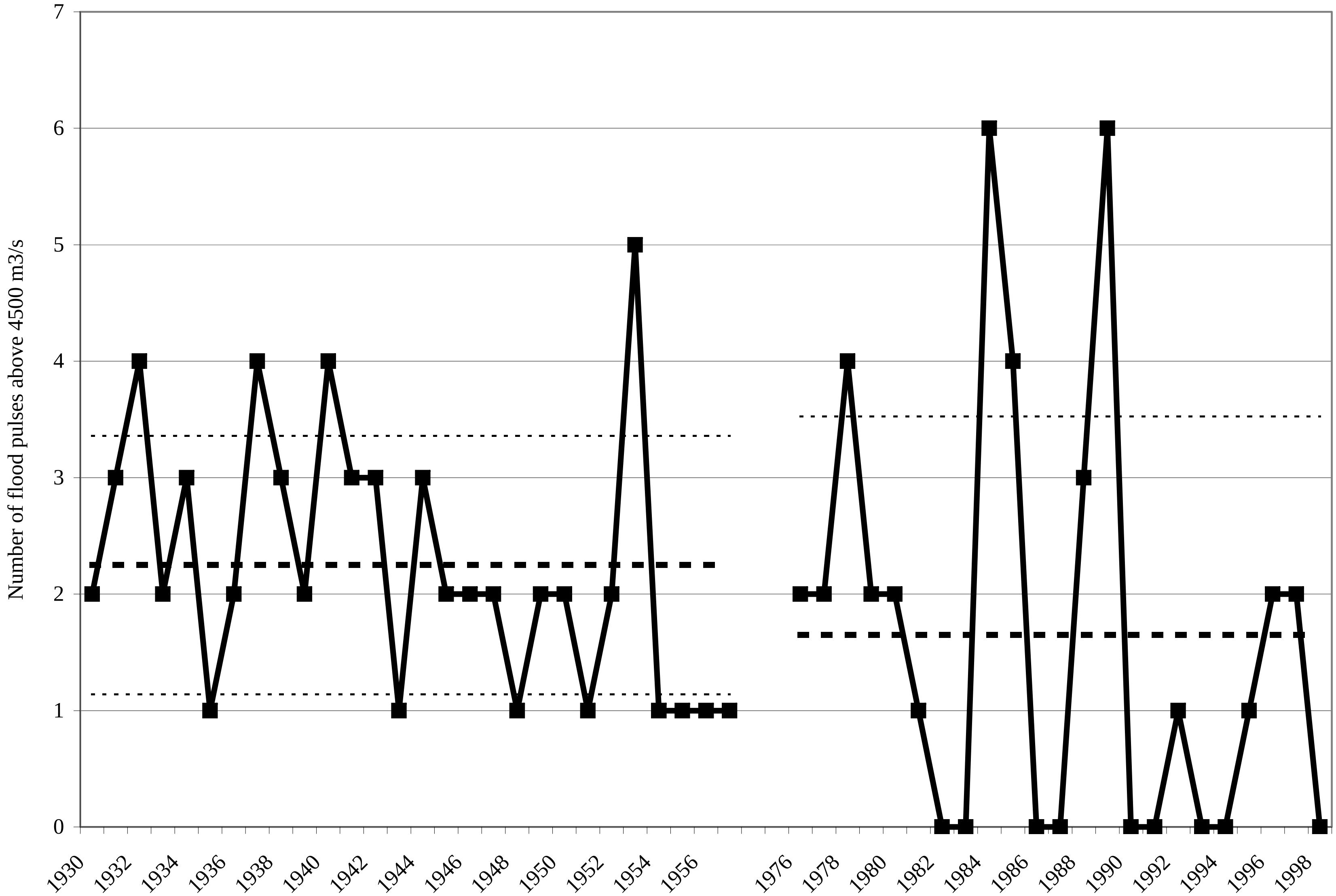

Figure 8. A comparison of annual series of annual number of flood pulses above 4500 m3/s for the Zambezi River at Muturara, before construction of Kariba Reservoir (1930-58) and after construction of Cahora Bassa Reservoir (1976-99).

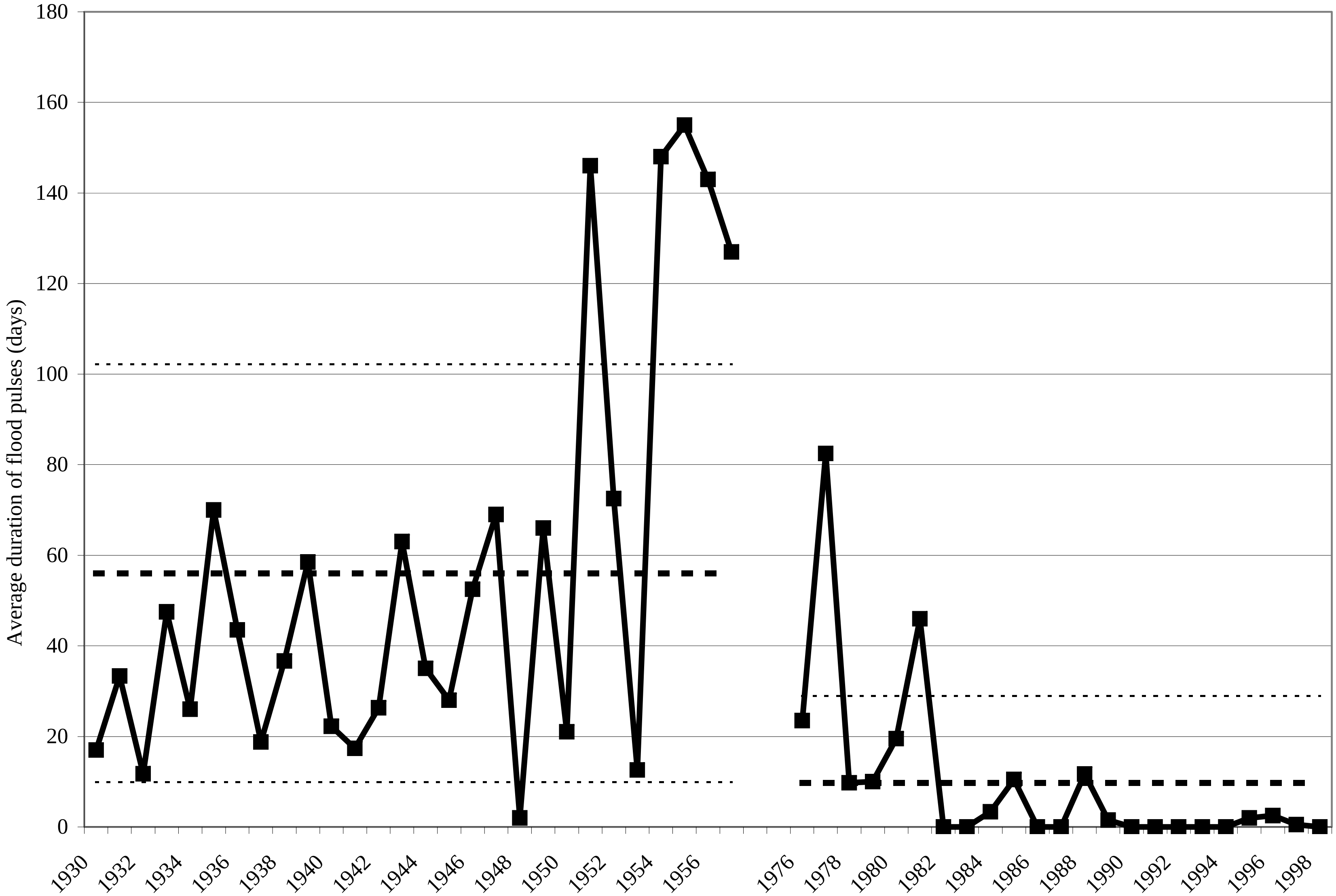

Figure 9. A comparison of annual series of annual average duration of high flood pulses above 4500 m3/s for the Zambezi River at Muturara, before construction of Kariba Reservoir (1930-58) and after construction of Cahora Bassa Reservoir (1976-99).

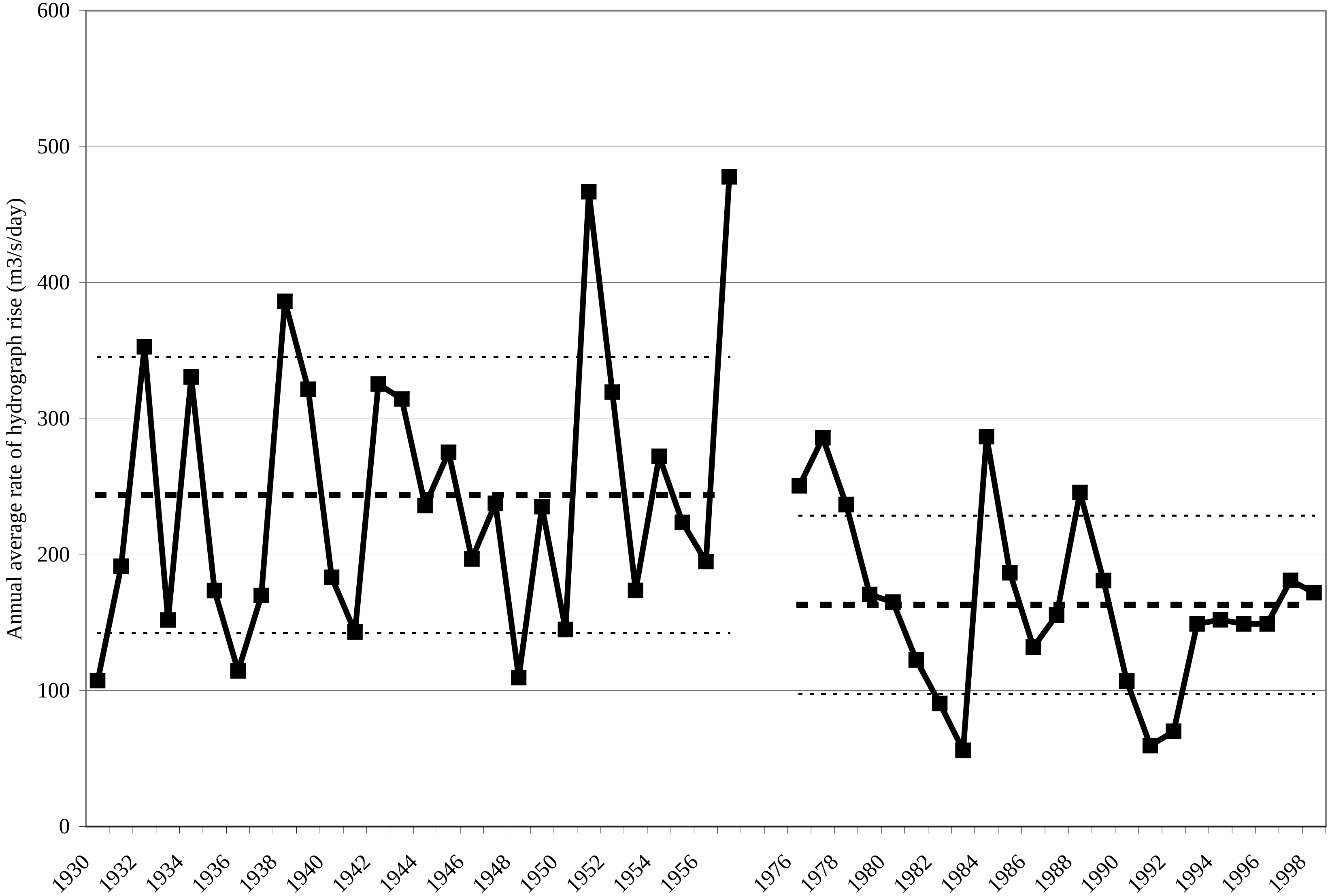

Figure 10. A comparison of the annual average rates of hydrograph rise for the Zambezi River at Muturara, before construction of Kariba Reservoir (1930-58) and after construction of Cahora Bassa Reservoir (1976-99).

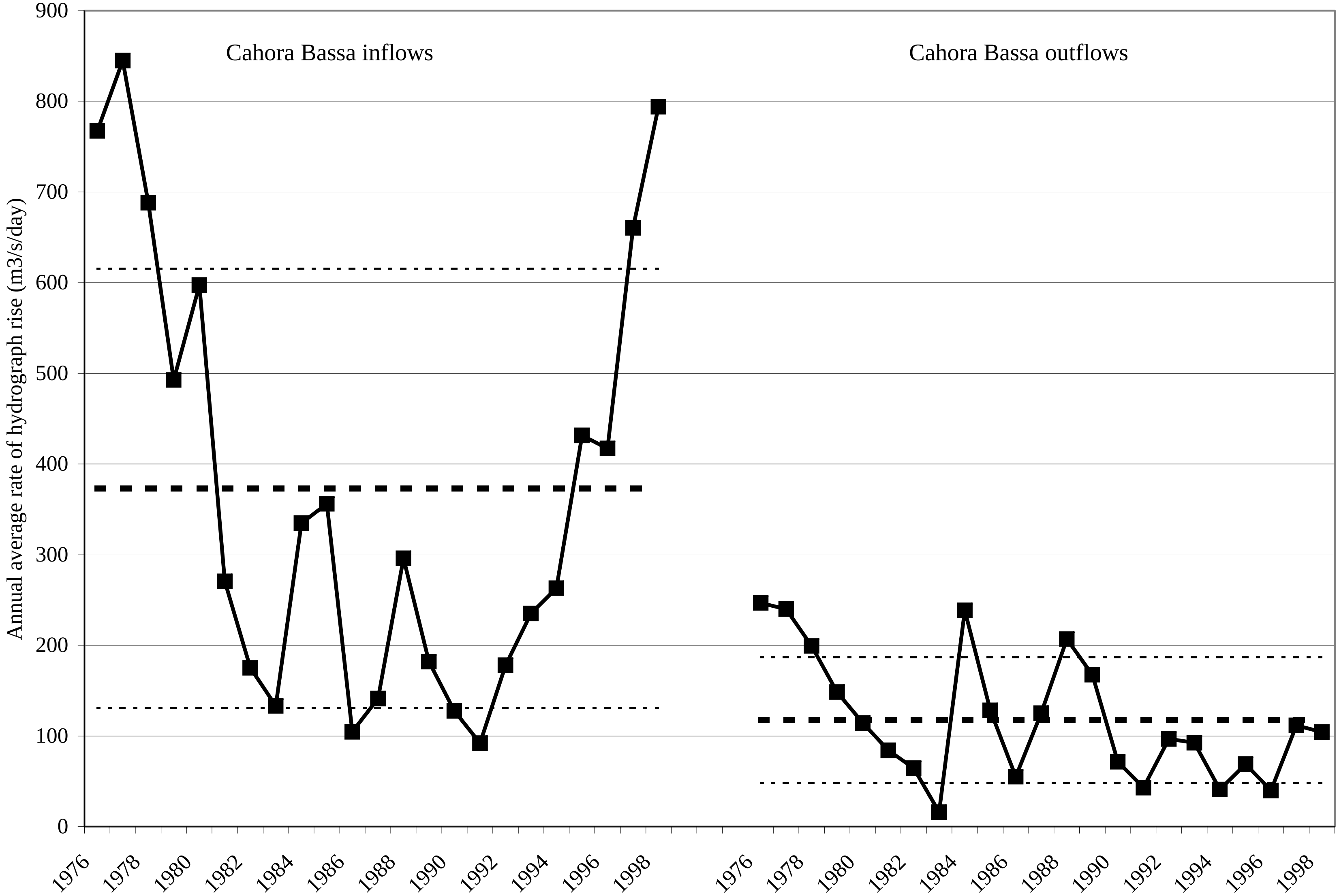

Figure 11. A comparison of the annual series of values for annual average rates of hydrograph rise for inflows and outflows at Cahora Bassa Reservoir.