PATTERNS OF HYDROLOGICAL CHANGE IN THE ZAMBEZI DELTA, MOZAMBIQUE

WORKING PAPER #2
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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PATTERNS OF HYDROLOGICAL CHANGE IN THE ZAMBEZI DELTA, MOZAMBIQUE

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*), Eastern White Pelican (*Pelecanus onocrotalus*), Wattled Crane (*Bugeranus carunculatus*), Black Stork (*Ciconia nigra*), 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.

In Working Paper #1, I reviewed the history of water resources development in the Zambezi system. In this working paper, I examine the hypothesis that these water resources development projects have resulted in substantial and fundamental hydrological changes in the Zambezi Delta. I test this hypothesis through four fundamental questions:

- *What are the historical patterns of runoff in the Zambezi system, and how have these patterns changed with water resources development?*
- *What are the historical flooding patterns in the delta, and how have these patterns changed with water resources development?*
- *What are the components of the delta water balance, and how has the relative magnitude of these components changed with water resources development?*
- *Are there key indicators of hydrological change in the Zambezi system, in terms of the social and ecological integrity of the delta?*

Subsequent working papers will focus on the specific relationship between hydrological degradation and vegetation change in the delta, and the opportunities and constraints for restoring the system through improved water management.

PATTERNS OF RUNOFF IN THE ZAMBEZI SYSTEM

Overview

Efforts to ameliorate adverse hydrological changes in the delta must begin with an understanding of long-term changes in the natural patterns of runoff. Rainfall throughout the Zambezi catchment is concentrated over a 4-6 month rainy season in response to the movements of the Inter-Tropical Convergence Zone[1]. This annual cycle of rainfall gives rise to unique patterns of runoff in each of the Zambezi sub-basins. Rivers draining the steep gorges of the Central African Plateau peak rapidly with the rains, reaching their maximum discharge between January and March and decreasing to minimal dry season flows by October-November. In the Zambezi headwaters, Kafue River, and Shire River basins, large floodplain systems capture floodwaters and may delay peak discharges until late in the rainy season or early dry season.

The construction of Kariba, Cahora Bassa, and other large dams in the Zambezi system has profoundly altered Zambezi runoff patterns. Kariba Reservoir regulates runoff from Zambezi headwaters region of the *Upper Zambezi catchment*[2] and the western portion of the *Middle Zambezi catchment*[2] between Victoria Falls and Kariba Gorge (the Gwembe Valley catchment), altering the timing, magnitude, duration, and frequency of flooding events. Cahora Bassa Reservoir regulates runoff from the remaining Middle Zambezi catchment between the Kariba and Cahora Bassa Gorges, including regulated flows from the Kafue River and unregulated flows from the Luangwa River, as well as regulated outflows from Kariba. Below Cahora Bassa, runoff from the Shire River catchment is partially regulated by engineering structures. Only runoff from tributaries of the Moravia-Angonia and Manica Plateaus in the *Lower Zambezi catchment*[2] is unaffected by river regulation.

In this section, I examine the historical runoff patterns in each of the Zambezi sub-basins, and how these patterns have changed over time with the regulation of the Zambezi River. Related changes in the seasonal flooding patterns and long-term water balance of the delta are explored in subsequent sections.

Methods

To analyze natural and dam-induced patterns of runoff in the Zambezi system, I compiled and analyzed time series data for rainfall, evaporation, and runoff from key locations in the Zambezi catchment. Locations were selected to characterize the mean and variation in hydrological conditions in each sub-basin in the catchment and to demonstrate the influence of major features, especially large floodplain wetlands and reservoirs, that have the capacity to modify the Zambezi flow regime.

I obtained time series data for rainfall from forty-nine gauging stations in the Zambezi catchment (Table 2-1). Data include mean, maximum, and minimum monthly rainfall, 24-hour maximum rainfall, and mean and maximum number of rainy days, as well as temperature and humidity, for each station. The reliability of rainfall data is discussed in Appendix 1. I estimated the mean and standard deviation of monthly and annual rainfall for each data series, and plotted histograms of mean monthly and annual rainfall to characterized patterns of variability for different sub-basins. I also plotted dimensionless differential mass curves[3] to compare differences in cumulative rainfall among the different Zambezi sub-basins using selected groups of stations.

I obtained monthly time series data for evaporation from fourteen gauging stations in the Zambezi catchment (Table 2-2). Evaporation data are measured from Class A evaporation pans, using a standard coefficient of 0.9. I estimated the mean and standard deviation of monthly and annual evaporation for each data series, and plotted histograms to characterize patterns of variability for different sub-basins. I calculated net evaporation for each sub-basin as the difference between mean monthly rainfall and evaporation from selected groups of stations. Estimated evapotranspiration from the Kafue Flats is based on the Shawinigan-Lavalin and Hidrotécnica Portuguesa (1990a) studies. The reliability of evaporation and evapotranspiration data is discussed in Appendix 1.

I obtained runoff time series data from twenty-two stream gauging stations in the Zambezi catchment (Table 2-3). For the Kariba and Middle Zambezi catchments, 91-year monthly runoff sequences at Victoria Falls, Kariba Gorge, and Itezhitezhi Gorge were compiled from previous studies (Shawinigan-Lavalin and Hidrotécnica Portuguesa 1990a&b, Batoka Joint Venture Consultants 1993b, and Li-EDF-KP Joint Venture Consultants 2000a). I generated a new 91-year time series for Cahora Bassa Gorge by modifying the Li-EDF-KP Joint Venture Consultants (2000a) data series to reflect recent revisions to the

Table 2-1. Location, altitude, period of record, and mean annual rainfall of selected rainfall gauging stations used for the analysis of runoff patterns in the Zambezi catchment. Records marked with an asterisk have significant periods of missing data. Data sources include Institute of Meteorology in Mozambique, Departments of Meteorology in Zambia and Zimbabwe, and archival reports from Halcrow and Partners (1954), FAO (1968), Hidrotécnica Portuguesa (1965b), Zambezi River Authority (1961-89), RPT (1979), Shawinigan-Lavalin and Hidrotécnica Portuguesa (1990b), Batoka Joint Venture Consultants (1993a), and Li-EDF-KP Joint Venture Consultants (2000b).

Station	Country	Lat (S)	Long (E)	Alt (m)	Period of record	Mean annual rainfall (mm)
Liwonde	Malawi	14 00	33 39	180	1904-55	836
Nsanje	Malawi	16 20	35 05	175	1931-51	862
Beira	Mozambique	19 51	34 51	7	1951-00	1493
Bene	Mozambique	15 04	32 56	175	1955-84	808
Capoche	Mozambique	15 19	32 49	145	1958-68	668
Chinde	Mozambique	17 35	36 30	3	1949-80	1154
Chingoze	Mozambique	16 07	33 39	140	1958-00	637
Fingoe	Mozambique	15 25	32 23	205	1933-85	1031
Inhaminga	Mozambique	18 30	35 00	370	1945-76	1052
Luenha	Mozambique	16 31	33 26	150	1959-00	551
Marromeu	Mozambique	18 18	36 03	10	1945-76	966
Mazoe	Mozambique	15 50	32 20	210	1969-79	604
Metengo	Mozambique	16 05	33 41	135	1958-82	775
Milange	Mozambique	16 06	35 47	305	1926-51	1702
Mopeia	Mozambique	18 00	35 40	14	1945-80	1114
Morrumbala	Mozambique	17 32	35 26	505	1947-76	1106
Muturara	Mozambique	17 26	35 04	40	1945-76	711
Tambara	Mozambique	16 33	34 15	60	1949-83	624
Quelimane	Mozambique	17 55	36 50	3	1945-00	1398
Songo	Mozambique	15 35	32 42	240	1973-00*	734
Tete	Mozambique	16 09	33 35	120	1910-00*	660
Zumbo	Mozambique	15 37	30 25	320	1933-84	692
Chipata	Zambia	13 38	32 39	1150	1910-99	1012
Choma	Zambia	16 50	26 58	900	1917-99	813
Itezhitezhi	Zambia	15 47	26 02	965	1971-99	818
Kabompo	Zambia	13 36	24 12	1120	1950-99	1120
Kaoma	Zambia	14 48	24 48	1138	1920-99	943
Kasama	Zambia	10 13	31 08	1400	1925-99	1291
Kasempa	Zambia	13 28	25 50	1228	1910-95	1129
Lusaka	Zambia	15 25	28 19	760	1938-99	843
Mongo	Zambia	15 17	23 08	1054	1950-00	959
Mumbwa	Zambia	14 49	27 04	1218	1979-97	811
Mwinilunga	Zambia	11 45	24 26	1355	1920-99	1396
Namwala	Zambia	15 44	26 27	1100	1919-89	798
Nkana	Zambia	12 50	28 12	1250	1929-89	1301
Ndola	Zambia	13 00	28 39	1269	1913-99	1181
Sesheke	Zambia	17 28	24 18	1021	1910-99	690
Livingstone	Zambia	17 52	25 51	907	1910-99	779
Zambezi	Zambia	13 34	23 06	1085	1920-99	1074

Table 2-1 (continued).

Station	Country	Lat (S)	Long (E)	Alt (m)	Period of record	Mean annual rainfall (mm)
Bulawayo	Zimbabwe	20 09	28 37	1343	1910-99	593
Chinoyi	Zimbabwe	17 22	30 12	1250	1910-99	828
Gokwe	Zimbabwe	18 13	28 56	1282	1912-99	799
Guruve	Zimbabwe	16 39	30 42	1320	1912-99	779
Gweru	Zimbabwe	19 27	29 51	1105	1910-99	673
Harare	Zimbabwe	17 48	31 03	1520	1910-99	824
Hwange	Zimbabwe	18 38	27 00	1079	1910-99	581
Kadoma	Zimbabwe	18 19	29 53	1230	1910-99	762
Kariba	Zimbabwe	16 31	28 53	518	1961-99	766
Karoi	Zimbabwe	16 50	29 37	1343	1925-99	835

Table 2-2. Location, altitude, period of record, and mean annual evaporation of selected evaporation gauging stations used for the analysis of runoff patterns in the Zambezi catchment. Data sources include Institute of Meteorology in Mozambique, Departments of Meteorology in Zambia and Zimbabwe, and archival reports from Halcrow and Partners (1954), FAO (1968), Central Africa Power Corporation/ Zambezi River Authority annual reports and accounts (1961-89), and Batoka Joint Venture Consultants (1993a).

Station	Country	Lat (S)	Long (E)	Alt (m)	Period of record	Mean annual evaporation (mm)
Lilongwe	Malawi	13 59	33 45	180	1951-56	1980
Chikwawa	Malawi	16 02	34 52	350	1951-56	1718
Beira	Mozambique	19 51	34 51	7	1951-00	1920
Tete	Mozambique	16 09	33 35	120	1930-99	2483
Livingstone	Zambia	17 52	25 51	907	1961-68	2291
Lusaka	Zambia	15 25	28 19	760	1959-68	2243
Mongu	Zambia	15 17	23 08	1054	1963-68	1961
Ndola	Zambia	13 00	28 39	1269	1961-68	2080
Sesheke	Zambia	17 28	24 18	1021	1963-68	1862
Binga	Zimbabwe	17 37	27 17	620	1959-90	2270
Bulawayo	Zimbabwe	20 19	28 37	1343	1959-90	1993
Gokwe	Zimbabwe	18 13	28 56	1282	1958-86	2160
Harare	Zimbabwe	17 48	31 03	1520	1971-89	1668
Kariba	Zimbabwe	16 32	28 37	518	1958-99	2394

inflow data collected at Cahora Bassa Reservoir. For the Lower Zambezi catchment, I generated 40-year daily runoff time series for the Luia and Luenha catchments. The derivation of these data series and their reliability are described in Appendix 1.

For each data series, I estimated the mean and standard deviation of monthly and annual flows. I plotted hydrographs of mean monthly flows to compare the magnitude, duration, and timing of flood flows among different Zambezi sub-basins and quantify the changes in flow patterns within different sub-basins resulting from flood attenuation by large wetland systems. I plotted annual time series data for each station as a percentage of mean annual flow to contrast the inter-annual variability of runoff within and among different sub-basins. I also calculated dimensionless runoff coefficients for each sub-basin as the ratio of mean annual flow volume to rainfall volume over the catchment (with catchment area estimated from digitized maps of the Zambezi catchment using Arc View 3.1 software). I plotted flood frequency curves for maximum daily discharges in the lower Zambezi tributaries using the Extreme Value

Table 2-3. Name, location, catchment area, and period of record of selected discharge gauging stations used for the analysis of runoff patterns in the Zambezi catchment. Records marked with an asterisk have significant periods of missing data. Data sources include Direcção Naçional de Aguas (DNA) in Mozambique, Zambezi Electrical Supply Corporation Limited (ZESCO) in Zambia, Ministry of Water Affairs in Malawi, Zambezi River Authority (ZRA) in Zambia and Zimbabwe, and archival reports from Hidrotécnica Portuguesa (1965c,d,e,f,&g), Shawinigan-Lavalin and Hidrotécnica Portuguesa (1990b), Batoka Joint Venture Consultants (1993a), and Li-EDF-KP Joint Venture Consultants (2000b).

Catchment covered by gauge	Station ID	Catchment area (km2)	Period of record
Zambezi catchment at Lukulu	---	209,257	1949-00
Zambezi catchment at Senanga	190900	278,298	1949-00
Zambezi catchment at Katima Mulilo	KM-01	456,000	1945-86
Zambezi catchment at Victoria Falls	---	507,200	1907-98 (derived)
Zambezi catchment at Kariba Gorge	---	663,800	1907-98 (derived)
Kafue catchment at Itezhitezhi Gorge	---	105,600	1907-98 (derived)
Kafue catchment at Kafue Gorge	KG-08	151,000	1907-69
Luangwa catchment at Great East Rd.	54005	143,000	1955-98
Zambezi catchment at Cahora Bassa Gorge	---	900,000	1907-98 (derived)
Upper Luia catchment at Luia 2	E322	11,031	1960-68
Capoche catchment at Capoche 2	E360	14,686	1959-68
Cherize catchment at Cherize Drift	EH20	1,917	1960-63
Luia catchment at Zambezi confluence	---	28,000	1976-00 (derived)
Zambezi catchment at Boroma	E304	938,000	1948-55
Zambezi catchment at Tete	E320	940,000	1946-00
Zambezi catchment at Tete-Matundo	E387	940,000	1958-92*
Mavudezi catchment at Mavudezi	EH21	3,154	1961-63
Revuboe catchment at Chingoze	E302	15,540	1954-00
Upper Luenha catchment at Luenha 2	E296	17,183	1959-00*
Mazoe catchment at Mazoe 1	E383	34,216	1951-63
Luenha River at Luenha 1	E348	54,144	1959-75
Luenha catchment at Zambezi confluence	---	54,544	1976-00 (derived)
Zambezi catchment at Lupata gorge	E327	1,017,000	1958-84*
Zambezi catchment at Muturara	E294	1,035,900	1930-00*
Shire catchment at Liwonde	1.B.1	130,250	1948-83
Shire catchment at Matope	1.P.2	133,750	1952-81
Shire catchment at Chiromo	1.G.1	144,790	1952-81
Ruo catchment at Sinoya	14.D.1	4,640	1952-81
Shire catchment at Zambezi confluence	---	154,000	1952-81 (derived)
Zambezi catchment at Marromeu	E285	1,223,000	1960-62

Type I and Type III distributions to determine the best goodness-of-fit for the data series. The combined flood frequency curves for the Moravia-Angonia and Manica Plateaus and Shire tributaries were calculated by taking the maximum of the summed daily discharge data for all stations, assuming a time lag of less than one day among stations. Flood recurrence intervals were determined from these graphs.

I obtained inflow, outflow, and water level time series data for the four major reservoirs in the Zambezi system (Table 2-4). At each reservoir location, I quantified the magnitude, duration, and timing of runoff prior to dam construction. For the period of reservoir operation, I quantified inflows and outflows and plotted hydrographs of the mean monthly data for each flow series. I plotted monthly time series data to assess the changes in flow patterns during filling and other periods of operation. Reservoir water levels were plotted to show the affects of reservoir storage on patterns of discharge and downstream runoff. For the Shire basin, I regressed Lake Malawi outflows (partially regulated) against discharge in the lower Shire River.

Table 2-4. Name, period of record, and measurement methods of selected reservoir gauging stations used for the analysis of runoff patterns in the Zambezi catchment. Data sources include Hidroeléctrica de Cabora Bassa (HCB), DNA, ZESCO, and ZRA.

Reservoir	Period of record	Inflows	Outflows
Kariba	1961-2000	Water balance using outflows and evaporation	Turbine, spillway from reservoir water levels
Itezhitezhi	1978-2000	Rating curve using upstream water levels	Spillway from reservoir water levels
Kafue Gorge	1970-2000	Rating curve using upstream water levels	Turbine, spillway from reservoir water levels
Cahora Bassa	1976-2000	Water balance using outflows and evaporation	Turbine, spillway from reservoir water levels

I obtained water level data from four gauging stations in the delta region (Table 2-5). From these data, I plotted hydrographs of daily and monthly water level fluctuations in the delta corresponding to periods of upstream development. I also calculated the average duration (in days) of Zambezi Delta flood stages above a given threshold, and ranked the maximum annual flood stages at Muturara and Marromeu. I plotted the historical stage-discharge curve for Marromeu from stage-discharge measurements collected during 1962-64, published in Hidrotécnica Portuguesa (1965c).

Table 2-5. Station ID, elevation, and period of record of selected water level gauging stations used for the analysis of runoff patterns in the Zambezi catchment. Records marked with an asterisk have significant periods of missing data. Data sources include DNA and an archival report from Hidrotécnica Portuguesa (1965c).

Gauging station location	Station ID	Elevation (m amsl)	Period of record
Muturara	E294	50	1930-00*
Caia	E291	20	1954-73*; 1998-00
Marromeu	E285	10	1926-00*
Luabo	E284	7	1970-00*

Analysis of runoff patterns in the Zambezi catchment

The Upper Zambezi catchment

Zambezi headwaters region

The Zambezi headwaters region includes two major physiographic features, the Northern Highlands and the Central Plains, of the North Kalahari Basin (Figure 2-2). Deep aeolian Kalahari sands, underlain by Karoo sedimentary deposits and basalt formations cover the region (Balon and Coche 1974). The Northern Highlands catchment (220,570 km^2) consists of a belt of high ground at 1000-2000 m above mean sea level (amsl) on the south side of the Equatorial Divide that gives rise to the Zambezi and its headwater tributaries. The region is dominated by high-step deciduous *Brachystegia-Julbernardia* miombo woodland. From its origin near the Kalene hills in the far northwest corner of Zambia (elevation 1370 m) the Zambezi winds through east central Angola, capturing runoff from the Chifumage and Luena Rivers and other tributaries of the Angolan highlands. When the Zambezi reenters far-western Zambia some 338 km downstream at Chavuma Falls, it has a total drainage area of 75,970 km^2 (Sharma and Nyumbu 1985). Further downstream near the town of Lukulu, the Zambezi captures runoff from its two largest headwater tributaries, the Kabompo River of northwestern Zambia (with a catchment area of 72,200 km^2) and Lungwebungu River of central Angola (47,400 km^2). These headwater river systems are all confined to fairly distinct channels in this region with relatively steep slopes and rapids where the channels have eroded through the Karoo formations, and runoff coefficients are high (Balek 1971a).

Average annual rainfall over the Northern Highlands catchment is 1100-1200 mm, with considerably higher rainfall near the Zambezi source. The monthly and annual distribution of rainfall for selected long-term stations is given in Table 2-6. Rainfall is concentrated during the period from November to March, with peak rainfall occurring in December and January. Runoff drains rapidly from the open terrain and steep channels, peaking in February or early March. Mean annual runoff from the region is about 26.8 x 10^9 m^3, providing an average annual Zambezi flow of 850 m^3/s.

Table 2-6. Mean monthly and annual rainfall (mm) for selected stations in the Northern Highlands of the Zambezi headwaters region. See Table 2-1 for station locations and period of record.

Station	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Ann
Mwinilunga	91	209	264	239	213	255	96	10	1	0	2	17	1396
Zambezi	48	135	228	239	208	170	42	3	0	0	0	0	1074
Kabompo	37	193	219	243	209	166	43	5	1	0	0	3	1120
Kasempa	39	142	255	248	212	171	38	3	0	0	1	4	1106
Kaoma	34	111	217	210	192	128	42	3	0	0	0	4	943
Average	**50**	**158**	**237**	**236**	**207**	**178**	**52**	**5**	**0**	**0**	**1**	**6**	**1128**

Below Lukulu, the Northern Highlands give way to the Central Plains catchment (286,970 km^2) (Figure 2-2). The Central Plains cover a broad flat plateau at 1000-1500 m amsl characterized by mopane woodland and broad open grasslands (Balon and Coche 1974). For the next 200 km, the Zambezi River meanders through the Barotse Plain, a vast floodplain grassland more than 40 km wide bordered by sandy escarpment. During the rainy season, the floodplain is inundated by Zambezi floodwaters to form a large shallow lake that significantly attenuates Zambezi runoff. Although peak runoff from the Northern Highlands typically reaches Lukulu by February-March (following the period of peak rainfall), Zambezi floodwaters take 4-6 weeks to pass through the Barotse Plain and peak discharge near the downstream outlet (Senanga gauging station) is often delayed until April or early May (Figure 2-3). Floodwaters recede slowly from the Barotse Plain during the six-month dry season, with high evaporation losses throughout the year (Table 2-7). The Barotse Plain captures runoff from four major Zambezi tributaries, the Luanginga (catchment area 34,600 km^2), Luampa (20,500 km^2), Lueti (8,575 km^2) and Lui (11,890 km^2), all of which also feature significant floodplains. Overall, the Barotse Plain attenuates runoff from a catchment area of more than 335,000 km^2 (27% of the total Zambezi catchment), with an average annual storage capacity of 8.5 x 109 m^3. During the major Zambezi flood of 1958, total storage within the Barotse Plain was estimated to be approximately 17 x 10^9 m^3, more than half of the mean annual discharge of the Zambezi headwaters region (Sharma and Nyumbu 1985).

At the southern extent of the Barotse Plain the escarpment narrows and the Zambezi anabranches merge into a single incised channel at 900-1000 m amsl. The Zambezi cuts south through a plateau of semi-evergreen woodland, cascading over Sioma Falls and capturing additional runoff from the Lumbe (6,500 km^2), Njoko (6,700 km^2), Machili (15,515 km^2), and Ngwezi (5,210 km^2) catchments. At Sesheke, the Zambezi River turns east and again spreads over a vast anabranching floodplain system, the Chobe Swamps (3000 km^2) – historically the site of a large inland lake (Timberlake 1998). As with the Barotse Plain, the Chobe swamps are very important in capturing flood waters and attenuating flood peaks (see discussion below). The floodplain narrows near the confluence with the Chobe River at Kazungula and the Zambezi cascades over a series of outcrops of Karoo Basalt, including the Katambora Rapids, until

Table 2-7. Mean monthly and annual Class A pan evaporation, rainfall, and net evaporation (mm) at Mongu meteorological station in the Barotse Plain. Net evaporation is defined as the difference between mean monthly rainfall and evaporation. See Table 2-1 for station location and period of record.

Data	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Ann
Evaporation	269	178	168	160	142	175	175	175	160	188	231	284	2306
Rainfall	33	103	199	215	204	148	38	4	0	0	1	3	948
Net evap	**236**	**75**	**-31**	**-55**	**-62**	**27**	**137**	**171**	**160**	**188**	**230**	**281**	**1358**

plunging 98 m over Victoria Falls.

Along the southward path of the Zambezi from headwaters to Sesheke, rainfall decreases with elevation and becomes more variable. Maximum annual rainfall at Mwinilunga is 1400 mm with a coefficient of variation of 0.13. Near Sesheke, mean rainfall falls to 767 mm with a coefficient of variation of 0.31. Runoff per unit rainfall decreases with decreasing rainfall (Sharma and Nyumbu 1985) and the rate of evaporation increases correspondingly, with large evaporative losses from floodplains of the Central Plains. The drainage density also decreases, from about 1 km/km in the Northern Highlands to about 0.03 km/km in the Central Plains. Runoff coefficients (based on annual rainfall and runoff) range from 0.20-0.25 near the Zambezi source to 0.08-0.13 in the mid-reaches above Victoria Falls. Thus, although larger in size that the Northern Highlands region, the Central Plains generate considerably less annual runoff, about 6.1 x 10^9 m^3. Between Chavuma Falls and Victoria Falls the total catchment of the Zambezi increases 7-fold, but total annual runoff only doubles (Sharma and Nyumbu 1985).

Mean annual rainfall for the entire Upper Zambezi catchment is about 1000 mm. The mean annual discharge is 32.9 x 10^9 m^3 (1044 m^3/s), with a coefficient of variation of 0.40. The long-term (92-year) annual discharge series is given as a percentage of mean annual discharge in Figure 2-4. Runoff varies considerably from year to year, from a remarkable 72.8 x 10^9 m^3 in 1957/58 to as low as 12.3 x 10^9 m^3 in 1995/96. Approximately 50% of annual rainfall over the catchment, on average, contributes to Zambezi baseflow (Sharma and Nyumbu 1985).

The hydrograph of mean monthly runoff from the Upper Zambezi catchment is shown in Figure 2-5. Discharge typically begins rising during the early rainy season, increasing sharply from February to April. The mean date for the arrival of peak flows at Victoria Falls is April 19th, with a standard deviation of 19 days. Zambezi discharge generally peaks earlier during years with large flooding events that exceed the storage capacity of the Barotse Plain and pass downstream with relatively minimal attenuation. Minimum flows at Victoria Falls generally occur during the first week of November. The mean monthly discharge in April is about 2700 m^3/s. The annual series of monthly inflows is shown in Figure 2-6. The highest recorded peak monthly discharge (8720 m^3/s for March 1959) is an order of magnitude greater than the lowest recorded peak monthly discharge (871 m^3/s for May 1995). The maximum daily discharge recorded is 9331 m^3/s during March 1958, and the probable maximum flood from the Zambezi headwaters region is upwards of 19,000-22,200 m^3/s (Batoka Joint Venture Consultants 1993a).

The annual flow series reveals long-term cycles of high, medium, and low runoff. From 1907-46 and again from 1982-1999, runoff from the Upper Zambezi catchment was appreciably lower than the long-term average. Runoff during the period 1947-1981 was significantly higher than average[4] (Mukosa *et al.* 1995). Mean annual discharge over this latter period was 44.0 x 10^9 m^3, including the sixteen wettest years on record. Annual runoff since 1983 has averaged only 23.2 x 10^9 m^3, with 15 of the past 17 years below the long-term average.

Comparison of dimensionless differential mass curves for Upper Zambezi catchment runoff (Figure 2-7) and rainfall patterns (Figure 2-8) suggests that long-term runoff cycles can be primarily explained by cycles of rainfall. Rainfall was high from 1915-25, followed by a period of low rainfall during the 1930s and 1940s. Over three decades from 1950-80, rainfall was generally well above the long-term average. Since 1980 there has been a very sharp reduction over the whole basin. Changes in unit runoff with increasing rainfall also contribute to the trend. A sequence of particularly low rainfall years in the catchment, such as occurred during the early 1900s and again during the period 1980-98, can significantly reduce the proportion of annual rainfall that occurs as runoff (Sharma and Nyumbu 1985). Land use and land cover changes are unlikely to have had a significant effect on Zambezi runoff patterns. The Zambezi headwaters region, covered by relatively infertile Kalahari sands, is frequently burned and cleared for small agricultural plots (*machambas*) but retains dense forest cover over most of the region (Kasimona and Makwaya 1995). Water diversions are currently negligible relative to the mean annual flow, and unlikely to affect runoff patterns in the near future[5].

The Cuando/Chobe River basin

The Cuando River rises in Angola and drains approximately 133,200 km^2 (26% of the Zambezi headwaters region) (Figure 2-2). The middle reaches of the Cuando are bordered by a narrow band of floodplains, 10 km in width, that are flooded annually during the rainy season to form a shallow lake. As it reaches the broad flat plains of the Caprivi Strip, the Cuando discharges directly into the upper end of the Chobe River floodplain. The resulting Chobe Swamps form an extensive 3000 km^2 wetland complex adjacent and to the south of the main Zambezi channel.

The Cuando River floodplains and Chobe Swamps strongly attenuate peak runoff from the Cuando/Chobe catchment. During the early part of the flood season, the Chobe River flows in an easterly direction from the Chobe swamps towards the main Zambezi channel, and may contribute substantial runoff to Zambezi system (Balek 1971b). As Zambezi levels rise, however, floodwaters spill from the Zambezi back into the Chobe swamps. The Chobe River reverses direction and flows to the northwest towards Lake Liambezi (Debenham 1948). Floodwaters spread over the dry plains and are lost through evaporation. Net evaporation (evaporation minus rainfall) from the Chobe swamps is more than 900 mm per annum (Table 2-8). Overall, the contribution of Cuando River runoff to Zambezi River flow is counterbalanced by evaporation losses from Zambezi floodwaters that overflow into the Chobe floodplain, and net discharges to the Zambezi are negligible relative to runoff from the headwaters region. Between 1945 and 1986, the difference between mean annual runoff in the Zambezi River upstream of the Chobe confluence at Katima Mulilo and runoff downstream at Victoria Falls was only 2 m3/s, and part of this runoff may be attributed to the Machili and Ngwezi tributaries that drain to the Zambezi over this reach.

Table 2-8. Mean monthly and annual Class A pan evaporation, rainfall, and net evaporation (mm) at Sesheke meteorological station near the Chobe River floodplain.

Data	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Ann
Evaporation	203	175	150	132	122	152	163	160	135	124	160	185	1862
Rainfall	33	103	199	215	204	148	38	4	0	0	1	3	948
Net evap	**170**	**72**	**-49**	**-83**	**-82**	**4**	**125**	**156**	**135**	**124**	**159**	**182**	**914**

The vast Okavango River system draining more than 150,000 km^2 of southern Angola, the Caprivi Strip, and northwestern Botswana, is not considered to be part of the Zambezi River system in this analysis. The Okavango system is hydrologically connected to the Zambezi system through the Selinda-Makwegana spillway that links the upper Okavango Delta to the Chobe River (Balek 1971b), but the spillway has not contributed significant runoff to the Chobe River system in recent history and may have been (temporarily?) severed by small tectonic movements (Handlos and Williams 1985). Bond (1975) considered the Okavango to have been a major tributary of the Zambezi during historical periods of high rainfall.

The Middle Zambezi catchment

The Gwembe Valley catchment

Between Victoria Falls and Cahora Bassa Gorge, the Zambezi River drains the Middle Zambezi catchment (Figure 2-2). Immediately below Victoria Falls are extensive areas of Karoo basalt into which the Zambezi has incised spectacular gorges, including Batoka Gorge and Devil's Gorge, for a distance of 120 km (Balon and Coche 1974). Tributaries are minor in this region, with most runoff from the Kalomo River draining southern Zambia between Choma and Zimba. From Devil's Gorge to Kariba Gorge, the Zambezi River cuts through deep gorges of the Gwembe Rift Valley at the eastern extent of the vast Central African Plateau, collecting runoff from several large tributaries. The plateau varies in elevation from about 1350 m in the south to about 650 m in the north, covering a catchment area of about 156,180 km^2 (Balek 1971b). Sedimentary deposits cover much of the western side, with basement granites often exposed in the east. Dry mopane woodland covers most of the region.

The Gwayi, Sengwa, and Sanyati Rivers drain about 64% of the Gwembe Valley catchment[6] from the northern Zimbabwe Highlands. The Gwayi River (catchment area 54,610 km^2) rises on the Limpopo/ Zambezi watershed near Bulawayo and flows northwest to join the Zambezi at the head of Kariba Reservoir. The Sengwa catchment (25,000 km^2) drains to the middle reaches of Kariba Reservoir. The Sanyati River basin (43,500 km^2) outflows to Kariba Reservoir about 30 km upstream of Kariba Gorge. The total north bank drainage area is about 19,970 km^2.

Average annual rainfall in the Gwembe Valley catchment is about 700 mm (Table 2-9). Rainfall is concentrated during the period from November to March, with peak rainfall occurring from December to February. The rivers of the Gwembe Valley catchment are characterized by fairly steep gradients, with incised channels and no significant floodplains (Balon and Coche 1974). Thus, unlike the Zambezi headwaters region, there is little to no natural regulation of river discharges and runoff tends to be flashy in response to rainfall events. Tributary flows begin increasing with the onset of rains in November, with one or more peaks in January and February, and decrease back to minimal flow by early in the dry season. Few of the Gwembe Valley catchment rivers are perennial. The hydrograph of average monthly runoff from the Gwembe Valley catchment is shown in Figure 2-5.

Table 2-9. Mean monthly and annual rainfall for selected stations in the Gwembe Valley catchment of the Zambezi River. Hwange and Bulawayo are located in Gwai River catchment. Gokwe and is located in the Sengwa River catchment. Gweru is located in the Sanyati catchment. Karoi is located near the east end of Kariba Reservoir.

Station	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Ann
Hwange	16	54	126	159	136	67	17	5	0	0	0	1	581
Bulawayo	28	84	125	131	112	68	27	11	2	1	1	5	593
Gokwe	22	88	172	211	168	97	32	5	2	0	0	3	799
Gweru	28	95	156	143	132	74	24	8	3	1	1	8	673
Karoi	16	79	179	203	191	115	36	6	3	1	1	3	835
Average	**22**	**80**	**152**	**169**	**148**	**84**	**27**	**7**	**2**	**1**	**1**	**4**	**696**

The mean annual discharge from the Gwembe Valley catchment is 7.2 x 10^9 m^3 (232 m^3/s), with a coefficient of variation of 0.44. The long-term (92-year) annual discharge series is given as a percentage of mean annual discharge in Figure 2-10. As with the Zambezi headwaters region, runoff from the lower catchment varies considerably from year to year. The highest recorded annual discharge volume, 23.6 x 10^9 m^3, is more than seven times greater than the lowest annual discharge (3.1 x 10^9 m^3). That both the highest and lowest annual discharges on record occurred during the same years in the Upper Zambezi and Gwembe Valley catchments reflects the significance of the Inter-Tropical Convergence Zone[1] in controlling regional rainfall patterns and especially extreme rainfall events. The strong cyclical pattern in the annual flow series in the upper catchment is also evident in the lower catchment. The dimensionless differential mass curve in Figure 2-7 shows similar patterns of runoff in the lower and upper catchments. The mass curve for rainfall in the lower catchment is shown over the same time period in Figure 2-8. As with the headwaters region, runoff trends are primarily related to rainfall patterns and are not likely due to substantial changes in land use. Water rights holdings in the Gwembe Valley catchment are negligible, and existing tributary dams in Zimbabwe, including the McIlwaine (reservoir capacity 38.8 x 10^6 m^3) and Ngesi (26 x 10^6 m^3), do not have a significant effect on the cumulative runoff from the region. Proposed large dams on the mainstem Zambezi, however, may have an adverse impact on runoff in the future[7].

Kariba Dam and Reservoir

Some 385 km downstream of Victoria Falls at the eastern extent of the Gwembe Valley, the Kariba Reservoir was created by the damming of Kariba Gorge, an intrusion of granitic gneiss into which the Zambezi has incised a deep gorge (Balon and Coche 1974) (Figure 2-2). The 131 m high, 633 m long double-curved concrete arch dam was closed in December 1958. The reservoir, extending 280 km from Devils Gorge to Kariba Gorge and 30 km at its widest point, is the third largest in Africa and inundates 5250 km^2 of the Gwembe Valley floor. Kariba Reservoir has a total capacity of 64,798 x 10^6 m^3, with 54 x 10^6 m^3 of dead storage (Olivier 1977).

The total catchment area of Kariba Reservoir is 663,540 km^2 (54% of the Zambezi catchment). Estimated mean annual runoff into Kariba Gorge since 1907 is 40.2 x 10^9 m^3 (1276 m^3/s), with a coefficient of variation of 0.39. The time series of long-term annual runoff into Kariba Gorge is shown in Figure 2-11. The highest annual inflow volume, 97.8 x 10^9 m^3, was recorded in 1957/58, the last year before the Zambezi was regulated. The minimum inflow, 15.5 x 10^9 m^3, occurred in 1995/96 at the end of a prolonged drought period.

The distribution of mean monthly inflows to Kariba Reservoir is given as a function of runoff from the Upper Zambezi and Gwembe Valley catchments in Figure 2-5.. Runoff from the lower catchment generates the characteristic early Zambezi flood, known locally as *Gumbora*, while the delayed runoff from the upper catchment generates the major annual Zambezi inundation (*Mororwe*) that typically peaks in April (Davies 1986). The recession limb of the inflow hydrograph is flattened by the delayed releases from the Barotse floodplain during the dry season.

Kariba Reservoir operates to regulate the Zambezi flow regime for hydropower production. The total generating capacity of Kariba hydropower station is 1275 MW, including the 600 MW North Bank power station and 675 MW South Bank power station (Figure 2-9). Currently, Zambia and Zimbabwe use almost all the electricity generated at Kariba. Kariba Dam has six spillgates that can discharge up to 9515 m^3/s in combination with turbine outflow at maximum flood level. This discharge capacity is not sufficient to pass the 1:10,000 year design flood of 19,600 m^3/s (Batoka Joint Venture Consultants 1993b), so adequate volume must be set aside in the reservoir before each flood season to store part of the inflows. A design flood rule curve (see Working Paper #4) is used to set maximum end-of-month water levels for the reservoir, resulting in periodic drawdowns prior to each flood season.

The operation of Kariba Dam for hydropower generation has greatly altered the flow regime of the Zambezi River. The hydrograph of mean monthly flows below Kariba Gorge is given for the period before and after dam construction in Figure 2-12. The magnitude of monthly flows is sharply reduced during the peak-flooding season, including a 41% reduction in the mean monthly flow in April and 36% reduction in March. This reduced magnitude of flood flows translates to a dramatic decrease in the inundated area of floodplains below Kariba Gorge, including the Mana Pools National Park (A World Heritage Site) (Du Toit 1994). Average dry season flows have more than tripled, from 255 m^3/s to 812 m^3/s in October, changing the dry season character of the Zambezi River from a meandering sandbank river to a single down-cut channel (Guy 1981, Nugent 1983).

Because some of the long-term changes in the monthly flow regime may be attributed to cyclical changes in climate (discussed above), I also compared inflows and outflows at Kariba since dam construction. The hydrograph of mean monthly inflows, outflows, and evaporation losses (water abstraction from reservoir by water rights holders in Zambia amounts to only about 4 m^3/s) is given in

Figure 2-13.. Kariba reduces mean monthly flows by 37% (r^2=0.53, SE=1359), 48% (r^2=0.63, SE=1399), and 46% (r^2= 0.57,SE=958), respectively, during the peak flooding months of March, April, and May. Evaporation contributes in part to this loss. Net evaporation from the reservoir is 955 mm on average[8], and about 11% of inflows are lost to evaporation during the peak flooding months (Table 2-10). The reduced duration of flood flows is equally significant. Prior to regulation Zambezi inflows typically exceeded 1750 m^3/s, the threshold for overbank flooding in the middle Zambezi floodplains, from February through May (Begg 1973). The maximum mean monthly outflow from Kariba Reservoir is now only 1665 m^3/s (mean maximum outflow = 2167 ± 1220 m^3/s), with few days spiking above 1750 m^3/s. Over the past 20 years, the mean maximum monthly outflow is only 1200 m^3/s.

Table 2-10. Mean monthly and annual reservoir evaporation, rainfall, and net evaporation (mm) at Kariba meteorological station. A coefficient of 0.9 was applied to tank evaporation data.

Data	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Ann
Evaporation	192	179	152	143	129	145	136	121	104	108	127	158	1694
Rainfall	16	76	164	195	156	97	27	5	1	1	0	1	739
Net evap	**176**	**103**	**-12**	**-52**	**-27**	**48**	**109**	**116**	**103**	**107**	**127**	**157**	**955**

Mean monthly conditions give only a partial picture of the changes in the hydrological regime of the Zambezi River below Kariba Dam. Time series data of monthly inflows and outflows at Kariba Dam is shown in Figure 2-14. Three periods of operation are evident. The filling phase for Kariba (which at the time was the world's largest reservoir) lasted four years. During the first seven months the dam was sealed, there was no outflow at all except for a small trickle in March-April 1959 (Scudder 1972). Downstream flood flows were completely eliminated during 1959, 1960, and 1961, and substantially reduced in 1962. Mean annual outflows during this period were less than 20% of inflows. From 1962-81, Kariba entered a period of normal operation, including a constant turbine discharge for hydropower generation and spillage through the sluice gates in accordance with the design flood rule curve. Although seasonal flood flows were generated during most years, the period was characterized by erratic water releases. During 1963/64, the flood cycle was reversed, with *maximum* outflow in November, and *minimum* outflow in April/May. In 1965/66, peak flows were generated in December and July.

Prolonged drought beginning in 1981 marked a period of significantly reduced inflows. For the next 20 years, from June 1981 to March 2001, only turbine outflows were released from Kariba Reservoir and all downstream flooding was eliminated. As reservoir levels fell close to minimum operating levels in the mid-1980s and again in the early and mid-1990s (Figure 2-15), even relatively large inflow events (as in 1989, 1992, and 1998) were absorbed by the reservoir.

Overall, Kariba Reservoir has operated to cause substantial and long-term changes in Zambezi runoff patterns. These changes, in addition to resulting in numerous social and environmental impacts upstream and downstream of the reservoir (Reynolds *et al.* 1999), have had a profound effect on the hydrological regime of the Zambezi Delta and on the opportunities for improving water management in the lower Zambezi Valley.

The Kafue River Basin

Below Kariba Reservoir, the Zambezi briefly flows due north and captures runoff from several small, seasonal rivers including the Lusito. As the Zambezi bends again to the east, it flows through a series of deep gorges and is fed by two major tributaries draining the Central Africa Plateau, the Kafue River and the Luangwa River. Although the catchments of these two river systems are similar in size, they differ significantly in geomorphology and yield very different runoff patterns. Hydrological processes in the Kafue River basin, with extensive floodplain systems and two large dams, are particularly complex.

The Kafue River basin (154,200 km^2) drains most of the northern portion of the Middle Zambezi catchment[9] (Figure 2-2). The Kafue River headwaters rise on the plateau of the South Equatorial Divide in the Copperbelt region of Zambia. The Upper Kafue basin (50,480 km^2) includes the Munyonshi and Luswishi tributaries and is largely mountainous and forested with headwater dambos (Balek and Perry 1973). The Kafue River is deeply incised in this region with fairly steep gradients and rapid runoff (FAO 1968). Annual rainfall averages 1100-1200 mm (Table 2-11).

Table 2-11. Mean monthly and annual rainfall for selected stations in the Kafue River catchment. Ndola and Kasempa are in the Kafue headwaters and Lufupa sub-catchments of the Upper Kafue basin, respectively. Choma is in the Middle basin and Lusaka is in the Lower basin.

Station	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Ann
Ndola	24	130	278	282	246	177	37	4	0	0	1	2	1181
Kasempa	39	142	255	248	212	171	38	3	0	0	1	4	1106
Choma	21	94	190	200	174	100	25	5	0	0	0	2	813
Lusaka	16	87	195	227	188	98	26	4	0	0	0	1	843
Average	**27**	**113**	**227**	**233**	**202**	**135**	**34**	**4**	**0**	**0**	**0**	**3**	**977**

Downstream of the Luswishi confluence, the Kafue River bends sharply to the west and the south bank opens up into the vast Lukanga Swamp (2600 km^2). During peak flow periods, Kafue floodwaters spread overbank and inundate the floodplain through the Munwinu and Lukanga channels (Macrae 1934). As with the Barotse Plains on the mainstem Zambezi, the Lukanga Swamp significantly attenuates Upper Kafue basin runoff; reducing and delaying flood peaks downstream. Dry season evaporation losses from floodplain exceed 1100 mm/annum.

Below Lukanga Swamps, the middle Kafue River flows west and captures runoff from the vast Lunga and Lufupa catchments and then cuts through an extensive high desert ridge (1000-m amsl) at Itezhitezhi Gorge. The gorge has been dammed to form Itezhitezhi Reservoir, which is used to regulate the Kafue River for downstream hydropower generation. Itezhitezhi controls about 70% (105,620 km^2) of the total Kafue catchment. The hydrograph of mean monthly Kafue runoff at Itezhitezhi, and mean annual rainfall in the basin is shown in Figure 2-16. Peak flows, attenuated by Lukanga Swamp, typically occur about two months after peak rainfall over the upper catchment.

Annual runoff to Itezhitezhi Gorge is given as a percentage of the long-term (92-year) mean annual discharge in Figure 2-17. Mean annual runoff is 8.8 x 10^9 m^3 (279 m^3/s), with a coefficient of variation of 0.50. Although runoff patterns in the Kafue and Zambezi headwater regions are highly correlated (Mukosa *et al.* 1995), the Kafue catchment has contributed several major flood peaks to the Middle Zambezi River during years of only average runoff in the Zambezi headwaters region. The maximum probable flood discharge at Itezhitezhi is about 4250 m^3/s (SWECO 1971).

Below Itezhitezhi Gorge, the lower Kafue River meanders over the Kafue Flats, an extensive floodplain area up to 60 km wide and 250 km long with an average gradient of only 2.7 cm/km. Along its course, the Kafue River is fed by a series of flashy tributaries that drain the surrounding plateau, including the Mbuma, Baunza, Banga, Lukomezi, Nansenga, Lutale, Nkala, Nanzhila, Sikaleta, Itu, Nangoma, Mwembeshi, and Kaleya Rivers. Before construction of the Itezhitezhi Reservoir, seasonal runoff from the Kafue River and its tributaries inundated the Kafue Flats to create a mosaic of floodplain grassland and permanent lagoons (Handlos 1982). Water levels in the flats started to rise in late November or early December, shortly after the onset of rains in the lower Kafue basin (Table 2-11). Between December and February, runoff from local tributaries caused widespread shallow flooding and waterlogging of the flats (Shawinigan Lavalin and Hidrotécnica Portuguesa 1990a). Peak runoff reached the upstream end of the Kafue Flats in March. The historical peak annual flood was about 500 m^3/s, with a 100-year flood of about 3000 m^3/s (Sichingabula 2000). Floodwaters spread slowly over the flats for several months, inundating up to 5650 km^2 during very wet years. Downstream of the Kafue Flats, the Kafue River peaked in late May, well after the local rains had ended (Figure 2-16).

The vast extent of shallow floodwaters across the Kafue Flats resulted in very high evaporative water losses (Table 2-12). Potential evaporation exceeds rainfall in all except the peak rainfall months. Net evaporation over the annual hydrological cycle is about 1050 mm.

Table 2-12. Mean monthly and annual evaporation, rainfall, and net evaporation (mm) from the Kafue Flats. Evaporation is estimated from the Penman (1948) equation using data from the Namwala meteorological station.

Data	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Ann
Evaporation	171	148	167	144	115	93	102	130	168	205	177	164	1784
Rainfall	16	76	164	195	156	97	27	5	1	1	0	1	739
Net evap	**155**	**72**	**3**	**-51**	**-41**	**-4**	**75**	**125**	**167**	**204**	**177**	**163**	**1045**

Below the Kafue Flats, the river cascades through Kafue Gorge, dropping 600 m over a distance of 24 km. The entrance to the Kafue Gorge was dammed to form the Kafue Gorge Reservoir. Beyond the Kafue Gorge and the foot of the escarpment the river flows across the floor of the Rift Valley to join the Zambezi some 60 km downstream of Kariba Dam. The total length of the Kafue River from source to confluence is 1550 km.

The first dam on the Kafue River was completed at the Kafue Gorge site in 1972. Kafue Gorge Dam is a gravity, earth-rockfill dam, with a crest height of 50 m at 981.5-m amsl. Kafue Gorge Dam operates to re-regulate outflow from the Itezhitezhi Reservoir through the Kafue Gorge hydroelectric station (Figure 2-9). Six turbines generate 900 MW at capacity, with a maximum discharge of 252 m^3/s. Total reservoir capacity is 885 x 10^6 m^3, with a dead storage of 20 x 10^6 m^3. The normal operating level of Kafue Gorge is 975.3 m from August to November, rising to full retention of 976.6 m from December through March. At full retention level, the Kafue Gorge reservoir inundates the eastern half of the Kafue Flats up to Nyimba. From 600-1600 km^2 of former seasonally inundated floodplain is permanently inundated by the dam, such that the downstream half of the Kafue Flats is now considered part of Kafue Gorge reservoir (Turner 1984, Chabwela and Siwela 1986). The difference between the annual maximum and minimum water levels was reduced from 4-5 m to 1.2 m (Balasubrahmanyam and Abou-Zeid 1982b).

Because high evaporation losses from the Kafue Flats reduces the water available for power generation at Kafue Gorge, a second dam was designed to stabilize river flows below 250 m^3/s, the discharge at which overbank flooding occurs (DHV 1980). Construction of Itezhitezhi Dam commenced in 1973 and began impounding water in December 1976. The dam is a gravity earth-rockfill dam, with a crest height of 65 m and length of 1800 m. Reservoir capacity is 5700 x 10^6 m^3, with a dead storage of 780 x 10^6 m^3 (SWECO 1971). The reservoir was designed with extra storage capacity to enable prescribed flood releases to the Kafue Flats over a four-week period in March each year. Net evaporation from Itezhitezhi Reservoir is about 780 mm/annum (Table 2-13).

Table 2-13. Mean monthly and annual reservoir evaporation, rainfall, and net evaporation (mm) at Itezhitezhi.

Data	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Ann
Evaporation	210	140	140	120	100	140	130	120	90	120	140	170	1620
Rainfall	20	90	200	210	180	120	20	0	0	0	0	0	840
Net evap	**190**	**50**	**-60**	**-90**	**-80**	**10**	**110**	**120**	**90**	**120**	**140**	**170**	**780**

Releases from Itezhitezhi Dam are dictated by power generation needs at Kafue Gorge Dam, typically about 168 m^3/s except during periods of exceptional runoff from the upper catchment areas. During a four week period each March an ecological freshet of 300 m^3/s is supposed to be released (DHV 1980), but this has rarely occurred in recent years. As a result, the extent of flooding in the western portion of the Kafue Flats has been greatly reduced (Sharma 1984). Before impoundment, flow in the western flats ranged from 30-1400 m^3/s, with a mean maximum inundated area of 4820 km^2 (Minderhoud 1982).

Under current conditions, only intermittent flooding occurs in the western flats, with erratic dry season flows (Chabwela 1992). In 1991-92, maximum monthly flows in the lower Kafue occurred at the end of the dry season in October (Sichingabula 2000).

Inflows to the Zambezi River from the Kafue River have changed significantly over time as a result of hydropower development on the Kafue River system. The distribution of mean monthly flows at Kafue Gorge is shown for the period before and after the construction of upstream reservoirs in Figure 2-18. On average, peak flows through the Gorge have been reduced by 27% during the months of April, May, and June. There has been a corresponding increase in low flows during September-December, with the annual minimum monthly flows at the end of the dry season nearly three times the historical rate. The time series of monthly outflows at Kafue Gorge is shown in Figure 2-19. Annual peak monthly runoff from the Kafue catchment varied from 105-1918 m^3/s prior to river regulation, with a maximum daily inflow of 2629 in 1977/78, but mean maximum monthly runoff since 1971 is only 448 m^3/s. Mean annual runoff has decreased only slightly since construction of Kafue Gorge Dam, from 288 to 260 m^3/s, suggesting that the reduction in evaporative water losses from the Kafue Flats since regulation has largely offset the reduced catchment runoff during the prolonged regional drought of the 1980s and early 1990s.

The direct effects of hydropower generation on Kafue runoff since 1977 are illustrated in Figure 2-20. Flows downstream of Itezhitezhi Reservoir, already attenuated by Lukanga Swamp, have been reduced a further 37% on average during the peak runoff months of February-April. Peak flows below Kafue Gorge Dam, delayed 2-3 months by Kafue Flats and the Kafue Gorge Reservoir, show significantly lower seasonal variation (163-340 m^3/s) than upper-middle catchment runoff (49-717 m^3/s).

As with the Kariba Reservoir catchments, Kafue runoff patterns show a clear cyclical pattern over time. The convergence between the dimensionless differential mass curve for runoff from the Kafue and Zambezi catchments is shown in Figure 2-7. A general increase in runoff occurred in the Kafue catchment from the late 1930s until the early 1980s, followed by sharp decrease over the past 20 years. SWECO (1971) showed an exponential increase in runoff as a percent of rainfall as a function of annual rainfall, but rainfall over the same period does not follow this trend, reflecting instead short-term cyclical patterns. The mass curve for rainfall in the Kafue catchment is shown in Figure 2-8. FAO (1968) reported a significant increase in surface water runoff per unit rainfall from the Kafue headwaters region during the 1950s and 1960s. Changes in the pattern of runoff may be due to deforestation in the Copperbelt region (Mumeka 1986). Throughout the last century, urban populations in Zambia have been increasing in towns along the railway lines, many of which lie in the upper catchment of the Kafue. The removal of woodland has been particularly serious because of the demand for structural timber in the mines and also, during the 1940s and 1950s, because of its use as a fuel for the production of electric energy from a local power station (Bolton 1983).

There are few large-scale agricultural developments in the Kafue headwaters region. Water supply for agriculture and domestic use in lower Kafue catchment is tied to a series of water rights with a total maximum allowed use of 15 m^3/s. More than half of this water returns to the system, however, so maximum net water use is less than 7 m^3/s (Kasimona and Makwaya 1995). Traditional land systems in and around flats consist mostly of herding cattle and growing maize. Future development projects may have a more significant influence on the Kafue system, however[10].

The Luangwa River Basin and other tributaries of the Middle Zambezi

Below the confluence with the Kafue River, the Zambezi flows gently through the Central African plateau for 180 km to its confluence with the Luangwa River just upstream of Cahora Bassa Reservoir. Over much of this distance, Lower Zambezi National Park flanks the Zambezi on the north bank and Mana Pools National Park on the south bank. Both parks feature narrow zones of floodplains that were annually inundated by floodwaters prior to Kariba Reservoir regulation.

The Luangwa River basin (151,400 km^2) rises on the South Equatorial Divide west of Lake Malawi (Figure 2-2). The Luangwa generally follows the base of the Luangwa Rift Valley that forms an extension of the East African rift system and links with the Gwembe Rift Valley (Mhango 1977). Much of the

Luangwa River is fed by short, steeply falling tributaries draining from the rift escarpment, most notably the Luwumbu, Lundazi, Lukusuzi, and Lutembwe Rivers. In its lower reaches, the Luangwa captures runoff from the vast Lunsemfwa River catchment that drains the Muchinga Escarpment in central Zambia (44,000 km^2)(Balek 1971b). The Luangwa River discharges to the Zambezi in the vicinity of Feira at the western end of Cahora Bassa Reservoir. For the last few kilometers it forms the international boundary between Zambia and Mozambique.

The Luangwa flows for most of its length through an incised channel and there are no bordering floodplains similar to those found in the upper Zambezi and Kafue Basins (Balek 1971b). Thus the Luangwa catchment has very different hydrological characteristics than these other systems. Mean annual rainfall in the upper catchment region is comparable to the Kafue headwaters region, about 1000-1200 mm/annum (Table 2-14), but mean annual runoff is 547 m^3/s; nearly double that of the similarly sized Kafue catchment.

Table 2-14. Mean monthly and annual rainfall for selected stations in the Luangwa catchment. Kasama and Chipata are located in the upper Luangwa basin; Zumbo is located in the lower basin near the Zambezi confluence.

Station	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Ann
Kasama	20	146	267	275	247	246	79	9	0	0	0	2	1291
Chipata	13	84	218	251	223	170	47	4	1	0	1	1	1012
Zumbo	7	64	188	192	176	97	13	3	0	0	1	0	692
Average	**17**	**115**	**243**	**263**	**235**	**208**	**63**	**7**	**1**	**0**	**1**	**2**	**1152**

The hydrograph of mean monthly runoff from the Luangwa catchment is shown in Figure 2-21. Discharge typically rises rapidly in November with the onset of the rainy reason, with peak discharge typically in February and March following peak rainfall in the catchment. Discharge decreases rapidly until May, then recedes steadily through the dry season. The time series of monthly inflows from the Luangwa River is given for the period since 1955 in Figure 2-22. Discharge in the Luangwa River tends to be highly variable from year to year, with a mean maximum monthly discharge of 1769 m^3/s. Peak monthly discharges may reach more than 3100 m^3/s, but are negligible during periods of prolonged drought such as occurred in the early 1990s.

Just below its confluence with the Luangwa River at Zumbo (elevation of 330 m), the Zambezi flows into Cahora Bassa Gorge, part of the upper Zambezi Rift Valley. Cahora Bassa is fed by a series of tributaries draining an area of about 80,600 km^2 in Mozambique and Zimbabwe. The north bank tributaries drain from a hilly region with steep slopes dissected by streams and gullies and shallow, rocky lithosols. The south bank is a more gently undulating, weakly dissected terrain covered by loamy sand to sandy clay loams (Li-EDF-KP Joint Venture Consultants 2000b); runoff tends to be less flashy than from the north bank.

The perennial Panhane River is the most significant tributary along the course of the Zambezi through Cahora Bassa Reservoir, capturing runoff from the Angwa and Hunyani River catchments and draining 23,897 km^2 of eastern Zimbabwe and central Mozambique (Figure 2-2). The Panhane discharges into upper reaches of the reservoir, along with the Metamboa River (north bank), Funomoe' River (south bank), and other intermittent streams. In the middle reaches, the perennial Messengue'zi River adds runoff from the Umvukwe Range in Zimbabwe and the intermittent Mucanha and Duangua Rivers drain the Moravia Plateau from the north. The lower reaches are fed by a series of small, flashy tributaries that drain the bordering escarpment.

The climate in this portion of the Upper Rift Valley is semi-arid. Average annual rainfall ranges from 550-650 mm in low lying areas, increasing to 750-850 mm in the southern catchment of Zimbabwe and to more than 1000 mm/annum in the northern highlands (Table 2-15). Rainfall is concentrated between December and March. Late dry season temperatures can reach extremes of more than 40^o C, and potential evaporation is high.

Table 2-15. Mean monthly and annual rainfall for selected ungauged tributaries in the Middle Zambezi catchment. Chinoyi and Guruve are located in the Panhane River catchment. Fingoe is located on the escarpment to the north, Mazoe to the south, and Songo to the east of the Cahora Bassa Reservoir.

Station	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Ann
Guruve	17	74	176	201	172	113	31	8	2	0	1	3	799
Chinoyi	26	94	171	206	173	107	32	8	2	1	2	5	828
Fingoe	7	87	229	252	230	167	36	6	8	5	3	2	1031
Mazoe	9	35	142	187	120	90	11	3	5	2	0	0	604
Songo	6	49	105	128	138	105	35	14	6	5	3	0	734
Average	**13**	**69**	**170**	**196**	**171**	**113**	**28**	**7**	**4**	**2**	**2**	**2**	**789**

The time series of annual runoff in the Middle Zambezi catchment below the Kafue River confluence[11] is shown in Figure 2-23. Mean annual incremental inflow is 28 x 10^9 m^3 (888 m^3/s), with a coefficient of variation of 0.47. About 60-65% of runoff is derived from the Luangwa catchment, suggesting a mean annual discharge of about 16.8-18.2 x 10^9 m^3 for the Luangwa River.

Runoff from this portion of the middle Zambezi shows a fairly pronounced trend, although the pattern diverges from that of the Upper Zambezi and Kafue catchments. Runoff increased steadily over a prolonged period from the 1920s to the early 1970s, and then decreased sharply over the past 30 years (Figure 2-7). This pattern is not strongly reflected in the rainfall series (Figure 2-8), which has fluctuated over much shorter cycles. Increasing runoff patterns in the catchment may in part have been the result of changes in the vegetation and land cover. Bolton (1984b) noted that the valleys in the south and east of Zambia are actively eroding at a much higher rate than in central Zambia. These erosion rates have accelerated as a result of human activity, heightened by colonial land use policies from the turn of the century. By the 1950s, lands in the vicinity of Chipata were reportedly suffering very serious erosion.

Water resources development in the catchment of the Luangwa River and other Middle Zambezi tributaries has a negligible influence on runoff patterns. The mainstem Luangwa is not regulated. Two hydropower dams regulate runoff from the Lunsemfwa tributary[12] but they have minimal storage capacity relative to total catchment runoff (Balek 1971b). The Panhane is partially regulated by the Chivera Reservoir on the Angwa River in Zimbabwe and the largest reservoir for municipal water supply in the Zambezi basin (with a capacity of 490 x 10^6 m^3) at Darwendale on the Hunyani River (Durham 1995). Future development projects in this reach may have a more significant influence on Zambezi runoff, however[13].

Cahora Bassa Dam and Reservoir

Some 240 km below the its confluence with the Luangwa River, the Zambezi passes through a major gorge incised into large intrusive rock masses (Figure 2-2). The eastern end of the gorge is dammed to form Cahora Bassa Reservoir. Cahora Bassa is a concrete arch dam, 163 m high and 303 m wide. The dam crest altitude, 331 m, is designed to provide the maximum possible storage without backing up water into Zambia and Zimbabwe. Cahora Bassa Reservoir has a dead storage of 12.5 x 10^9 m^3, a live storage of 51.7 x 10^9 m^3 up to the maximum operating level of 326 m amsl, and surge flood storage capacity of 8.0 x 10^9 m^3 up to the maximum crest height. Total surface area is 2700 km^2 at 326 m (Olivier 1977).

The total catchment area of Cahora Bassa is 1,050,000 km^2 (86% of the total Zambezi catchment). Estimated mean annual runoff into Cahora Bassa Gorge since 1907 is 79 x 10^9 m^3 (2494 m^3/s), with a coefficient of variation of 0.36. The long-term annual series of inflows to Cahora Bassa Gorge is given in Figure 2-24.. Inflows of more than 137 x 10^9 m^3 (two standard deviations above the mean) have occurred four times in the historical record, 1957/58, 1962/63, 1968/69, and 1977/78. These events correspond to the four highest recorded annual inflows to Kariba Reservoir, as well as periods of substantial runoff from the middle catchment. The highest annual inflow volume, 153 x 10^9 m^3, was recorded in 1962/63. The minimum inflow volume, only 24.3 x $10^9 m^3$, occurred at the end of the prolonged drought in 1994/95. Annual runoff since 1957/58 is affected by evaporative water loss from Kariba Reservoir, although the magnitude of the net reduction is uncertain because of the potential for a corresponding increase in rainfall over the reservoir area. Since 1970, runoff is also affected by the impounding of the Kafue River.

The historical distribution of mean monthly inflows to Cahora Bassa Gorge, 1907-58, is given as a function of runoff from the Upper Zambezi, Gwembe Valley, Kafue, and the remaining middle Zambezi catchment prior to Zambezi River regulation in Figure 2-25. Runoff from the Luangwa River, Gwembe Valley catchment, and smaller tributaries of the middle Zambezi generated the early Zambezi flood in the gorge. Zambezi discharges rose sharply with the onset of the rainy season, and peaked in March with a mean monthly runoff of 5948 m^3/s. Runoff from Upper Zambezi catchment sustained peak flood discharges in March-April, and controlled the dry season recession of floodwaters. Mean monthly runoff at the end of the dry season in October-November dropped to 522 m^3/s. The heavily attenuated floods from the Kafue River, the largest catchment in the Middle Zambezi, do not have a significant effect on the shape of the inflow hydrograph relative to the other sources of runoff.

The recent distribution of mean monthly inflows to Cahora Bassa Reservoir is shown for the period 1974-00 in Figure 2-26. Inflows now occur as a function of Kariba Reservoir outflows, Kafue Gorge Reservoir outflows, and remaining Middle Zambezi catchment inflows below the Kafue confluence. The increased significance of unregulated runoff from the Luangwa River relative to historical conditions is evident. Despite the regulation of more than 78% of the catchment above Cahora Bassa Reservoir, high volume flood discharges from the Luangwa and other tributaries of the Middle Zambezi below Kariba/Kafue maintain the basic shape of the inflow hydrograph relative to pre-regulation conditions.

The relative magnitude of maximum and minimum flows has changed substantially, however. Mean monthly flows over the flooding season from January-May are 36% lower than occurred during the period prior to Zambezi regulation. The recession limb of the inflow hydrograph during the dry season is flattened by hydropower releases from Kariba and Kafue Gorge Dams, with dry season flows dipping only slightly below 1000 m^3/s, an 88% increase relative to pre-regulation conditions.

Cahora Bassa Reservoir operates to regulate the Zambezi flow regime for hydropower production. The total generating capacity of Cahora Bassa hydropower station is 2075 MW through 5 hydraulic turbines (Figure 2-9). Currently, the dam operates with four turbines at full capacity and the electricity generated at Cahora Bassa is exported to South Africa and Zimbabwe. The deep, narrow reservoir has a very high hydropower output per unit reservoir area, 1.4 MW/km^2, relative to Kariba Reservoir (0.3 MW/km^2). The storage ratio—reservoir capacity divided by mean annual inflows—is 0.86, compared to 3.5 for Kariba Reservoir. This has important implications for water release patterns from Cahora Bassa as discussed below.

Each turbine discharges about 452 m^3/s at maximum output. Cahora Bassa Dam has eight spillgates, each 7.8 m x 6 m at their outlet, at a lower sill level of 231 m, together with a single weir emergency spillgate at the crest level of 331 m. The total discharge capacity is about 16,250 m^3/s, which is not sufficient to pass the 1:10,000 year design flood of 30,226 m^3/s (Li-EDF-KP Joint Venture Consultants 2000b). Because of the low storage ratio of Cahora Bassa Reservoir, water storage in the reservoir is balanced between maintaining water levels close to the maximum permissible elevation (to maximize hydraulic head on the turbines) and releasing water from the reservoir before each rainy season (to accommodate and store incoming floodwaters without breaching the dam wall). A design flood rule curve is used to set maximum end-of-month water levels for the reservoir (Working Paper #4). Following years of above-average inflows, rule curve operation results in large drawdowns during the end of the dry season to ensure adequate storage volume before the next flood season. Water levels in the reservoir fluctuate by more than 18 m between wet and dry years (Figure 2-27). The theoretical range of water levels between full supply level and minimum operating level is 34 m.

The operation of Cahora Bassa for hydropower generation has dramatically altered the flow regime of the Zambezi River. The hydrograph of mean monthly flows below Cahora Bassa Gorge is shown for the period before and after dam construction in Figure 2-28. Discharges below the gorge since construction of Cahora Bassa Dam are nearly constant throughout the year. The magnitude of monthly flows is sharply reduced during the entire flooding season, including a 64% reduction in the mean monthly flow during February-April and 45% reduction in January and May. Average monthly flows in November have nearly quadrupled, from 542 m^3/s to 1958 m^3/s in October. Most of the period since construction of Cahora Bassa Dam corresponds to a period of extreme drought in the Zambezi catchment, however. As a result, estimated mean annual flows into Cahora Bassa gorge since 1974/75 are about 30% lower than during the long-historical period from 1930-74.

Direct comparison of inflows and outflows at Cahora Bassa over the period since dam construction controls for changes due to climate or land use practices. The hydrograph of mean monthly inflows, outflows (discharge through turbines and spillage through sluice gates), and evaporation losses is shown in Figure 2-29. Mean monthly inflows during the flood season, already attenuated by upstream dams, are further reduced by 46% during the peak flooding months of February and March, and 20% in January and May. Dry season flows are likewise further stabilized, with a 106% increase in monthly flows during November. The near constant outflow hydrograph reveals little discernable flooding or dry season flow pattern below the dam. The maximum mean monthly outflow is less than the 75th percentile of mean monthly inflows, and the minimum mean monthly outflow is more than the 25th percentile of mean monthly inflows.

The time series of monthly inflows and outflows at Cahora Bassa is shown in Figure 2-30. The outflow series bears little resemblance to the inflow series in terms of the magnitude or timing of monthly flows[14]. The period 1976-1983 gives a good indication of the standard operating procedures for Cahora Bassa Dam. Annual outflows typically include multiple peaks of different magnitudes in an unpredictable pattern. From October 1983 until June 1997 only minimal electricity (15 MW) was generated from Cahora Bassa due to sabotage of the transmission lines. During this period, the dam continued to follow the design flood rule curve, storing inflows during the flood season and releasing drawdown discharges during the dry season. Although peak inflows occur within a narrow time window from mid-January to early-April, the maximum annual discharge has occurred in every calendar month of the hydrological cycle.

Average annual evaporation at Cahora Bassa is 2200 mm, with monthly evaporation ranging from 281 mm (October) to 128 mm (June). Local rainfall on the reservoir averages only 650-700 mm/annum, and net evaporation from the reservoir is more than 1500 mm on average (Table 2-16). The annual volume of water lost to evaporation (4.7 x 10^9 km^3, or approximately 7% of total inflows) is considerably less than that from Kariba Reservoir because of the relatively small surface area of Cahora Bassa. A schematic of the net water balance of Cahora Bassa Reservoir is shown in Figure 2-31.

Table 2-16. Mean monthly and annual reservoir evaporation, rainfall, and net evaporation (mm) at Cahora Bassa. A coefficient of 0.9 was applied to tank evaporation data.

Data	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Ann
Evaporation	281	234	185	176	146	169	156	147	128	142	190	245	2200
Rainfall	7	49	145	169	145	97	20	7	4	2	1	0	677
Net evap	**274**	**185**	**40**	**7**	**1**	**72**	**136**	**140**	**124**	**140**	**189**	**245**	**1523**

Overall, Cahora Bassa Reservoir has operated to cause substantial and long-term changes in Zambezi runoff patterns. These changes, in addition to resulting in numerous social and environmental impacts upstream and downstream of the reservoir (Bolton 1984a, Suschka and Napica 1986, Beilfuss *et al.* 2000), have had a profound effect on flooding patterns in the Zambezi Delta. They have also diminished the opportunities for improving water management in the lower Zambezi Valley[15].

The Lower Zambezi catchment below Cahora Bassa Reservoir

The Zambezi basin below Cahora Bassa covers an area of approximately 340,000 km^2 from the upper Rift Valley highlands to the Zambezi Delta. The Lower Zambezi is a complex physical system with four river-floodplain zones comprising narrow gorges, mobile sand-braided reaches, anabranching reaches, and coastal distributaries (Davies *et al.* 2001). The course of the Zambezi reflects the extensive tectonic patterns of the region, following the E-W and then SE fault lines on its path to the Indian Ocean (Li-EDF-KP Joint Venture Consultants 1999). The main tributaries in this region include the Luia and Revuboe of the Moravia-Angonia Plateaus, Luenha River of the Manica Plateau, and the Shire River of the lower Rift Valley. The Zangue River is also important as an historical hydrologic link between the Zambezi and Pungue River systems.

<u>The Moravia-Angonia and Manica Plateau tributaries</u>

Immediately below Cahora Bassa Dam, the Zambezi cuts east for 35 km through a deeply incised, steep-sided granite gorge of the Moravia-Angonia Plateaus (Figure 2-2). The drainage morphology of the plateau region is directly related to the geology of the region. The plateaus are underlain by pre-Cambrian formations composed of highly metamorphic granites and gneisses that form strongly dissected hills and mountains. Karoo and post-Karoo sediments associated with large outcrops of volcanic rock overlie these basement rocks. Drainage from these sediments is only weakly incised, with occasional river terraces. Distinctive red lateritic soils cover the region (Li-EDF-KP Joint Venture Consultants 1999).

The Luia River, entering the Zambezi 30 km below Cahora Bassa Dam, is the first major tributary of the Lower Zambezi catchment (Figure 2-2). The Luia catchment (28,000 km^2) includes the Capoche, Upper Luia, and Cherize Drift basins. The Capoche River rises on the Moravia Plateau at 1000-1500 m in eastern Zambia, and captures runoff from the Sadeza, Pivanhe, and Nhimbe Rivers over a total catchment area of 14,686 km^2. The Upper Luia rises further to the east on the Angonia Plateau, also at 1000-1500 m, and captures the Vuboe, Muangadeze, and Luangua Rivers over an 11,031 km^2 catchment. Some 23-km upstream of its confluence with the Zambezi, the Luia River captures runoff from the Cherize River catchment (1917 km^2). Most of the Luia basin is covered in mopane woodland, with dry deciduous miombo at higher elevations.

Average annual rainfall in the Luia catchment ranges from 600 mm in the lower catchment to upwards of 1500 mm in the northern highlands near the Zambia border. The monthly distribution of rainfall from long-term gauging stations at Bene (Upper Luia catchment) and Capoche (Capoche catchment) is given in Table 2-17. The rainy season begins in November, peaks from December to February, and decreases during March and April. Runoff from the Luia River catchment occurs rapidly in response to individual rainfall events, with multiple spikes from late December to early April (Figure 2-32). The average time to peak is 30 hours, with flood hydrograph duration of about 80 hours (RPT 1980). Annual peak flow typically occurs in February and to a lesser degree in January and March. Rainfall is negligible from May to October, and dry season runoff is minimal.

The hydrograph of mean monthly and mean maximum monthly runoff from the Luia catchment is shown in Figure 2-33. Estimated mean annual runoff from the Luia catchment is 3.7 x 10^9 m^3 (117 m^3/s). Maximum mean monthly flow occurs in February and March, following the period of peak rainfall over the catchment. Minimum monthly flow occurs at the end of the dry season in October.

The Luia catchment can significantly contribute to peak flooding in the Lower Zambezi catchment. The maximum estimated flood discharge during the period of record was 2484 m^3/s. Based on direct gauging measurements during the 1960s, the estimated 20-year return period flood for the Luia is more than 3000 m^3/s, including 1700 m^3/s from the Capoche catchment (Figure 2-34) and 1800 m^3/s from the Upper Luia catchment (Figure 2-35).

Downstream of the Luia confluence, the Zambezi bends 45 degrees to follow a SE trajectory towards its outlet at the Indian Ocean. Here, the valley-floor-trough widens to several kilometers, but gradients remain high and boundary sediments (mostly fine gravel and sand) are highly mobile, so a braided sand-bed river dominates (Davies *et al.* 2001). Further downstream, the Zambezi discharges through the

Table 2-17. Mean monthly and annual rainfall for selected tributaries on the Moravia-Angonia and Manica Plateaus.

Station	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Ann
Luia catchment													
Bene	17	70	199	199	158	115	29	8	4	1	1	7	808
Capoche	12	53	159	186	148	80	16	3	6	2	2	1	668
Revuboe catchment													
Metengo	15	54	157	190	184	127	30	8	2	2	3	3	775
Chingoze	9	55	131	187	147	79	14	8	3	3	1	1	637
Luenha catchment													
Harare	32	92	174	191	173	103	34	11	3	1	3	7	824
Luenha	10	34	109	140	152	67	10	4	2	1	2	1	551
Mainstem Zambezi													
Tete	4	53	131	153	140	80	16	3	3	2	2	2	589
Tambara	9	54	142	156	117	77	26	14	12	8	6	4	624
Mutarara	4	64	130	169	118	133	30	15	11	23	6	8	711

narrow Mepanda Uncua gorge and broadens to more than 1-km width. After capturing runoff from the Mavudezi River catchment (3154 km^2) and several smaller tributaries, the Zambezi River reaches Tete, the first major city of the lower Zambezi Valley. The total catchment between Cahora Bassa Gorge and Tete is 40,000 km^2.

From Tete to the Lupata Gorge, two major tributaries, the Revuboe and the Luenha (Figure 2-2) feed the Zambezi. The Revuboe catchment (15,540 km^2) is very similar to the Luia catchment, rising on the north bank near Mount Domue' of the Angonia Plateau, a region of high rainfall (1000-1400 mm annual), and capturing runoff from the Ponfi and Condedezi Rivers and several smaller tributaries. Rainfall and runoff characteristics in the Revuboe catchment are also very similar to those in the Luia catchment. The monthly distribution of rainfall from long-term gauging stations in the Revuboe catchment at Metengo (upper catchment) and Chingoze (lower catchment) are given in Table 2-18. Hydrographs of daily flows for wet, dry, and average rainfall years in the Revuboe catchment are given in Figure 2-36. Heavy rainfall events may generate flood peaks of more that 2000 m^3/s during wet years. Flood flows are negligible during dry years.

The hydrograph of mean monthly and mean maximum monthly runoff from the Revuboe catchment is shown in Figure 2-37. Estimated mean annual runoff from the Revuboe catchment is 3.0 x 10^9 m^3 (95 m^3/s), with a coefficient of variation of 0.50. As with the Luia catchment and upper valley tributaries, maximum mean monthly flow occurs in February and March, following the period of peak rainfall over the catchment. Average maximum monthly flow is more than 725 m^3/s in February. Minimum monthly flow occurs at the end of the dry season in October. The maximum recorded flood discharge during the period of record was 2375 m^3/s. The estimated 20-year return period flood is about 1800 m^3/s (Figure 2-38).

The Luenha River, the largest tributary of the plateau region, rises on the south bank of the Zambezi. The Luenha catchment (54,144 km^2) includes three major tributaries. The upper Luenha channel rises in the Inyanga Mountains of the Manica Plateau at 1000-1500 m amsl, the Ruia River rises in the Mvuradona Mountains of Zimbabwe at 500-1000 m amsl, and the Mazoe River (catchment area 34,216 km^2) rises also in the Zimbabwe Highlands near Harare. Throughout its lower course, the Luenha is a braided sand-bed river with high sediment fluxes. Rainfall and runoff characteristics in the Luenha catchment differ from those in the Luia and Revuboe catchments. Annual rainfall is lower in the region south of the Zambezi, with maximum rainfall of 800-850 mm in the rocky Zimbabwe highlands and average rainfall of 500-600 mm per annum in the lower catchment. Rainfall in the southern region is also affected earlier by the movement of the ITCZ, and typically peaks from late December to early February, especially in the headwaters region. The monthly distribution of rainfall is given in Table 2-18.

A hydrograph of daily runoff from the Luenha River near its confluence with the Zambezi is shown in Figure 2-39. Several distinct flood peaks are typical, corresponding to individual rainfall events, but peaks are sustained for a longer duration over the large catchment area. Runoff from the south arrives earlier, with peak flooding typically in January and February and occasionally in December. Flood flows are negligible during dry years.

The hydrograph of mean monthly and mean maximum monthly runoff from the Luenha catchment is given in Figure 2-40. Estimated mean annual runoff from the Luenha catchment is 4.8 x 10^9 m^3 (152 m^3/s). Average maximum runoff during January is nearly 1400 m^3/s (compared to about 500 m^3/s at Luia and Revuboe) and 1231 m^3/s in February. The estimated maximum recorded flood discharge was 2682 m^3/s. Based on intermittent direct gauging records from 1959-1974, the estimated 20-year return period flood is more than 3500 m^3/s (Figure 2-41).

Below the Luenha confluence, the Zambezi follows a well-defined channel between 800 and 1000 m wide. After passing through the narrow Lupata Gorge at 95 m amsl, river channel energy decreases and the valley opens up into the first significant floodplains of the lower Zambezi Valley, an anabranching channel system 3-5 km wide with ill-defined banks (Davies *et al.* 2001). The Zambezi may flow in several channels in the dry season that merge together into a single, swift-flowing body of water during the wet season. Several small, seasonal tributaries drain this region, including the Minjova River from the north bank and the Muira, Pompe, Sangadeze, and Mepuse Rivers from the south bank. The floodplain-anabranch zone continues past the Zambezi confluence with the Shire River and Zangue River systems to the apex of the Zambezi Delta.

Cumulative runoff patterns for the Zambezi catchment are measured at Muturara (Dona Ana gauging station), located immediately upstream of the confluence with the Shire and Zangue River systems at 40 m amsl (Figure 2-2). The total catchment area commanded by the gauge is 118,800 km^2. Between 1930 and 1958, mean annual runoff volume at Muturara was approximately 102 x 10^9 m^3 (3200 m^3/s). Over the past 25 years, runoff is only about 70 x 10^9 m^3 (2200 m^3/s).

Daily flood hydrographs for years of average, high, and low runoff in the lower Zambezi at Muturara are shown for the period prior to regulation in Figure 2-42. Zambezi flows begin to increase in early December, with several small peaks in response to local rainfall-runoff events. A significant early peak in December is often generated from runoff in the Luenha and south bank tributaries. Early peak flows as high as 6740 m^3/s have been recorded in December. The second, main Zambezi flood typically begins in January, peaking in February-March. This pattern tends to hold for years of moderate to extreme flood flows. During dry years such as 1948/49, when rains failed in the lower catchment, a single peak may occur corresponding to upper Zambezi catchment runoff. Maximum annual peak Zambezi flows vary widely from 5000-20,000 m^3/s, with an extreme maximum of 22,500 m^3/s in 1957/58 and minimum of 4970 m^3/s in 1948/49. The mean maximum flow is about 11,500 m^3/s. Flows decrease steadily from April to November, reaching the annual minimum of about 300-900 m^3/s (mean minimum of 500 m^3/s) between late October and early December.

The estimated average daily hydrograph for runoff at Muturara since construction of Cahora Bassa Dam is shown in Figure 2-43. Flows begin to increase, on average, during the late dry season in October and November, in response to drawdown releases from Cahora Bassa Reservoir. Early flood peaks from the lower Zambezi catchment occur in December and January. The maximum flood peak occurs on average in February-March, although peaks have occurred in all months between November and April. Mean annual maximum discharge is about 5900 m^3/s, ranging between 1900 m^3/s and 10,000 m^3/s in all years except 1977/78 when an estimated maximum discharge of 16,000 – 19,500 m^3/s occurred. Flows recede to a dry season minimum of 1500 m^3/s on average. These data give an indication of the magnitude of hydrological change that has occurred in the Zambezi catchment since construction of Cahora Bassa Dam. A detailed analysis of runoff patterns at Muturara, in terms of key indicators of hydrologic change in the Zambezi basin, is provided in Section 2-5.

The importance of runoff from the Moravia-Angonia and Manica Plateaus to the hydrological regime at Muturara cannot be under-estimated. The annual runoff from the region is about 13 x 10^9 m^3 (410 m^3/s)[16], with a coefficient of variation of 0.45. Tributary runoff is particularly important in terms of the timing and magnitude of peak floods that help offset the constant and irregular-timed releases from Cahora Bassa Dam. The combined 5-year return period for runoff from the plateau region is more than 4000 m^3/s (Figure 2-44); comparable to the mean maximum discharge from Cahora Bassa of 4474 m^3/s. The estimated 20-year return period flood contribution from the plateau region is more than 6000 m^3/s.

None of the upper tributaries is currently regulated to a significant degree. The Luenha catchment includes three small impoundments on the Mazoe River for irrigation and water supply. There are also many smaller unplanned, haphazard dams associated with gold panning that have little effect on seasonal runoff patterns (Mkwanda 1994). However, any future development activities that regulate runoff from these tributaries or the mainstem Zambezi could have severe consequences for flooding patterns in the delta, especially the proposed Mepanda Uncua Dam[17].

Lake Malawi and the Shire River basin

Downstream of Mutarara, the Zambezi River bisects the Great Rift Valley as it traverses eastern Africa from the Red Sea to central Mozambique. The Shire River, the largest tributary in the lower Zambezi catchment, drains 154,000 km^2 of the Rift Valley in southern Tanzania, Malawi, and Mozambique north of the Zambezi (Figure 2-2).

The Shire River originates as outflow from Lake Malawi, the only large natural lake in the Zambezi basin. Lake Malawi is the third largest lake in Africa, spanning 580 km in length and 16-80 km in width with a surface area of 29,610 km^2 (Pike 1968). The catchment area of Lake Malawi is 126,550 km^2. Heavy rainfall occurs in the Nyika Plateau, Livingstonia, the Vipya Mountains, and the Angonia Highlands surrounding the lake. Balek (1971b) estimated that the average annual water balance of Lake Malawi is composed of 2272 mm rainfall, 472 mm runoff, 2078 mm evaporation, and 666 mm outflow to the Shire Valley. The seasonal variation in the lake levels is typically about 1-1.2 m (up to 2 m maximum), but long-term cyclical fluctuations of more than 6 m are known (Figure 2-45).

A natural sandbar at the Shire inlet historically controlled outflow from the lake. In 1915, following a 20-year sequence of low rainfall and decreasing lake levels, the Shire was blocked by an extreme flood event that deposited a large volume of sediment behind the bar (Halcrow and Partners 1954). This effectively cut off the outflow from the lake and there was no flow out of the lake in to the Upper Shire until 1934 when (following a 20-year period of strong and steady rise in lake levels) the bar was overtopped and flow recommenced. Average lake levels continued rising until 1940, then decreased until 1946, and have since fluctuated over the period of record.

About eight km below the Shire River inlet, at 470 m amsl, the river spreads over Lake Malombe, a shallow floodplain 30 km long and 15 km wide. Below Lake Malombe, the river meanders along a very flat gradient until reaching Liwonde where it again spreads over a broad flat floodplain. Both floodplains attenuate flood flows in the Upper Shire catchment. Tributaries to the upper catchment are highly seasonal and flashy. Mean monthly and annual rainfall at Liwonde is given in Table 2-18. Peak rainfall occurs between December and March, and may exceed 1000 mm/annum in the high escarpment. Runoff from the upper Shire River at Liwonde (catchment area 3700 km^2 below Lake Malawi) is given in Figure 2-46. Average annual runoff is 12 x 10^9 m^3. Peak runoff generally occurs in April and May when Lake Malawi reaches maximum annual water levels. Maximum-recorded lake outflow was 480 m^3/s in 1947.

The middle catchment covers a distance of about 80 km through a deeply incised, narrow gorge fed by a few perennial tributaries. The river drops more than 380 m through a series of rapids and cascades, two of which have been dammed for hydropower production (Nkulu and Tedzani Falls). Mean monthly runoff in the middle Shire River at Matope (catchment area 7200 km^2 below Lake Malawi) is given in Figure 2-46. Tributary runoff from this reach contributes to earlier peak flooding in the Shire, which typically occurs in February-March following peak rainfall.

In the lower Shire catchment, the hills recede to form a broad floodplain extending from Chikwawa to the Zambezi confluence. The Elephant Marsh covers about 400 km^2 and extends nearly 50 km from

Table 2-18. Mean monthly and annual rainfall in the lower Shire Valley. Liwonde is located in the upper Shire basin and Nsanje is located in the middle basin. Milange is located in the headwaters of the Ruo River, the largest tributary of the lower basin.

Station	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Ann
Liwonde	15	58	168	211	180	140	38	8	5	5	5	3	836
Nsanje	18	97	163	185	173	132	46	13	12	10	9	5	862
Milange	43	127	244	297	309	283	162	63	68	47	35	24	1702
Average	**25**	**94**	**192**	**231**	**221**	**185**	**82**	**28**	**28**	**21**	**16**	**11**	**1133**

Chikwawa to Chiromo, with maximum width of about 15 km. The marsh is covered by dense growth of Phragmites and Papyrus reed swamps that significantly attenuate peak flood levels on the Shire. Evaporation from the floodplains is high, averaging 2000-2000 mm/annum, and greatly exceeds average annual rainfall (750 mm) in the lower Valley. Several perennial tributaries drain into the marsh but do not directly connect to the main channel. Average annual runoff at Chiromo is 15 x 10^9 m^3 (483 m^3/s), with a coefficient of variation of 0.40. Mean monthly runoff in the lower Shire River at Chiromo (catchment area 18,240 km^2 below Lake Malawi) is given in Figure 2-46. Peak flows typically occur in February and March, with maximum flows of more than 1200 m^3/s in February and March. Minimum discharge during the dry season ranges from 64-765 m^3 over the period of record. The time series of monthly flows at Liwonde and Chiromo are shown for the period from 1953-81 in Figure 2-47, illustrating the importance of Lake Malawi outflows and tributary contribution to the system. About 37% of the variation in Chiromo flows is explained by Lake Malawi outflows.

Immediately downstream of Chiromo, the Shire captures runoff from the Ruo River, the largest of the Shire tributaries. The Ruo drains an area of 4700 km^2, including the catchment of the Milange Mountains of Malawi. Most of the Milange Mountain range is above 1500 m amsl, with the peak rising more than 3000 m, and orographic rainfall is very high (Table 2-18). Mean monthly runoff from the Ruo catchment is given in Figure 2-46. Mean annual runoff from the Ruo is about 1.8 x 10^9 m^3 (57 m^3/s), with a coefficient of variation of 0.32. The Ruo can contribute substantially to peak flooding in the lower Shire Valley. Runoff increases rapidly with the onset of the rains in November, reaching a mean maximum discharge of 500 m^3/s in January. The five-year return period for Ruo River peak runoff is 1000 m^3/s. Peak Shire runoff below the Ruo confluence is partially attenuated by the Ndindi marsh that borders much of the lower Shire to the Zambezi confluence.

The total catchment area of the Shire Valley below Lake Malawi is 31,760 km^2. The estimated mean annual runoff volume is about 17 x 10^9 m^3, with a coefficient of variation of 0.40. Estimated mean monthly Shire River flow near the Zambezi confluence is shown in Figure 2-46. Runoff rises sharply from December to January, peaking on average in February-March, and receding steadily from April to November. Mean monthly runoff during peak flooding is about 800 m^3/s, with maximum annual flows ranging from 1000-1800 m^3/s. The 20-year return period runoff from the Shire River (1800 m^3/s) is substantially lower than from the Moravia-Angonia and Manica Plateaus, reflecting the significant attenuation of peak floods by lower Shire floodplains (Figure 2-48).

When the Zambezi is in flood, it backs water up the Shire Valley nearly 80 km upstream (Halcrow and Partners 1954). The Zui Zui channel functions as an overflow channel from the mainstem Zambezi, running north and east across the southern end of the Ndindi Marsh to join the Shire some 50 km upstream. During years of above average Zambezi runoff, the Zui Zui may discharge a quantity of water into the Shire that far exceeds the flow of the Shire itself. The right bank of the Zambezi opposite the Shire confluence has a high railway embankment designed to withstand overtopping during floods (the embankment was constructed 1 m higher than the 1952 flood maximum). This has the effect of channelizing the Zambezi and raising it slightly above its normal maximum flood level in this reach

Since 1960, Lake Malawi outflow has been partially regulated by the Liwonde Barrage. The dam is operated to maintain high dry season flows in the Shire River for run-of-river hydropower generation at

Nkulu and Tedzani Falls stations[18] (Shawinigan-Lavalin and Hidrotécnica Portuguesa 1990b). At high lake levels, outflow to the lower Shire is largely unaffected.

Runoff in the lower Shire Valley is also affected by slash and burn agriculture in the densely populated highlands. High rates of erosion and rapid surface water runoff were first reported from the Ruo River catchment and elsewhere in the valley nearly 50 years ago (Halcrow and Partners 1954). Future development projects in the Shire catchment may further alter runoff patterns[19].

The Zangue system

South of the Zambezi River, the Great Rift Valley extends from the Shire confluence to the Pungue River basin. The Zangue, a seasonal sandbank river (Figure 2-2) drains this stretch, known as the Urema Trough. The Zangue follows a very flat, meandering course on the Rift floor, collecting runoff from the surrounding escarpment. The total catchment area of the Zangue is about 8500 km^2 (Loxton, Hunting and Associates *et al.* 1975a).

Historically, the Shire River drained through the Urema Trough to the Pungue River system, reaching the Indian Ocean coast at present-day Beira (Timberlake 1998). Pleistocene faulting processes in the Rift Valley eventually caused a northward tilting of the land surface sufficient to produce the north-flowing Zangue River that now drains back to the Zambezi (Tinley 1977)[20]. The extent of the upper Zangue is defined by its former levee, bar, and splay deposits which now act as a drainage divide on the Rift floor (Tinley 1994). In years of exceptional flooding, the Lower Zambezi flood backs up into the Zangue, which may overtop the divide and spill into the Pungue (Davies 1986), although a flood of this magnitude is unlikely (Loxton, Hunting and Associates *et al.* 1975a).

Rainfall on the Rift Valley floor is approximately 600-700 mm/annum, but much higher (1000-1300 mm/annum) on the valley highlands. Loxton, Hunting and Associates *et al.* (1975a) estimated the total volume of Zangue runoff generated from valley rainfall at 60-65 mm, resulting in a mean annual discharge to the Zambezi of about 0.5 x 10^9 m^3 (15.9 m^3/s). This flow contribution is negligible relative to Zambezi flows.

The Zambezi Delta

About 40 km downstream of the Rift Valley confluence, the Zambezi anabranches give way to a distributary channel network of the Zambezi Delta (Figure 2-2). The delta is a broad, flat alluvial plan, 0-100 m amsl, supporting a vast mosaic of grassland, palm, thicket, woodland, and mangrove communities. From its apex near Mopeia, 120 km from the main mouth of the Zambezi, the delta forms a large triangle with the Indian Ocean coast. The delta extends 200 km along the coast from mouth of Zuni River in the south to the Cuacua River outlet near Quelimane in the north. The delta covers an estimated total area of 1.2 million ha.

Water levels in the upper Zambezi Delta at Marromeu reflect the cumulative runoff patterns from the Zambezi catchment. The estimated volume of annual runoff reaching the delta is approximately 108 x 10^9 m^3 (3424 m^3/s), with a substantial range of annual variation (Table 2-19). Each sub-basin is capable of generating significant flood flows in the delta region, independent of runoff elsewhere in the catchment. When large runoff events occur in two or more of these catchments, exceptional floods can result in the delta region (Appendix 2). Liesegang and Chidiamassamba (1997) found written records of such floods dating back to 1648 and descriptions of large floods causing major inundations are common in the oral histories of the delta dating back to 1830. The flood of 1840 is considered to be the largest in cultural memory, opening up the Zui Zui channel into the Shire River and creating the island of Inhangoma (White 1993).

Hydrographs of daily water level fluctuations at Marromeu are given for the period prior to Zambezi regulation in Figure 2-49. River levels typically begin rising in late December in response to rainfall in the lower Zambezi catchment, with an early spike in late-January. The main peak arrives from the Upper and Middle Zambezi catchments in February-March. During years of heavy rainfall in the Shire Valley, Shire River runoff coincides with runoff from the Upper and Middle Zambezi catchments and peak

Table 2-19. Summary of estimated mean annual runoff (with 95% confidence intervals) for sub-basins in the Zambezi catchment.

Zambezi sub-basins	Catchment area (km^2)	Mean annual runoff ± 95% confidence interval (x 10^9 m^3)	Mean annual discharge ± 95% confidence interval (m^3/s)
Upper Zambezi catchment	507,200	32.9 ± 25.7	1046 ± 815
Gwembe Valley catchment	156,600	7.2 ± 6.2	222 ± 196
Total to Kariba Gorge	663,800	40.1 ± 31.4	1268`± 997
Kafue River catchment	154,200	9.0 ± 8.8	285 ± 279
Luangwa River and ungauged Middle Zambezi catchments	232,000	28.0 ± 25.8	888 ± 818
Total to Cahora Bassa Gorge	1,050,000	77.1 ± 60.4	2442 ± 1917
Plateau tributaries	177,500	13.0 ± 11.5	412 ± 365
Shire Basin	154,000	17.0 ± 13.3	539 ± 422
Zangue Basin	8,500	0.5 ± 0.4	16 ± 14
Total to Zambezi Delta	1,390,000	107.6 ± 84.4	3424 ± 2675

flooding may be prolonged well into April. The mean maximum water level prior to Zambezi regulation was 6.94 m, with a maximum annual flood peak of 8.00 m (about 22,000 m^3/s) and a minimum annual peak of 4.14 (about 4000 m^3/s). Water levels exceeded 5.0 m, the flood alert stage corresponding to a discharge of 4500-5000 m^3/s, during 26 of the 28 years (93%) prior to river regulation (Figure 2-50). The average duration of overbank flooding above this threshold was 72 days (Table 2-20). Water levels receded to their annual minimum of about 1-2 m in late November. Runoff patterns contributing to the large historical floods of 1939, 1952, and 1958 are described in Appendix 2.

Table 2-20. Average duration (in days) of Zambezi Delta flood stages above given thresholds.

Water level exceedance	1930/31-57/58	1958/59-73/74	1974/75-2000/01 (with gaps)
> 5.0 m	72	72	42
> 5.5 m	52	52	30
> 6.0 m	39	33	19
> 6.5 m	26	20	9
> 7.0 m	18	14	6
> 7.5 m	9	8	2
> 7.85 m	4	2	0

With the completion of Kariba Dam in 1959, average flood levels in the Zambezi began to decline. During the first two years of filling Kariba Dam, peak flood levels in the delta dropped to record lows (Figure 2-51). Over the entire period 1959-74, the mean maximum water level was 6.30 m. Flood levels fell below the 5.0-m flooding threshold in 3 of the 15 years. Following the extreme drought of 1972, maximum water levels reached only 3.5 m in the delta. Overall, the shape of the delta hydrograph did not change significantly because this period coincided with extended above-average rainfall in the Zambezi catchment (Figure 2-8). The average duration of overbank flooding was comparable to the pre-dam period (Table 2-20).

Since 1974, the operation of Cahora Bassa Dam has greatly changed runoff patterns in the delta. Although data are available from only a limited number of years during this period[21], the average daily hydrograph from 1974-77 give an indication of the magnitude of these changes (Figure 2-52). In 1975, two overbank flood peaks occurred, one rising sharply following a large discharge from Cahora Bassa Dam in mid-March, and the second during the middle of the dry season in mid-July. In 1976, flood levels peaked above the level of overbank flooding three times, with sharp peaks mid-April and again in mid-May, and prolonged flooding during the dry season from mid-June to early-August. In 1976/77, flood levels shot up in late December, remaining near or above flood stage until mid-March. Smaller peaks occurred in mid-July and mid-September. The major inundation of 1978 (described in Appendix 2) resulted from high volume, short-duration releases from Cahora Bassa in response to the perceived risk of overtopping the dam wall. Flood peaks during the mid-1990s, when turbines were not operating, were derived from local runoff in the lower Zambezi as Cahora Bassa released a constant discharge of about 1700 m^3/s. Flood peaks in the delta below Cahora Bassa dam reached only 3.6 m in 1993. Overall, the average duration of flooding has decreased sharply (Table 2-20), and this divergence would be even more pronounced if continuous data were available from the 1980s because water levels remained below 5.0 m until the end of the decade.

Summary

Prior to water resources development in the Zambezi catchment, each Zambezi sub-basin contributed independently to the characteristic pattern of runoff in the delta. Rapid runoff from the broad Central African plateau in Zimbabwe, Zambia, and central Mozambique contributed to one or more early flood peaks during December and January. Attenuated runoff from the Zambezi headwaters below the Barotse Plain and Chobe Swamps, Kafue River below the Lukanga Swamps and Kafue Flats, and Shire River below the Elephant and Ndindi marshes delayed peak flooding in the delta and maintained early dry season runoff.

Over the past 40 years, the management of Kariba, Itezhitezhi, Kafue Gorge, and Cahora Bassa Reservoirs for hydropower generation has altered these runoff patterns. Runoff in the lower Zambezi basin is now a function of regulated outflows from Cahora Bassa, flashy runoff from the Mozambique plateau, and partially regulated Shire River inflows. These new patterns of runoff have a profound effect on the flooding regime of the Zambezi Delta and the social and ecological systems that depend on the annual flood pulse, as discussed below. They also pose severe constraints on the potential for improving the delta's hydrological regime in the future (Working Paper #4).

FLOODING PATTERNS IN THE ZAMBEZI DELTA

Overview

Efforts to ameliorate adverse hydrological changes in the Zambezi system also depend on an understanding of long-term changes in delta flooding patterns. The delta flooding regime results from the complex interaction of regional runoff patterns with local geomorphology, rainfall-runoff, and tidal fluctuations. As discussed in the previous section, the hydrological regime of the Zambezi Delta is substantially affected by changes in runoff patterns from the Zambezi catchment. In the delta region, roads and embankments that impede the movement of floodwaters from the mainstem Zambezi to the delta floodplains further alter the flooding regime. In this section, I examine the seasonal flooding patterns in the delta, and assess how flooding has changed over time due to changes in the degradation of the delta floodway system. Related changes in the water balance of the floodplain are assessed in section 2-4.

Methods

To assess changes in flooding patterns, I used a combination of field surveys, topographic data, historical written records, and oral history data. I approximated the minimum discharge necessary to spill floodwaters into the delta distributaries by measuring water levels at each channel inlet and relating stage measurements to Zambezi flow data using the Marromeu rating curve (Hidrotécnica Portuguesa 1965c). I estimated the minimum discharge necessary to overtop the road/railway embankment by measuring embankment height at fixed locations and relating elevation information to the Marromeu rating curve. I estimated thresholds for flow movement through the Inhaminga-Marromeu abandoned railway based on observation during the peak of the 2001 floods.

I assessed flooding extent in the delta corresponding to different Zambezi discharges using topographic data. Using a complete set of 1:50,000 maps of the Zambezi Delta region, I produced a 1 m contour topographic map of the delta with the assistance of a GIS analyst (Hidrotécnica Portuguesa 1965i). Flood distributary channels, embankments, and other physical features were digitized from a 2000 Landsat ETM image and overlayed on the topographic map. I estimated the Zambezi River stage corresponding to different discharge levels using the Marromeu rating curve, and estimated flooding extent directly from river stage levels during peak flooding events when river and floodplain water levels are roughly equivalent. This approach provides a general approximation of flooding extent for the purpose of assessing the movement of floodwaters between the mainstem Zambezi and delta floodplains[22].

Historical accounts of Zambezi flooding were compiled from a number of written records in English and Portuguese, most notably the journals and letters from early Portuguese missions and the Livingstone expeditions, and natural history surveys of the Lower Zambezi from the early 1900s. Historical accounts of hydrological conditions in the Zambezi Delta region were collected during interviews with local chiefs and other long-term residents of the study area. Interviews were conducted in several areas throughout the delta, including the villages of Marromeu, Luabo, Malingapans, and Chinde along the main Zambezi channel, and scattered settlements along the Cheringoma escarpment. In addition to answering a series of informal questions about the magnitude, timing, duration, and frequency of historical floods and droughts, informants were asked to identify historical normal and extreme high water marks and other hydrological indicators in the field. These measurements were related to Zambezi flow data where possible.

Analysis of flooding patterns in the Zambezi Delta

Junk *et al.* (1989) describe the spread of floodwaters as a nutrient-rich *moving littoral zone* that traverses the floodplain as flooding and drawdown take place. The spread of floodwaters is affected by water already present on the floodplain from rainfall, local runoff, groundwater upwelling, and antecedent moisture conditions (Mertes 1997) and the soils and drainage geomorphology of the floodplain system (Leopold *et al.* 1964).

The Zambezi Delta formed from the accumulation of sediments and alluvium transported downstream by the Zambezi River over several thousand years. Alluvial plains, colluvium, and eluvium from the Quaternary cover the entire delta region, with mosaics of various clays, clay loams, and organic silts underlying much of the permanently and seasonally flooded plain (Loxton, Hunting and Associates *et al.* 1975c&d). Most of the delta is covered by heavy textured, gleyed soils. At the floodplain periphery and on the reverse slopes of river levees, vast areas of the delta are dominated by hydromorphic vertisols that swell during the rainy season, with minimal permeability, and become dry and deeply cracked during the dry season. These soils often feature hummocky microrelief. In the extensive lowland depressions of the central delta plains, humid gleys become dominant. These areas either remain saturated or have highwater table conditions throughout the dry season (Tinley 1994). The thin top soils, on drying, forms a hard crust that is impermeable when the first rains arrive.

At the onset of the rainy season, local rainfall saturates and pools on the delta soils. Rainfall over the delta, as elsewhere in the Zambezi catchment, is strongly influenced by the movement of the Inter-Tropical Convergence Zone[1]. The main rainy season in the delta usually occurs over a 4-6 month period between October and April, and is characterized by brief periods of thunderstorms followed by periods of drier weather[23]. The delta is subject to torrential rains from cyclones that can occur in any month from December to March and cause widespread local flooding. The maximum 24-hour rainfall is 251 mm at Chinde and 146 mm further inland at Marromeu.

As the rainy season continues, local runoff from the surrounding Rift Valley escarpment more deeply inundates floodplains along the northern and western perimeter of the delta. On the north bank, rainfall drains from the undulating terrain of the Morrumbula Plateau that separates the Shire and Zambezi Valleys. The plateau is covered in fairly dense woodlands from which emerge towering outcrops of sedimentary rocks of the Great Rift Valley. The Morrumbula surface is covered by deep unconsolidated eluvium of fine-grained sands, incised by a series of rivers (including the perennial Luaua and Licuria Rivers and several smaller streams) that drain southwards into the northern delta floodplains (Loxton, Hunting and Associates *et al.* 1975d). The quartz-rich sands may attain a thickness of 30 m on the upper escarpment, but thin to less than 100 cm where the plateau surface folds under the deltoid plain (Smidt 1988). Runoff that is not channelized moves as subsurface and groundwater flow through the sands and discharges to the sandy, hydromorphic soils at the base of the escarpment. The total catchment area of the northern escarpment draining to the delta is approximately 25,000 km^2.

On the south bank, the gentle backslope of the Cheringoma Plateau rises gradually from the western alluvial lowland plains at a 3^{o} -5^{o} incline to an elevation of 394 m, and forms the eastern side of the Rift Valley. The plateau is composed of Cretaceous and Tertiary limestones, overlain by Quaternary sands (Tinley 1977). Characteristic red loamy soils cover the upper summit area, with Pleistocene sands over clay subsoils on the backslope. The Mungari, Ruave, Sanga, and Zuni Rivers rise on the crest slope of the Cheringoma escarpment and fan out in distinct outwash plains of alluvial sand fans along the western edge of the Zambezi Delta. The convex fan surfaces support miombo woodland, with wet grassland on the interdistributary slacks. The total catchment area of the Cheringoma escarpment is 10,766 km^2, of which approximately 8,300 km^2 drains directly delta. The Zuni River discharges to the far southeastern corner of delta, and is tidal in its lower reaches as it follows a torturous path through coastal mangroves to the Indian Ocean. Along the western edge of the Marromeu floodplains, the Nhandue River drains runoff from the escarpment, especially the Ruave and Sanga channels, and discharges to the coast along a narrow, meandering path incised through mangrove mudflats. Runoff from the Mungari River drains into the Marromeu floodplains, and combines with runoff from the Cuncue distributary of the mainstem Zambezi channel. These streams follow an anastomosing flow path through the low-lying delta floodplains, and drain to the sea via the broad outlet channel of the Luaua River. Surface water runoff from smaller streams collects in a series of shallow lakes and lagoons in this region.

Inundation of the entire delta occurs when the Zambezi River overtops its banks and spreads laterally over the delta or through distributary channels. As the Zambezi enters the delta region, the river divides into a complex network of distributary channels (Figure 2-53). The Cuacua waterway breaks off first, just south of Mopeia, to feed the dense distributary network of the north bank plains. Historically, the Cuacua was a major perennial branch of the Zambezi River. Early explores and traders, including Livingstone, traveled up the Cuacua channel from Quelimane to reach the mainstem Zambezi and points further inland (*e.g.*, Livingstone 1857). The Cuacua collects substantial wet season runoff along its course adjacent to the Morrumbula plateau. Several channels break off and drain to Indian Ocean between Quelimane and Chinde, flooding low-lying areas along the coast and eventually discharging into a vast papyrus swamp (<0.5 m amsl) along the northwest perimeter of the delta. The Muta River runs parallel to the Cuacua to the south, exchanging runoff during high flows. Much of the remaining north bank region south of the Muta is characterized by relict channels that served as distributaries from the mainstem Zambezi before the river down-cut to its present-day base level. These channels include the Mucacau, Bazar, Nhangone, and Inhamara Rivers that drain local runoff directly to the coast and the Inhaombe and Maucane Rivers that drain into the Catarina branch of the Zambezi River.

Along the south bank of the mainstem Zambezi between Chupanga and Marromeu, three distributary channels drain to the low-lying floodplains (0-1 m amsl) of the Marromeu complex (Figure 2-53). The Salone River breaks off first, flowing along the western edge of the delta and collecting runoff from the Cheringoma plateau before discharging into the northwestern portion of the Marromeu complex. The Cuncue River drains directly into the northern portion of Marromeu floodplain. The Nhasaua River flows parallel to the mainstem Zambezi and discharges to the eastern portion of the Marromeu floodplain. Figure 2-54 shows a cross-sectional profile of the Zambezi downstream of this reach. Historically, these channels began discharging to the delta when Zambezi flows exceeded about 4500 m^3/s. The south bank drains from the delta to the Indian Ocean coast through the Luaua, Nhandue, and Zuni outlets. Floodwaters collecting in the broad central depressions of Marromeu floodplains maintain ponded or saturated soil conditions throughout the dry season, lost slowly through evapotranspiration.

At about 5000 m^3/s, the Zambezi reached bankful capacity and spread laterally into the upper floodplains. On the north bank, floodwaters spread across the floodplains near Mopeia and formed a large shallow lake with the Cuacua and Muta channels. South bank floodwaters moved slowly as overland sheet flow through the Salone depression from the mainstem Zambezi to the southwest corner of the delta. Highland areas near the present-day villages of Marromeu and Luabo formed natural islands in the floodplain that were inundated only during exceptional flooding events.

About 25 km downstream of Marromeu the Mucelo River branches off from the mainstem Zambezi. The Mucelo, which defines the eastern boundary of Marromeu Reserve, follows a flat, meandering path to the coast through coastal grasslands (2-3 m amsl) and dense mangroves. The Mucelo captures runoff from the relict Sagasse River channel that rises on old alluvium and flows parallel to the mainstem Zambezi below Marromeu. During peak flooding, the Mucelo spills overbank into the surrounding floodplains and forms a broad channel to the ocean.

Further downstream, some 30 km from the coast, the main Zambezi channel divides in two, with the Chinde River to the north and the mainstem Zambezi River to the south. Figure 2-55 shows a cross-sectional profile of the delta just downstream of this reach. The Chinde River meanders eastward to form a navigable channel leading to a shallow harbor at the coastal port of Chinde. Near the coast, the Chinde captures runoff from the Maria River, a small channel that breaks from the mainstem Zambezi just north of the Chinde River divide and collects runoff from the northern floodplains. The main Zambezi channel divides a final time about 15 km from the sea, opening up into two large coastal outlets, the Zambezi mouth (*Boca do Zambeze*) and smaller Catarina River. The lower Zambezi channels near the coast have gently sloping banks, and much of the region is inundated as floodwaters rise.

Flooding patterns near the delta coast are also influenced by oceanic tides (Hidrotécnica Portuguesa 1965l). The delta region has the highest tidal variation in Mozambique and one of the highest along the East African coast (Tinley 1971). At spring tide, the maximum tidal amplitude is 4.1 m at Chinde and 4.7 m at Quelimane. During the rainy season, high tide levels back up Zambezi flows and spread floodwaters over the coastal plains. During the dry season, tidal influence is evident for 80 km upstream.

Over the past century, flooding patterns in the delta have been affected by the operation of Kariba and especially Cahora Bassa Dam, the construction of embankments along the mainstem Zambezi, upper delta floodplains, and coastal plains, and the down-cutting of the main Zambezi channel. The effect of Zambezi River regulation on delta runoff patterns was discussed in section 2-2. Zambezi flows now rarely exceed the minimum threshold of 4500 m^3/s for discharging into the upper delta waterways. Overbank flooding is mostly limited to the brackish coastal region under tidal influence.

Even during years of heavy runoff from the Zambezi catchment, however, the movement of floodwaters from the mainstem Zambezi to the delta floodplain is severely obstructed by large dikes constructed for the roadway and railway line along the Zambezi and the abandoned railroad levee between Marromeu and Inhaminga (Figure 2-56). Roadway dikes along the mainstem Zambezi now prevent Zambezi runoff from spreading overbank unless water levels exceed 7.5-7.6 m (approximately 13,000 m^3/s). The abandoned railway line (built above the maximum probable flood level) blocks all sheetflow movement in the Salone depression from the southern floodplains. Flow along this 30 km stretch is restricted to two narrow culverts that pass local runoff in the Salone and Cuncue channels. Near the villagers of Marromeu and Luabo, embankments protecting the Sena sugar fields confine the Zambezi River to its mainstem channel and impede floodwaters from spreading into the southern Marromeu complex. These embankments were set at the height of the 1926 flood, at an elevation of 7.85 m amsl (approximately 18-19,000 m^3/s) (Figure 2-54). Floods above this magnitude have occurred only six times in the past century (Appendix 2). Floodwaters must now recurve southwards downstream of Marromeu village to inundate the southern delta area. The southern delta is thus only inundated by large floods, and the vast annual flooding of the Marromeu complex no longer occurs. The widespread flooding of 2001 (reaching a maximum elevation of 7.69 m) overtopped parts of the roadway and railway line, but did not overtop the Sena sugar embankments nor the abandoned railway line. Exceptional rainfall in the Cheringoma escarpment – 800 mm was unofficially recorded during January 2001 at the Zambezi Delta Safari camp in the Marromeu Complex (Dr. Patrocinio da Silva *pers.*

comm.) – contributed to most of the flooding in the delta plains.

Embankments also affect the north bank region, although to a lesser degree than the south bank. The Sena sugar fields at Mopeia were abandoned during the 1930s and the protection dikes were subsequently washed away during the floods of the 1940s and 1950s (Loxton, Hunting and Associates *et al.* 1975d), although relict embankments affect surface flow movement in the north bank plains. When Zambezi discharge reaches about 4000 m^3/s, floodwaters discharge through the Cuacua distributary channel towards Quelimane and flood overbank into the low-lying floodplain at the base of the Morrumbula escarpment (Figure 2-57). At 7-9000 m^3/s, low areas of floodplain opposite Marromeu are also inundated, but water movement to the southern floodplains is impeded (Figure 2-58). At flows above 13,000 m^3/s, widespread areas of the north bank opposite Marromeu are inundated but little of the south bank is flooded (Figure 2-59). Upstream at the Shire confluence, Zambezi floodwaters spread over Inhangoma Island at this magnitude and the south bank between Mutarara and Caia is completely inundated to the railway embankment with water backing up the Zangue River. Only during exceptional flooding events (flows exceeding 19,000 m^3/s) do floodwaters spread over most of the delta including the highland areas at Marromeu and Luabo (Appendix 2). Along the north bank coastline, the road connecting Chinde and Quelimane disrupts the movement of tidally-influenced floodwaters and affects soil salinity (Loxton, Hunting and Associates *et al.* 1975f), as reflected in local vegetation distribution patterns (Working Paper #3).

Flooding patterns in the delta are also affected by the degradation of the mainstem Zambezi. Historically, the lower Zambezi was a braided river of wide, shallow channels, with rapid movement of bed materials and lateral shifting of the river course between the outer floodplain banks and levees (Jackson 1961). Over the past 40 years of river regulation, the Zambezi has down-cut a channel in the floodplain alluvium, as much as 2-3 m below its former level. The river has degraded below the base level of most of its upper distributary channels, with bars of alluvium blocking the upper distributary inlets. For the Cuncue and Nhasaua, these bars are only overtopped when the Zambezi discharge exceeds about 8-10,000 m^3/s. Zambezi floodwaters enter the Cuacua and Salone channels at lower discharge thresholds (about 4000-4500 m^3/s), but none of the upper distributaries are perennial. Overall, the pattern of high dry season flows and reduced flood season flows has resulted in the dominance of a few permanent channels where previously there were several active, shifting channels. Most of the lower Zambezi River is now a stable braided chain of rivulets weaving between consolidated islands, resulting in permanent sandbars with riverine grassland and cultivated fields near Marromeu (Davies *et al.* 2001).

Summary

The exchange of floodwaters between the mainstem Zambezi and delta floodplains is highly sensitive to regional hydrological changes in the Zambezi catchment, local obstructions to flow movement, and geomorphic changes along the mainstem Zambezi. Under historical conditions, the annual floods spread floodwaters over vast areas of the delta plain. In recent years, however, regulated outflows from Kariba and Cahora Bassa Dams and high embankments along the mainstem Zambezi and floodways have combined to drastically alter flooding patterns in the delta. Zambezi flows rarely exceed the minimum threshold for inundating the north bank floodplain. And the south bank is flooded only during very large flooding events. These changes have lead to a fundament shift in the delta water balance, from a flood-driven system to a rainfall-driven system.

WATER BALANCE OF THE ZAMBEZI DELTA

Overview

The water balance is an essential tool for understanding the hydrological regime of floodplain systems (*e.g.*, Balek 1977, LaBaugh 1986, Mitsch and Gosselink 1993) and assessing the impact of development activities (Sutcliffe and Parks 1989, Thompson and Hollis 1995). Several studies have examined the overall water balance of the Zambezi catchment, most notably Balek (1971b).

The basic water balance for the Zambezi Delta can be expressed in the form,

$$\Delta S = S_{t+1} - S_t = P_t + R_t + G_t + Q_t - ET_t - g_t - q_t - D_t$$

where S is the volume of water stored in the floodplain, P is rainfall, R is runoff from the surrounding Rift Valley escarpment, G is groundwater inflow, Q is surface water inflows from the Zambezi River, ET is evapotranspiration, g is groundwater outflow, q is surface water outflow to the Zambezi River, and D is surface water drainage to the coast, at time t. Other offtakes, such as diversions for irrigation and water supply, are considered negligible. The volume of water stored in the floodplain includes both surface water and subsurface water in the rooting (phreatophytic) zone. Water moving below the phreatophytic zone is considered groundwater outflow, either to deep aquifers or the ocean.

The central tendency and variation of each of these inputs and outputs over the same time period define the delta water balance. If regional climatic conditions are stationary (no long-term shift in mean conditions) and rainfall-runoff characteristics in the catchment remain unchanged over long periods of time, there is no net change in water storage in the floodplain and the long-term annual water balance can be restated as,

$$P + R + G + Q = E + g + D + q$$

or simply that the sum of long-term mean annual rainfall, local runoff, groundwater, and Zambezi River inflows is balanced by evapotranspiration, groundwater, coastal, and Zambezi outflows.

The period of time over which the water balance is computed is critical to accurately assessing changes in the water regime. Within years, the relative magnitude of different water balance components change daily, monthly, and seasonally and water levels rise and fall accordingly. Errors in the estimation of individual water balance components also tend to be high (Winter 1981). Among years, water levels may undergo periods of net annual increase or decrease depending on the influence of climatic cycles on different water balance components (*e.g.,* Van der Valk 1978, Finlayson 1991). Over longer time periods, however, water balance components in undisturbed wetlands will generally vary around a long-term mean value (*e.g.,* LaBaugh 1986).

When water resources development projects change runoff conditions in the catchment, however, the mean and variance of certain water balance components may shift. Sutcliffe and Parks (1989) and Thompson and Hollis (1995) observed long-term declines in storage (soil moisture recharge) at the end of successive dry seasons for African floodplains affected by upstream dams. If floodwaters fail to inundate the delta, the extent and depth of surface waters is greatly reduced. Rainfall is generally insufficient to maintain saturated soil conditions through the dry season in all but the deepest depressions on the floodplain. The recharge of underlying aquifers decreases, and local and regional water tables may fall. Vegetation becomes water-limited during the dry season, and rates of evapotranspiration decrease. Surface water outflow and drainage to the ocean decrease in relation to the decreasing magnitude of flows. Over time, the annual water balance deficit may compound to such an extent that periodic large flooding events cannot recharge water levels, and the shift in the wetland water balance may become permanent.

In this section, I examine the delta water balance, and examine the hypothesis that changes in Zambezi runoff patterns and local flooding patterns due to water resources development have significantly altered the relative magnitude of different water balance components over time. Two time periods are considered, the historical period prior to development of the Zambezi catchment and the recent period since Zambezi development, using long-term time series data.

Methods

To quantify changes in the Zambezi Delta water balance over time, I estimated the mean and variability of annual rainfall, evapotranspiration, local runoff, groundwater inflow and outflow, Zambezi River inflow and outflow, and coastal drainage under historical (pre-impact) and current conditions. True pre-impact conditions correspond to the period prior to embankment construction, which dates back to the early 1900s. The earliest available data for the Zambezi catchment, however, date back to 1907 and reliable data on rainfall and runoff in the lower Zambezi basin are only available since the 1930s. Therefore, I simulated the water balance of the delta under pre-impact and current conditions using the same time series data. Rainfall and local runoff are assumed to be stationary over the long-term. Other water balance components are assumed to change in response to water resources development projects in the Zambezi catchment. Potential sources of error in the estimation of each component are discussed in Appendix 1.

Rainfall data for the delta region is recorded at Chinde, Marromeu, Mopeia, and Quelimane (Table 2-1). I estimated average rainfall for the delta as the weighted-average (based on the proportion of the total area closest to each gauge) of these four stations, and estimated variance from the averaged time series data. Sources of rainfall data include the Institute of Meteorology and Direcção Naçional de Aguas (DNA) in Mozambique and the Loxton, Hunting and Associates *et al.* (1975b) reports. I tested long-term rainfall records at Quelimane and Beira, which include also recent data from the period 1975-00, for shifts in the mean annual series. I estimated average evaporation for the delta using the data from the meteorological station at Beira. I increased the mean monthly and annual pan evaporation data by 5% to account for higher rainfall and lower temperatures at Beira relative to the delta. I derived an estimate for evapotranspiration at Mopeia from agricultural measurements reported in Loxton, Hunting and Associates *et al.* (1975h). The rate of evapotranspiration in the delta is a function of soil moisture availability during the dry season, which in turn depends on the duration of flooding, and is therefore not assumed to be stationary between the pre-impact and current periods of record.

Direct measurements of local runoff and groundwater movement in the delta are not available. I estimated runoff from the Rift Valley escarpment using local rainfall records from Inhaminga and Morrumbala (Table 2-1) and unit runoff coefficients taken from other areas in the Zambezi catchment with comparable topography, soils, vegetation, and land use practices (Sharma and Nyumbu 1985). Groundwater inflow includes baseflow feeding the perennial streams that drain the escarpment (included in the estimate of local runoff) and subsurface flows discharging at the base of the Rift Valley escarpment. The latter groundwater input is estimated from infiltration studies on the escarpment surface. Horizontal groundwater movement in the delta is considered negligible because of the dense underlying clay soils (hydraulic conductivity less than 0.09 m/day) and flat topography (Smidt 1988). Although most of escarpment woodlands have been selectively cleared over time for shifting subsistence agriculture and logging operations, and uncontrolled fires have become more frequent (Saket *et al.* 1999), the cumulative effects of these changes on escarpment runoff are unknown. Long-term mean annual local rainfall-runoff is assumed to be stationary, but could be increasing slightly in areas of local deforestation.

I estimated long-term monthly and mean annual flow into the Zambezi Delta in two steps. First, Zambezi River runoff from the catchment above the delta was estimated. Historical flows were estimated for the period 1930-58 as the sum of measured mean monthly flows at Muturara and estimated mean monthly flows for the Shire River near the Zambezi confluence. Inflows from the Zangue River (less than 0.5% of total Zambezi flows) were ignored. Recent flows for the period 1976-00 were estimated as the sum of mean monthly outflows from Cahora Bassa Dam, estimated mean monthly inflows from the Plateau region of the lower Zambezi Valley, and estimated mean monthly inflows from the Shire River. Sources of runoff data include the DNA, Hidroeléctrica de Cabora Bassa (HCB), and Ministry of Water Affairs in Malawi.

Long-term mean annual Zambezi runoff is assumed to be stationary. Higher rates of runoff due to land use changes in the catchment are assumed to be roughly balanced by lower rates of runoff due to net reservoir evaporation. Because of the prolonged drought in the lower Zambezi catchment from 1980-95, however, mean annual runoff since 1976 is 37% lower than mean annual runoff prior to construction of Kariba Dam.

I considered four scenarios for estimating the effects of Zambezi regulation and infrastructure development on the magnitude of runoff from the Zambezi River into the delta. Inflows to the delta corresponding to unregulated conditions were estimated for the period 1930-58, first assuming no embankments or other obstructions to flow in the delta, and then assuming full obstructions (the current situation). This provides an estimate of delta inflows under historical conditions and the impact of local development works. Inflows to the delta corresponding to the period 1976-00 were next estimated with regulated Zambezi conditions, with and without local impediments to flow as above.

I estimated runoff from the Zambezi River to the Delta with no obstructions using two threshold discharges. When Zambezi discharge is less than 4500 m^3/s, I estimated that 5% of Zambezi flows enters the delta through the Salone and Cuacua distributaries, and the remainder is discharged directly to the Indian Ocean. Twenty-five percent of Zambezi flows above the 4500 m^3/s threshold are assumed to discharge into the delta floodplain based on the estimated capacity of the upper Zambezi distributary channels. When the Zambezi exceeds bankful capacity (5000 m^3/s), all flows in excess of this threshold are assumed to discharge into the delta floodplain. The proportion of days during which Zambezi flows exceed the given thresholds were estimated from long-term daily data at Muturara for the period 1930-58.

I estimated runoff from the Zambezi River to the Delta under current conditions using three threshold discharges. When Zambezi discharge is less than 4500 m^3/s, all flow is discharged directly to the Indian Ocean. Ten percent of Zambezi flows above the 4500 m^3/s threshold are assumed to discharge into the delta north bank based on the estimated capacity of the Cuacua and Salone distributaries. Twenty five percent of Zambezi flows above 5000 m^3/s are assumed to discharge into the north bank floodplain as overbank flooding is initiated. When Zambezi flows exceed the elevation of the road and railway embankments along the south bank (13,000 m^3/s), all flows in excess of this threshold are assumed to discharge into the delta floodplain. Much of the south bank is not inundated by floodwaters; however, until flows exceed 18-19,000 m^3/s. The proportion of days during which Zambezi flows exceed the given thresholds were estimated from long-term daily flow data at Muturara for the periods 1930-58 and 1976-00. All runoff estimates are converted from discharges to depths (over the 1.2 million ha. delta) for comparison to other water balance components.

The proportion of Zambezi inflows that finally leave as channel outflows depends on the geometry of the channel system and floodplain, and the degree to which the floodplain is restricted by lateral boundaries of higher ground. Sutcliffe and Parks (1989) showed a strong linear relationship between inflows and outflows for the Senegal, Niger, and Sudd floodplain systems, with channelized outflows anywhere from 50-90% of inflows. Direct or indirect methods for estimating the proportion of inflows discharging back to the Zambezi during flood recession and draining directly to the ocean through coastal inlets were not available. Zambezi River outflows were thus estimated as the residual in the water balance equation. Consumptive water use in the delta is currently negligible, but may become significant during the dry season with the rehabilitation of the Sena Sugar estates[24].

Analysis of the delta water balance

Floodplain storage

The volume of water stored in the floodplain includes both surface water and subsurface water in the rooting (phreatophytic) zone. The hydromorphic vertisols and humid gley soils that cover most of the delta plain swell during the rainy season and have minimal permeability. Rain and floodwaters pond in low-lying areas and slowly infiltrate as the rainy season progresses. Some surface water is stored in shallow lakes and papyrus swamps across the floodplain at the end of the dry season, particularly near the Rift Valley escarpments, but most is absorbed by the shallow (unconfined) aquifer and lost through evapotranspiration and seepage to the underlying (deep) aquifer. The total volume of soil moisture recharge is a function of soil texture and surface flooding patterns, particularly the depth and duration of inundation. Highest rates of infiltration to the floodplain substrate occur in the stratified alluvia of the recent levee and channel system that tongues into the deltoid grasslands (Lamorce *et al.* 1995).

Historically, the fine-grained soils maintained highwater table conditions in the shallow aquifer during the dry season (Tinley 1994). During years of exceptional flooding, widespread areas of open water lakes and backwater swamps remained at the end of the dry season. Local wells were recharged to the soil surface. Over the past 25 years or longer, however, water table levels have been steadily declining due to persistent drought and the failure of the annual floods. On the delta south bank, groundwater levels have fallen 5 m or more below the soil surface at the end of the dry season. Local villagers have sunk deep boreholes in areas that were formerly saturated at the end of the dry season (Mr. Antonios Cocorico *pers. comm.*). Despite the prolonged and extensive flooding of the Zambezi Delta during the 2001 wet season, the local water table in the Salone depression fell rapidly during the dry season and at one site reached a minimum of 7 meters below the soil surface in November 2001 (Mr. Joaquim Soza *pers. comm.*).

Rainfall

Mean annual rainfall in the delta is approximately 1130 mm (Table 2-21). The annual volume of rainfall over the 12,000 km^2 delta is estimated at 13.6 $m^3 \times 10^9$ (Figure 2-60). Rainfall is highest along the coastal zone, particularly near Quelimane, and decreases gradually moving inland. Rainfall is highly variable among years, with a coefficient of variation of 0.33. Annual rainfall was 1606 mm in 1962/63, but fell to only 259 mm three years later in 1965/66. Rainfall during one month of a very wet year may exceed the entire annual rainfall during a dry year (the maximum-recorded monthly rainfall is 822 mm in February 1946). Rainfall patterns are generally independent of water resource development activities in the Zambezi catchment, and long-term mean annual rainfall is assumed to be stationary[25]. Statistical analysis of long-term rainfall records at Beira and Quelimane indicates that there is no significant difference between rainfall in the coastal region between 1940-74 and 1975-00.

Table 2-21. Estimated mean monthly and annual rainfall for the Zambezi Delta. Average rainfall is estimated as the weighted-average of four delta rainfall stations.

Station	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Ann
Mopeia	22	80	156	204	177	165	72	37	40	32	20	9	1014
Marromeu	23	56	150	207	162	167	78	37	34	24	18	12	966
Chinde	23	59	158	192	176	172	107	82	74	56	36	18	1154
Quelimane	13	92	171	258	262	254	106	77	65	55	31	14	1398
Delta	**20**	**72**	**159**	**215**	**194**	**190**	**91**	**58**	**53**	**41**	**25**	**12**	**1130**

Open water evaporation and potential evapotranspiration

Solar insolation is high in the delta region for much of the year, resulting in high rates of evaporation and evapotranspiration. Evaporation is highest at the inland extent of the delta, decreasing towards the coastline. Evaporation rates are highest during the period from October to March when temperatures and insolation are at their maximum. Minimum evaporation occurs during the coolest months of June-July. The estimated magnitude and variability of monthly and annual evaporation in the delta region is given in Table 2-22. The coefficient of variation of annual pan evaporation is about 0.23, although actual year-to-year variation in open water evaporation is likely lower. Variability is highest at the end of the dry season.

Table 2-22. Estimated mean monthly and annual open water evaporation for Zambezi Delta. Evaporation is estimated using adjusted Class A evaporation pan data from Beira.

Station	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Ann
Delta	200	210	210	210	180	200	160	130	100	110	130	160	2000

Evaporation exceeds rainfall in all but the wettest months. Potential evapotranspiration from the high watertable soils covering much of the delta floodplains can be assumed to be occurring without moisture limitation during the peak rainy season and during the remaining months in permanently flooded areas. Some degree of moisture limitation occurs during the dry season in seasonally inundated areas. Under these conditions, mean annual water loss from the delta through evapotranspiration is estimated as 1730 mm (Table 2-23). This is approximately 86% of pan evaporation. Highest rates of potential evapotranspiration occur during the end of the dry season and early rainy season months. Evapotranspiration decreases during the cool part of the dry season.

Table 2-23. Estimated mean monthly and annual potential evapotranspiration (mm) from the Zambezi Delta. Evapotranspiration is estimated using Class A evaporation pan data and meteorological data with the modified Penman approach.

Station	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Ann
Delta	186	194	206	200	176	172	137	99	70	67	93	130	1730

The rate of water loss through evaporation and evapotranspiration is a function of the depth and extent of flooding in the delta. Evaporation occurs from dry soil and wet muds in the delta, as well as open water bodies. Evapotranspiration from floodplain grasslands and emergent macrophyte communities, including Phragmites reedswamp, is generally considered to be slightly higher than open water evaporation (Linacre 1976), although the rate of evapotranspiration from Papyrus swamps may be less than that from open water (Rijks 1969). During years when the entire delta has adequate soil moisture (corresponding to successive years of widespread overbank flooding from the Zambezi River), the total volume of water loss is perhaps 20.8 x 10^9 m^3. This is probably an upper limit for the volume of water lost through evaporation and evapotranspiration. During drought years and especially during years when floodwaters do not inundate the plains, water stress occurs and the total volume of evaporative water loss may be significantly reduced. Since construction of Kariba and Cahora Bassa Dams, there has been a dramatic reduction in the area of floodplain inundation. The total area of perennially wet grassland, permanent deepwater swamp, and coastal mangrove is now about 260,000 ha, or 22% of the total delta area (see Working Paper #3). There has been an 18% reduction in permanently flooded areas since 1960, and a 12% reduction in perennially wet grassland. The average duration of inundation in the hydromorphic vertisols along the western edge of the floodplain has decreased from 4-6 months per year in the past to 2-3 months per year today. These changes suggest that moisture conditions have become limiting in many areas of the floodplain. Most of the delta grasslands now burn during the dry season, and deciduous Acacia savanna covers much of the higher delta plain.

Several studies have attempted to define stress coefficients for the reduction in evaporation when moisture is limiting (*e.g.*, Ponnambalam and Adams 1985, Ritchie 1985). Hatfield and Wanjura (1985), for example, showed that actual evaporation was only 15-60% of potential evapotranspiration in semi-arid agricultural systems during the course of the year. Although the magnitude of reduction of evapotranspiration is likely less in the sub-humid delta climate, a decrease of 10% or more is likely, as soils remain parched during the dry season. An adjusted value of 18.7 x 10^9 m^3 is therefore used for evapotranspiration in the current delta water budget. Actual losses may be substantially less during very dry years.

Runoff from the Rift Valley escarpment

Rising to the north and west of the Zambezi Delta, the high plateaus of the Rift Valley provide an important source of freshwater runoff to the delta floodplains. Average annual rainfall on the Rift Valley escarpment is 1000-1100 mm in the Cheringoma plateau and 1100-1300 mm in the Morrumbula plateau (Table 2-24). Rainfall patterns are similar to the delta lowlands, but with relatively heavier rainfall in November at the onset of the rainy season. Peak rainfall occurs from December to March. Rainfall is highly variable among years. Annual rainfall at Inhaminga has ranged from 384-1546 mm. At Morrumbula, annual rainfall has ranged from 750-1617 mm. The maximum-recorded monthly rainfall in January is 648 mm at Inhaminga. As on the delta plains, rainfall is generated by fairly brief, intense thunderstorms between periods of dry weather. There are only 69 rainy days per year on average at Morrumbula (88 at Inhaminga).

Runoff from the Rift Valley escarpment occurs as channelized streamflow and subsurface percolation through the escarpment sands. Direct overland runoff (*e.g.*, Horton 1940) is likely minimal. Runoff patterns are a function of the topography, soils, vegetation, infiltration rates, and antecedent moisture

Table 2-24. Estimated mean monthly and annual rainfall on the Rift Valley escarpment. Inhaminga (elevation 370 m amsl) is located on the Cheringoma escarpment. Morrumbula (505 m amsl) is located on the Morrumbula escarpment.

Station	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Ann
Inhaminga	20	99	179	236	184	166	57	29	30	18	19	15	1052
Morrumbala	30	113	158	234	211	187	61	20	23	27	23	19	1106

conditions of the plateau. Runoff is generally low on the gently sloping, grassy, and highly permeable sands of the escarpment. However, high water table conditions and reduced infiltration during heavy rainfall periods can result in rapid, high volume runoff. Sharma and Nyumbu (1985) calculated unit runoff coefficients over a wide range of conditions in the Upper Zambezi catchment based on annual rainfall distribution. Estimated runoff for conditions similar to the Rift Valley escarpment range from 20-40 mm per 700 mm annual rainfall (3-6%) to 280-350 mm for 1400 mm rainfall (20-25%). More than 600 mm runoff may result from an extreme rainfall of 2000 mm. These relationships generally hold across spatial scales (for comparing different catchments) and temporal scales (the proportion of runoff is much higher in particularly wet years when high water table conditions are maintained over a prolonged period of time). The proportion of runoff from steeper and rockier Morrumbula plateau is somewhat higher than from the Cheringoma.

Based on these relationships, mean annual runoff from the Cheringoma plateau is approximately 150 mm (14% of rainfall), resulting in a runoff volume of 1.2 x 10^9 m^3 for the 8,300 km^2 catchment area draining directly to the delta. Most runoff is transported via the Mungari, Ruave, Sanga, and Zuni Rivers that rise on the Cheringoma escarpment and fan out in along the western edge of the Zambezi Delta. Runoff is significantly higher during wet years. During 2001, vast areas of the western Marromeu complex were inundated 1-2 m from local rainfall-runoff (an estimated 300-500 mm runoff).

Average annual runoff from the Morrumbula plateau is approximately 200 mm (18% of rainfall), resulting in a runoff volume of 4.5 x 10^9 m^3 for the 25,000 km^2 Morrumbula catchment. More than 25 streams drain the plateau, including the perennial Sassune, Chiramba, Tiade, Lungozi, Mocobezi, Luaua, Momede, and Licuari Rivers. The Morrumbula runoff streams are more deeply incised than the Cheringoma streams and have not developed significant alluvial fans.

Total estimated runoff to the delta from the Rift Valley escarpment is therefore 6.7 x 10^9 m^3, or 558 mm averaged over the 1.2 million ha. delta. During a 20-year extreme drought, mean annual runoff may be reduced to only about 9% of mean runoff during normal rainfall conditions (Loxton, Hunting and Associates *et al.* 1975g&h). An estimate of mean monthly runoff from the Cheringoma and Morrumbula plateaus, using the middle range of average annual runoff with runoff distributed in proportion to the average rainfall during the peak rainfall months, is given in Table 2-25.

Groundwater inflow

The main source of groundwater inflow to the delta is from the adjacent Rift Valley escarpment (surface water infiltration to the floodplain aquifer is considered under floodplain storage, discussed above). The majority of rainfall generated in the escarpment region infiltrates to the sandy eluvium. Mean annual infiltration is approximately 900 mm, about 86% of rainfall on the Cheringoma and 82% of rainfall on the Morrumbula. During very dry years, this may decrease to only 200-300 mm. During very wet years, when the proportion of runoff is also much higher, infiltration may increase to more than 1500 mm/annum.

During the wet season some of the infiltrated rainfall percolates downslope as shallow subsurface runoff (with hydraulic conductivities in the range of 9 m/day) and drains to the delta through alluvial fans (Smidt 1988). The deeper infiltrated water discharges slowly downslope and saturates the hydromorphic outwash sands at the delta junction or discharges into a series of shallow lakes at the ecotone. During normal rainfall years, these groundwater flows are sufficient to maintain a trickle of perennial baseflow

Table 2-25. Estimated mean monthly and annual runoff (mm) from the Rift Valley escarpment. Runoff from the Cheringoma escarpment drains to the western edge of the delta. Runoff from the Morrumbula escarpment drains to the northern edge of the delta.

Station	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Ann
Cheringoma	0	14	29	39	31	24	9	2	1	1	0	0	150
Morrumbala	1	20	32	46	41	35	12	3	3	3	2	2	200

(perhaps 1-2 m^3/s) in the Ruave, Luaua, Licuari, and other semi-perennial escarpment streams. This runoff is included as part of the estimate of surface water runoff from the Rift Valley plateau (above). The remaining infiltrated water is lost through evapotranspiration or seepage to deep underlying aquifers. Potential evapotranspiration is about 1800-1900 mm/annum on the plateau.

The total contribution of groundwater has not been measured, but Smidt (1988) estimated groundwater recharge for the Licuari River catchment as 5-10% of annual rainfall. Extrapolating these figures over the entire Rift Valley escarpment catchment yields an annual volume of groundwater inflow of approximately 0.4-0.8 x 10^9 m^3 from the Cheringoma escarpment and 1.4-2.8 x 10^9 m^3 from the Morrumbula escarpment. Groundwater discharged to shallow surface water bodies at the delta ecotone is lost through evaporation and seepage, with minimal lateral movement to the central delta floodplains due to the low gradients and low hydraulic conductivity of the delta alluvium. These inflows are locally important for maintaining high water table conditions at the ecotone, however, and are sufficient to reduce woody species encroachment from the escarpment.

Groundwater outflow

Groundwater outflow is defined as water moving below the phreatophytic zone, either to deep underlying aquifers or the ocean. Deep aquifer recharge may occur on coarser sandy soils with underlying clay strata near abandoned alluvial channels and backslope levees (Loxton, Hunting and Associates *et al.* 1975i&j), but these features cover a relative small percentage of the surface area of the delta. The large-scale movement of water from the shallow surface aquifer to the deep aquifer and ocean front probably occurs only during extreme flooding events that deeply inundate the floodplain for a prolonged period of time, and are minimal on average compared to other water balance components. Sutcliffe and Parks (1989) compared the water balances of four Africa floodplains (the Okavango Delta, the Sudd, the Senegal Delta, and the Inner Niger Delta), and considered deep aquifer recharge to be negligible in all four systems.

Regional runoff from the Zambezi River

Regional runoff patterns and flooding patterns in the Zambezi Delta were assessed in previous sections of this working paper. Estimated long-term mean monthly and annual runoff at the Zambezi Delta is given in Table 2-26 for the historical period prior to Zambezi regulation and the recent period since construction of Cahora Bassa Dam. Long-term mean annual runoff for the entire period of record is about 3424 ± 2675 m^3/s (Table 2-19). Prior to Zambezi regulation, mean monthly runoff from January to May was of sufficient magnitude to inundate portions of the delta floodplain. Since 1976, the *maximum*-recorded mean monthly runoff is only 3000 m^3/s. The coefficient of variation for Zambezi flows between 1930-58 is 0.44. For the period 1976-00, the coefficient of variation is much higher (0.75).

The duration of flows above various thresholds for Zambezi River at Muturara is given in Table 2-27 for the period 1930-58. Prior to construction of Kariba Dam, flows exceeded 4500 m^3/s for 93 days on average, with a maximum of 155 days in 1956. Flows exceeded the bankful discharge of 5000 m^3/s in 96% of all years, for a duration of 78-days on average. Flows exceeded the threshold of 13,000 m^3/s in 18% of all years, with an average duration of 4 days and a maximum duration of 40 days.

The duration of flows above various thresholds for the Zambezi River at Muturara are given in Table 2-28 for the period 1976-00. Since construction of Kariba and Cahora Bassa Dams, flows have exceeded

Table 2-26. Estimated mean monthly and annual runoff (m^3/s) from the Zambezi River catchment above the delta. The period from 1930-58 reflects unregulated conditions prior to construction of Kariba Dam. The period 1976-00 reflects regulated conditions since construction of Cahora Bassa Dam.

Period	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Ann
1930-58	1066	936	1899	4534	7274	8257	6563	5105	3969	2876	2048	1496	3833
1976-00	1999	2376	2652	2833	3001	2854	2539	2329	2309	2341	1929	1891	2418

4500 m^3/s in only 54% of all years, for 26 days on average. Flows exceeded the bankful discharge of 5000 m^3/s for a duration of 20 days on average. Flows exceeded the threshold of 13,000 m^3/s only once (4% of all years) for a total of 20 days.

Estimated mean monthly and annual Zambezi River inflows to the delta are given in Table 2-29 for historical and current conditions. Historical inflows are estimated for the period 1930-58, assuming surface water inflow to the delta is approximately 18.3 x 10^9 m^3 per annum, with maximum inflows of more than 50 x 10^9 m^3 during extreme floods. Inflows occur during the period from December to June, but are concentrated during the peak flooding months of February and March. About 85% of Zambezi runoff discharges directly to the Indian Ocean.

Under current conditions, with regulated Zambezi runoff and impeded local flow movement, the estimated mean annual discharge into the delta is reduced to 42 m^3/s (110 mm) (Table 2-29). The average annual volume of surface water inflow to the delta is approximately 1.3 x 10^9 m^3 per annum. Inflows may occur anytime between November and July, depending on reservoir drawdown releases from Cahora Bassa Dam. Estimated inflows for the same period without local obstructions is 145 m^3/s (381 mm). Since Cahora Bassa regulation, inflows rarely exceed the threshold for overtopping the mainstem Zambezi embankments. During the majority of years, there is no meaningful Zambezi runoff into the delta floodplains. More than 98% of Zambezi runoff bypasses the delta floodplains and discharges directly to the ocean.

When local obstructions to delta flooding patterns are considered without the impact of dams, inflows are reduced by 69% to 178 m^3/s (468 mm). This reflects actual flooding conditions in the delta over the period 1930-58, suggesting that local embankments have had a serious impact on the magnitude and duration of flooding in the delta for decades. The magnitude of regulated discharge into the delta floodplains, assuming long-term average rainfall patterns rather than the recent drought conditions, is between 110 and 468 mm/annum. The average annual volume of surface water inflow to the delta is thus estimated as the average of this range (289 mm), approximately 3.5 x 10^9 m^3 per annum.

A proportion of flood flows emptying into the delta is ponded across the delta surface in backwater swamps, pools, and oxbows, infiltrating into the subsoils and later lost through evaporation. Under current conditions, most of this inflow occurs on the delta north bank. The remaining floodwaters discharge back to the Zambezi during flood recession, or drain directly to the ocean through distributary channels.

Summary

The water balance of the Zambezi Delta is highly variable in space and time. In the central floodplains, evapotranspiration exceeds rainfall and local runoff. If floodwaters fail to inundate the floodplains, all but the deepest depressions in the delta are desiccated during the dry season. Areas close to the coast and adjacent to the Rift Valley escarpment are less vulnerable to the failure of Zambezi flooding. Rainfall and runoff in this region exceed evapotranspiration on average, and shallow lakes and saturated soils persist throughout the dry season. During years of drought, all but the lowest-lying areas are water-stressed. Extreme floods may inundate vast areas of the delta under 1-2 m of surface water, maintaining open water

Table 2-27. Duration of flows (in days) above indicated magnitude for the Zambezi River at Muturara, 1930-58.

Year	Days >4500	Days >5000	Days >7000	Days >9000	Days >11000	Days >13000	Days >15000	Days >17000	Days >19000
1930/31	34	21	0	0	0	0	0	0	0
1931/32	100	83	26	6	0	0	0	0	0
1932/33	47	40	22	12	8	0	0	0	0
1933/34	95	79	26	0	0	0	0	0	0
1934/35	78	63	26	16	8	0	0	0	0
1935/36	70	58	27	9	0	0	0	0	0
1936/37	87	65	16	3	0	0	0	0	0
1937/38	75	54	8	0	0	0	0	0	0
1938/39	110	99	56	42	36	23	18	12	0
1939/40	117	108	62	31	14	2	0	0	0
1940/41	89	49	10	4	0	0	0	0	0
1941/42	52	22	0	0	0	0	0	0	0
1942/43	79	71	38	21	0	0	0	0	0
1943/44	63	51	33	22	12	7	5	2	0
1944/45	105	94	31	6	0	0	0	0	0
1945/46	56	46	17	7	2	0	0	0	0
1946/47	105	93	11	3	0	0	0	0	0
1947/48	138	121	66	39	24	0	0	0	0
1948/49	2	0	0	0	0	0	0	0	0
1949/50	132	118	59	23	5	0	0	0	0
1950/51	42	29	0	0	0	0	0	0	0
1951/52	146	136	100	67	50	39	9	3	2
1952/53	145	133	77	19	6	0	0	0	0
1953/54	63	30	6	0	0	0	0	0	0
1954/55	148	129	68	46	10	0	0	0	0
1955/56	155	145	101	32	8	0	0	0	0
1956/57	143	130	68	23	13	0	0	0	0
1957/58	127	121	92	72	57	40	25	16	11
# years	**28**	**27**	**24**	**21**	**14**	**5**	**4**	**4**	**2**
% all years	**100**	**96**	**86**	**75**	**50**	**18**	**14**	**14**	**7**
Mean	**93**	**78**	**37**	**18**	**9.0**	**4.0**	**2.0**	**1.2**	**0.5**
St Dev	**40**	**41**	**32**	**20**	**15**	**11**	**5.9**	**3.7**	**2.1**
Max	**155**	**145**	**101**	**72**	**57**	**40**	**25**	**16**	**11**
Min	**2**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**

lakes, papyrus swamps, and saturated soil conditions in the central floodplains through the dry season.

Estimates of the long-term average water balance of the delta are given in Table 2-30 for historical (pre-development) and current conditions. The historical water balance represents conditions that occurred until the first embankments were constructed in the delta, more than 30 years before the construction of Kariba Dam. The current water balance represents conditions that would be expected to occur over the next 20 or more years of Zambezi River regulation. Mean annual rainfall and local runoff are assumed to be stationary over this period. Zambezi surface water outflow is estimated as the residual of the water balance calculation and represents 80-85% of the Zambezi inflows under both historical and current conditions.

Table 2-28. Duration of flows (in days) above indicated magnitude for the Zambezi River at Muturara, 1976-00.

Year	Days >4500	Days >5000	Days >7000	Days >9000	Days >11000	Days >13000	Days >15000	Days >17000	Days >19000
1976/77	49	47	37	4	0	0	0	0	0
1977/78	166	165	145	63	35	20	9	0	0
1978/79	51	39	0	0	0	0	0	0	0
1979/80	23	20	8	0	0	0	0	0	0
1980/81	56	39	19	4	0	0	0	0	0
1981/82	54	46	0	0	0	0	0	0	0
1982/83	0	0	0	0	0	0	0	0	0
1983/84	0	0	0	0	0	0	0	0	0
1984/85	28	20	7	0	0	0	0	0	0
1985/86	50	42	2	0	0	0	0	0	0
1986/87	0	0	0	0	0	0	0	0	0
1987/88	0	0	0	0	0	0	0	0	0
1988/89	67	35	23	10	0	0	0	0	0
1989/90	50	9	0	0	0	0	0	0	0
1990/91	0	0	0	0	0	0	0	0	0
1991/92	0	0	0	0	0	0	0	0	0
1992/93	0	0	0	0	0	0	0	0	0
1993/94	0	0	0	0	0	0	0	0	0
1994/95	0	0	0	0	0	0	0	0	0
1995/96	2	2	1	0	0	0	0	0	0
1996/97	10	5	1	0	0	0	0	0	0
1997/98	7	1	0	0	0	0	0	0	0
1998/99	0	0	0	0	0	0	0	0	0
1999/00	0	0	0	0	0	0	0	0	0
# years	13	13	9	4	1	1	1	0	0
% all years	54	54	38	17	4	4	4	0	0
Mean	26	20	10	3	1	1	0	0	0
St Dev	38	36	30	13	7	4	2	0	0
Max	166	165	145	63	35	20	9	0	0
Min	0	0	0	0	0	0	0	0	0

Under historical conditions, Zambezi runoff was the most important component of the annual water balance. During the six month flooding season from November to April, the delta received 82% of total annual rainfall, more than 95% of total annual runoff and groundwater inflow from the escarpment, and 95% of total annual regional surface water inflows, and lost about 62% of total annual evapotranspiration and about 75% of total annual Zambezi surface waters back to the main channel. The volume of water storage in the delta increased during the flood season by an estimated 9.6 x 10^9 m^3, or 800 mm on average over the entire delta surface. Dry, cracked vertisols were hydrated by the early rains, swelling and expanding to pond rainfall during the peak months of January-February. When peak Zambezi floodwaters arrived during February-March, they spread over the vast inundated plains. On the south bank deep floodwaters accumulated in the Marromeu floodplains and coastal grasslands and on the north bank floodwaters filled the papyrus swamps of the Cuacua distributary. Floodwaters were lost primarily through evapotranspiration and surface water drainage during the dry season, with some subsurface seepage along the coastline.

Table 2-29. Estimated mean monthly and annual discharge from the Zambezi River to the Zambezi delta, expressed as average depth of flooding (in mm) over the 1.2 million ha. area. The 1930-58 period with unobstructed flows provides an estimation of historical inflows. The 1976-00 period with obstructed flows provides an estimation of current inflows. The other two scenarios examine intermediate conditions, including historical runoff patterns with obstructed flows, and current runoff patterns with unobstructed flows.

Scenario	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Ann
1930-58 Unobstructed	0	0	11	115	410	623	280	66	12	0	0	0	1524
1976-00 Obstructed	0	1	7	7	23	34	16	9	8	6	0	0	110
1930-58 Obstructed	0	0	3	27	134	210	72	18	3	0	0	0	468
1976-00 Unobstructed	0	5	29	29	60	105	64	37	31	23	0	0	381

Under current conditions, Zambezi runoff is minimal and rainfall and local escarpment runoff are the most important components of the delta water balance. Because escarpment runoff is localized to the western and northern portions of the delta, and evapotranspiration equals or exceeds rainfall during most of the rainy season, vast floodplain areas in the central delta dry out soon after the end of the rainy season. Evapotranspiration during the dry season is reduced as moisture becomes limiting in the delta grasslands. Soil moisture recharge in the floodplain decreases steadily as floods fail from year to year, replenished partially during periodic large flooding events, such as the floods of 1978 and 2001 when Zambezi inflows exceeded 40 x 10^9 m^3. The net decrease in soil moisture recharge was about 70 mm/annum during recent years, and water table levels may have declined by 3 m of more over the past 40 years. The floodplain water table is expected to continue to decline at a rate of 35 mm/annum in the future even under a wetter climatic cycle. Runoff from the Rift Valley escarpment now provides a critical source of

Table 2-30. A comparison of the Zambezi Delta water balance under historical conditions (pre-development), recent conditions since 1975 (Zambezi regulation and embankments), and projected future conditions (assuming long-term average Zambezi flows with no change in Zambezi regulation and embankments).

Water balance component	Historical long-term mean annual volume (m^3 x 10^9)	Recent long-term mean annual volume (m^3 x 10^9)	Projected long-term mean annual volume (m^3 x 10^9)
Rainfall	13.6	13.6	13.6
Runoff from escarpment	6.7	6.7	6.7
Groundwater inflow	2.7	2.7	2.7
Surface water inflow from Zambezi	18.3	1.3	3.5
Total inflows	**41.3**	**24.3**	**26.5**
Evapotranspiration	20.8	18.7	18.7
Groundwater outflow and coastal seepage	0.5	0.0	0.0
Surface water outflow to Zambezi River and coast	20.0	6.4	8.2
Total outflows	**41.3**	**25.1**	**26.9**
Annual change in storage	**0**	**-0.8**	**-0.4**

freshwater to the western and northern floodplains of the delta (Tinley 1994). Future development activities that alter local runoff patterns could have a profound effect on the water regime of the delta[26].

INDICATORS OF HYDROLOGICAL CHANGE IN THE ZAMBEZI DELTA

Overview

The engineering of the Zambezi system has resulted in adverse changes in regional runoff and local flooding patterns and profoundly altered the floodplain water balance. To assess the impact of these changes on local production systems and biological diversity, a subset of hydrological parameters must be selected that are closely linked to socio-economic and ecological conditions in the Zambezi Delta. 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 (King *et al.* 1999), 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 section, I adapt the RVA to evaluate the socio-economic and ecological consequences of hydrological change in the Zambezi Delta. Using time series data from the lower Zambezi system, I estimate the means and coefficients of variation for the following indicators of hydrological alteration related to the operation of Kariba and Cahora Bassa Dam:

- 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.

The implications of these hydrological changes on the vegetation of the Zambezi Delta are considered in detail in Working Paper #3.

Methods

I assessed long-term changes in flow patterns at Muturara for the periods 1930-58 and 1976-00, illustrating historical changes in the hydrological regime of the Zambezi Delta corresponding to the period before and after significant Zambezi regulation. The 1930-58 flow series covers the period prior to construction of Kariba Dam. The 1976-00 flow series covers the period since construction of Cahora Bassa and Kariba Dams. 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. Because flow data are not available from the Muturara gauge for most of the 1976-00 period, I generated a twenty-five year daily runoff time series for the Moravia-Angonia ad Manica Plateau catchments using data from the long-term gauging station at Revuboe and rainfall and runoff data for the Luia and Luenha catchments (Appendix 1). I added these inflows to Cahora Bassa outflows to extend the time series for Muturara to 1976-00.

I also assessed the relative values of inflows and outflows at Cahora Bassa Reservoir for the period 1976-00, illustrating ongoing changes in the Zambezi system due to reservoir operation. I calculated the same 32 parameters for inflows and outflows, respectively, and the magnitude of deviation and percentage difference. For both the Cahora Bassa and Muturara data, 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.

Analysis of indicators of hydrological change

The mean values for key hydrological indicators describing temporal changes in Zambezi flow patterns at Muturara between 1930-58 and 1976-00 are given in Table 2-31. The mean values for hydrological indicators describing spatial changes in Zambezi flow patterns above and below Cahora Bassa Dam are given in Table 2-32 for the period 1976-00. 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. Mean monthly flows were used to describe changes in runoff patterns in the Zambezi catchment in section 2-2. 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 1976-00 in Figure 2-61. 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 1976-00. 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 generally drier climatic cycle over the past 25 years.

A comparison of the inflow-outflow hydrograph for Cahora Bassa Reservoir (Figure 2-29), 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.

Table 2-31. Five groups of hydrological indicators for the Zambezi River at Muturara, comparing parameters for the periods 1930-58 and 1976-00. The magnitude and percent of deviation are given for the means and coefficients of variation for each parameter.

Indicator	1930-58 Mean	1976-00 Mean	Dev Mag	%	1930-58 CV	1976-00 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 2-32. Five groups of hydrological indicators for Cahora Bassa Reservoir, comparing inflows and outflows for the period 1976-00. 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

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 2-62. 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 1976-00 period. The 3-, 7-, 30-, and 90-day mean maximum flows follow a similar pattern (Table 2-31).

The effect of Cahora Bassa regulation on maximum 1-day flows is revealed in Figure 2-63. 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)[27].

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 of higher nutrient content (Working Paper #3). 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 2-64. 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[28].

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 2-65. 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 2-66). 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 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 2-67), 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 2-68. 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 2-69. 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 2-31). 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 2-31). 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 Working Paper #3.

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 2-70. 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 2-31). 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 2-71). 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 2-32). 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).

CONCLUSIONS AND FURTHER RESEARCH

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 consequences for the social and ecological health of the delta. In the Working Paper #3, I assess the cumulative impact of these changes on the distribution and dynamics of vegetation in the delta.

Efforts to understand and improve hydrological conditions in the delta depend on an accurate appraisal of the sources and patterns of hydrological change from past to present, and from present to future. Interpreting the hydrological history of the delta, through available databases, archival reports, scientific studies, interviews, and observations, is confounded by significant gaps in the historical record. Perhaps one of the least appreciated tragedies of war and its aftermath, such as the prolonged conflict in Mozambique, is its impact on collection and analysis of the data needed to improve post-war conditions. Although many of these data gaps can never be filled—rating curves at unstable sections cannot be reliably extrapolated back in time, long period of missing data can only be interpolated at best, and historical patterns of flooding cannot be recreated with present developments—any efforts to improve the breadth and quality of data collection will yield invaluable insights.

Meteorological stations at Marromeu, Luabo, and Chinde, discontinued since the civil war, should be reinstated at the rehabilitated Sena Sugar Estates. A reliable evaporation monitoring station, with atmospheric data sufficient to estimate evapotranspiration, should be maintained at the Marromeu station. Stations at Quelimane and Mopeia should also be revamped. These data, necessary for estimating water needs for irrigated crops, are fundamental to understanding the delta water regime and should be part of the National Meteorological network.

If better information is needed to assess runoff from the Rift Valley escarpment, a gauging program with automated recorders should be established on one or more streams near the hunting camps. The accurate assessment of groundwater movement and recharge will require more advanced scientific study, using a network of nested piezometers to assess vertical and horizontal gradients and conductivities from the escarpment to the floodplain, and from the floodplain surface to the lower aquifer.

One of the most pressing needs is for a major expansion of the hydrological and water quality monitoring network in the lower Zambezi. Gauging stations must be established at stable sections throughout the Zambezi system, most notably for the Luia, Luenha, and Shire tributaries, and reliable rating curves are needed for the Zambezi River at Tete, Caia, Marromeu, and Luabo. Zambezi outflow to the Indian Ocean cannot be directly measured because gauging stations downstream of Luabo are unreliable because of the instability of lower river sections and especially the influence of tides. But changes in flow between Caia and Luabo will provide an estimate of discharge into the upper delta distributary channels – especially the Cuacua, Salone, and Cuncue—which are most vital for inundating the floodplains. Basic water quality measures, especially salinity, should be an integral part of the delta monitoring system. The cost of establishing and maintaining these gauging stations is easily justified by the need to improve the quality of data for hydrological decision-making in the Zambezi, especially for dam management, flood forecasting, and flood warning systems (RPT 1979).

The water balance of Cahora Bassa Reservoir would be improved by establishing a reliable rating section for the Zambezi River at Zumbo and for the Luangwa and Panhane Rivers, and a meteorological network around the reservoir. Accuracy in the measurement of evaporation for Cahora Bassa would be greatly improved by replicating the submersed tank used at Kariba.

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.

APPENDIX 1 DERIVATION AND RELIABILITY OF HYDROLOGICAL DATA

Rainfall data

Rainfall stations used for assessing patterns of hydrological change in the Zambezi system are given in Table 2-1. Data stations in Zambia and Zimbabwe, which include a number of continuous records dating back to 1910, were reviewed for the SADCC 3.0.4 Hydroelectric Hydrological Assistance Project

(Shawinigan-Lavalin and Hidrotécnica Portuguesa 1990b) and are considered to be of good quality. Recent rainfall data from Malawi were not available for this study, but historical data were compiled from past consultancy reports. The quality of the Shire Valley data is not known.

In Mozambique, there are good historical data prior to 1975, including records from eight stations in the Zambezi Delta region (Chinde, Inhaminga, Marromeu, Mopeia, Morrumbala, Mutarara, Quelimane, and Vila Fontes). Data include mean, maximum, and minimum monthly rainfall, 24-hour maximum rainfall, mean and maximum monthly number of rainy days, temperature, and humidity data for each station. However, data collection was severely curtailed after independence and the onset of civil war. There are only three continuous records dating back to the 1950s (with many gaps) for the entire Lower Zambezi Valley, and only one station (Quelimane) covering the Zambezi Delta region. Rainfall records from Quelimane provide some indication of long-term rainfall patterns in the delta region, but rainfall at Quelimane is strongly influenced by coastal systems and data are not a reliable indicator of conditions further inland. Additional rainfall data may be available in the future as Department of Meteorology staff input archival records into the database.

There is a reasonably uniform distribution of long-term rainfall records over the Zambezi Basin, and several isohyetal maps have been prepared for the basin. Mean annual rainfall maps for the Lower Zambezi Basin were prepared by Hidrotécnica Portuguesa (1965b) and for the Zambezi Delta region by Loxton Hunting and Associates (1975a&b). Data are insufficient to produce more recent maps, and there maps are therefore of limited use because they do not reflect the recent long-term drought period. Rainfall distribution maps for Zambia and Zimbabwe, compiled from mean annual rainfall over the 30 year period from 1950 to 1980, were produced by Shawinigan-Lavalin and Hidrotécnica Portuguesa (1990b), along with more detailed maps of the Kafue Basin. There is also an older map compiled in 1956 by the former Federal Meteorological Department in Zambia, which covers Zambia, Zimbabwe, and Malawi and also extends into portions of Angola, Botswana, and Mozambique. These maps display considerable detail and together provide good information on the distribution of mean annual rainfall over a substantial portion of the Zambezi catchment, although there are minor discrepancies at the borders of the individual maps and the data cover somewhat different periods (Batoka Joint Venture Consultants 1993a).

Evaporation/evapotranspiration data

Evaporation stations used for assessing patterns of hydrological change in the Zambezi system are given in Table 2-2. Evaporation at each site is estimated from Class A pan data. The evaporation pans are screened for birds, and use a pan factor of 0.8 to 0.9. Although pan evaporation data may be considered sufficient for defining the net evaporation (or aridity) of different regions of the basin, the data are not particularly accurate for estimating the water balance of large reservoirs that have considerable heat storage and relatively stable temperatures. In order to provide improved estimates for Kariba Reservoir, the Zambezi River Authority installed a 15.24 m x 12.19 m x 1.22 m deep-water evaporation tank in 1961. Tank data was correlated to potential evaporation estimation using the Penman equation (Penman 1948), and a “tank evaporation factor” of 0.9 was calculated. Evaporation estimates from Cahora Bassa Reservoir are much less reliable, however. Evaporation data are estimated simply from Class A pan data collected at Songo, with a standard coefficient of 0.9.

A number of studies have been undertaken to assess potential evaporation and evapotranspiration in the delta region for crop production. Loxton, Hunting and Associates *et al.* (1975g&h) used Class A pan data, meteorological data, and the Penman formula to estimate monthly potential evapotranspiration and water surplus/deficit at Mopeia, Morrumbala, and Muturara. These estimates are considered to be reliable. Shawinigan-Lavalin and Hidrotécnica Portuguesa (1990b) estimated evapotranspiration from the Kafue Flats for their hydrological model of the Kafue River basin.

The meteorological station at Beira provides the only evaporation record for the Zambezi Delta region, but is located in a zone of higher rainfall and lower temperatures that is not directly representative of conditions in the delta. Mean annual potential evapotranspiration at Beira, estimated by FAO (1984) is only 1583 mm. Thus, Beira provides only an approximate measure of mean evaporation conditions and trends. For the present study the mean annual evaporation rate at Beira (1920 mm) was revised to 2000 mm/year for the Zambezi Delta region, based on estimates for total evaporation from comparable areas in the Zambezi catchment. Monthly evaporation totals were then scaled proportionately from the Beira series.

Local runoff data

There are no previous studies of monthly or annual distribution of overland runoff from the Cheringoma or Morrumbala escarpments to the Zambezi Delta. More than thirty streams drain these areas, several of them perennial, but access to stable cross-sections is limited and none is gauged. Opportunity for accurate rainfall-runoff modeling is also limited. Rainfall data for estimating runoff from the Cheringoma escarpment are available from only one station (Inhaminga), and similarly only one station for the Morrumbula escarpment (Morrumbula) (Table 2-1). Furthermore, as discussed above, these rainfall stations were not maintained during the civil war period and recent data are not available.

Local runoff was thus estimated using unit runoff coefficients derived for the Upper and Middle Zambezi catchment, based on the hydrological studies of Sharma and Nyumbu (1985). Runoff coefficients were adopted from areas with comparable topography, soils, vegetation, and land use practices, using local rainfall data. The total volume of runoff was estimated for each catchment, with catchment area derived from topographic maps. The monthly distribution of runoff was estimated using the relative proportion of rainfall during the peak rainfall months. The reliability of these data is unknown but assumed to be within the range of uncertainty of the delta water balance components.

Groundwater data

There are no previous studies of groundwater movement on the Quaternary Deltoid Plain, and no quantitative data are available. The shallow unconfined freshwater aquifers in the delta region occur in alluvium of the major drainage channels, in sands comprising the raised beaches near the coast, and in eluvium overlying sedimentary rocks of the surrounding escarpment. Most of the remaining delta is underlain by a brackish to highly saline aquifer in alluvial soils. Hydraulic conductivities and flow gradients, and hence groundwater flow rates, are thus very low and presumably negligible relative to other water balance components. Meaningful groundwater inflow occurs as baseflow feeding the perennial streams that drain the escarpment, which are included in the estimates of local runoff, and subsurface flows discharging at the base of the Rift Valley escarpment. The latter groundwater input is estimated from infiltration studies on the escarpment surface (Loxton, Hunting and Associates *et al.* 1975g&h). The reliability of these data is unknown but assumed to be with the range of uncertainty of the delta water balance components.

Zambezi catchment runoff data

All available streamflow data and associated rating curves for the Zambezi catchment were procured for the present study. Data sources included the Direccao Nacional de Aguas in Mozambique, the Zambezi Electrical Supply Corporation Limited (ZESCO) in Zambia, the Ministry of Water Affairs in Malawi, and the Zambezi River Authority in Zambia and Zimbabwe, and compiled from various consultancy reports including Halcrow and Partners (1954), FAO (1968), Hidrotécnica Portuguesa (1965c,d,e,f,&g), Zambezi River Authority (and former Central Africa Power Corporation) annual reports and accounts (1961-89), RPT (1979), SWECO (1982), Shawinigan-Lavalin and Hidrotécnica Portuguesa (1990a&b), Batoka Joint Venture Consultants (1993a&b), and Li-EDF-KP Joint Venture Consultants (2000a&b) (Table 2-3).

Due to historical warfare and poor economic conditions among Zambezi basin countries, there are no long-term gauging records with fully reliable and regularly tested stage-discharge curves and all discharge gauging data must be treated as approximate. Several of the gauging stations occur at stable sections, and produce fairly reliable long-term records despite limited direct discharge measurements (*e.g.*, Victoria Falls, Kafue Gorge). Other gauging stations are located in unstable sections, and records are reliable only for the period during which active stage-discharge measurements were made. Those data sets include most significantly the Zambezi River at Tete gauging station E320 (1945-2000 data series, but no discharge measurements between 1970 and 1999), the Zambezi Delta at Marromeu (1930-2000 data series with gaps, but no discharge measurements since 1964), and many of the plateau tributaries gauge records (no discharge measurements since the early 1960s). For the Chirundu, Luangwa, Revuboe, and Dona Ana gauging stations, rating curves are also out-of-date but river sections are marginally stable and data may be extrapolated with caution. Several data sets were rejected because further analysis revealed significant inconsistencies in the data series that suggested errors in recording.

The Upper Zambezi catchment

In 1988, Shawinigan-Lavalin was commissioned to undertake a thorough review of the hydrological data in the upper and middle portions of the Zambezi basin for the SADCC 3.0.4 Hydroelectric Hydrological Assistance Project. The study aimed to establish a definitive database of hydrological information that could be used for basinwide hydroelectric investigations. The studies included a thorough review of the level and stage discharge data at all key gauging stations and existing power plants in the Zambezi basin. One of the key outputs was the production of a "Compendium of Data" that provides details and a discussion of the reviewed and recalculated hydrometric data produced during the course of the study.

As part of this process, Shawinigan Engineering and Batoka Joint Venture Consultants (subsequently commissioned to study the design and operation of the proposed Batoka Gorge Dam), re-evaluated long-term inflow data for Kariba Reservoir. The analysis includes Zambezi River flows for the catchment area above Victoria Falls, and incremental inflows to the Zambezi River between Victoria Falls and Kariba Dam. The long-term monthly flow series for the Upper Zambezi catchment, gauged at Victoria Falls, were reconstituted using various gauging records from Victoria Falls.

The first gauging station on the Zambezi River was established at the Victoria Falls Northbank pumping station and maintained for the period 1906-24, followed by the Livingstone Northbank pump station that was maintained from 1924-73. New gauging stations established at the Big Tree pumping station in 1965, and the Victoria Falls Pump House in 1967, and are still operated. Continuous daily water measurements are made at one or the other of these stations since their establishment. Shawinigan-Lavalin and Hidrotécnica Portuguesa (1990b) and Batoka Joint Venture Consultants (1993a) correlated the water levels from the various gauges and constructed a continuous daily water level record for Victoria Falls for the period 1924-89. Li-EDF-KP Joint Venture Consultants (2000a) extended this series through 1998.

The current stage-discharge curve used to estimate flow at Victoria Falls (Q in m^3/s) from water levels at the Livingston Pump House (LIVPH in m) is

$$Q = 368.1242 * (LIVPH + 0.457)^{1.9543}.$$

Monthly data only are used for the period 1908-23 from the Victoria Falls Northbank gauge, because stage measurements at this gauge were only made in weekly to monthly intervals. These data are not highly accurate, but give a general sense of the seasonal and inter-annual variation in flows. Low flows recorded during this period are closely correlated to the low flows recorded for the headwaters of the Kafue River (Mukosa *et al.* 1995).

The long-term flow records at Victoria Falls gauging station are based on the application of a stage-discharge curve that was derived from ratings carried out in the 1950s and early 1960s, which were applied retroactively to water level records extending back to the early years of the century. Although the control section is straight and stable, there is some degree of uncertainty with regard to the accuracy of the discharges derived. The accuracy of the rating curve depends on changes to the topography of the lip of the falls, silting, or scouring of the river channel. There is good reason to believe that there has not been serious silting or scouring of the channel that would lead to significant changes in the control section, but minor drifts over the years are probable (Batoka Joint Venture Consultants 1993a).

The Middle Zambezi catchment

The Gwembe Valley catchment and Kafue Dam and Reservoir

Shawinigan-Lavalin and Hidrotécnica Portuguesa (1990b) also investigated the incremental inflows to the Zambezi River between Victoria Falls and Kariba Reservoir for the SADCC 3.0.4 Hydroelectric Hydrological Assistance Project, and found that—unlike with the Victoria Falls gauge that provides a clear measurement point for runoff from the Upper Zambezi catchment—there is not a single measurement point to adequately capture runoff from the lower catchment. The study found that there are a number of tributaries flowing directly to Kariba Reservoir, many of them ungauged, and the use of only the major gauged tributaries to estimate total catchment runoff (by correlation analysis) resulted in unacceptably large errors. The team therefore recommended a combination of methods to estimate inflows.

Direct measurements of runoff from the lower Kariba catchment prior to the construction of Kariba Reservoir are available for the period 1943-57 from the Chirundo gauging station. The contribution of the catchment between dam site and Chirundo (35 miles downstream) is small in volume through capable of producing a modest flash peak, and runoff at Chirundo is considered to be representative of that at Kariba. The rating curve at Chirundo is not considered to be accurate or reliable, however, so these data are useful only for assessing general runoff patterns.

Studies by the Zambezi River Authority provided estimates of inflows from the lower catchment using the Pitman rainfall/runoff modeling technique. The Pitman model uses basin soil characteristics (storage and infiltration), interception effects, lag times between rainfall and runoff, and evapotranspiration losses to relate precipitation over a basin to the runoff generated by that rainfall. Runoff values were synthesized for each of the five Gwembe Valley sub-catchments that have unique basin characteristics, and summed to derive a time series of total Gwembe Valley inflows for the period 1924-1961. These synthesized flows, despite being based on a mix of short flow records and estimated parameters for ungauged sites, are considered to be reliable because they accurately reproduce the observed inflow patterns at Kariba Reservoir over the period since 1961.

The discharges between Victoria Falls and Kariba for the period 1961 to present are derived from the water balance of Kariba Reservoir. The annual water balance is used to solve for Zambezi River inflows as a function of rainfall and evaporation over the reservoir, discharge from the reservoir, and the change in reservoir storage volume. Zambezi River inflows from the lower Kariba catchment are calculated by subtracting flows measured at the Victoria Falls gauging station from total reservoir inflows.

Batoka Joint Venture Consultants (1993a) commented that the results, even with revised time series data for Victoria Falls, include a significant number of negative monthly values for inflows from the Gwembe Valley. Notably, there is a predominance of negative values in the period May to August, such that the flow record does not satisfactorily reflect flood recession during the early dry season. There are also relatively high values for inflow in September and October, before the rains produce significant runoff.

Possible sources of error in this data series include underestimation of turbine flows, underestimation of spillage, underestimation of lake evaporation, temporary underground storage at the reservoir shoreline, losses through evapotranspiration at the reservoir periphery zone, leakage by infiltration under or around the dam, and overestimation of flows at Victoria Falls. Of these, flows at Victoria Falls were deemed to still be the most likely source of error, although the possibility of significant errors in one or more of the other terms in the water balance cannot be discounted. Batoka Joint Venture Consultants (1993a) concluded that the annual water balance data from the water balance study are reliable, but that the monthly proportion of flows derived from the Pittman modeling is more accurate. They used the ratio between the annual discharge derived by the reservoir water balance method and the Pittman modeling for the period 1961-1985 to increase the discharges derived by the Pittman model by 18% for the period

1925-1961. They also extended the data series back to 1907 to match the length of the Upper Kariba catchment and Kafue River series. For the period 1910-1924, a synthetic sequence of annual inflows was calculated by regression using a relationship between the local inflow and the Victoria Falls discharges and also the rainfall index for the local catchment that was derived form the period subsequent to 1924/25. For the three years earlier, 1907-1909, the local inflow has been taken as 27% of the flow at Victoria Falls. These annual values have then been distributed in accordance with the monthly distribution of the local inflows for the period 1925-1985. For the period 1962- 1990, annual inflows are calculated from the water balance method, using a monthly distribution based on the Penman method. Li-EDF-KP Joint Venture Consultants (2000a) extended the time series to 1998 using the same methods.

The Victoria Falls gauging data provide the only direct estimate of Zambezi runoff from the headwaters to Kariba Dam, and any further modifications to the hydrological record must await the completion of the river gauging program and a review of the stage-discharge relations over the whole data record. Preliminary indications are that the current stage discharge curve and discharge assessments are satisfactory over the low flow season but that the medium to high flows may be slightly underestimated (Batoka Joint Venture Consultants 1993a). Accordingly, the local inflows between Victoria Falls and Kariba are now probably slightly overestimated by the water balance. Despite their limitations, however, these data series provide a reasonable long-term record of flows in the Zambezi River above Kariba Reservoir and an important record of inter-annual hydrological variability.

Kafue River catchment

Although the Kafue River is only one of several important tributaries of the mainstem Zambezi, flow records are particularly important because of the effects of river regulation and natural floodplain storage on the contribution of runoff to the Zambezi. As noted in Chapter 2 the Kafue catchment is equal in size to the Luangwa River catchment, but generates less than half as much runoff.

Kafue River streamflow data are available for the catchment area above Itezhitezhi Reservoir from 1952-present using the Mankoya gauge (94,924 km^2 catchment area) from February 1952-June 1973, the Hook Bridge gauge (95,053 km^2) from October 1973-August 1976, the Itezhitezhi dam site gauge (105,620 km^2) from May 1955-April 1977, and Itezhitezhi Reservoir outflow from October 1978-present. Long-term time series is also available for the Lower Kafue River at Kasaka gauge (150,971 km^2) for the period October 1905-October 1970. The Kasaka gauge is now submerged by Kafue Gorge Reservoir. Long-term discharge data at Kasaka were analyzed in detail by FAO (1968), as well as by Balek (1971a, 1971b), Starmans and Shalash (1971), DHV (1980), and RPT (1980). Estimates of mean annual discharge in these studies range from $7.3\text{-}12.9 \times 10^9$ m^3.

Shawinigan-Lavalin and Hidrotécnica Portuguesa (1990a) assessed the correlation between Kasaka and upper catchment flows over the period of common record. The correlation coefficients for monthly flows between Itezhitezhi and Kasaka are poor when considered on a straight month-to-month basis, because of the attenuation of flows by the Kafue Flats. However, there is a strong cross correlation of Itezhitezhi flows on Kasaka flows using a lag-one and lag-two serial correlation. Flow at Itezhitezhi for month i was therefore modeled as a function of flows at Kasaka for months i-1, i, and i+1, with correlation coefficients ranging from 0.78-0.93. Using this model, Shawinigan-Lavalin and Hidrotécnica Portuguesa (1990b) extended the monthly series of inflows to Itezhitezhi Gorge back to 1907.

There are several sources of error in the data series. Flows recorded at Itezhitezhi from May 1955 to September 1960 are affected by the backwater effects of the Kafue Flats. At Kasaka, flow measurements at high flows were inaccurate because the river gauging measurements did not capture floodwaters that spilled overbank onto the Kafue Flats. Flows below 55 m^3/s were also poor because of low velocities at the river gauging location. Discharge in the middle range in considered fair.

For reservoir simulation studies, the incremental inflow between Itezhitezhi and Kafue Gorge is estimated as 20% of inflow to Itezhitezhi, based on the period of overlap between Itezhitezhi and Kafue Gorge. The high rates of evaporation from the Kafue Flats and the insufficient number of flow observations available on the tributaries of the Kafue River within the Flats make it difficult to more accurately reconstruct tributary inflows in this region. These data may be considered fair as a long-term average, but are inaccurate on a monthly basis.

Luangwa and ungauged Middle Zambezi catchments to Cahora Bassa

Incremental inflows below Kariba Dam were studied in depth by Hidrotécnica Portuguesa for the design and management of Cahora Bassa Dam. Hydrological studies in this region are constrained by the paucity of data from the middle Zambezi catchment. Prior to the construction of Cahora Bassa Dam, the only available gauging records on the mainstem Zambezi were from the Cahora Bassa gorge dam site for the period 1960-1971, and these data are unreliable (see discussion below). The only gauged tributary inflows in the Middle Zambezi catchment are from the Luangwa River, which covers about 64% of the total catchment area. Long-term gauging data are available from the Luangwa River near the Zambezi confluence at Great East Road Bridge for the period 1954-present. Mhango *et al.* (1977), Balek (1971b), Starmans and Shalash (1971), and RPT (1980) analyzed discharge data for the Luangwa River. Estimates of mean annual discharge range in these studies range from 13.4-19.2 x 10^9 m^3. Because Luangwa runoff can generally be considered representative of runoff conditions in the remaining catchment area, RPT (1980) multiplied Luangwa flows by 1.5 to generate a runoff series for the catchment. However, the discharge record from the station at Luangwa Bridge is unreliable because the cross-section is unstable due to heavy sediment loads in the Luangwa catchment and there few rating curve measurements have been made (Bolton 1983).

Because of the lack of gauges on the mainstem Zambezi between Kariba and Cahora Bassa gorges, and the absence or poor quality of tributary streamflow records, Hidrotécnica Portuguesa (1973) generated a time series of inflows to Cahora Bassa using data from the lower Zambezi catchment at Dona Ana (1930-1958) and Lupata (1959-1973). Cahora Bassa incremental inflows were derived by correlating flows measured at Dona Ana and Lupata to flows measured at Cahora Bassa during the common period of record from 1960-1971, after Kariba inflows were deducted. The Dona Ana gauge is located 150 km downstream of the Lupata Gorge gauge, but the drainage areas commanded by the Dona Ana and Lupata gauges are relatively similar and there are no substantial tributary inflows between them. Flows from the two gauges were combined using simple correlation to create one continuous data series.

The Hidrotécnica Portuguesa model uses daily data from Kariba and Dona Ana/Lupata, with a time lag of 5 days from Kariba to Cahora Bassa and a lag of 2 days from Cahora Bassa to Dona Ana/Lupata. Kariba inflows were taken from the Zambezi River Authority (and former Central Africa Power Corporation) studies for the period 1930-58, and from direct outflow measurements from Kariba reservoir for the period since 1959.

For the period October 1930-October 1973, the daily flow volume at Cahora Bassa (V_{CB}) was estimated from flow at Dona Ana/Lupata ($V_{DA/L}$) using the relationships

$$V_{CB} = 3195.58 * V_{DA/L}^{0.846} \quad ,$$

for flow volumes greater than 1900 x 10^6 m^3, and

$$V_{CB} = V_{DA/L}$$

for flow volumes less than 1900 x 10^6 m^3 (assuming that the flow contribution from the plateau region of the Lower Zambezi catchment is negligible during the dry season relative to mainstem Zambezi flows). The model used the convention that if Cahora Bassa measured flow is less than Dona Ana/Lupata flow, flow at Cahora Bassa is estimated by subtracting Kariba flow from Cahora Bassa measured flow, and if Cahora Bassa measured flow is greater than Dona Ana/Lupata flow, Cahora Bassa flow is estimated by subtracting Kariba flows from Dona Ana/Lupata measured flow.

For the brief period from November 1973 to November 1974, the only data available on the lower Zambezi is from the Tete gauging station. Hidrotécnica Portuguesa compared flows at Tete and Cahora

Bassa during the period of common record from 1960-71, and determined that the differences in flow between the two stations were minimal relative to the total runoff from the middle catchment (and therefore neglected inflows from the Luia catchment, discussed below). Flow data from Tete were used as a direct measure of Cahora Bassa flow data for this period.

Since construction of Cahora Bassa in 1974, daily inflow to the reservoir is measured using a water balance approach,

$$Pi + Qi + Ri - ETo - Q_{CB} = \Delta S,$$

where Pi is rainfall over the reservoir; Qi is Zambezi River inflows, Ri is runoff from the reservoir catchment, ETo is evaporation/evapotranspiration from the reservoir surface, Q_{CB} is discharge from the reservoir; and ΔS is change in reservoir storage. Incremental inflows below Kariba and Kafue, Q_{MC}, are estimated as,

$$Q_{MC} = Pi + Ri + Qi - Q_{Kariba} - Q_{Kafue}$$

where Q_{Kariba} is outflow from Kariba Reservoir and Q_{Kafue} is outflow from Kafue Gorge Reservoir. These equations are combined and rearranged to yield,

$$Q_{MC} = ETo + \Delta S + Q_{CB} - Q_{Kar} - Q_{Kafue}$$

Incremental inflows to Cahora Bassa from December 1974 to present are thus based on measured outflow from Cahora Bassa, Kariba, and Kafue Gorge Reservoirs, estimated evaporation from the reservoir, and the change in reservoir storage.

Batoka Joint Venture Consultants (1993b) extended the Cahora Bassa local inflows back from 1930 to 1908 by a process similar to that used for generating the Victoria Falls/Kariba local inflow time series. Local inflows to Cahora Bassa were correlated to the sum of the Kariba and Kafue natural inflows, and an annual rainfall index was used to model runoff from the remaining catchment area. This record is not considered to be reliable, but is sufficient for exploring the probable behavior of the Zambezi River during the period of low flows that prevailed in the early years of the century.

The time series data for the Middle Zambezi catchment was created to estimate inflows to Cahora Bassa for purpose of design flood calculations and firm energy simulations, and is considered to be adequate for that purpose (Shawinigan-Lavalin and Hidrotécnica Portuguesa 1990b). In adapting this series for other purposes, however, there are numerous sources of error that must be considered. Sources of error include the reliability of the Dona Ana rating curve, the reliability of the Cahora Bassa Gorge rating curve, the relationship between Cahora Bassa and downstream flows at Dona Ana/Lupata and Tete, the estimation of evaporation/evapotranspiration from Cahora Bassa reservoir, the measurement of storage change in the reservoir, and the estimation of discharge from Kariba, Kafue Gorge, and Cahora Bassa Dams.

Bolton (1983) noted that the first attempt to produce an accurate stage-discharge rating curve at Dona Ana was not made until 1958. Even then, the rating was done indirectly by measuring discharge at Lupata Gorge. Although Lupata Gorge provides a relatively stable cross-section for flow rating, the statistical relationship between flows at Lupata and Dona Ana changes from year to year and requires the use of different correlation parameters for each year from 1958 to 1961. These results suggest that the Dona Ana section may be very unstable, and RPT (1979) noted that the riverbed at the gauging station is fairly mobile. The Hidrotécnica Portuguesa hydrologists who undertook the study believed that the changes observed were due to the changes in the river regime resulting from the operation of Kariba Reservoir. On this basis, they made the questionable assumption that the rating curve obtained during the 1958 flood season could be applied to historical gauge data dating back to 1930. The reliability of the historical flow series at Dona Ana is thus unknown, and likely to have periods of inaccuracy.

The temporary gauge at the Cahora Bassa dam site, from 1960-71, is also of questionable reliability. The rating curve is derived from discharge measurements at Tete, which may be accurate during the dry season but is not reliable during the rainy season when the 40,000 km^2 catchment area between Tete and Cahora Bassa gorge can generate significant local runoff. Comparisons between discharge records at Cahora Bassa, Boroma, Tete, and Tete-Matundo Cais (Table 2-3) reveal significant divergence between the records, and they are unsuitable for use in estimating the flow contribution of the incremental catchment above Tete (see discussion below).

Similarly, the equation derived for the relationship between runoff at Cahora Bassa and Dona Ana/Lupata is based on the assumption that tributary inflows between Cahora Bassa and Dona Ana are highly correlated to inflows from the Middle Zambezi catchment. Only one discharge series from the lower Zambezi catchment, at the Revuboe gauging station (26,600 km^2), is available to test this assumption. Simple linear regression of the annual data series reveals that incremental runoff from the Middle Zambezi catchment and runoff at Revuboe are very poorly correlated ($r^2 = 0.27$) with significant scatter. The correlation between direct measured discharge in the Luangwa and Revuboe Rivers is also very poor ($r^2 = 0.31$). Based on these findings, flood season flows at Cahora Bassa are not well predicted by flows at Dona Ana/Lupata.

The data series since 1974, based on the water balance model, should be significantly more accurate than the historical data series based on measurements in the lower Zambezi catchment. However, there are numerous negative values in the Shawinigan-Lavalin and Hidrotécnica Portuguesa/Batoka Joint Venture Consultants data series during the dry season and in some months discharge from Kariba alone is higher than estimated inflow to Cahora Bassa, resulting in negative monthly inflows in the time series. In other months, measured discharge at Luangwa is greater than the estimated incremental inflows from the entire Middle catchment including Luangwa. Possible sources of error include the underestimation of evaporation and/or evapotranspiration from Cahora Bassa Reservoir, the overestimation of changes in reservoir storage, the overestimation of outflows (turbine and sluice gate discharge) from Kariba or Kafue Gorge, the underestimation of Cahora Bassa outflows, and the underestimation of reservoir storage due to temporary underground storage at the reservoir shoreline and water loss through leakage by infiltration under or around the dam.

The accuracy of inflows to Cahora Bassa depends on the estimation of evaporation from the reservoir surface. Historically, evaporation losses have received little attention in studies of the hydrology of the reservoir, and there has been confusion over the use of gross evaporation and net evaporation estimates (Bolton 1983). Evaporation is unlikely to be a major source of error relative to the stream gauging problems discussed above, however. The discharge associated with 1 mm of evaporation in a month is only about 1 m^3/s at the full supply level (surface area of 2700 km^2). Thus errors in measuring evaporation would not fully account for the negative incremental inflows calculated for some months.

The change in reservoir storage (S) for a given change in reservoir water level (H) is determined from an empirical stage-storage relationship,

$$S_{CB}\ (10^6\ m^3) = 0.22218\ (H_{CB} - 256.5)^{2.95873}$$

derived during the reservoir design studies (Hidrotécnica Portuguesa 1965n). The equation simplifies the complex geomorphology of the submerged gorge, and is unlikely to be an accurate measurement of the total reservoir storage volume for at a given water level. However, errors related to small incremental changes in reservoir storage are unlikely to be a source of significant error relative. Waves or unstable water levels at the reservoir staff gauge could also result in inaccurate elevation readings, but the gauge site is fairly well protected.

The effects of temporary underground storage at the reservoir shoreline, and leakage by infiltration under or around the dam are unknown. However, the magnitude of infiltration and seepage necessary is likely negligible relative to the vast surface area of the reservoir.

Errors in the Cahora Bassa inflow series may be related to errors in discharge measurements from Kariba, Kafue Gorge, and Cahora Bassa Dams. The lag between Kariba and Cahora Bassa is about 5 days, so it would not account differences in the monthly or annual series. Although turbine outflow is estimated from electrical generation and sluice gate outflow is estimated from hydraulic models (see below), errors in the measurement or discharge through the turbines and sluice gates are the most likely source for negative values in the inflow series during the dry season.

Li-EDF-KP Joint Venture Consultants (2000a) altered the data series to avoid negative monthly values in the incremental inflow series. They used the estimated annual inflow volume for each year with a fixed monthly distribution based on the relative proportions of monthly flows for the historical period, 1930-74. Since this series generates the same flood hydrograph each year (e.g., peak flows occur in February), it is no more useful than the original series that has variable monthly distribution with occasional negative numbers, and was rejected for the present study.

Overall, there are limited options available for improving the incremental data series for the middle Zambezi catchment. Reliable time series data from the middle Zambezi catchment, particularly at Luangwa, are needed to improve the estimates of inflows to Cahora Bassa. If a reliable rating curve system can be developed for Luangwa, inflows to Cahora Bassa can best be estimated as the sum of Kariba and Kafue Gorge outflows and inflows from Luangwa multiplied by a scaling factor to account for the ungauged portion of the catchment. This would provide a partially independent estimate of inflows to contrast with inflows calculated by the water balance method. For the time being, the Hidrotécnica Portuguesa time series and water budget calculations are assumed to provide a reasonable estimation of the long-term trends in the middle Zambezi catchment, if not specific daily values.

For the present study, I estimated total Middle Zambezi runoff below Kariba and Kafue Gorge Dams to be about 28 x 10^9 m^3. About 60-65% of this runoff is derived from the Luangwa catchment, suggesting a mean annual discharge of about 16.8-18.2 x 10^9 m^3 for the Luangwa River, which falls within the range of previous estimates of mean annual discharge.

The Lower Zambezi catchment

The Moravia-Angonia and Manica Plateau tributaries

Luia catchment

Several data sources are available from which to generate a monthly time series for runoff from the plateau catchments downstream of Cahora Bassa Dam. Long-term daily discharge data are available for the Zambezi River at Tete from 1946-present. The total catchment area below Cahora Bassa Dam to Tete is about 40,000 km^2, and includes the entire Luia catchment (28,000 km^2). Thus, the difference between the discharge measured at Tete and measured outflow at CB should be an adequate measure of the inflows from the Luia River plus other ungauged runoff. However, comparison of the hydrographs of long-term mean monthly discharge at Cahora Bassa and flow at Tete reveal serious problems with the data series (Figure A-1). Long-term mean monthly discharge during several of the dry season months is consistently lower at Cahora Bassa than at Tete, physical impossibility. Peak flood discharges are also unreliable. A comparison of daily and monthly discharges at Tete and Cahora Bassa on a year-to-year basis reveals that flows measured at Tete are regularly significantly lower than flows released from Cahora Bassa, even during peak flooding months. Therefore, this approach could not be used to establish a time series for the incremental flows below Cahora Bassa. Similarly, the erratic differences between flows measured at Cahora Bassa Gorge and at the Tete and nearby Tete Matundo-Cais stations during the period of common record from 1960-71, suggest that data from these stations are also unreliable.

Stream gauging data for the Luia catchment, including the Upper Luia, Capoche, and Cherize tributaries, were obtained from the Hidrotécnica Portuguesa (1965d) and data files at the Direccao Nacional de Aguas in Mozambique, but only cover a nine-year period from 1959-1968. Li-EDF-KP Joint

Venture Consultants (2000b) used these data to generate a monthly flow series for the design of Mepanda Uncua Dam, located below the Luia confluence some 80 km downstream of Cahora Bassa. Joint Venture used data from Stations E359 and E360 on the Capoche River, which capture runoff from 14,686 km^2, and assumed that unit runoff is the same for the gauged and ungauged portions of the catchment. Average annual runoff from the gauged portion of the catchment for the nine years of record was estimated as 63 m^3/s, or 7.9% of the average discharge from Cahora Bassa incremental catchment over the same period. Applying this percentage to the Cahora Bassa incremental annual discharges, a time series of annual discharges was derived. A fixed monthly time series was derived from the annual time series using the average distribution calculated from the 9-year record.

For the purpose of modeling annual and seasonal hydrological variability in the Zambezi Delta catchment, a different approach was undertaken for the present study. Since 1955, daily stage data are available from the Revuboe gauging station, the only long-term tributary gauging station in the lower Zambezi catchment. The Revuboe gauging section was evaluated by RPT (1979), who noted that the site is located on a straight section at a bridge crossing, founded on bedrock outcrops, with a fairly reliable rating curve. The total catchment area above the Revuboe gauge is 16,600 km^2.

The Luia and Revuboe basins, arising at the same latitude on the Moravia-Angonia Plateau, share similar geological formations, soils, and land cover characteristics. Annual and monthly rainfall patterns between the headwater gauges (Bene and Metengo) and lower basin gauges (Chingoze and Capoche) are highly correlated. Therefore, daily time series data for Luia were generated as a function of the Revuboe data series to better capture annual and monthly variation in lower Zambezi runoff. A short-term daily runoff record for the Luia catchment was compiled by combining daily streamflow records for the Upper Luia (station E322), Capoche (E360), and Cherize (EH20) catchments for the period of overlap between 1960-1968. These stations command 11,031 km^2, 14,686 km^2, and 1917 km^2, respectively, or 27,634 km^2 of the total Luia catchment area of 28,000 km^2. This discharge series (Q_{Luia}) was correlated to the daily discharge series for Revuboe ($Q_{Revuboe}$) over the same time period, where

$$Q_{Luia} = 1.07\ Q_{Revuboe} + 32.4$$

during the wet season and early dry season months of November-June, and

$$Q_{Luia} = Q_{Revuboe}$$

for the remaining dry season months of recession (r^2=0.89). This relationship was used to generate a streamflow series for the Luia basin for the period 1976-2000, corresponding to the period when outflow measurements from Cahora Bassa Dam are available. The time series data is considered to be fairly reliable, but would be greatly improved in the future will the establishment of a gauging station and reliable rating curve for the Luia River near its confluence with the mainstem Zambezi.

Luenha catchment

During the brief period from 1958-1965, thirteen hydrometric stations were operated in the Mozambique portion of the Luenha catchment, covering the Ruia, Mazoe, Niangadezi, Mudezi, and Caueresi tributaries of the Luenha River. The only long-term data available for estimating runoff from the Luenha catchment, however, is from the gauging station at Luenha 2 (station E296), maintained from 1959-present. The cross-section at Luenha 2 is very stable, and the rating curve (last calibrated during the early 1960s) is reasonably reliable for generating flow data. However, the Luenha 2 station occurs upstream of the confluence of the Luenha River with the Mazoe River (with a catchment area of 34,216 km2), and commands only 17,183 km2 or 31.7% of the total Luenha catchment (54,144 km2). Flow records from the Mazoe River are limited to the period 1951-63, providing only four years of common record. A gauging station on the Luenha River below the Mazoe confluence (Luenha 1) was maintained from 1959-75. Comparison of data from these stations reveals that during low flows the Luenha River is perennial and the Mazoe River dries out, and flows at the Luenha 2 station should provide a good indication of total Luenha flow. During the month of October, flow at Luenha 2 is 87-99% of the flow measured at Luenha 1. During peak flows, however, the Mazoe contributes substantial flows, and the relationship between flows at Luenha 2 and Luenha 1 is inconsistent. In January, Luenha 2 is 32-59% of Luenha 1 flows, in February it is 35-47%, and in March it is 43-63%. Based on these findings, the Luenha flow data is considered unreliable for estimating total catchment runoff to the Zambezi.

Inter-basin correlation studies are also of limited value. Although the Revuboe and Luia catchments share many characteristics, there are substantial differences between the Luenha and Revuboe catchments. The Luenha River, with a catchment area of 54,600 km^2, is the largest river system between the Luangwa and Shire River Valleys. The Luenha drains from a region of lower rainfall on the south bank of the Zambezi River, and unit runoff is lower than for the north bank tributaries. Peak runoff from the Luenha catchment tends to occur in January/February, compared to peak runoff in February/March from the north bank catchments. Thus, Revuboe gauging data cannot be reliably used to generate an accurate flow series for Luenha.

To best estimate the runoff from the Luenha catchment, a simple rainfall-runoff model was constructed from rainfall records in the Mazoe and Luenha catchments. Although monthly rainfall and runoff was poorly correlated, most likely due to lack of sufficient gauging stations to properly characterize the basin, annual rainfall from the catchment was strongly correlated to annual Luenha runoff at station E348 ($r^2 = 0.85$). An annual runoff series for Luenha was generated from the annual rainfall series, for the period 1976-2000. The daily distribution of runoff was then estimated using the daily variation in flows measured at the Luenha 2 station.

This model has the advantage of providing a runoff series based on the annual variation in rainfall, and is independent of runoff from the north bank region. The correlation between annual rainfall and estimated runoff for the period since 1975 could not be tested, however, so overall reliability is uncertain. This relationship will be improved in the future after stage-discharge measurements are take to establish a reliable rating curve for the Luenha 1 gauging station.

Shire River catchment

Flow data from various stations in the Shire River catchment cover the period 1950-82 only. These data were obtained from the Ministry of Water Affairs in Lilongwe. Rainfall-runoff data are also not presently available for the lower Shire Valley. Therefore, there is no information available to extend the Shire River data series to cover the period of Cahora Bassa Reservoir discharges, 1976-2000, nor to extend the data series back to cover the full period of Dona Ana gauging data, 1930-58. Should adequate discharge or rainfall data become available in the future, a streamflow series may be generated to fully extend the daily data series from Dona Ana to the Zambezi Delta. For the present analysis, long-term mean monthly and annual values are used to describe the importance of the Shire River runoff to the hydrology of the Zambezi Delta, but runoff modeling is limited to the Zambezi catchment up to Muturara.

Reservoir discharge data

Hydrological data for Kariba Reservoir was provided by the Zambezi River Authority, for Itezhitezhi Dam and Kafue Gorge Dam by ZESCO, and for Cahora Bassa Dam by the Direccao Nacional de Aguas and Hidrotécnica de Cahora Bassa (Table 2-4). Reservoir outflows are computed directly from hydraulic relationships for turbines and spillway, and these calculations are generally considered to be quite reliable. The turbine discharge is determined as

$$Q_t = \frac{0.102 * E}{e * H_g * \Delta t}$$

where Q_t is turbine discharge (m^3/s), E is energy output (kW-hr), e is turbine efficiency, H_g is gross head, and Δt is the time step.

Errors may be introduced by inaccuracies in any of these terms, although errors in estimating energy output and turbine efficiency are considered negligible by the dam operators. The most likely source of error is in the estimate of gross head, the difference between water levels in the reservoir and tailwater. Inaccuracies in reservoir water level may be due to wave action at the gauging site. Tailwater levels are estimated from a discharge-elevation-rating curve at each station. These curves have been recently tested and updated at Kariba, Itezhitezhi, and Cahora Bassa Dams. Because of the high head at Kafue Gorge Dam, errors in the estimating the gross head are considered negligible.

Sluice gate discharge is governed by the Bernoulli equation, and errors in estimating outflow through sluice gates are primarily limited to errors in the measurement of reservoir water levels, as discussed above. For Cahora Bassa, the following sluice gate discharge relationships were derived from physical models during the design phase, where

$$Q_s\ (m^3/s) = 1455.68660\ (H_{CB} - 244.95)^{0.5}$$

if the reservoir water level is less than 320.9 m, and

$$Q_s\ (m^3/s) = 1455.68660\ (H_{CB} - 244.95)^{0.5} + 21.2\ (H_{CB} - 320.9)^{1.5}$$

if the reservoir water level is greater than 320.0 m, but less than 324.9 m, and

$$Q_{CB}\ (m^3/s) = 1455.68660\ (H_{CB} - 244.95)^{0.5} + 29.6\ (H_{CB} - 321.6)^{1.5}$$

if the reservoir water level is greater than 324.9 m. These relationships, based on design specifications for the dam, are likely fairly reliable (Hidrotécnica Portuguesa 1965n). However, because of their importance to water management in the lower Zambezi basin, river gauging immediately below Cahora Bassa is needed to verify the accuracy of turbine and sluice gate outflows.

Zambezi Delta water level data

Water level data are available from a large number of stations throughout the Zambezi system. Most of these stations lack adequate stage-discharge rating curves to generate reliable stream flows data. For the present study, water level data were acquired for the Zambezi Delta region only at Muturara, Caia, Marromeu, and Luabo (Table 2-5). These water level data provide a valuable record of the seasonal and annual changes in water levels in the Zambezi Delta region, but cannot be reliably used to estimate river flows. The rating curve problems at Muturara (Dona Ana gauging station) are described above. The river section at Marromeu is also unstable, and the rating curve at Marromeu (based on measurements during the early 1960s) provides only a general approximation of discharge conditions (Figure 2-50). Rating curves for Caia and Luabo are unavailable.

APPENDIX 2 EXTREME FLOODS IN THE ZAMBEZI DELTA

Introduction

The social and environmental benefits of regular annual flooding are described in detail in this dissertation and many other works (see for example, Figure 2-1), but the role of extreme flooding events (*floods capable of inundating the entire Zambezi Delta, occurring about once every ten years on average*) in maintaining social systems and ecological processes is poorly understood. Large flooding events often cause tremendous hardship for floodplain communities—displacing people from their homes, destroying food supplies, drowning livestock—but the floods also deposit nutrient-rich sediments, flush accumulated salts, and recharge groundwater supplies that maintain agricultural systems in the long-run. Large floods may drown buffalo calves and other wildlife species that are unable to escape rising water levels, but they also improve conditions for wildlife by removing woody invaders from the floodplain grasslands, reducing dry season fires, flushing aquatic macrophytes from waterways, or dispersing seed to the floodplain margin. In this context the value of even a single large flooding event may take years or even decades to assess, if ever, especially given that the benefits and costs of large flooding events also change with changing patterns of settlement, rural development, and social custom.

What *is* known about large floods is that, despite a century of river regulation and flood protection works, they are a fact of life in the Zambezi system. Cahora Bassa and Kariba Reservoirs may operate to eliminate most small- and medium-sized floods, but they do not have sufficient storage capacity to store the great floods that periodically move through the Zambezi system, as occurred in 2001. Furthermore, each Zambezi sub-basin, including the lower Zambezi Valley, is capable of generating significant flooding events in the delta region, independent of runoff elsewhere in the catchment. In the sections below, I describe the hydrological characteristics of extreme flooding events in the Zambezi Delta for the periods before and since the onset of river regulation.

Extreme floods prior to Zambezi regulation

Liesegang and Chidiamassamba (1997) report written records of extreme floods dating back to 1648. Descriptions of major flooding events dating back to 1830 are common in the oral histories of the people of the delta region. Three historical floods are particularly noteworthy.

In 1939, the delta reached its highest water levels in recorded history (Table A-1). The flood was generated by extreme runoff from the Middle and Lower Zambezi Valley, as peak runoff from the Zambezi headwaters region was only about 3016 m^3/s (below the long-term mean). Heavy runoff from the Middle Zambezi was sustained over most of February and March and the 2-month flood volume (25×10^9 m^3) was one of the highest on record. In the Lower Zambezi, flows at Muturara peaked at 18,700 m^3/s, and remained above 12,000 m^3/s for 27 days. Immediately downstream of Muturara the Shire Valley generated the heaviest rainfall and runoff in cultural memory (Mandala 1990) as Lake Malawi reached the highest water levels in recorded history. The resulting flood in the delta region overtopped the dikes that were built in 1926 to protect the sugar estates at Marromeu and Luabo, and inundated most of the 1.2 million ha. delta. The dikes were overtopped again in 1940 and 1944, during what was probably the wettest period in the twentieth century.

Table A-1. Ranking of the ten highest annual maximum flood stages recorded in the Zambezi Delta at Marromeu gauging station, for the period over period 1930/31-present. Maximum daily discharges (and rank) at Muturara and Victoria Falls corresponding to these years of maximum water levels at Marromeu are also given. The flood warning level at Marromeu is 5 m amsl.

Year	Marromeu maximum water level (m amsl)	Rank	Muturara maximum discharge (m^3/s)	Rank	Victoria Falls maximum discharge (m^3/s)	Rank
1938/39	8.01	1	18,700	4	3016	42
1951/52	8.00	2	22,300	2	6084	6
1957/58	7.97	3	22,500	1	10,168	1
1943/44	7.97	4	18,200	5	2724	46
1977/78	7.92	5	19,500	3	6297	5
1939/40	7.91	6	13,200	6	5035	18
1925/26	(7.85)	7	--	--	4497	23
1962/63	7.85	8	13,200	7	7011	4
1947/48	7.85	9	12,600	9	6074	7
1954/55	7.77	10	12,300	10	3753	29

The most prolonged flooding on record occurred in 1952, with heavy runoff generated from each of the Zambezi sub-basins. The flood, known locally as *Cheia M'bomane* ("the flood that destroyed everything"), caused extensive damage to houses and crops on the delta plains (Liesegang and Chidiamassamba 1997). Floods began building up in December and by February the Upper Zambezi reached its sixth highest flood peak on record, the Gwembe Valley was contributing its fourth highest flows on record, and the Luangwa Valley and remaining Middle Zambezi catchments were generating the highest flows on record. On February 17, Zambezi discharge at Muturara reached 22,300 m^3/s (Table A-1). Flooding in the Lower Zambezi was prolonged by heavy runoff from the Shire Valley, as discharges from Lake Malawi remained near record highs and a maximum discharge of more than 1900 m^3/s was reported from the Ruo tributary, a statistical 1:100 year flood (Halcrow and Partners 1954). Water levels remained above flood stage for 130 days, and above the catastrophic flooding level of 7.9 m (nearly 13,000 m^3/s) a remarkable 37 days until early March (Table 2-27). For the fourth time since 1926, the dikes protecting Marromeu and Luabo were overtopped. Maximum water levels in the Zambezi Delta reached 8.0 m, just shy of the highest on record, on four occasions over this period.

In 1958, the final year before Kariba Dam began regulating Zambezi flows, the delta again experienced extreme flooding. Known as the *Cheia N'sasira (*"the flood that forced people to live on top of termite mounds"), the flood resulted from the highest runoff ever recorded in the Zambezi headwaters region. Reeve and Edmonds (1966) noted that a low pressure system developed over Southern Angola during the dry season and moist Congo Air arrived over the northern watershed in September, much earlier that usual. The low-pressure area persisted for months, moving slowly across the headwaters region from north to south and generating a belt of intense rain that moved slowly down the catchment. The prolonged, early rainfall produced an exceptionally large flood above the Barotse Plain[29] that quickly exceeded the storage capacity of the floodplain and passed downstream, where it was augmented by very heavy rain between Senanga and Livingstone. The Zambezi peaked about 4-5 weeks earlier than usual, reaching a record peak discharge of 11,800 m^3/s at Livingstone on March 8 (Table A-1) at the same time that the rivers of the Gwembe Valley catchments were in peak flood. This resulted in a phenomenal peak of 16-17,000 m^3/s in Kariba Gorge. The total volume of runoff during the three month flooding period exceeded 61 x 10^9 m^3, just shy of the estimated 1:10,000 year design flood (65 x 10^9 m^3) for the dam under construction. The floods scoured through the partially completed dam wall, causing extensive structural damage. Downstream of Kariba, near-record runoff from the remaining middle Zambezi catchment also contributed to the flooding, and peak discharge at Muturara (22,500 m^3/s) was the highest on record. Water levels in the delta reached near-record levels, and exceeded catastrophic flood levels for 26 days (Table 2-27). Large numbers of Cape buffalo and waterbuck were purportedly drowned by these large floods (Tinley 1994).

Extreme floods subsequent to Zambezi regulation

After the completion of Kariba Dam in 1959, large flooding events in the Zambezi Delta region were greatly curtailed. The 1969 flood was not remarkable in terms of the peak water levels in the delta (about 7.39 m), but is noteworthy because water levels remained above flood stage for 222 days from early January until mid-August (Table 3-27). Local villagers refer to this strange dry season flood as the *Cheia Nabwariri* ("water coming from the ground"). The unusual pattern of flooding was the result of prolonged releases from Kariba Reservoir. Kariba received a near-record inflow volume of 79 x 10^9 m^3 – comparable to inflows to Kariba Gorge during the 1958 flood season – including the third highest recorded flood discharge from the headwaters region (8204 m^3/s). Unlike the 1958 floods, however, most of this inflow volume was stored by the reservoir and floodwaters were subsequently discharged through the Kariba's sluicegates during the dry season to draw down reservoir levels according to the Design Flood Rule Curve. Kariba thus operated to significantly reduce peak flooding in the Zambezi Delta, but greatly prolonged the total duration of flooding. Several other years during which runoff from the Zambezi Headwaters region was among the highest on record, including 1961 (6032 m^3/s), 1962 (5425 m^3/s), 1966 (5233 m^3/s), 1968 (5340 m^3/s), and 1970 (4783 m^3/s), also resulted in relatively insignificant floods at Marromeu due to Kariba regulation.

Since the construction of Cahora Bassa Dam in 1975, large flooding events have resulted in extensive social and economic damage. Many of these costs can be attributed to the encroachment of people onto lowland areas of the Zambezi floodplains that had never been historically occupied before Kariba regulation. In 1978, flooding on the lower Zambezi caused an estimated $62 million worth of damage and necessitating flood relief operations costing about $40 million. As noted by RPT (1980), "this was the first flood since completion of Cahora Bassa, and destroyed the widely held belief that the dam would finally bring flooding under full control." The flood resulted from a combination of emergency releases from Cahora Bassa Dam and heavy runoff from lower Zambezi tributaries. During 1978, prolonged rainfall in Kariba catchment produced some of the highest inflows to Kariba Reservoir on record and the Zambezi River Authority opened four of the six sluice gates at Kariba to prevent overtopping of the dam. Maximum discharge reached 7300 m^3/s. Downstream, heavy runoff from the Luangwa catchment more than doubled the Zambezi flows below Kariba, and Cahora Bassa inflows steadily increased to a peak of 17,900 m^3/s. During this period, Cahora Bassa operated with only 3-4 sluice gates open, but in late March water levels neared design capacity, and reservoir managers opened the remaining sluice gates in rapid succession. On March 30 reservoir levels reached 327.9 m, and Cahora Bassa released a peak discharge of 14,900 m^3/s with all eight sluice gates and the emergency spillgate open. Peak discharge downstream at Muturara surged to 19,500 m^3/s, and water levels at Marromeu spiked to 7.92 m (Table A-1). Many floodplain residents were unable to evacuate to higher ground in time, and forty-five people died during floods. More than 100,00 people were displaced[30]. Subsequent studies by RPT (1980) showed that if the reservoir had released water in January and February, gradually stepping up the outflow to 7000 m^3/s, releases would have been significantly less than actually occurred (reaching a maximum of 10, 163 m^3/s during early part of April) with adequate time to evacuate the most flood-prone areas.

In 1989, runoff from the Upper Zambezi was not sufficient to force Kariba to spill floodwaters, but heavy runoff from the Luangwa Valley generated a peak inflow of 14,436 m^3/s to Cahora Bassa Reservoir. Cahora Bassa operated to attenuate inflows and reduce the magnitude of downstream flooding, but during peak flooding reservoir levels approached design capacity and outflows were rapidly stepped up from one sluice gate on February 6 to five sluice gates on February 12, reaching a maximum discharge of 7938 m^3/ (Vaz 1989). Combined with heavy runoff from the plateau region[31], runoff in the Zambezi Delta region surged to 11,000 m^3/s. Although this peak discharge was less than the mean annual peak discharge prior to Kariba regulation (about 11,500), the flood caused widespread damage to settlements that had encroached back to the delta floodplains. The flood is known locally as *Cheia Cassussa*, remembered locally because flood levels rose so rapidly there was no time to escape[32].

In 1997, flooding in the Zambezi Delta reached its highest level since 1978 with a peak of 7.61 m at Marromeu. Flooding was generated almost entirely within the Lower Zambezi catchment. Maximum runoff from the Zambezi headwaters region was only 1758 m^3/s, one of the lowest peaks in the 75-year historic record, and Kariba did not spill. Inflows to Cahora Bassa from the Luangwa Valley rose sharply from less than 4000 m^3/s on February 9 to a peak of 12,170 m^3/s on February 15, but then fell again below 4000 by February 25. Cahora Bassa captured most of this brief surge, and maximum discharge from the dam was only 2000 m^3/s. Downstream of Cahora Bassa, however, the lower basin experienced the second wettest year on record with rivers in central Mozambique reaching flood stage in mid-January. The Pungue River to the south reached its highest water levels in 30 years and the road linking Beira to Zimbabwe was severed. Runoff from the Shire Valley was the highest since the 1950s. Overall, the flood peak was not remarkable – only the sixteenth highest on record – but the flooding ripped through new settlements on the Zambezi banks and is known as the *Cheia N'selusso* ("flood of ill-fortune"). The media portrayed the flood as catastrophic and international evacuation efforts were widely televised.

The recent 2001 floods in the Zambezi Delta were the most prolonged since construction of Cahora Bassa Dam. Very heavy rainfall in the Zambezi headwaters region resulted in substantial inflows to Kariba Dam, which spilled floodwaters for first time since 1981. Two gates were operated, discharging a steady 3800 km^3 in addition to turbine outflows. Rainfall in the Middle Zambezi catchment was also heavy, and inflows to Cahora Bassa peaked at 13,978 m^3/s on February 22 and again at 11,379 m^3/s on

March 15. As water levels in Cahora Bassa reservoir approached design capacity, Mozambican authorities plead privately and publicly with the Zambezi River Authority to close the sluice gates and reduce Kariba outflows. Discharges from Cahora Bassa were stepped up to 9000 m^3/s on March 7-8 through five sluice gates. Downstream the Luia and Revuboe Rivers discharged a steady 2000-3500 m^3/s, the Luenha contributed 1000-1500 m^3/s, and heavy rains in the Shire Valley (that left 5 people dead and 22,454 people homeless) generated runoff from the Shire basin comparable to the 1997 floods. Water levels at Marromeu climbed above flood stage on January 20, and reached a maximum of 7.69 m on March 9. The navy began evacuating people from the delta region in January using rubber boats and later helicopters, but many people refused to leave their homes. Overall, eighty-one people died and more than 155,000 people were displaced by the floods (Hanlon 2001). Although tragic the damage could have been considerably worse if Hurricane Elise, which struck the central Mozambique a year earlier, had hit the delta region during peak flooding and forced Cahora Bassa authorities to open more sluice gates.

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ENDNOTES

[1] Rainfall patterns are influenced by the movement of the Inter-Tropical Convergence Zone (ITCZ). The ITCZ is the convergence of three distinct air currents, the *South East Trade Winds* of the Indian Ocean that cover Mozambique and Zimbabwe, the *North East Monsoon* (an extension of the air stream flowing out of the Asiatic High from the Arabian Sea that covers the East African coast), and the *Congo Air* (a monsoonal in-draught across the west coast of Africa that covers the Zambezi basin from a north easterly direction). The convergence between the South East Trade Winds and the Congo Air is generally aligned in an east-west direction, while the convergence between the North East Monsoon and the Congo Air lies in a north-south alignment. From November to March, the ITCZ moves south over the Zambezi Basin.

The convergence is identified with a shallow trough of low pressure. The trough may deepen at times, or closed centers of low pressure may develop in areas where convergence is intensified. These troughs move slowly as a function of surrounding pressure changes, but may remain near stationary for extended periods of time. When centers of low pressure form *equatorial lows* over southern Angola or northern Botswana, conditions are favorable for the moist Congo Air to move in and produce large rainfall events across the Zambezi basin. From April to October, the ITCZ shifts north and the Zambezi basin is influenced by a zone of high pressure with warm, sunny conditions (Hidrotécnica Portuguesa 1965h, Balek 1977).

[2] The Zambezi catchment is often divided into three distinct sub-catchments-- the Upper, Middle, and Lower catchments. The Upper Zambezi is typically described as the drainage area above Victoria Falls. Some authors include the Okavango River drainage system in Angola as part of the Upper Zambezi catchment (see discussion in main text). The Middle Zambezi is typically defined as the section of river between Victoria Falls and Cahora Bassa Gorge (*e.g.*, Coppinger and Williams 1994), although Timberlake (1998) defined the Middle Zambezi as the section of the river between Victoria Falls and the Lupata Gorge in Mozambique, based on biogeographical considerations. The Lower Zambezi is generally defined as the region downstream of Cahora Bassa Gorge to the Indian Ocean coast.

[3] The differential mass curve (DMC) plots the accumulation of the differences between each individual value and the average value for the whole series. When plotting the differential mass curve for two or more catchments on one graph, it is useful to normalize the data by plotting the accumulation of the differences between each individual value and the average value for the whole series divided by the average value for the whole series. This provides a dimensionless differential mass curve that enables the comparison of trends when rainfall or runoff differ significantly in magnitude.

[4] Several engineering studies conducted during the 1970s argued that annual flows in the Zambezi system were increasing over time as a result of changes in land use and runoff patterns in the catchment (*e.g.*, SWECO 1971, Balasubrahmanyam and Abou-Zeid 1982a), and that the trends observed from 1940s to 1970s would continue. These studies proposed rates of hydropower generation that far exceeded the Zambezi potential over the full 92-year record.

[5] Major inter-basin water transfers, such as the proposed diversion of 95 m^3/s of Zambezi headwaters to industrial areas in South Africa (Basson 1995), are unlikely in the foreseeable future. A small run-of-the-river generating plant at Victoria Falls (constructed in 1906 for thermal generation and upgraded for hydropower production in 1938) produces 108 MW (Figure 2-9) and is considered to be at maximum capacity without having a measurable effect on Zambezi flows and hence Victoria Falls tourism (Eskilsson 1974). The Katombora Dam has been proposed to regulate inflows to the Victoria Falls power station, and would impound about 9.0×10^9 m^3 with high evaporative losses (Figure 2-9). However, the Katombora Dam is politically unlikely because it would raise the base levels of the Zambezi and Chobe Rivers and inundate part of the Chobe National Park in Botswana and the Caprivi Strip in Namibia (Clayton 1985).

[6] The Gwembe Valley catchment is defined here for convenience as the entire region between Victoria Falls and Kariba Dam, including Batoka Gorge and Devil’s Gorge, although the term “Gwembe Valley” is typically reserved for the region below Devil’s Gorge to the Kafue River confluence. Batoka Gorge is a steep-sided basalt canyon with few tributaries. The Gwembe Valley is a trough structure associated with an ancient arm of the East African Rift System extending down through Kariba and Cahora Bassa Gorges (Handlos and Williams 1985).

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[7] Proposed new water resources developments in the lower Kariba catchment include the Batoka Gorge Dam and Devil's Gorge Dam (Figure 2-9). The Batoka Gorge Dam (1762 m amsl) would have a catchment area of 520,000 km^2, with a reservoir volume of 1.85 x 10^9 m^3 and 27 km^2 surface area. The Batoka Gorge hydropower station, if operated in conjunction with Kariba Dam, would enable Kariba to significantly reduce its flood season output in order to build up reservoir storage for the dry season. Batoka's high installed capacity of 1600 MW would be sufficient to satisfy regional power demands during the months of high Zambezi flows. Such operation would serve to further stabilize the Zambezi flow regime. The proposed damming of the Devil's Gorge, a 20-km reach of the Zambezi Valley at the western end of Kariba Reservoir (1595 m amsl), would impound a volume of 33 x 10^9 m^3, over a surface area of about 750 km^2. Evaporative water losses would be high from both of these reservoirs (Clayton 1985).

[8] Some authors have suggested that rainfall over Kariba Gorge may have increased relative to pre-impoundment conditions because of the substantial increase in evaporative water loss (*e.g.*, Balon and Coche 1974), but there are insufficient long-term gauging sites to test this hypothesis.

[9] Although the Kafue is typically regarded as part of the Middle Zambezi catchment, it was part of what is now the Upper Zambezi some hundreds of thousands of years ago. The Kafue catchment shares many geomorphological and biological characteristics with the Zambezi headwaters region.

[10] Proposed new water resources developments in the Kafue catchment include the Itezhitezhi Hydroelectric Power Plant and Kafue Gorge Stage 3. The proposed Itezhitezhi power plant would be built adjacent to the existing Itezhitezhi reservoir, with an installed capacity of 120 MW. The plant would be operated 24-hours per day, with greater generation during an 8- to 10-hour peaking period during daylight hours (Harza Engineering and Rankin Engineering Consultants 1999). Kafue Gorge Stage 3 would utilize the remaining 200-m head downstream of the existing Kafue Gorge Dam. Total generating capacity would be 450 MW. Construction of these hydropower stations would greatly increase the total capacity of the Kafue system, and could alter reservoir management practices basin-wide through the potential for a significant increase in firm capability of a joint system involving other Zambezi hydropower installations (Shawinigan-Lavalin and Hidrotécnica Portguesa 1990a).

[11] The contribution of the catchment between the Kariba and Kafue Gorges, a distance of 60 km with seasonal tributaries, is considered negligible relative to the remaining Middle Zambezi catchment.

[12] Hydropower projects in the Lunsemfwa catchment include the 20 MW Mulungushi Dam and Power Station (the first hydropower development in the Zambezi catchment, completed in 1923) and the 18 MW Mita Hills Dam and Lunsemfwa Power Station (completed in 1958) (Legge 1970). There are no hydropower projects on the mainstem Luangwa.

[13] Other proposed development projects in the Middle Zambezi catchment include the Mupata Gorge, located 30 km upstream of the confluence of the Zambezi and Luangwa (Figure 2-9). This is the only site for hydropower development between Kariba and Cahora Bassa Reservoirs on the mainstem Zambezi. The proposed Mupata Gorge Dam, with a catchment area of 840,000 km^2 would create a reservoir about one-quarter the size of Kariba Reservoir, with a volume of 19.8 x 10^9 m^3 and surface area of 1200 km^2. If constructed, it would inundate up to 10% of Mana Pools National Park and further alter runoff patterns in the middle Zambezi (Du Toit 1983).

[14] According to Davies (1998): "One of the most extreme cases of stream regulation and mismanagement took place below Cahora Bassa wall between December 1974 and April 1975. No discharge took place

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from commencement of filling on December 5 until late March-early April. The situation became so bad that apart from the gorge below the wall drying out, by mid-February, water abstraction equipment in the town of Tete also ran dry—at the peak of the flood season. After the reservoir filled too rapidly due to heavy rains in Zambia and Zimbabwe, emergency discharges from the dam took place. Thus, not only was the normal flood peak reduced to below dry-season flows in that year, but a flood was artificially generated at a time when the river should normally have begun to drop, post flood."

[15] The development of the Cahora Bassa Dam North Bank Power Station is currently under consideration. The North Bank would have two additional turbines and a design capacity of 884 MW (Li-EDF-KP Joint Venture Consultants 2000a). It would operate to further even out the flow regime of the Zambezi, increasing turbine outflows from 1200-1600 m^3/s to nearly 2000 m^3/s during the dry season and decreasing the volume of water available for managed flood releases (see Working Paper #4).

[16] This figure includes 11.5×10^9 m^3 cumulative runoff from the Luia, Revuboe, and Luenha catchments (98,084 km^2) and 1.5×10^9 m^3 additional runoff from the remaining ungauged catchments (37,816 km^2) between Cahora Bassa Dam and the Muturara gauging site.

[17] The Zambezi Valley Development Authority estimates that the net hydropower potential of the Zambezi basin is a remarkable 14,000 MW, more than five times the current capacity of 2075 MW at Cahora Bassa (Hidrotécnica Portuguesa 1965k, Gabinete do Plano do Zambeze 2001). This extreme estimate is probably based on studies from the 1960s, when the MFPZ proposed large-scale hydropower development in the region, including 15 dams in the Luia basin, 12 in the Revuboe basin, 12 in the Luenha basin, 14 on other tributaries, and 4 in the lower Shire Valley (Hidrotécnica Portuguesa 1961a,b,&c). Detailed follow-up studies of individual projects larger than 4 MW suggested that only 2 of the tributary projects were worth considering, the Luia 6 (16.5 MW) and the Luenha 7 (13.2 MW) (Hidrotécnica Portuguesa 1965a,m,p), however, and neither of these projects is currently under serious consideration.

On the mainstem Zambezi, four large dams have been proposed, including the Mepanda Uncua, Cambewe Foz, Boroma, and Lupata dams (Hidrotécnica Portuguesa 1965o&p)(Figure 2-9). The Mepanda Uncua Dam, located upstream of Tete with a local catchment are of 36,000 km^2 below Tete, is in advanced planning stages (Li-EDF-KP Joint Venture Consultants 2000a). The proposed dam is a run-of-river structure with installed capacity of up to 2400 MW, a live storage of 2.3×10^9 m^3, and a surface area of 96.5 km^2 at a full supply level of 205 m (Li-EDF-KP Joint Venture Consultants 2000a). Mepanda Uncua will capture runoff from the Luia tributary, further reducing the proportion of unregulated flows in the Zambezi catchment. Cahora Bassa Dam will continue to exert the greatest influence on Zambezi runoff, however. Mepanda Uncua will not result in significant attenuation of large floods, but may further dampen medium-sized floods and lose 130×10^6 m^3 in net evaporation. The hydroelectric station will also be used for peaking operation. Boroma Dam has been proposed to re-regulate peaking releases from Mepanda Uncua Dam, but it is currently considered economically unfeasible (Li-EDF-KP Joint Venture Consultants 2000a).

The plateau region is also rich in coal, iron, chromium, nickel, manganese, copper, and aluminum, and considerable mining and related development activities are likely in the future (Hidrotécnica Portuguesa 1965a&h). The ongoing Zambezi Valley Strategic Development Initiative is charged with evaluating the potential impacts of various development projects on the water resources of the lower Valley. Although runoff patterns are unlikely to be significantly affected by these development works, deleterious changes in water quality may be inevitable.

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[18] The Nkula Falls hydropower installations have a combined capacity of 104 MW. Further downstream, the Tedzani Falls hydropower installation has an installed capacity of 40 MW. A third dam on the middle Shire at Hamilton Falls is under construction.

[19] The Ruo River is the only Shire tributary considered suitable for hydropower development (Halcrow and Partners 1954). Regulation of the Ruo runoff would lead to a considerable reduction in peak flood flows in the lower Shire. Halcrow and Partners (1954) proposed an integrated program of flood control, hydropower production, and wetland reclamation for the Shire Valley, including drainage of the Elephant Marsh, Ndindi Marsh, and other floodplain areas for agriculture. Large-scale reclamation of these floodplains, which has occurred in part during past periods of extreme low flow, would reduce the attenuation of Shire floodwaters, resulting in earlier and higher peak discharges to the Zambezi. Suschka and Napica (1985) studied the potential for navigation on the Shire.

[20] Detailed analyses of the drainage evolution, tectonics, and geomorphology of the Zambezi basin are provided by Thiele and Wilson (1915), Thiele (1924), Thomas and Shaw (1988), and Nugent (1990). King (1972) describes the development of the coastal plain.

[21] See Appendix 1 for a discussion of the impact of civil war on data collection in Mozambique.

[22] Data are currently being collected to use a more advanced system (HEC-RAS) to model flooding patterns. Efforts to map flooding extent directly using Landsat satellite data and NOAH Meteosat imagery failed because of heavy cloud cover over the delta during the rainy season, especially during years of above-average flooding.

[23] There are only 10 rainy days on average during the peak months of January and February, and 70 rainy days per year occur on average.

[24] Data on water use in the Zambezi basin, as it affects the delta water budget, were compiled from several published reports, especially the proceedings of an IUCN workshop on water resource use in the Zambezi Basin that includes estimates of present, future, and proposed water abstractions from the Zambezi basin for Botswana (Sekwale 1995), South Africa (Basson 1995), Zambia (Kasimona and Makwaya 1995), Zimbabwe (Durham 1995, Mpande 1995), and Namibia (Heyns 1995). Estimates for water use in the Shire Valley in Malawi were obtained from the Ministry of Water Affairs. Estimates for water use in Mozambique were obtained from the Zambezi Valley Development Authority (GPZ) and DNA. Data on pumping and water use by the Sena Sugar Estates are currently not available.

[25] The impact of climate change on runoff and flooding patterns in the Zambezi Delta is beyond the scope of this study. The recent years of heavy flooding in southern Africa suggest that the drought period of the 1980s and early 1990s has broken, and that the permanent decrease in rainfall due to dams and deforestation suggested by some researchers is not substantiated. The full impact of climate change on Zambezi runoff remains to be investigated.

[26] Although part of the Cheringoma plateau is protected in the Nhapacue Forest Reserve, most of the region is unprotected and heavily logged. Recent proposals to convert large areas of escarpment woodland to Eucalyptus plantations, a species known for its very high rates of transpiration, are of particular concern.

[27] 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

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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.

[28] 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).

[29] Although runoff the Zambezi headwaters region was the highest on record in, rainfall was only about 17% higher than the long-term mean. Runoff was disproportionately high because the heaviest rains were centered along the main river channel and there was an unusually short time of concentration over the catchment as a whole.

[30] The 1978 floods are known locally as the *Cheia Maldeia* (“the flood that forces us to leave our homes and move to communal villagers”). The Government of Mozambique required flood victims to resettle into communal farming areas on higher ground to administer aid during the floods, and to promote agricultural development in subsequent years.

[31] Estimated contribution from Luia River, for example, included peaks of 3875 m^3/s on Feb 7 and 3865 on March 8, and remained above 3000 m^3/s from March 8-12.

[32] Because there was no hydropower transmission capability at Cahora Bassa turbine discharge was only 75 m^3/s throughout the flooding period rather than 1400-1600 m^3/s, resulting in a sharper increase in reservoir water levels.

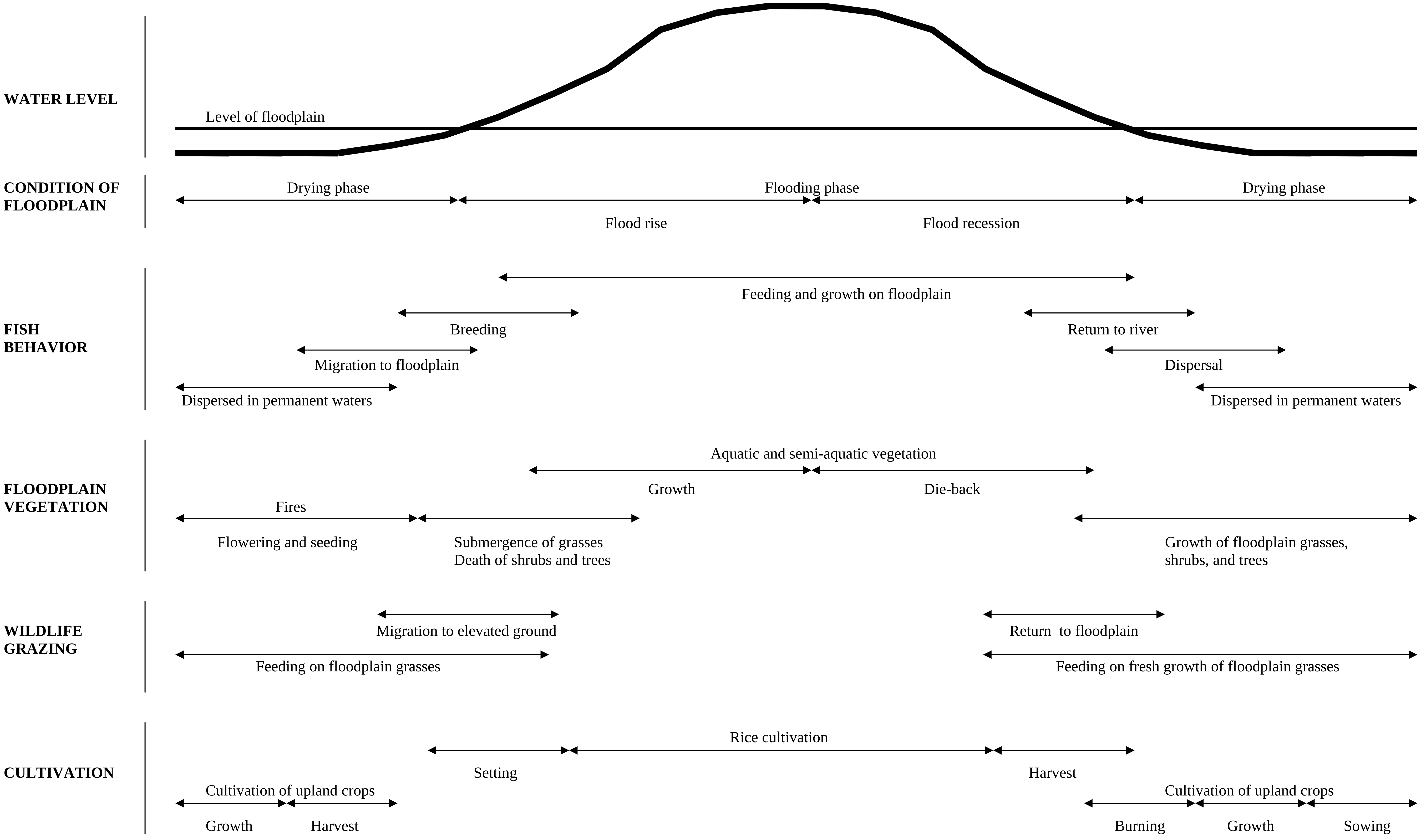


Figure 2-1. Annual cycles of fish behavior, floodplain vegetation, wildlife grazing, and cultivation on an undisturbed floodplain system. Adapted from Welcomme (1979) and SWECO (1983).

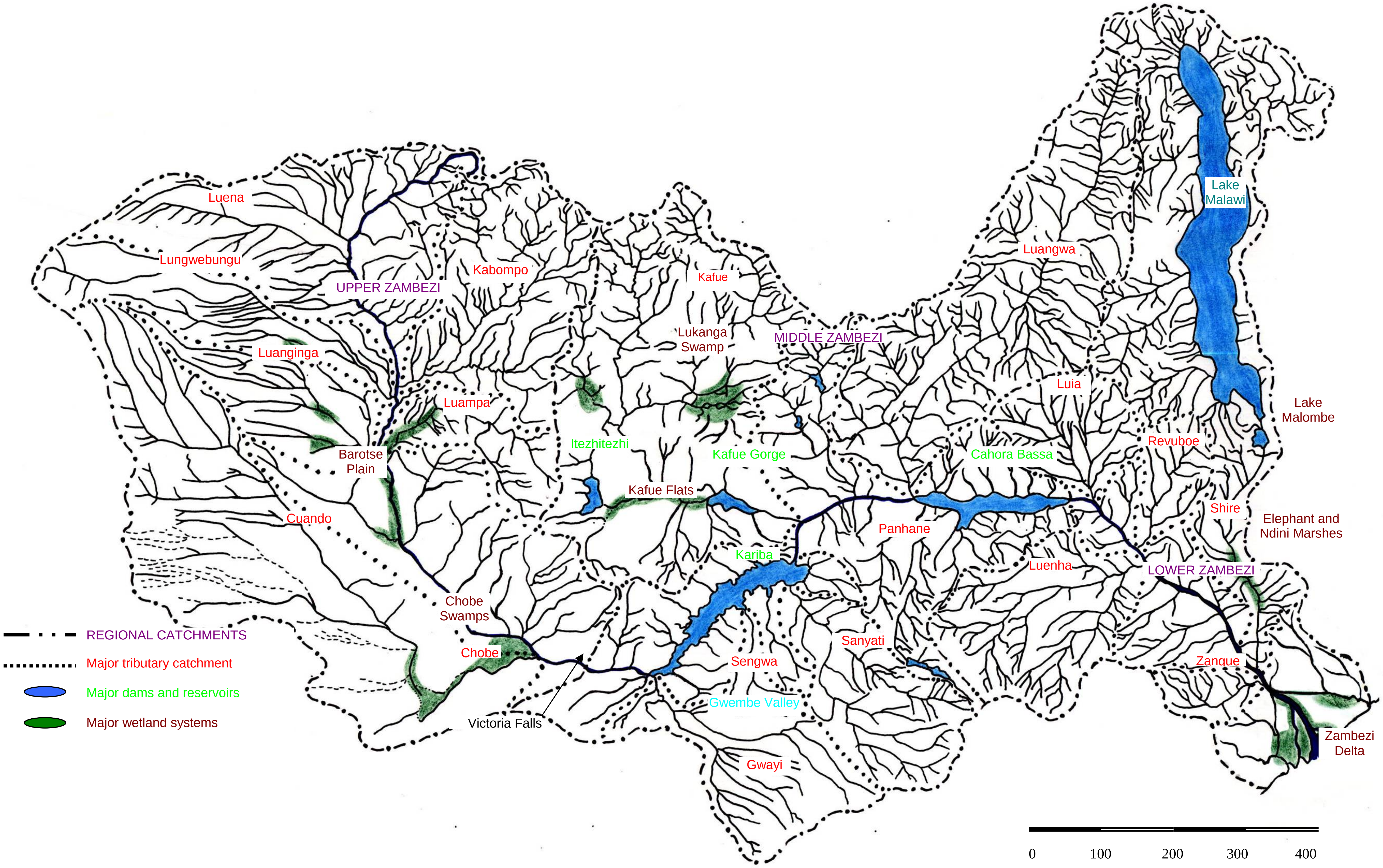


Figure 2-2. The Zambezi Basin showing regional catchments and major tributary systems, reservoirs, lakes, and wetland systems.

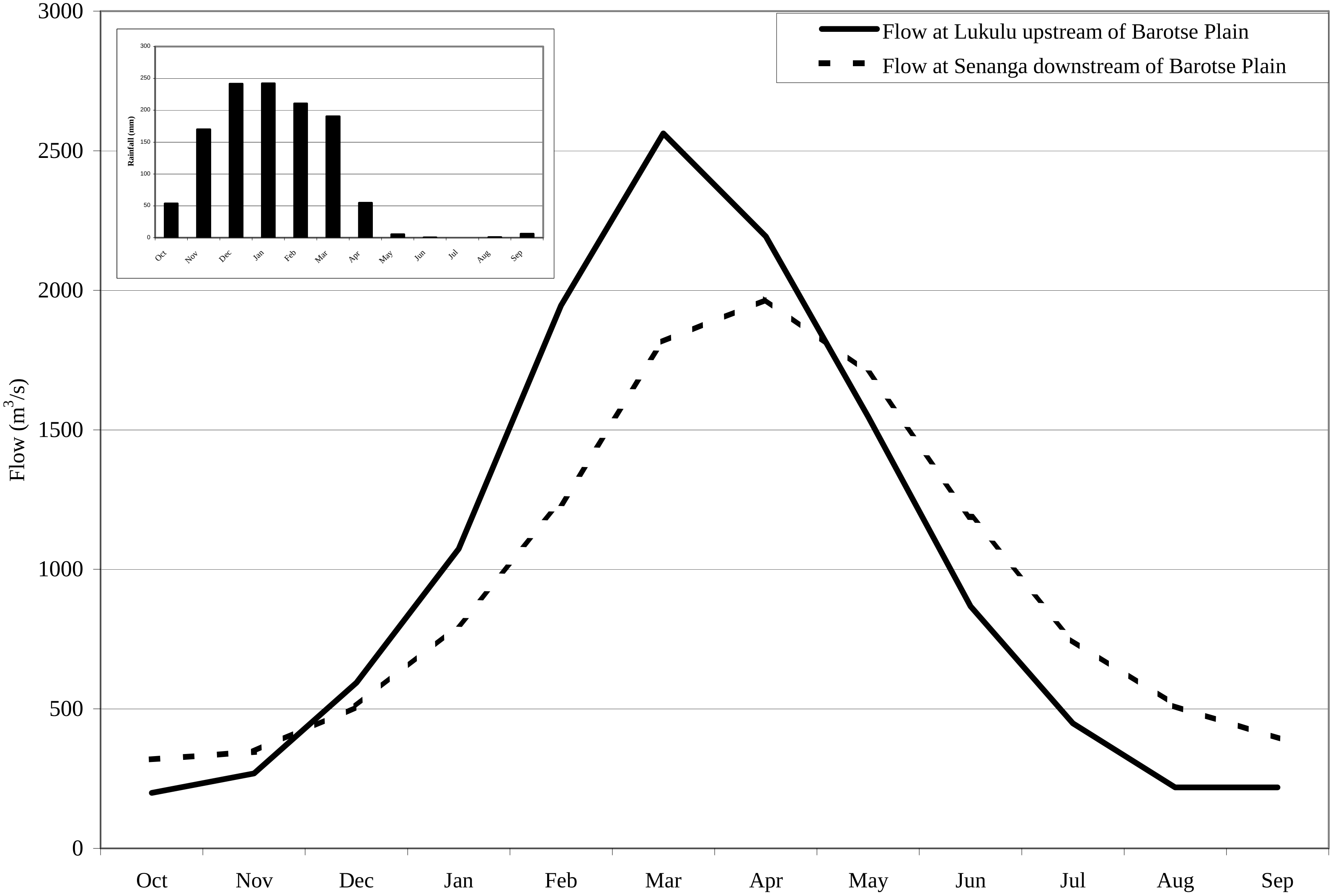


Figure 2-3. Mean monthly rainfall in the Zambezi headwaters region (inset), and hydrographs of mean monthly runoff upstream and downstream of the Barotse Plain, 1950-99, showing attenuation of peak runoff.

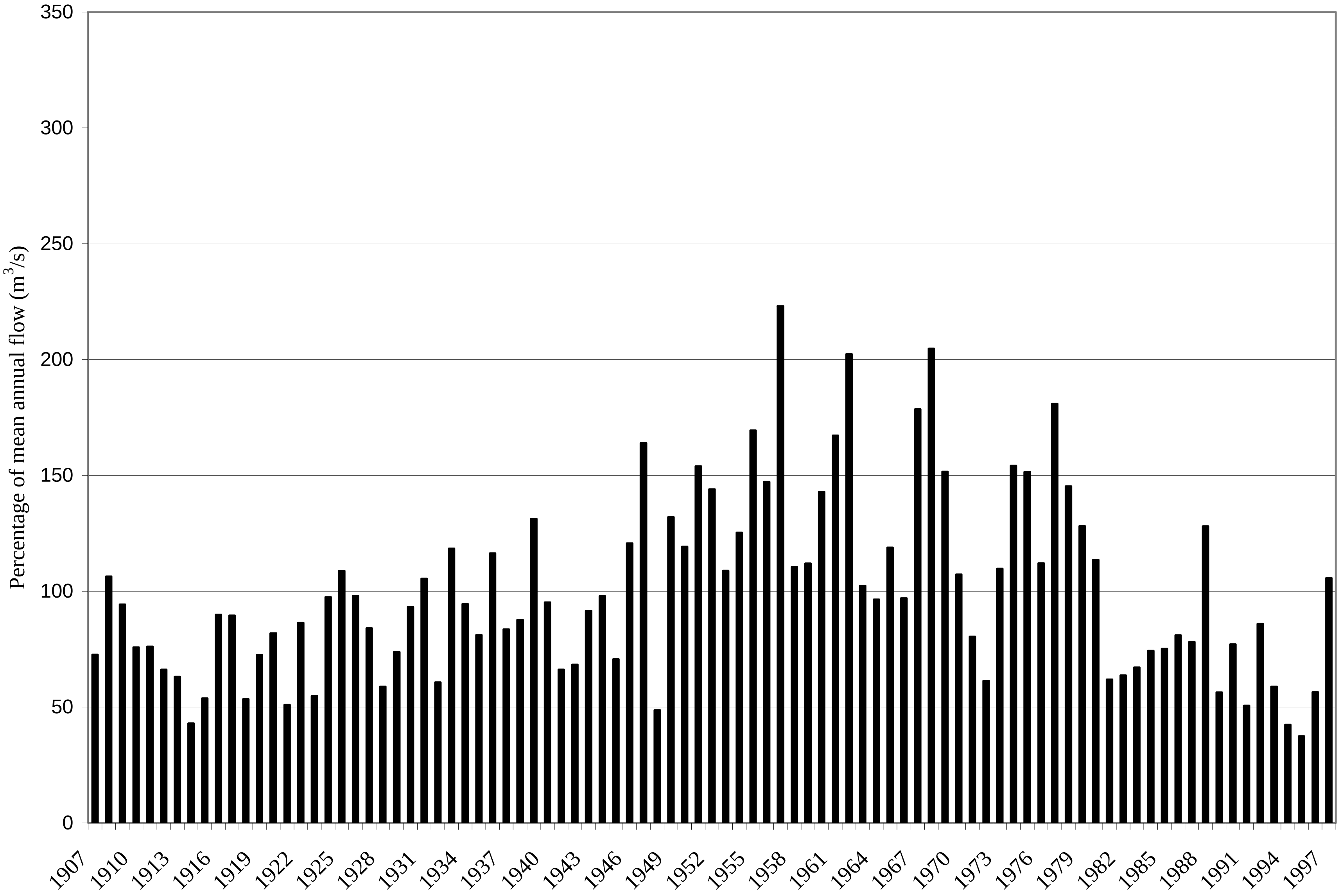


Figure 2-4. Time series of annual runoff from the Upper Zambezi catchment at Victoria Falls, as a percentage of mean annual runoff.

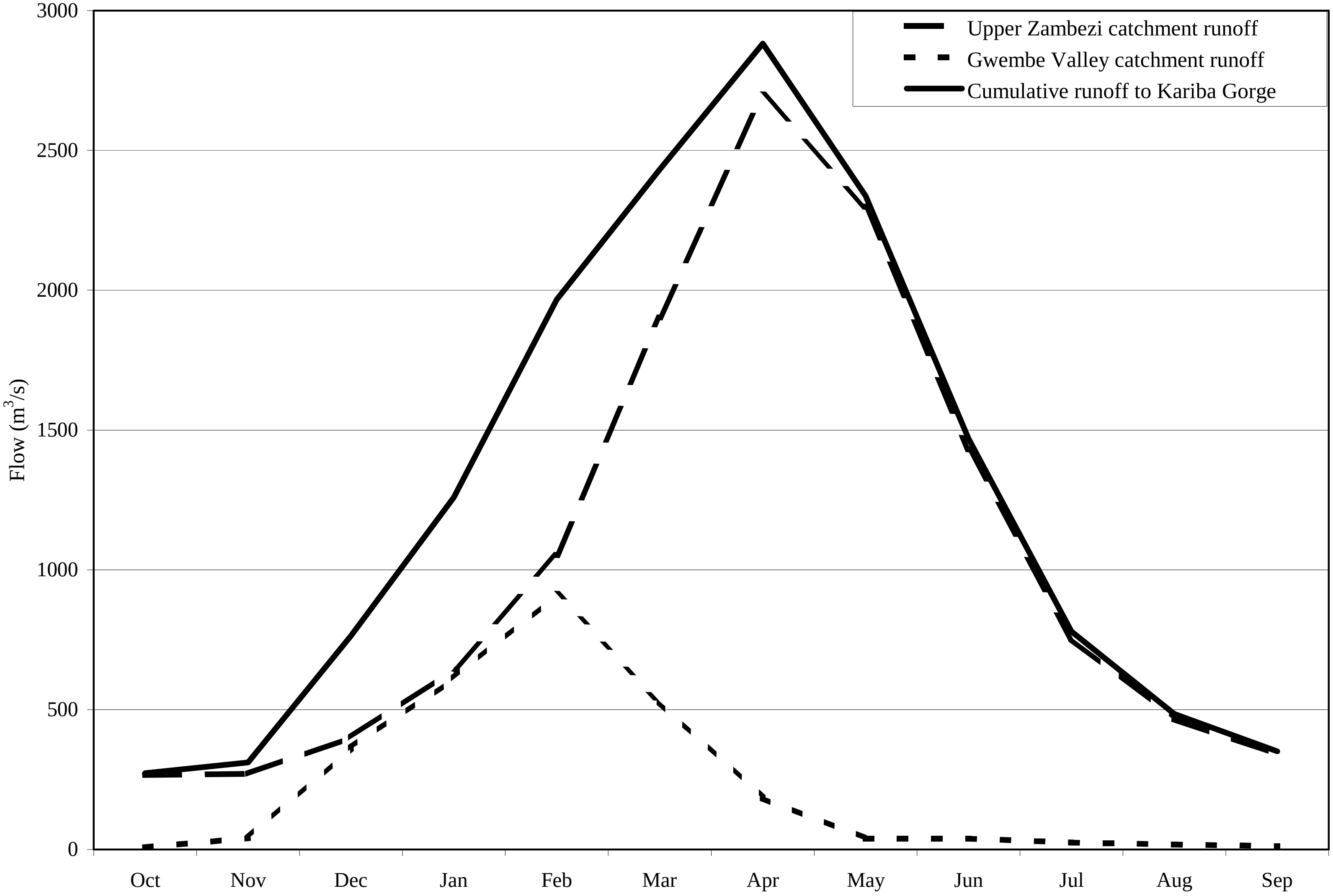


Figure 2-5. Hydrographs of mean monthly runoff from the Zambezi catchment above Kariba Gorge, 1907-98, showing runoff contribution from the Upper Zambezi catchment (*Mororwe*) and Gwembe Valley catchment (*Gumbora*).

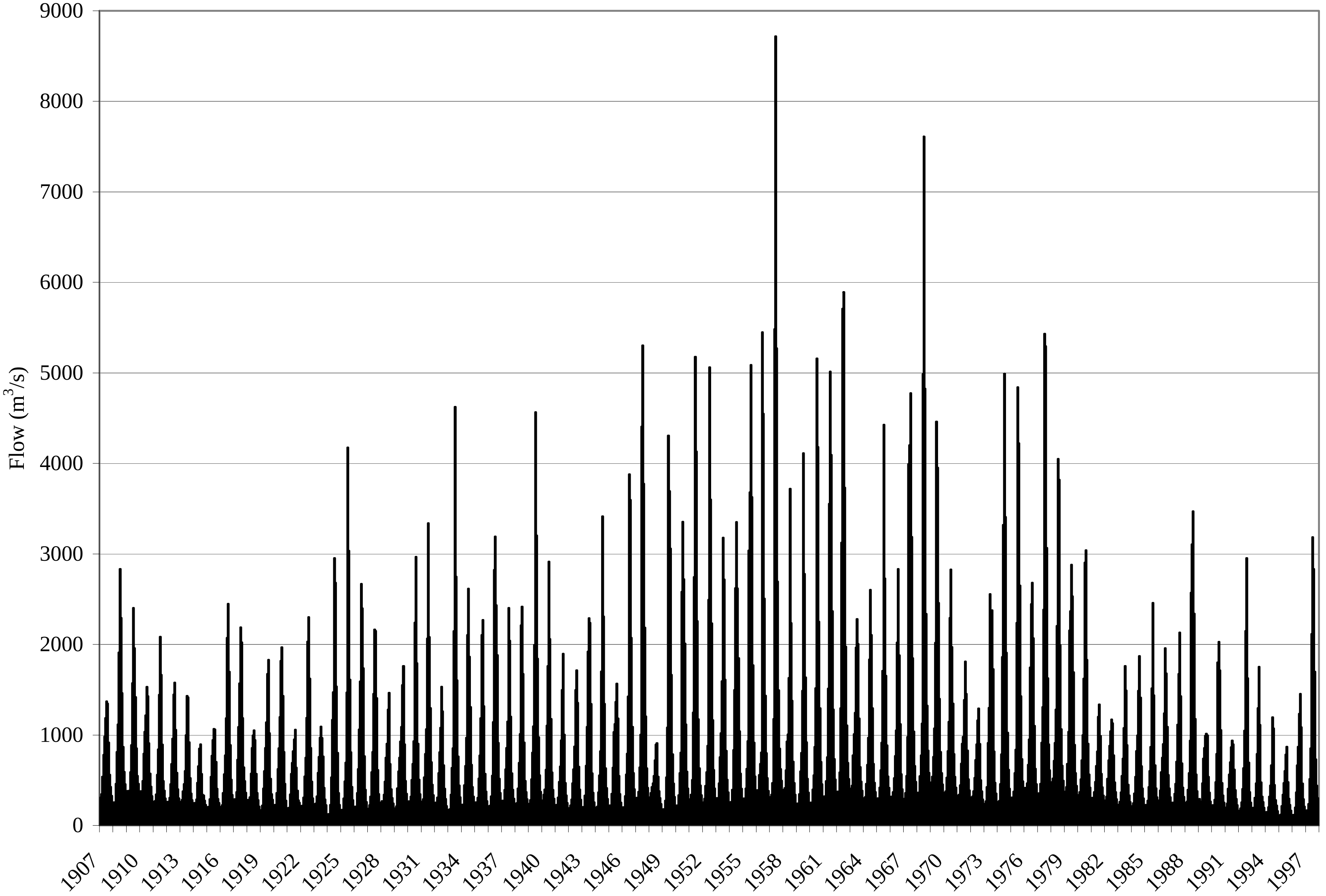


Figure 2-6. Time series of mean monthly runoff from Upper Zambezi catchment at Victoria Falls.

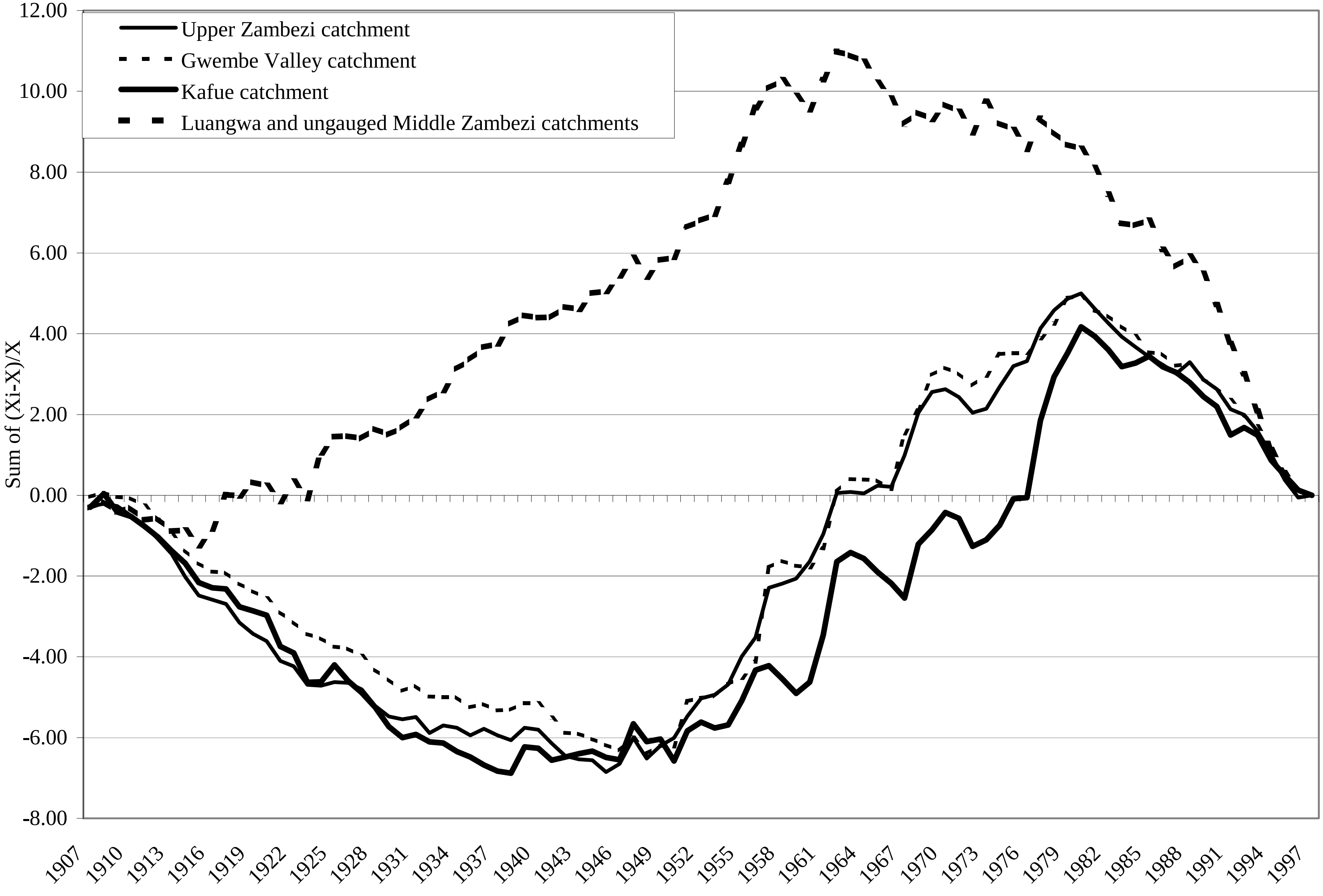


Figure 2-7. Dimensionless differential mass curves for annual runoff from major Zambezi River catchments above Cahora Bassa Gorge.

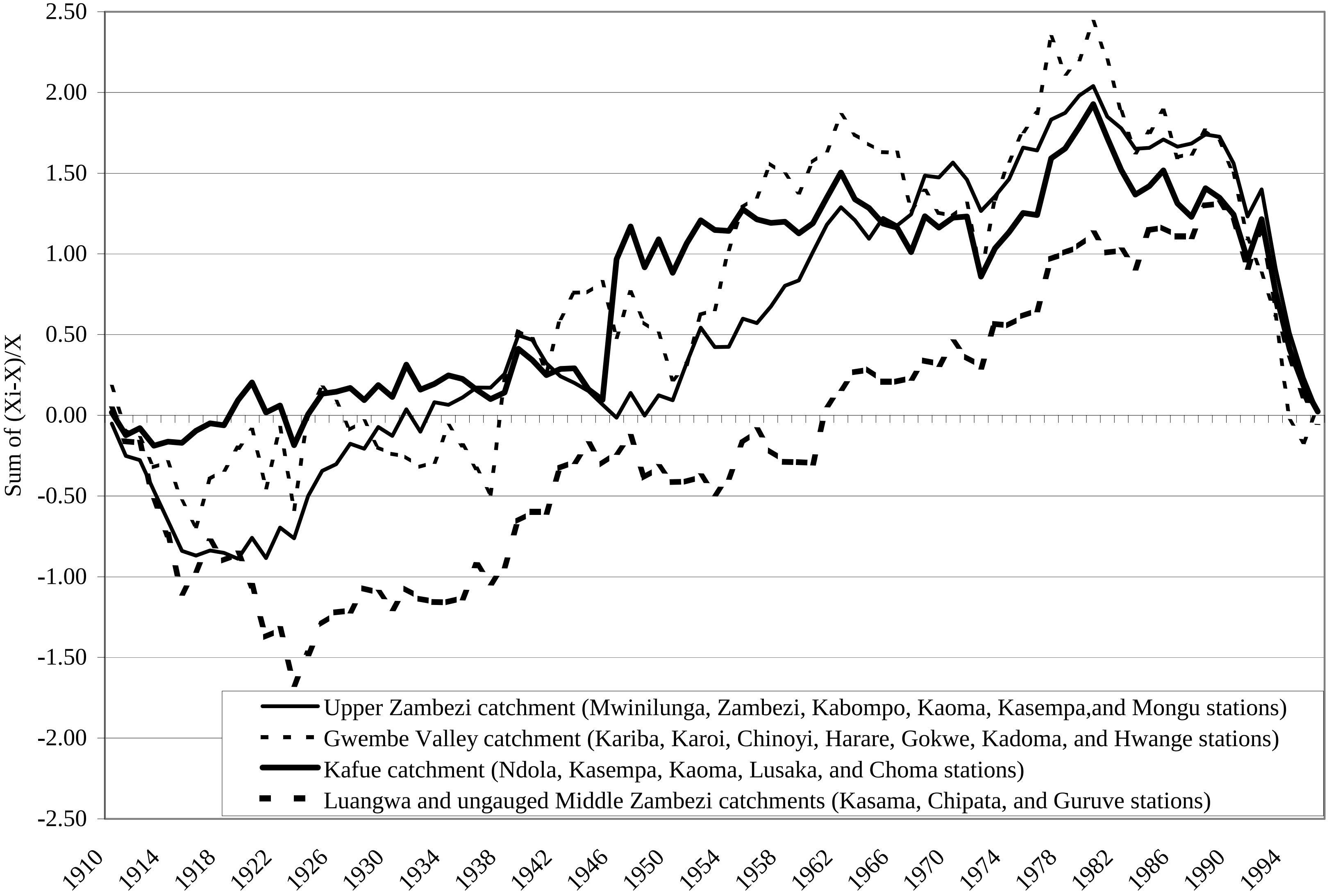


Figure 2-8. Dimensionless differential mass curves for annual rainfall from major Zambezi River catchments above Cahora Bassa Gorge.

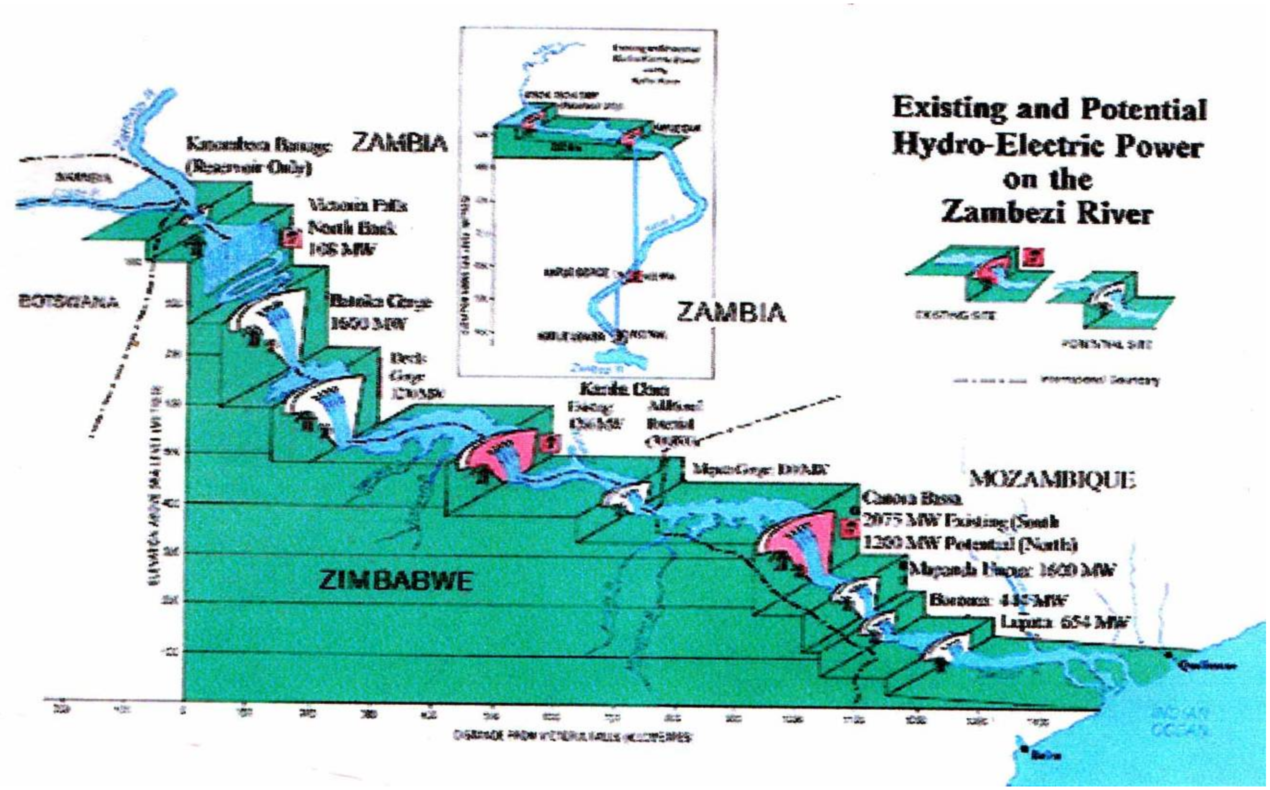


Figure 2-9. Schematic of existing and potential hydropower development sites in the Zambezi catchment (from Zambezi River Authority files).

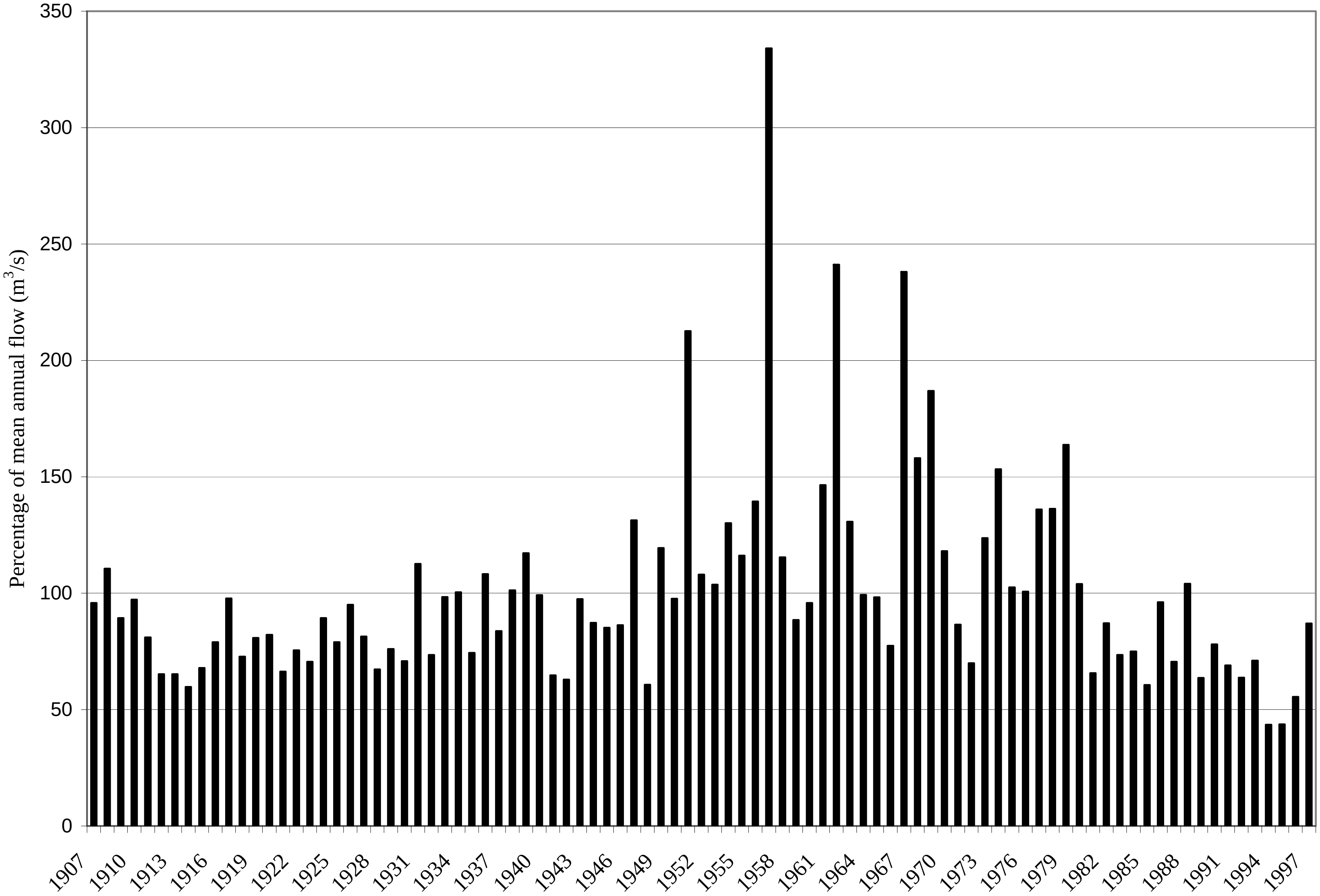


Figure 2-10. Time series of annual runoff from the Gwembe Valley catchment between Victoria Falls and Kariba Gorge, as a percentage of mean annual runoff.

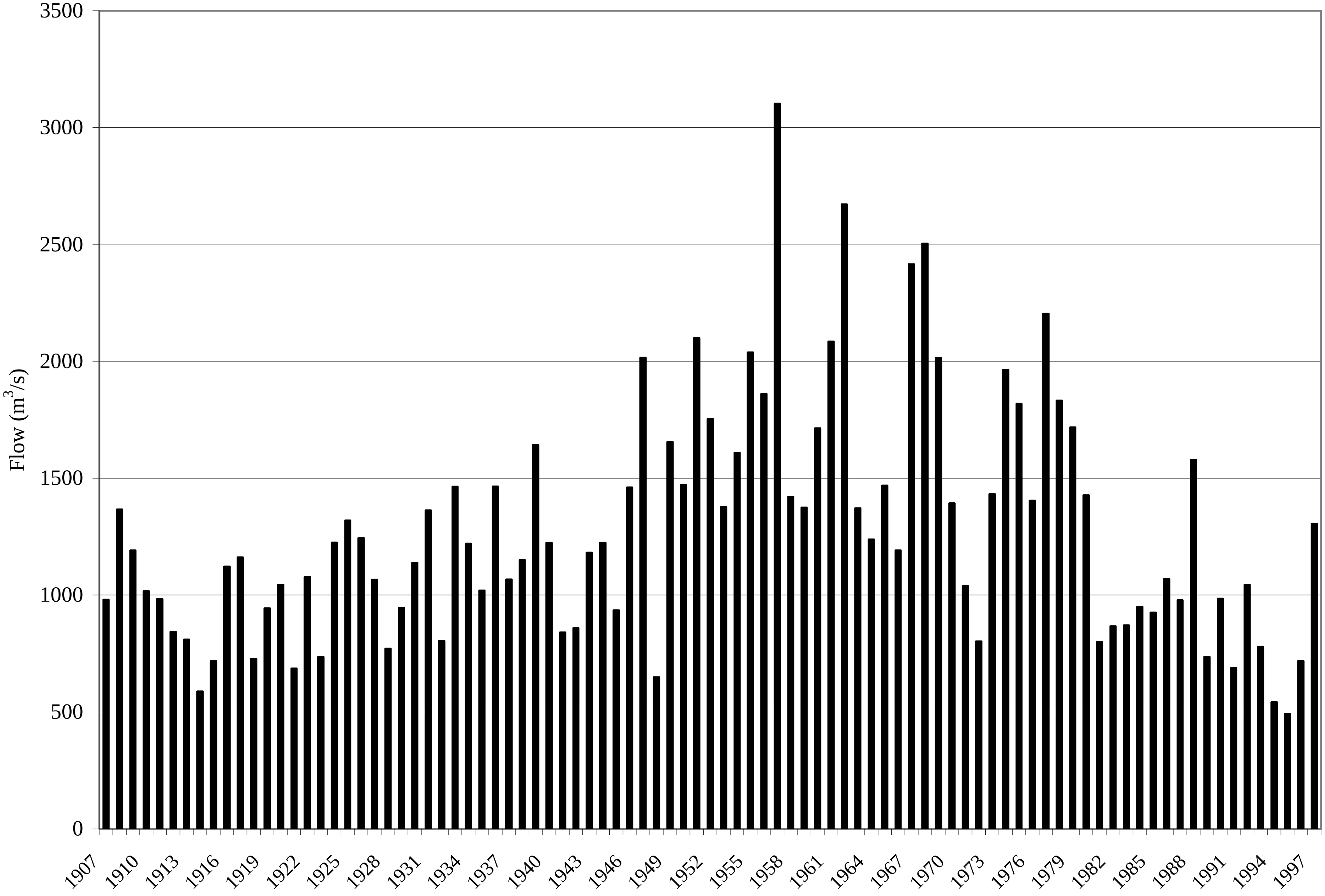


Figure 2-11. Time series of annual runoff from the entire Zambezi catchment above Kariba Gorge.

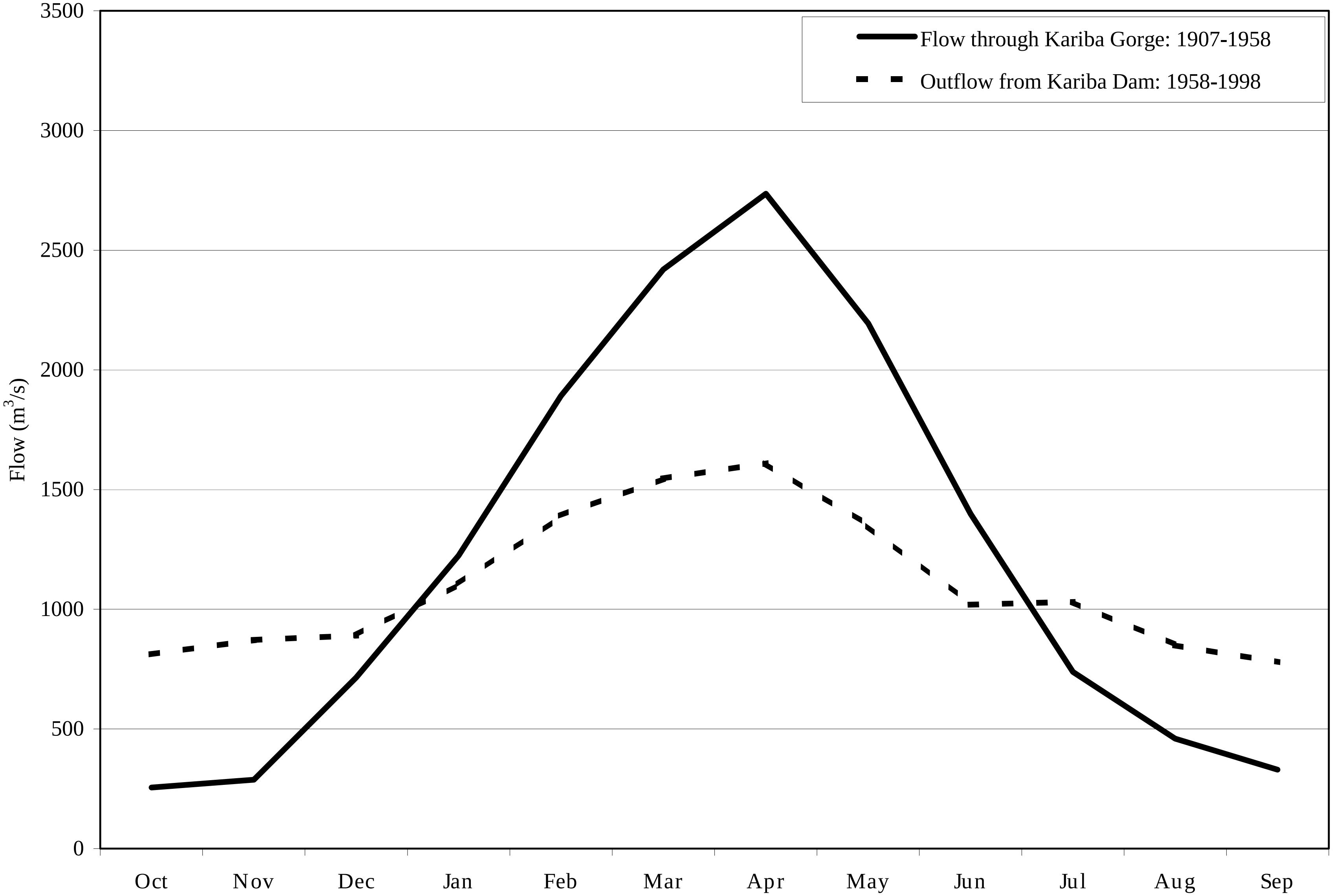


Figure 2-12. Hydrographs of mean monthly runoff at Kariba Gorge, before and after construction of Kariba Reservoir.

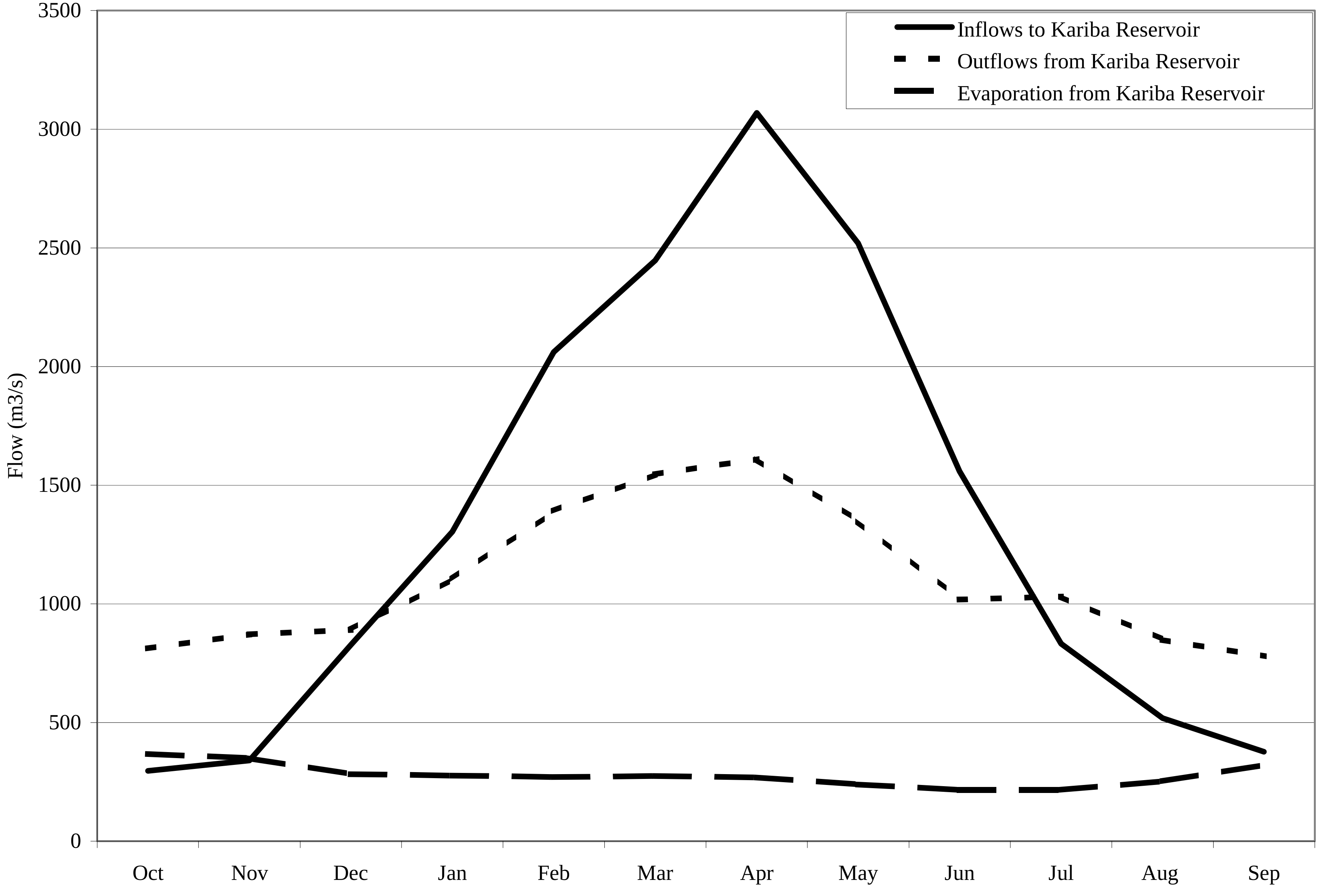


Figure 2-13. Hydrographs of mean monthly inflows, outflows, and evaporation at Kariba Reservoir, 1958-1998.

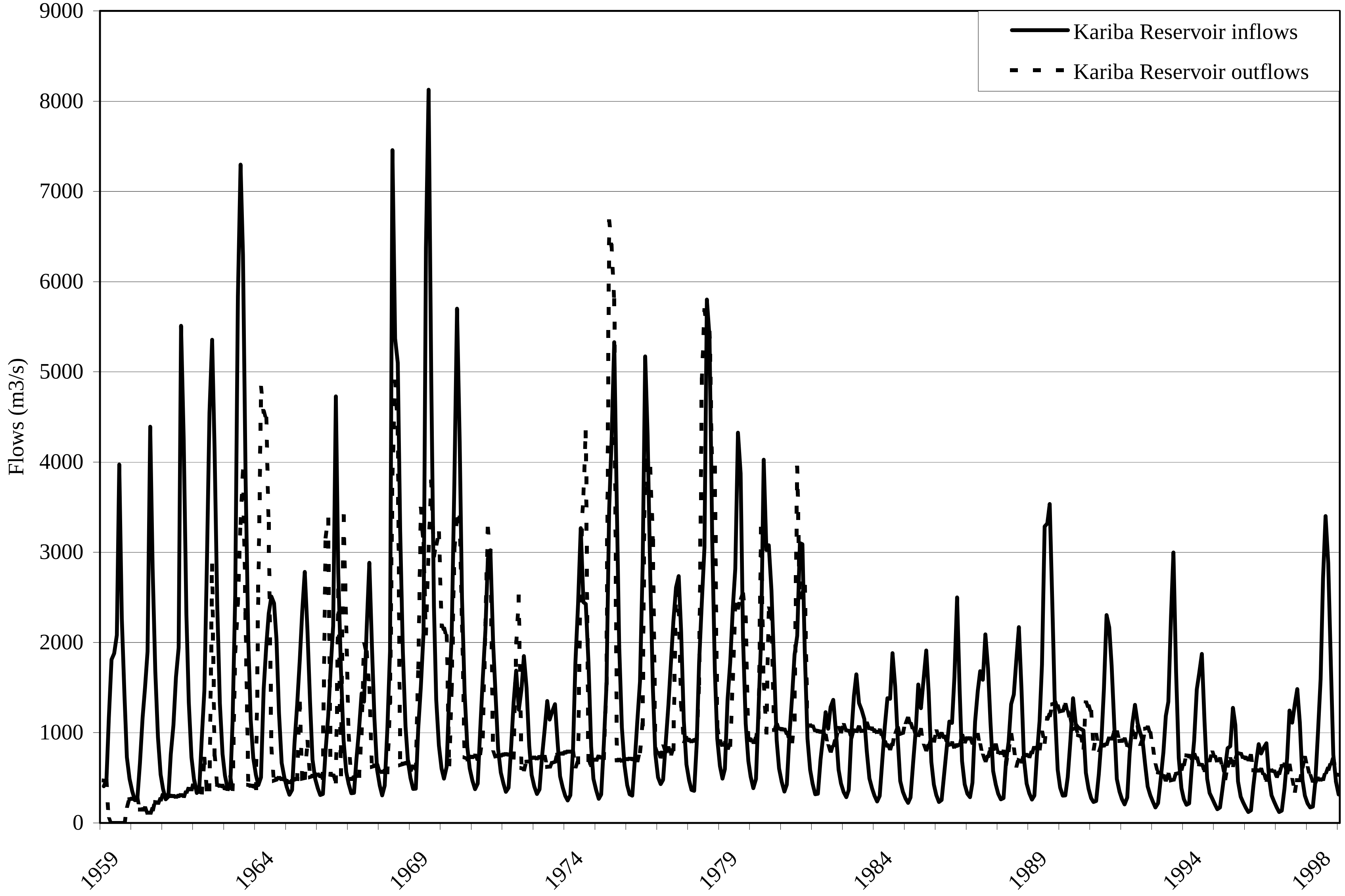


Figure 2-14. Time series of mean monthly inflows and outflows at Kariba Reservoir.

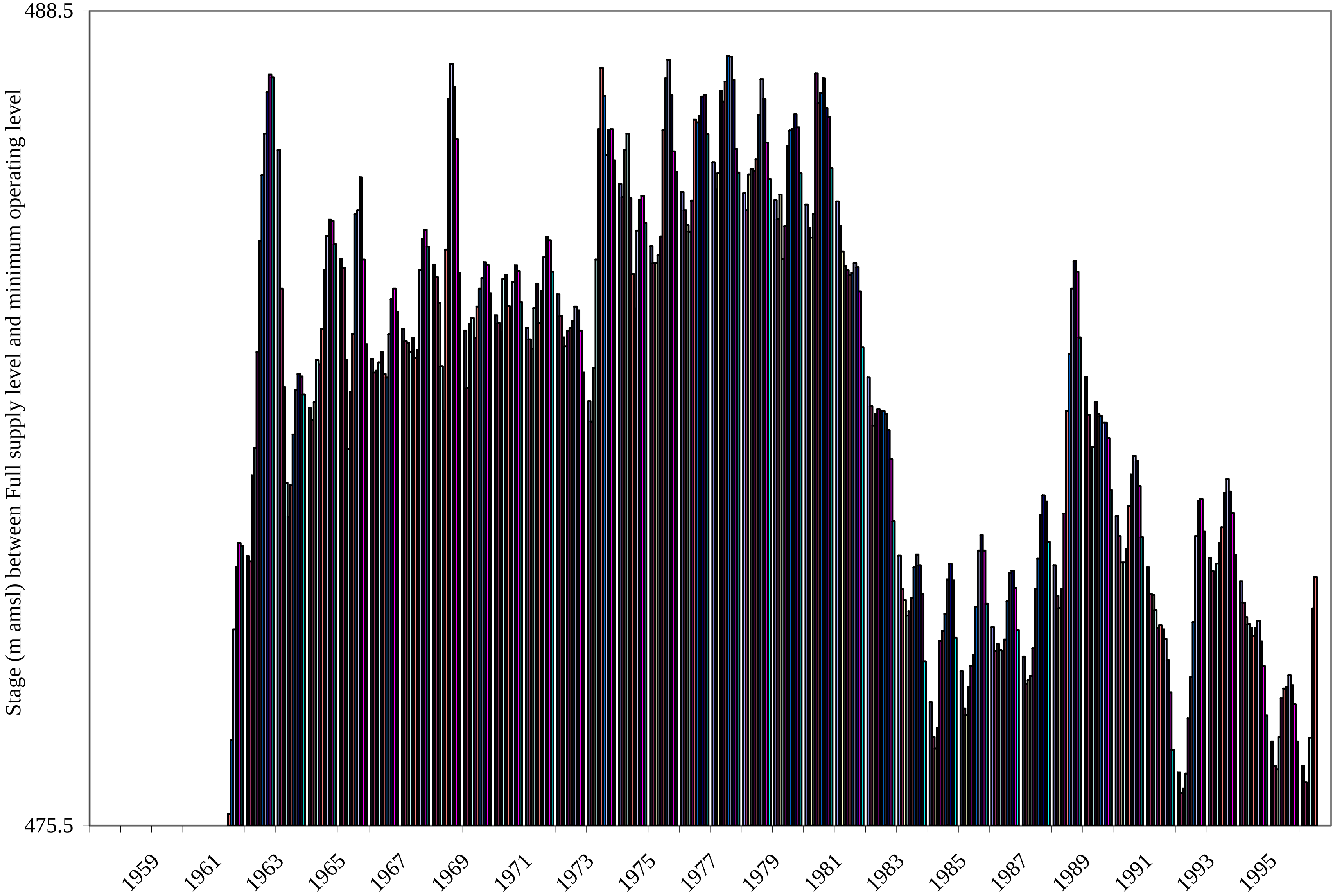


Figure 2-15. Time series of monthly water surface elevations at Kariba Reservoir.

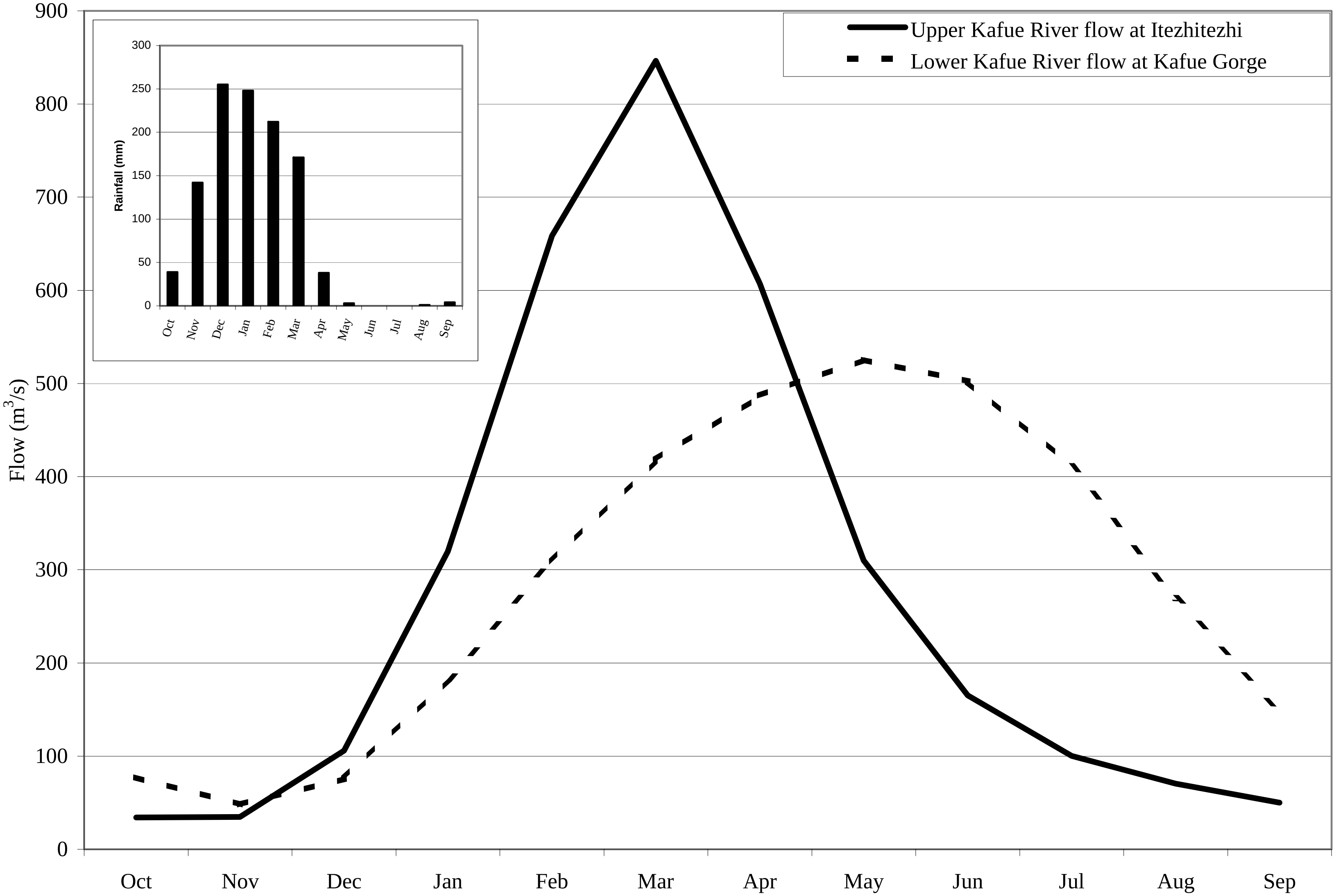


Figure 2-16. Mean monthly rainfall in the Upper and Middle Kafue catchment (inset) and hydrographs of mean monthly runoff upstream and downstream of the Kafue Flats, 1907-69, showing attenuation of peak runoff.

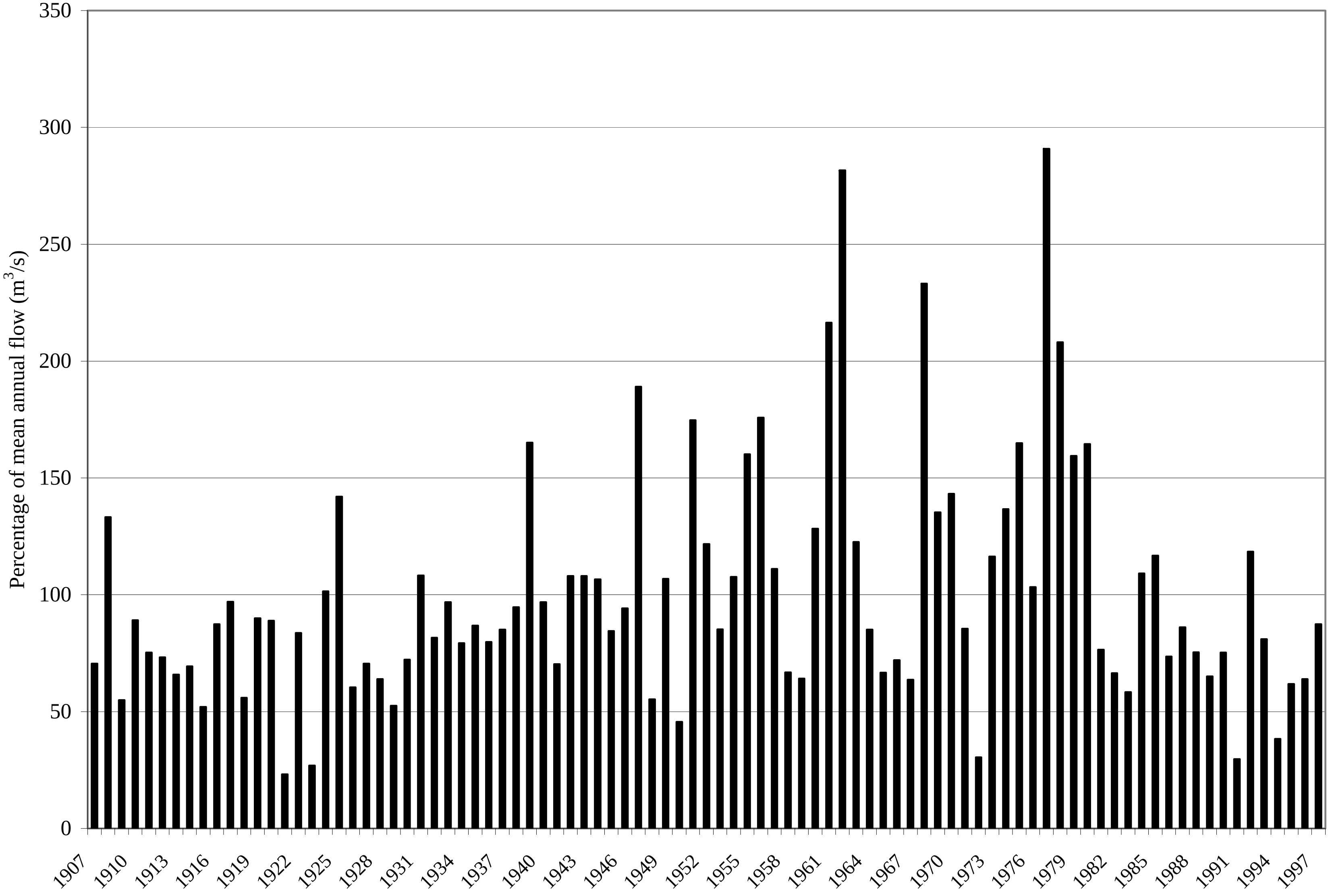


Figure 2-17. Time series of annual runoff from the Kafue catchment above Itezhitezhi Gorge, as a percentage of mean annual flow.

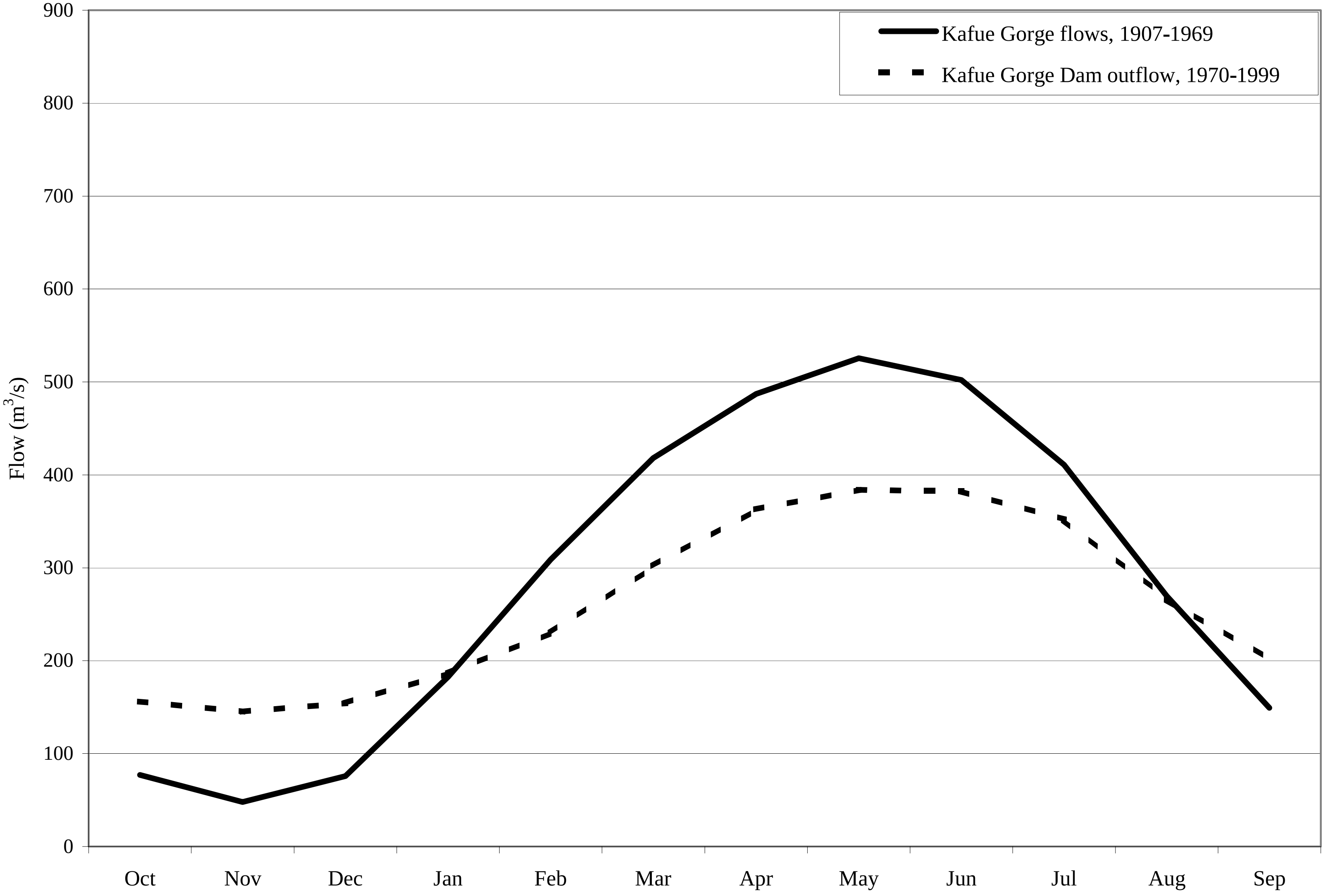


Figure 2-18. Hydrographs of mean monthly runoff below the Kafue River Gorge near the Zambezi River confluence, before and after construction of Kafue Gorge Dam.

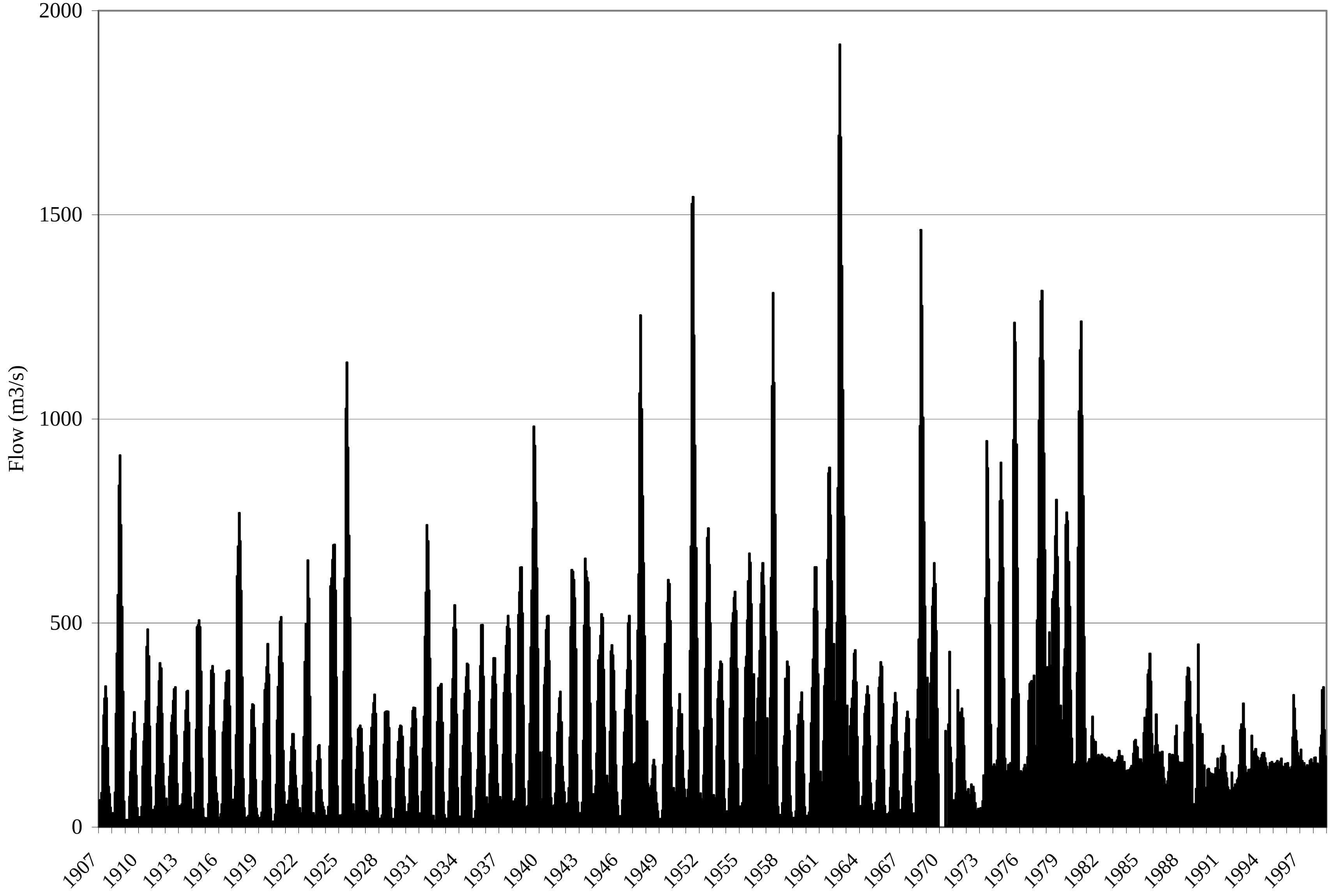


Figure 2-19. Time series of mean monthly runoff from the Kafue catchment.

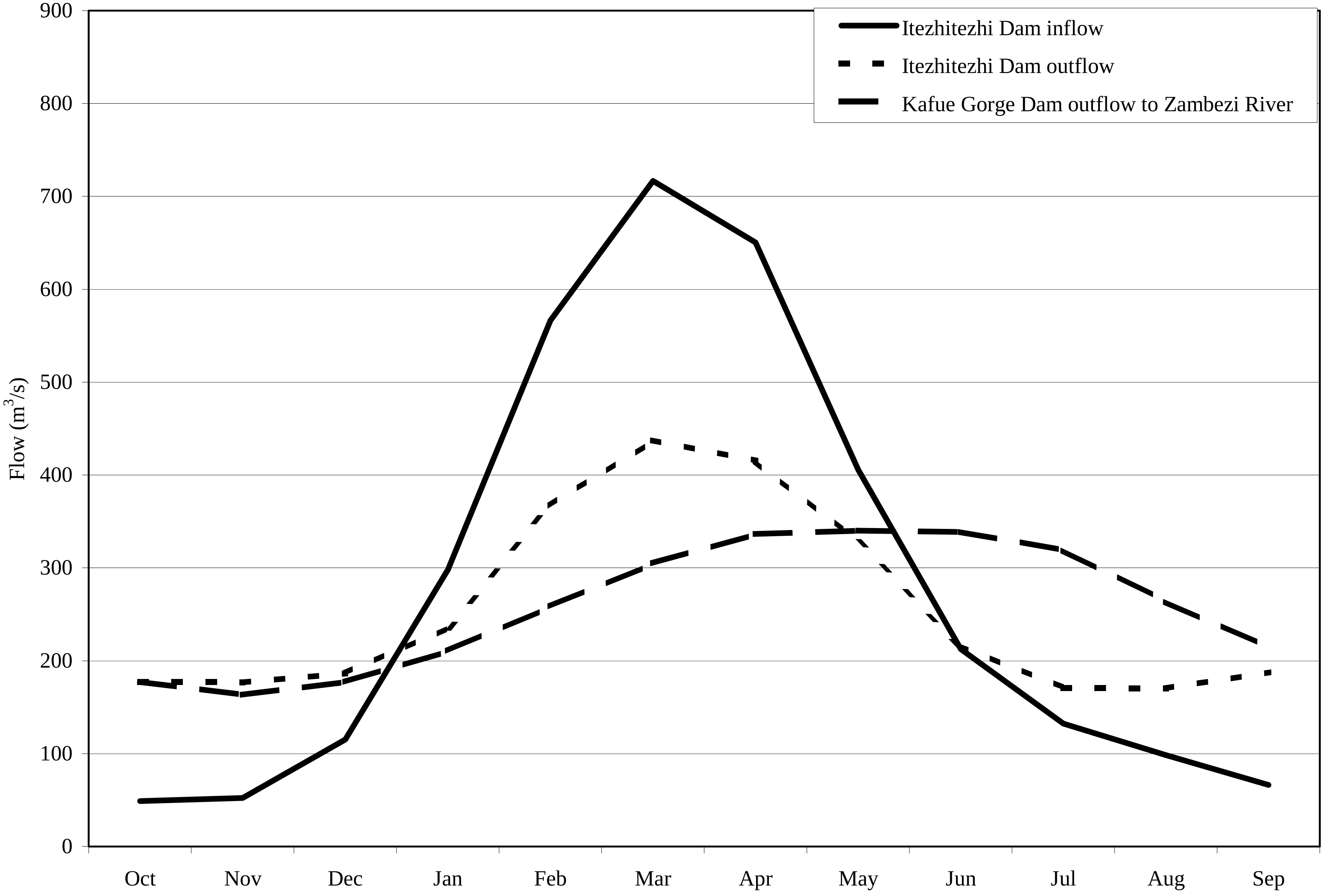


Figure 2-20. Hydrographs of mean monthly runoff from the Kafue catchment above and below Itezhitezhi Reservoir, and runoff below Kafue Gorge Dam, 1977-98.

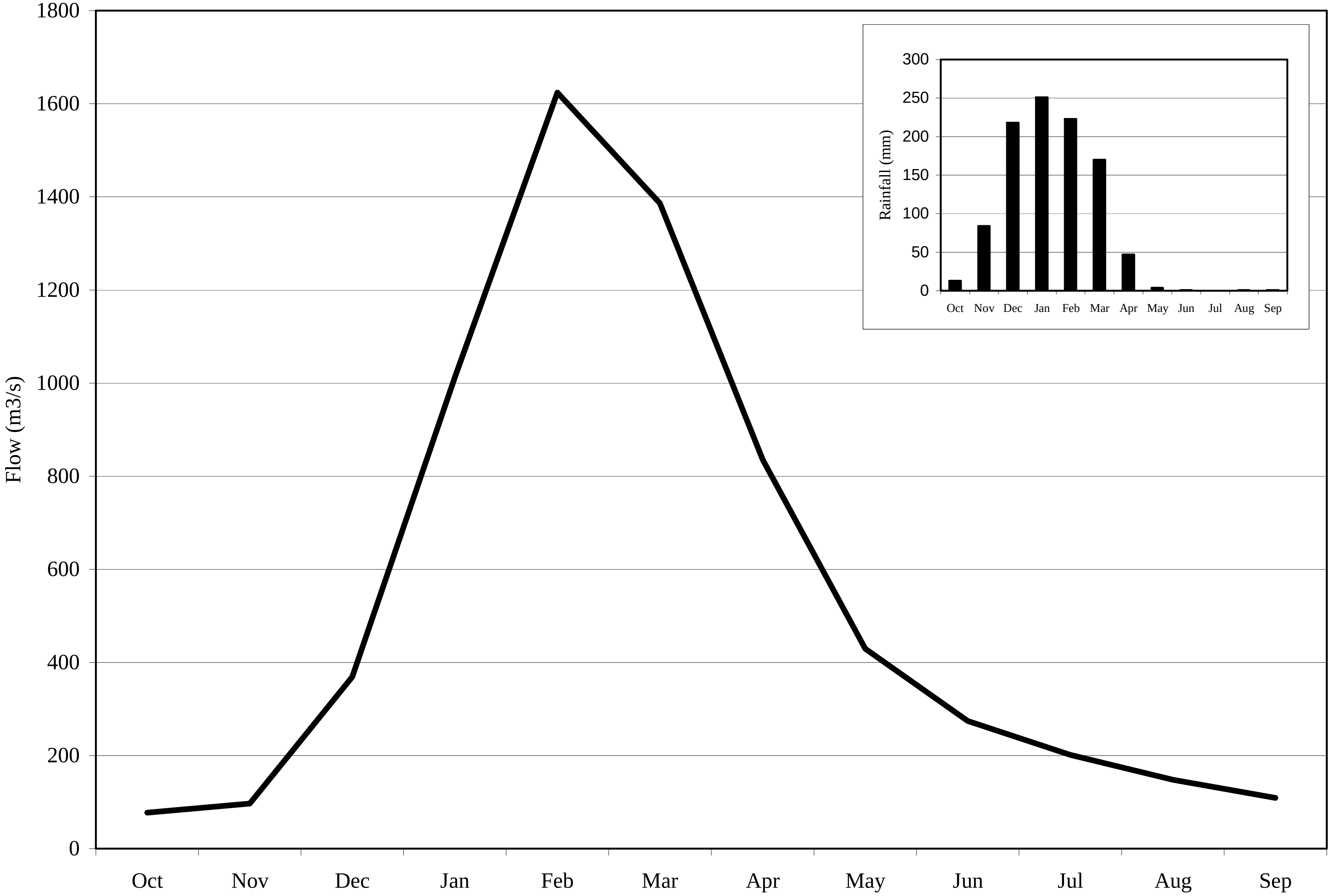


Figure 2-21. Mean monthly rainfall in the Luangwa headwaters region (inset), and hydrograph of mean monthly runoff from Luangwa catchment, 1955-96.

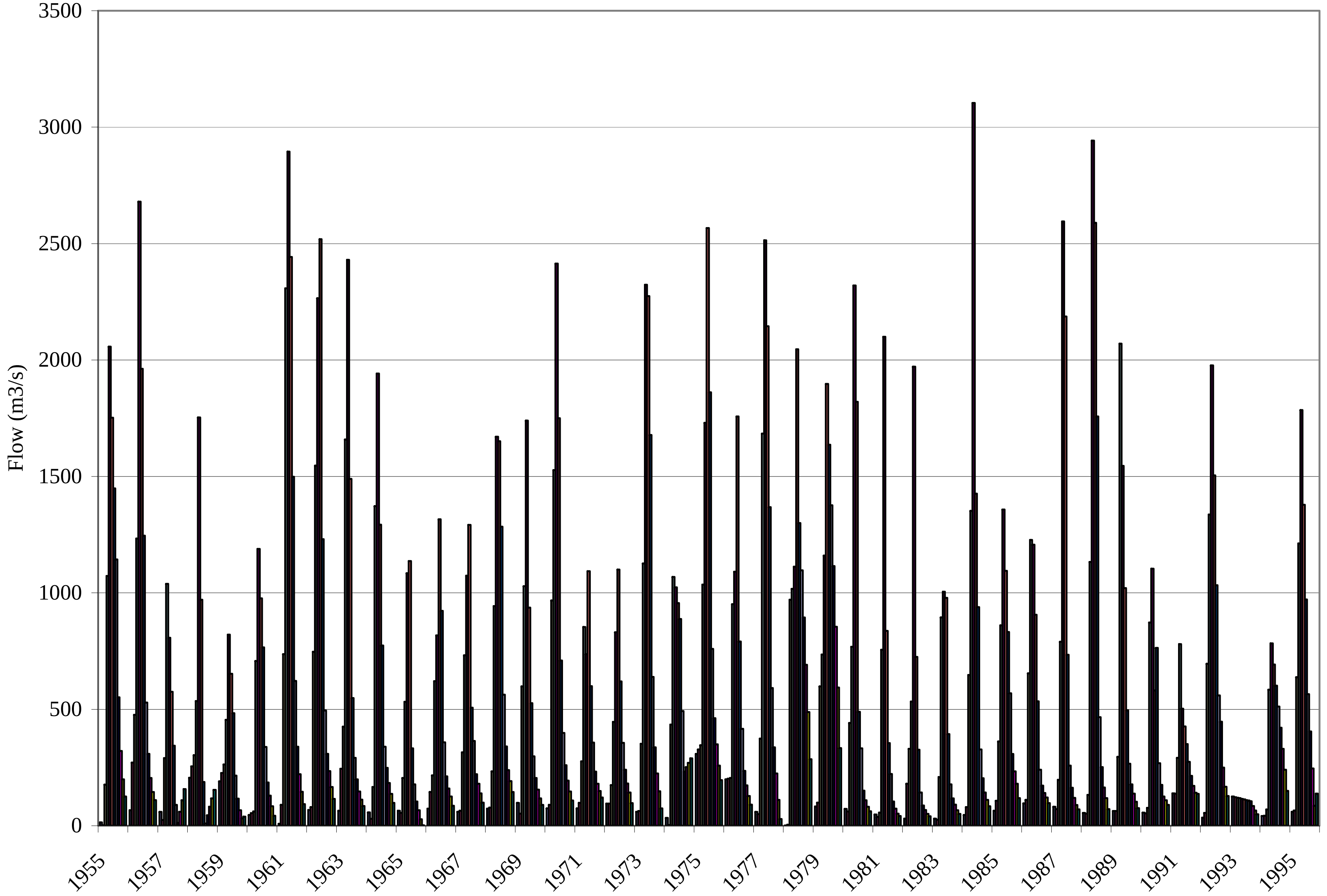


Figure 2-22. Time series of mean monthly runoff from the Luangwa catchment.

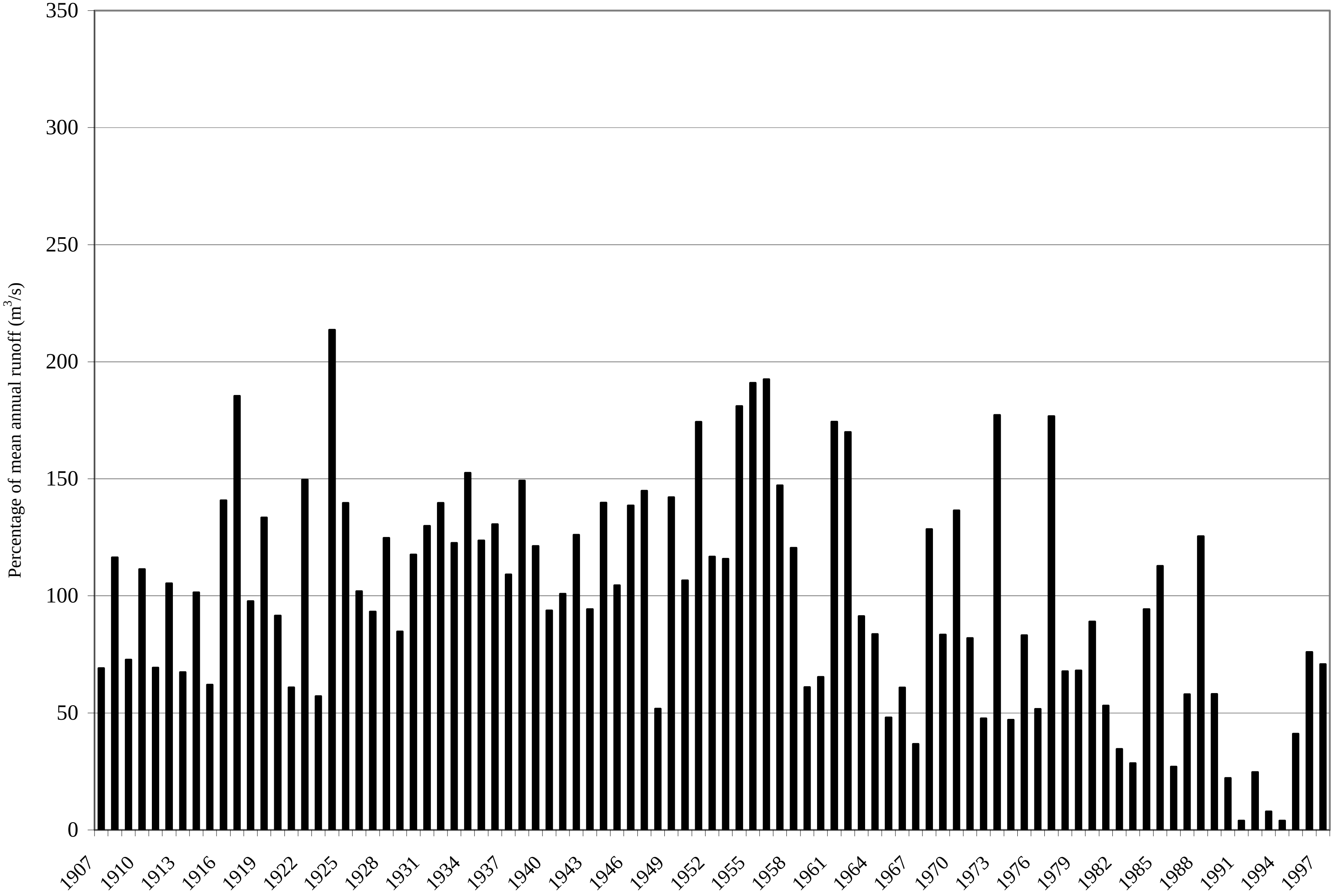


Figure 2-23. Time series of annual runoff from the Middle Zambezi catchment from the Kafue River/Zambezi River confluence to Cahora Bassa Gorge, as a percentage of mean annual runoff.

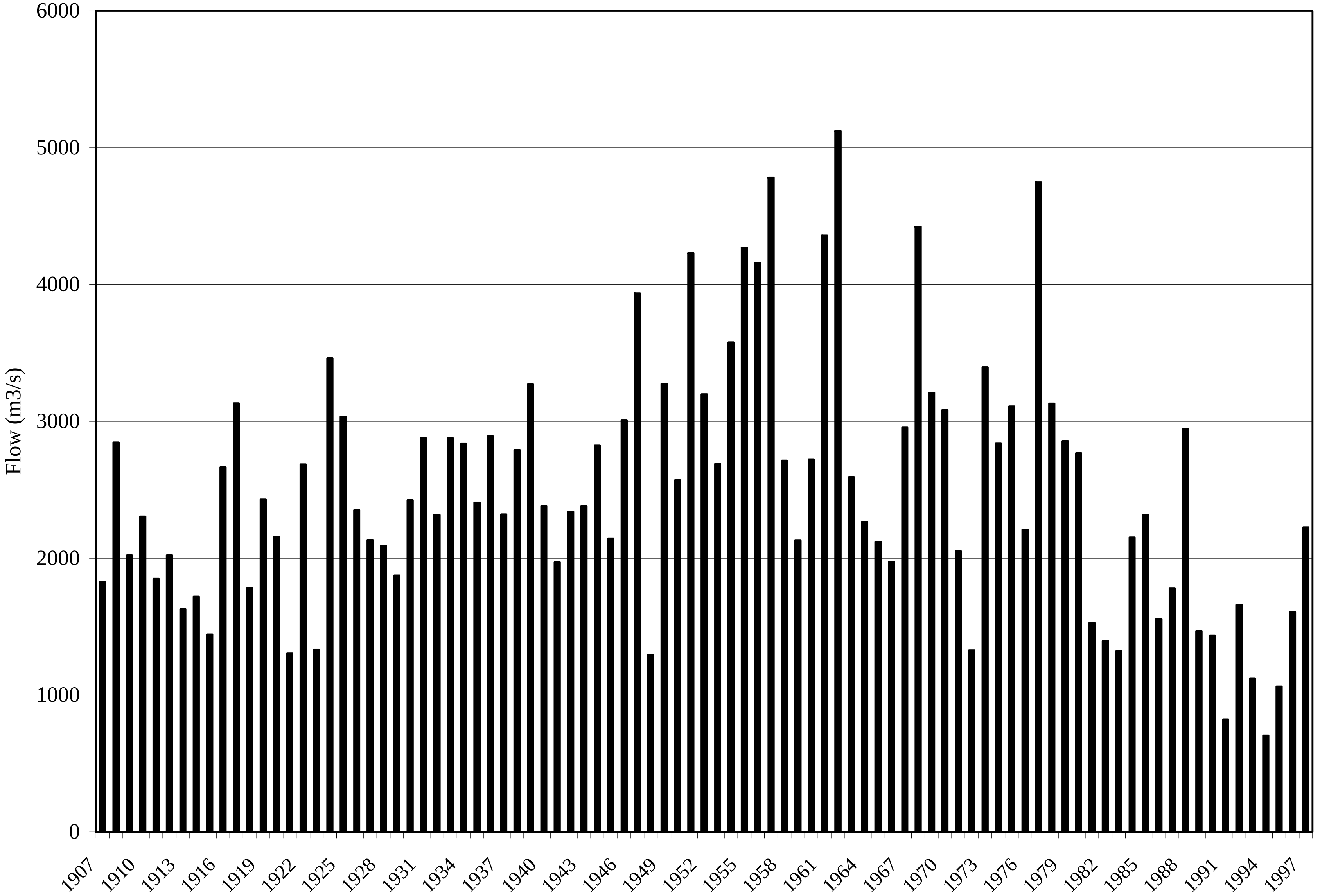


Figure 2-24. Time series of annual runoff from the entire Zambezi catchment above Cahora Bassa Gorge.

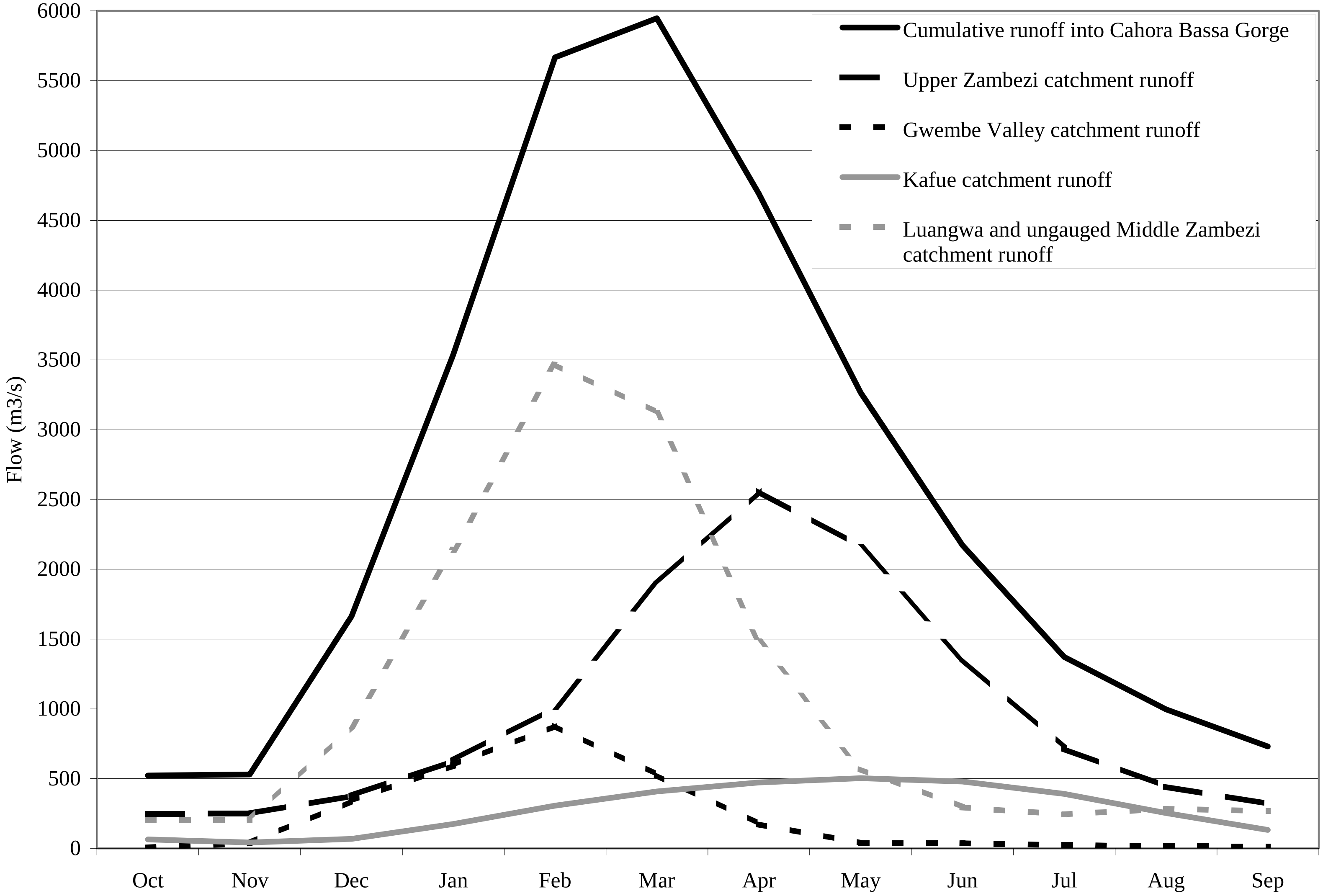


Figure 2-25. Hydrographs of mean monthly runoff to the Cahora Bassa Gorge catchment, 1907-58, showing contribution from Upper Zambezi catchment, Gwembe Valley catchment, Kafue catchment, and Luangwa and remaining Middle Zambezi catchments, prior to Zambezi River regulation.

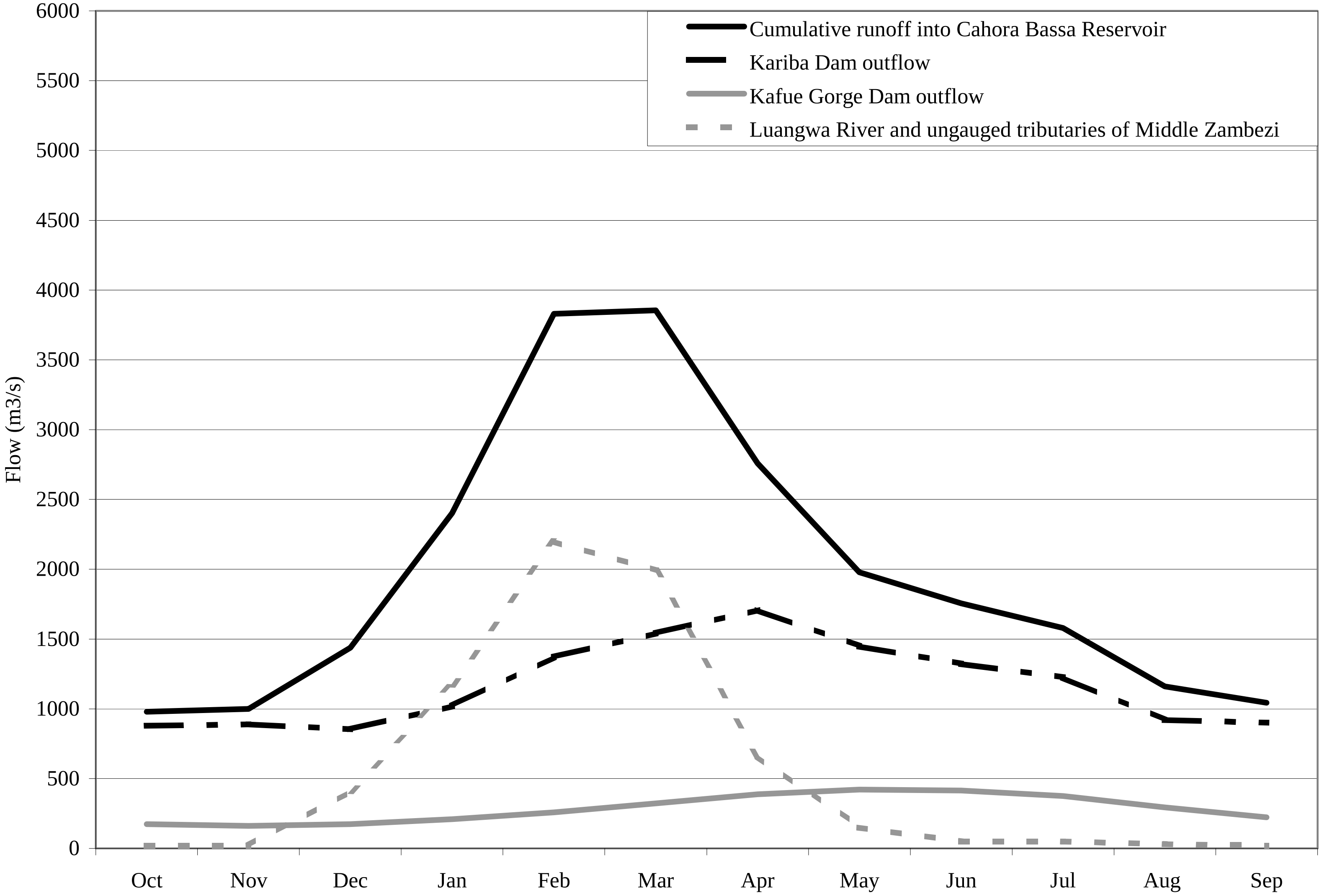


Figure 2-26. Hydrographs of mean monthly runoff from Cahora Bassa Gorge catchment, 1974-99, showing contribution from Kariba Dam outflow, Kafue Gorge Dam outflow, and Luangwa River and remaining Middle Zambezi catchment runoff, since construction of Cahora Bassa Reservoir.

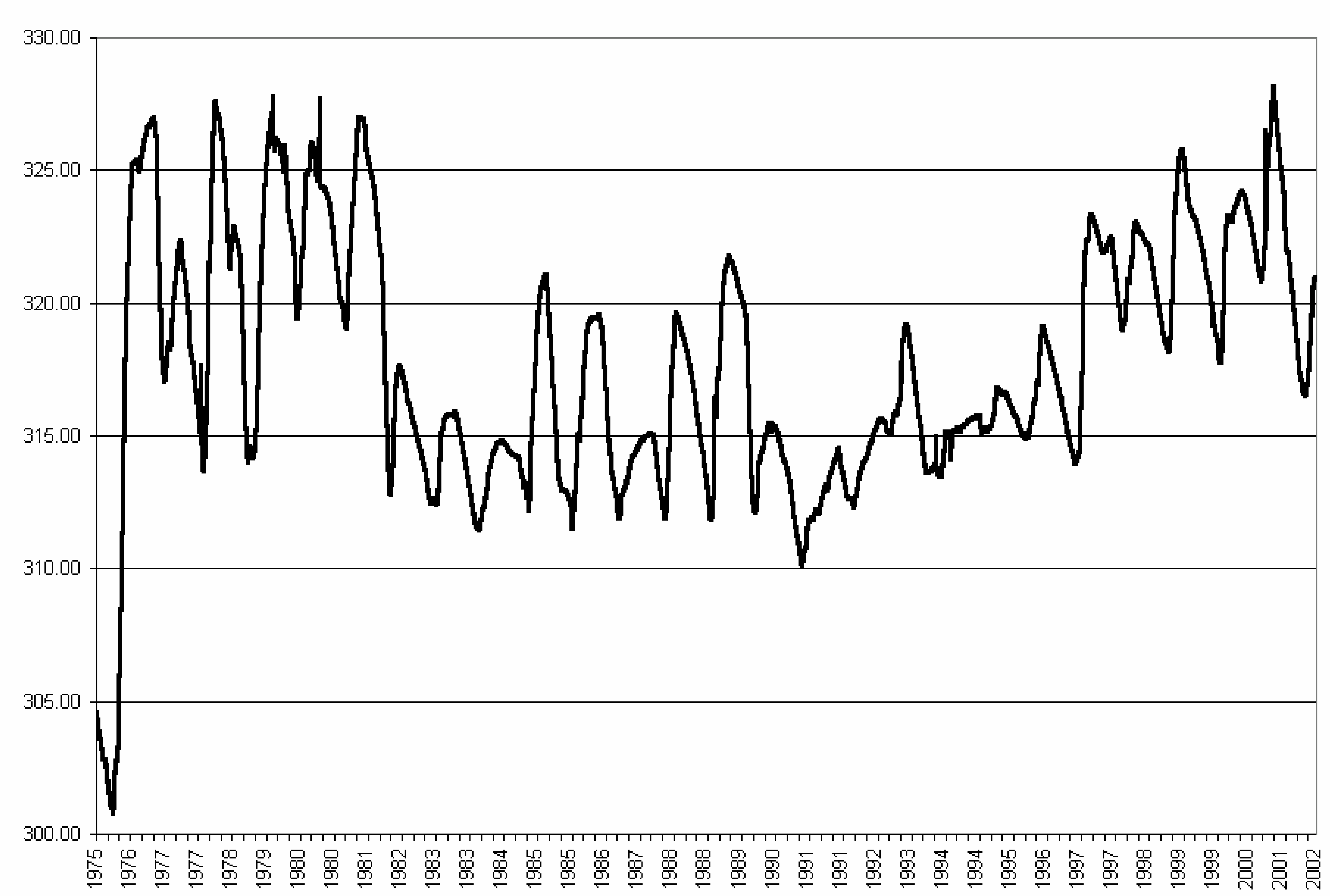


Figure 2-27. Time series of Cahora Bassa Reservoir monthly water surface elevations.

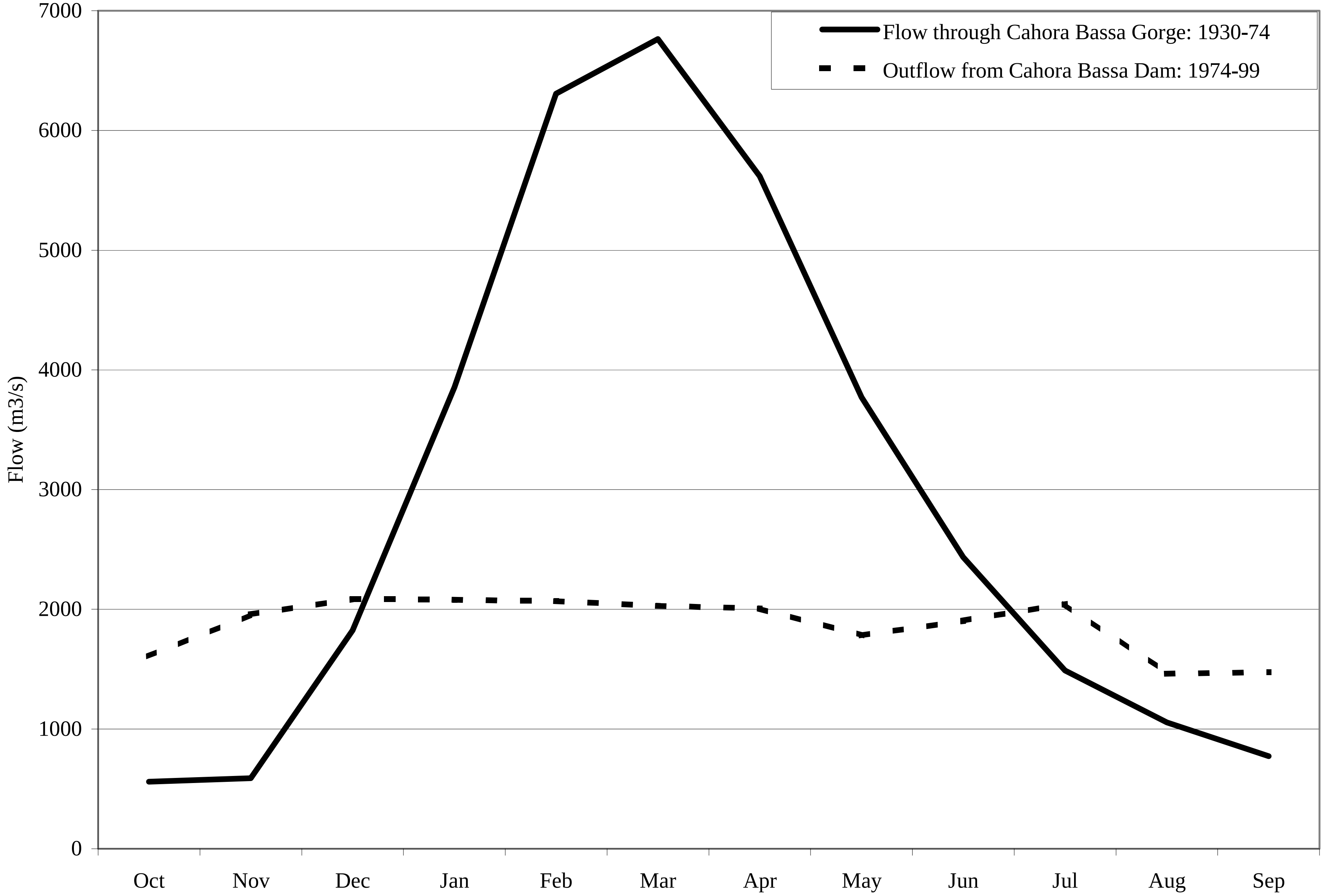


Figure 2-28. Hydrographs of mean monthly runoff at Cahora Bassa Gorge, before and after completion of Cahora Bassa Reservoir.

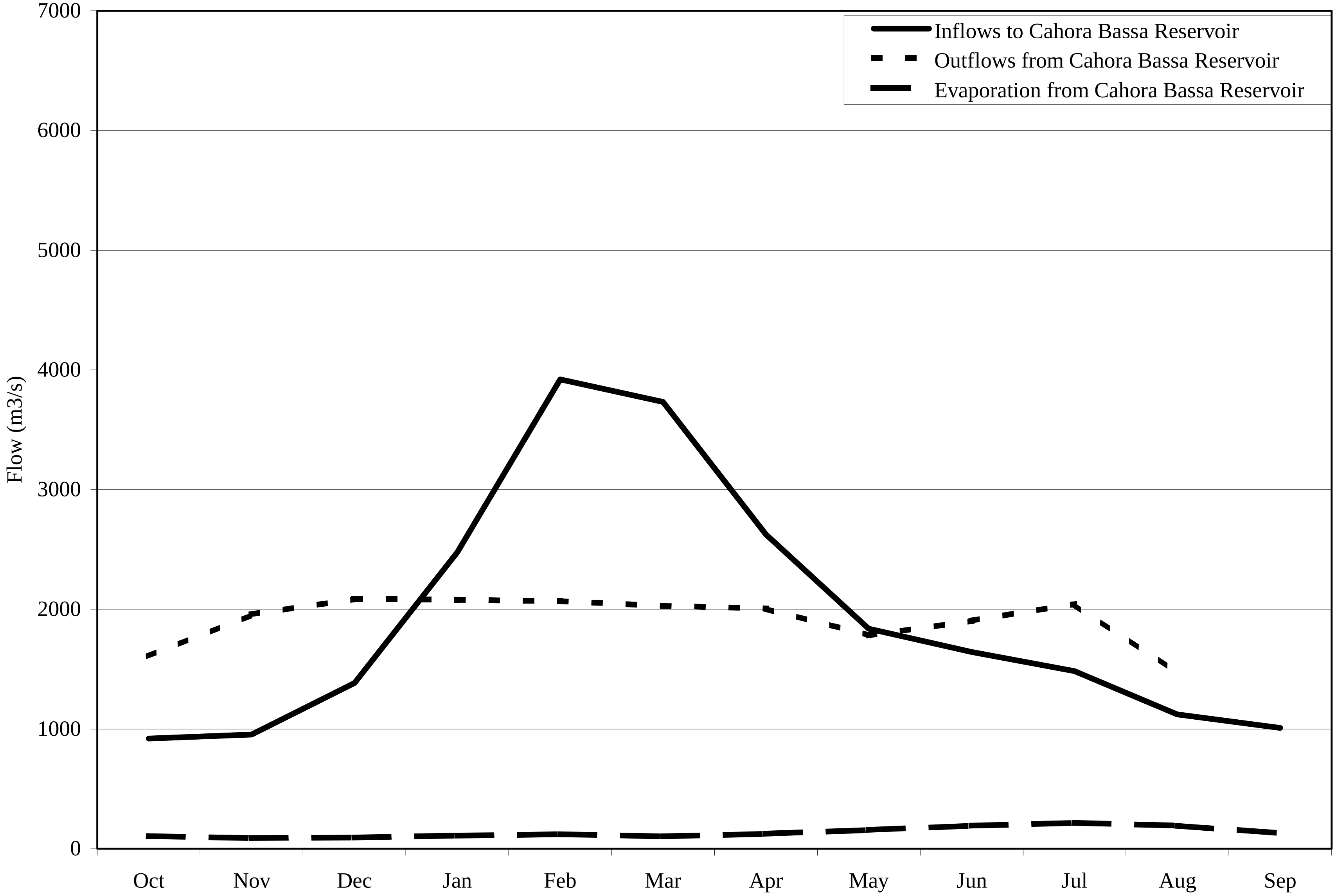


Figure 2-29. Time series of mean monthly inflows and outflows at Cahora Bassa Reservoir.

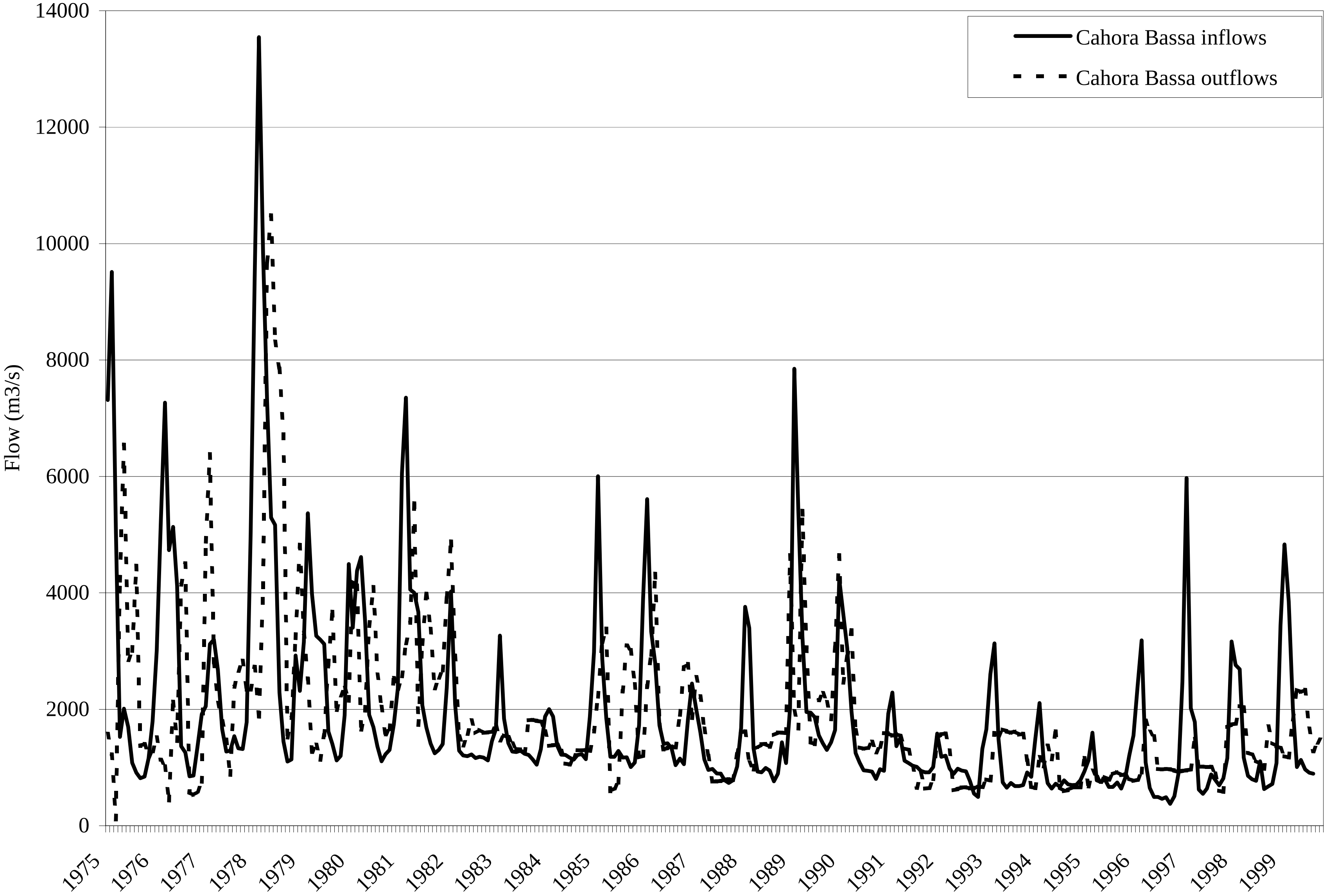


Figure 2-30. Time series of mean monthly inflows and outflows at Cahora Bassa Reservoir.

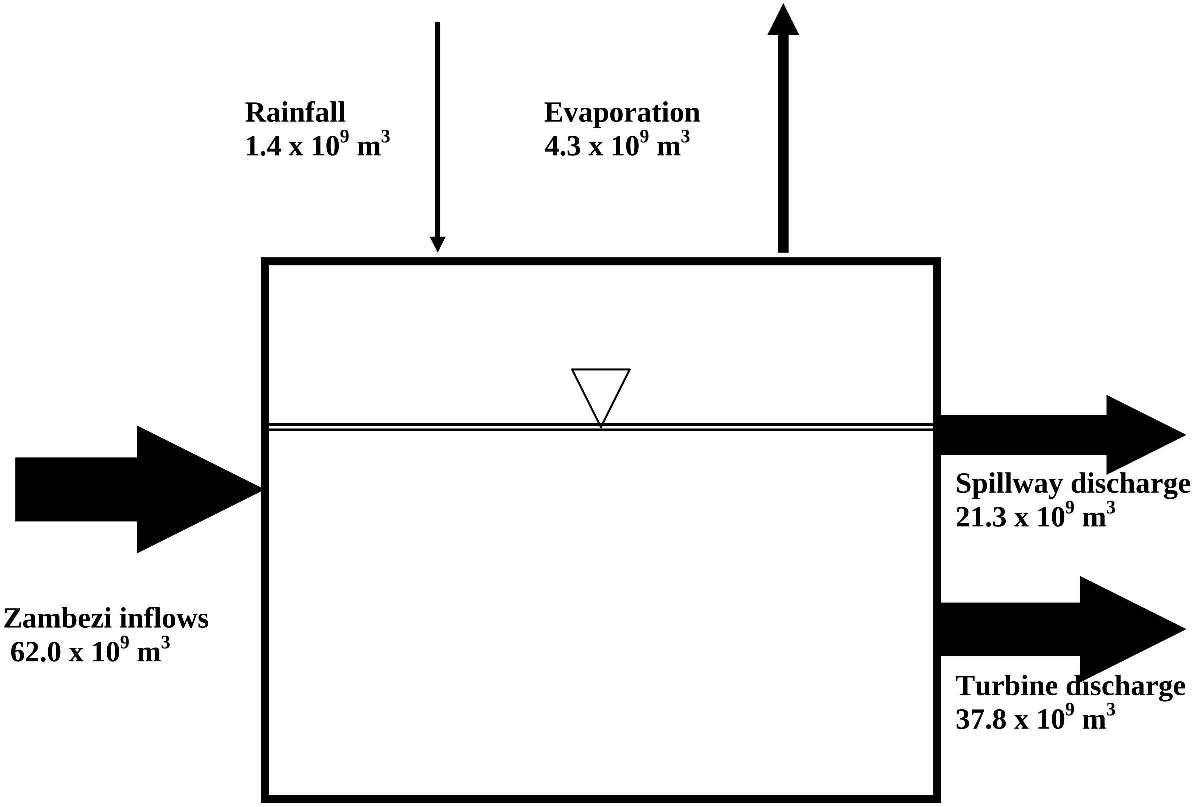


Figure 2-31. Average annual water balance for Cahora Bassa Reservoir, 1974-2000.

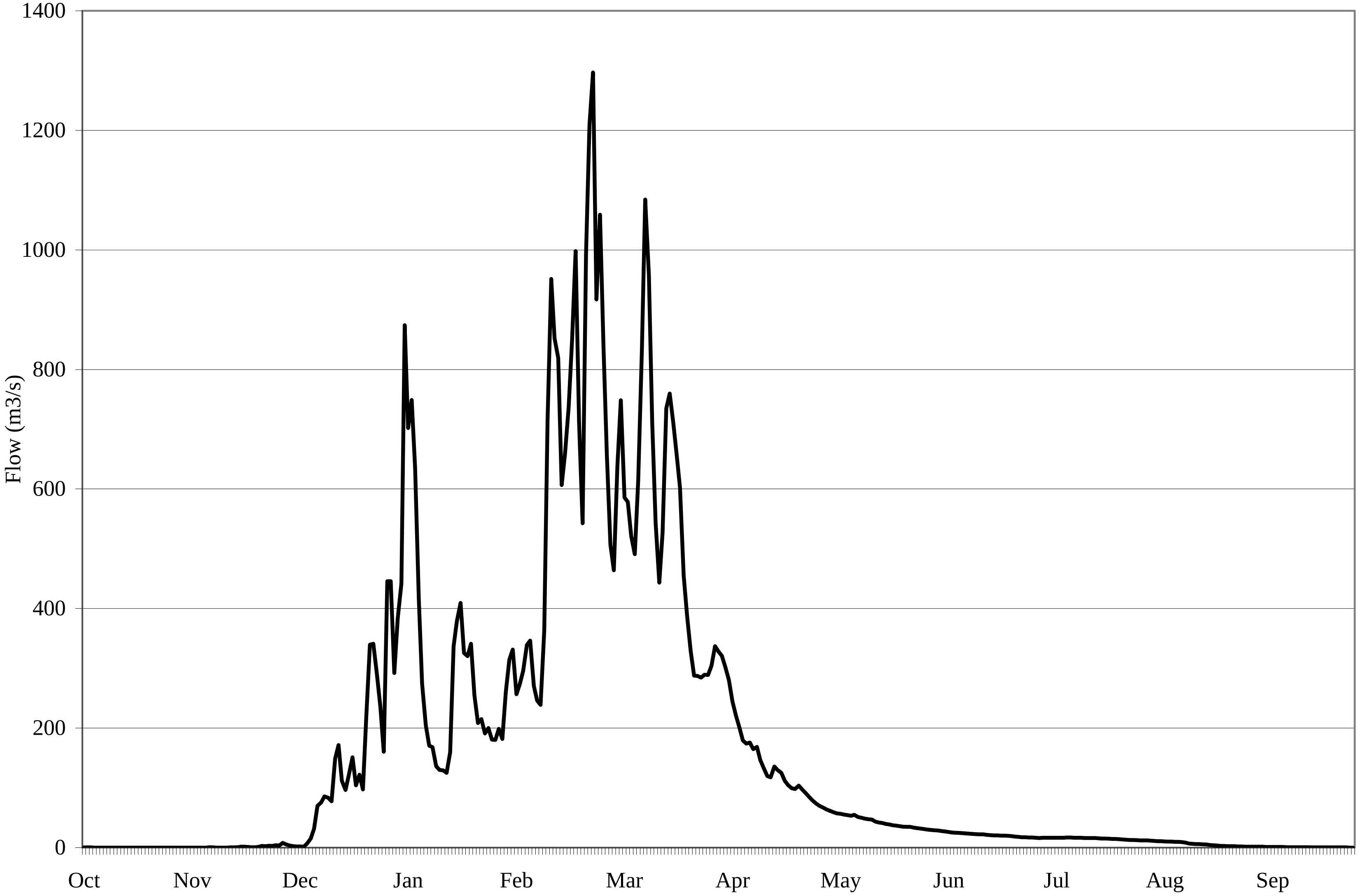


Figure 2-32. Typical hydrograph of daily runoff from the Luia catchment, including runoff from the Upper Luia, Capoche, and Cherize River sub-catchments (1962/63 hydrological year).

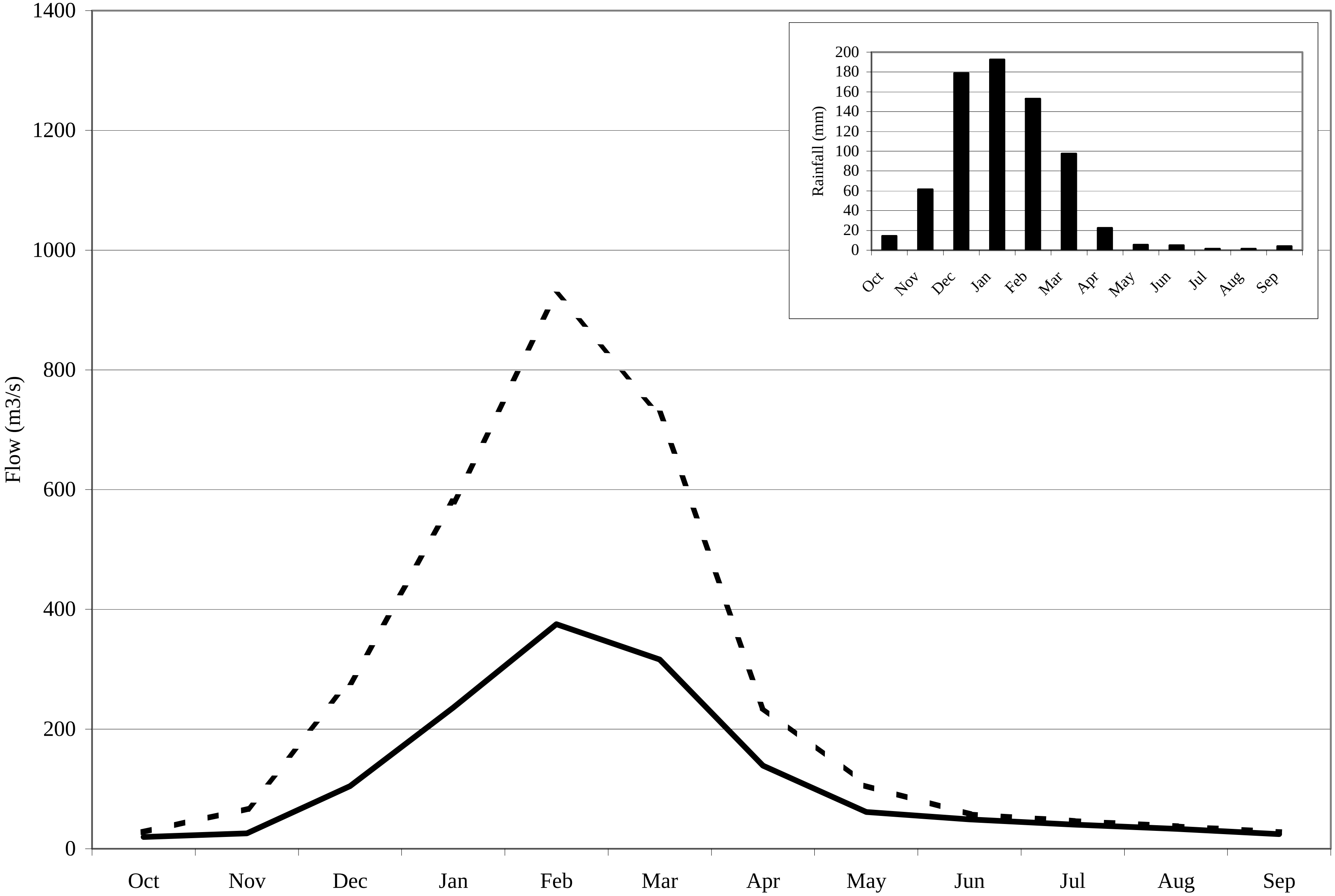


Figure 2-33. Figure 2-33. Mean monthly rainfall (inset), and hydrographs of mean monthly and mean maximum monthly runoff, for the Luia River catchment, 1975-2001.

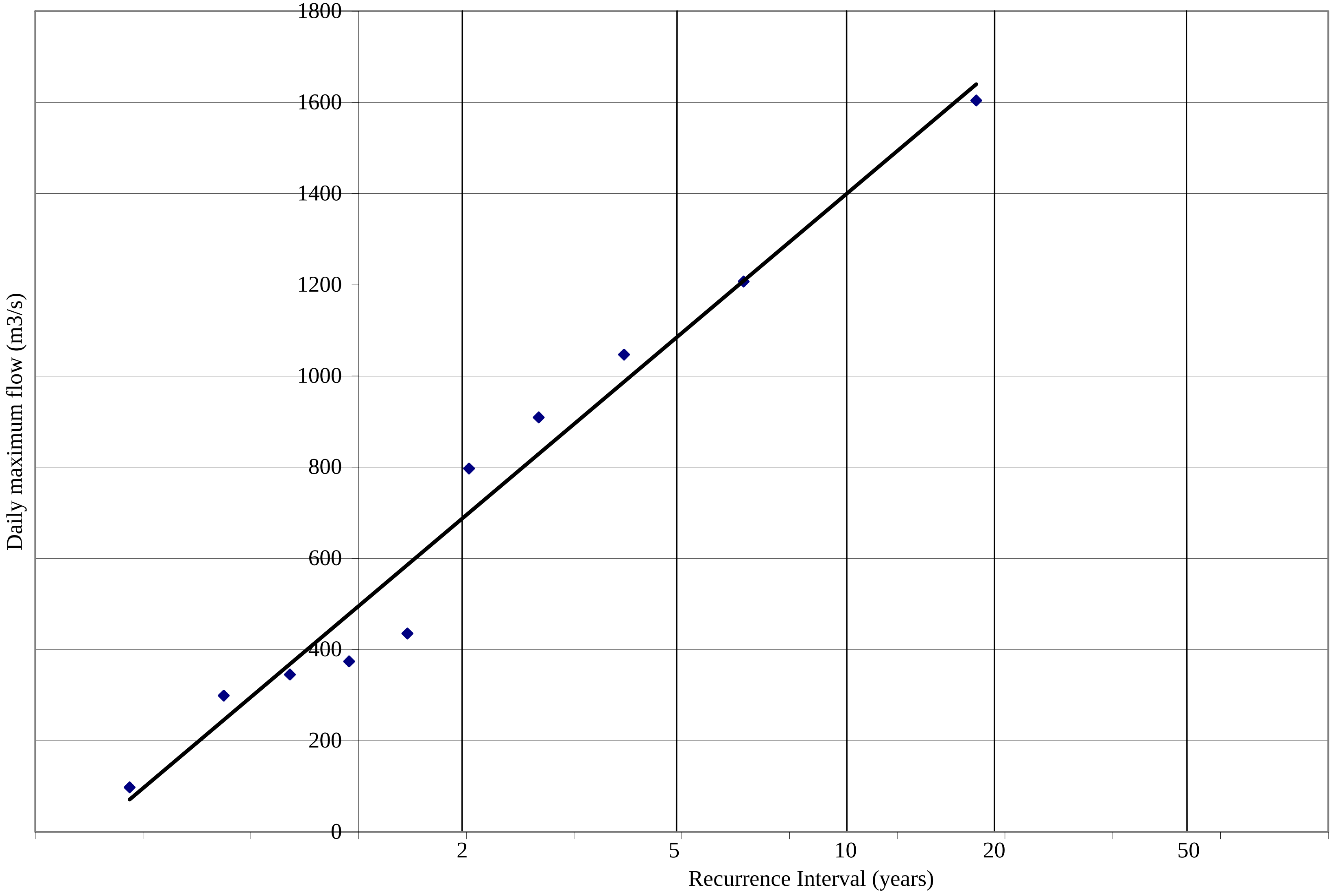


Figure 2-34. Flood frequency curve for annual series of maximum daily runoff from the Capoche River catchment, based on 1958-68 time series data.

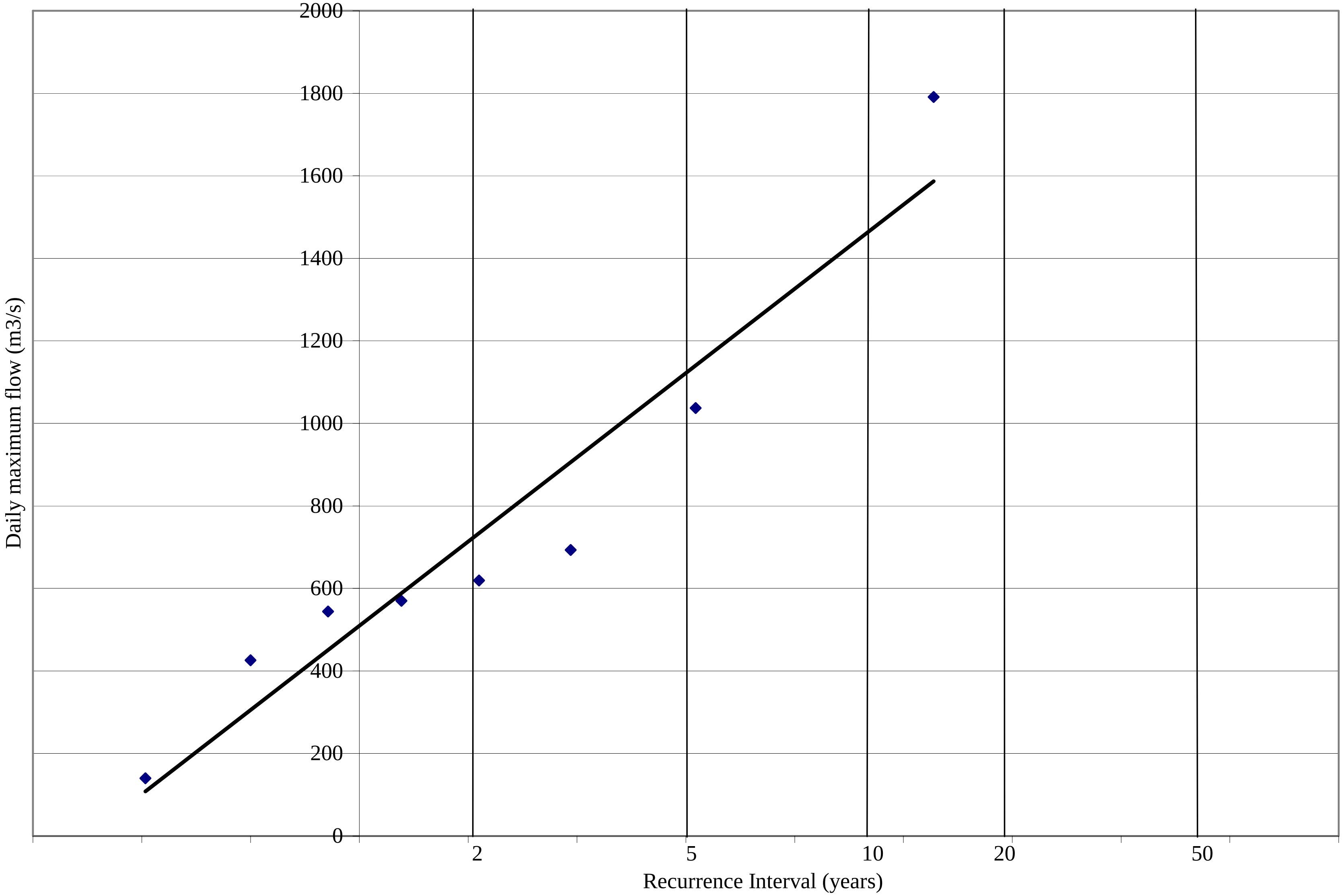


Figure 2-35. Flood frequency curve for annual series of maximum daily runoff from the Upper Luia River catchment, based on 1960-68 time series data.

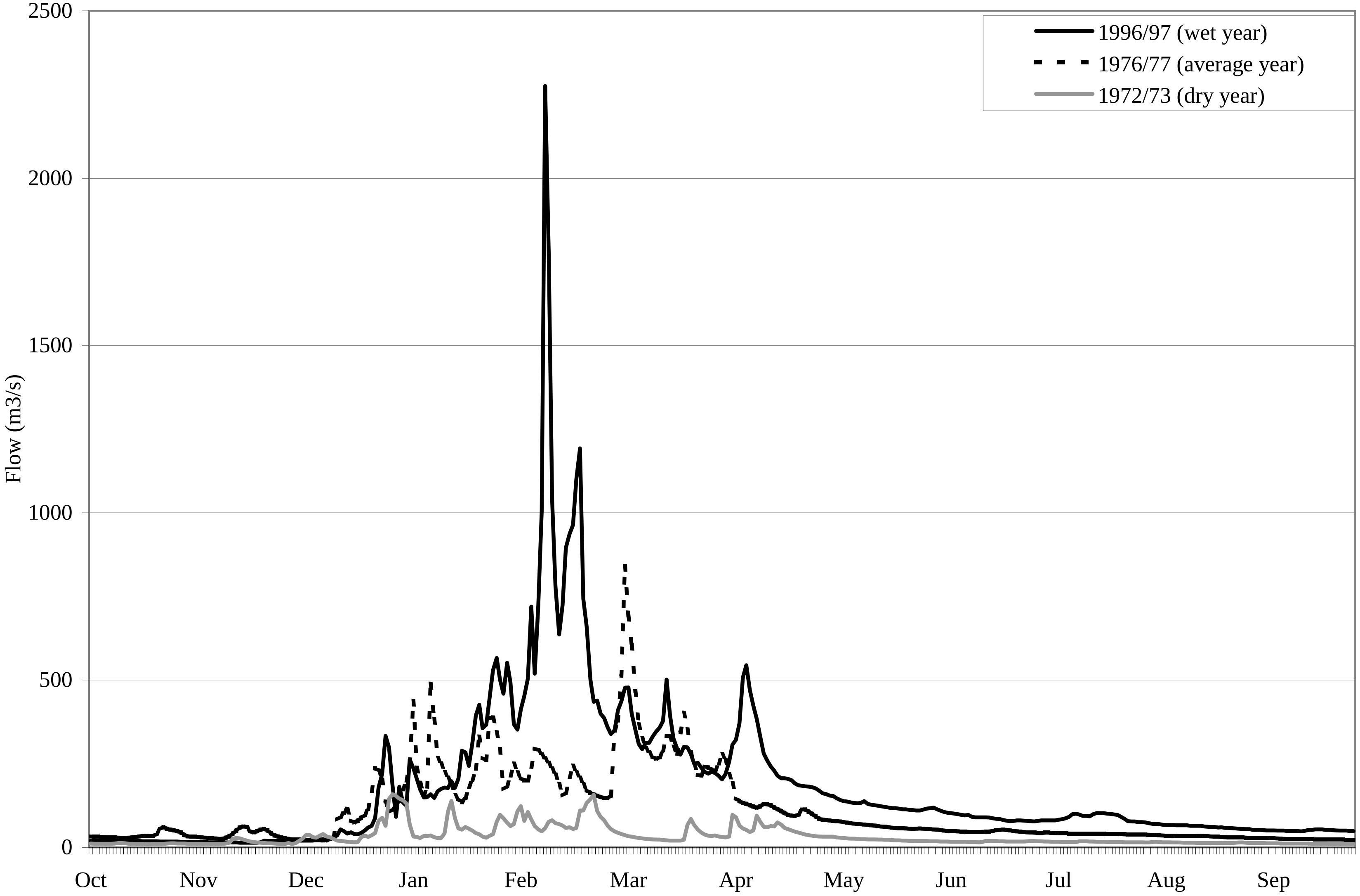


Figure 2-36. Typical hydrographs of daily runoff from the Revuboe River catchment during above-average, average, and below-average rainfall years.

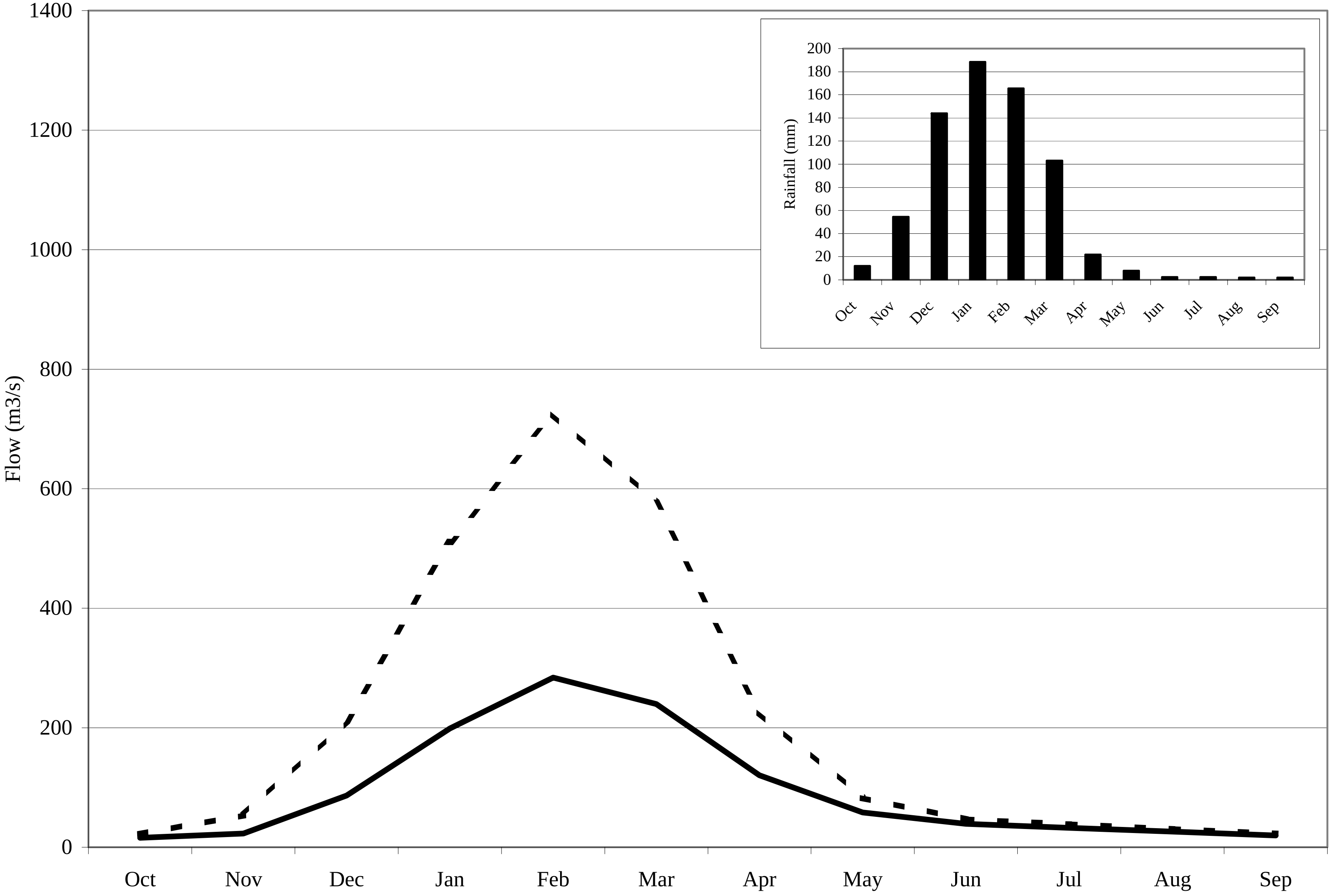


Figure 2-37. Mean monthly rainfall (inset), and hydrographs of mean monthly and mean maximum monthly runoff, for the Revuboe catchment, 1955-2000.

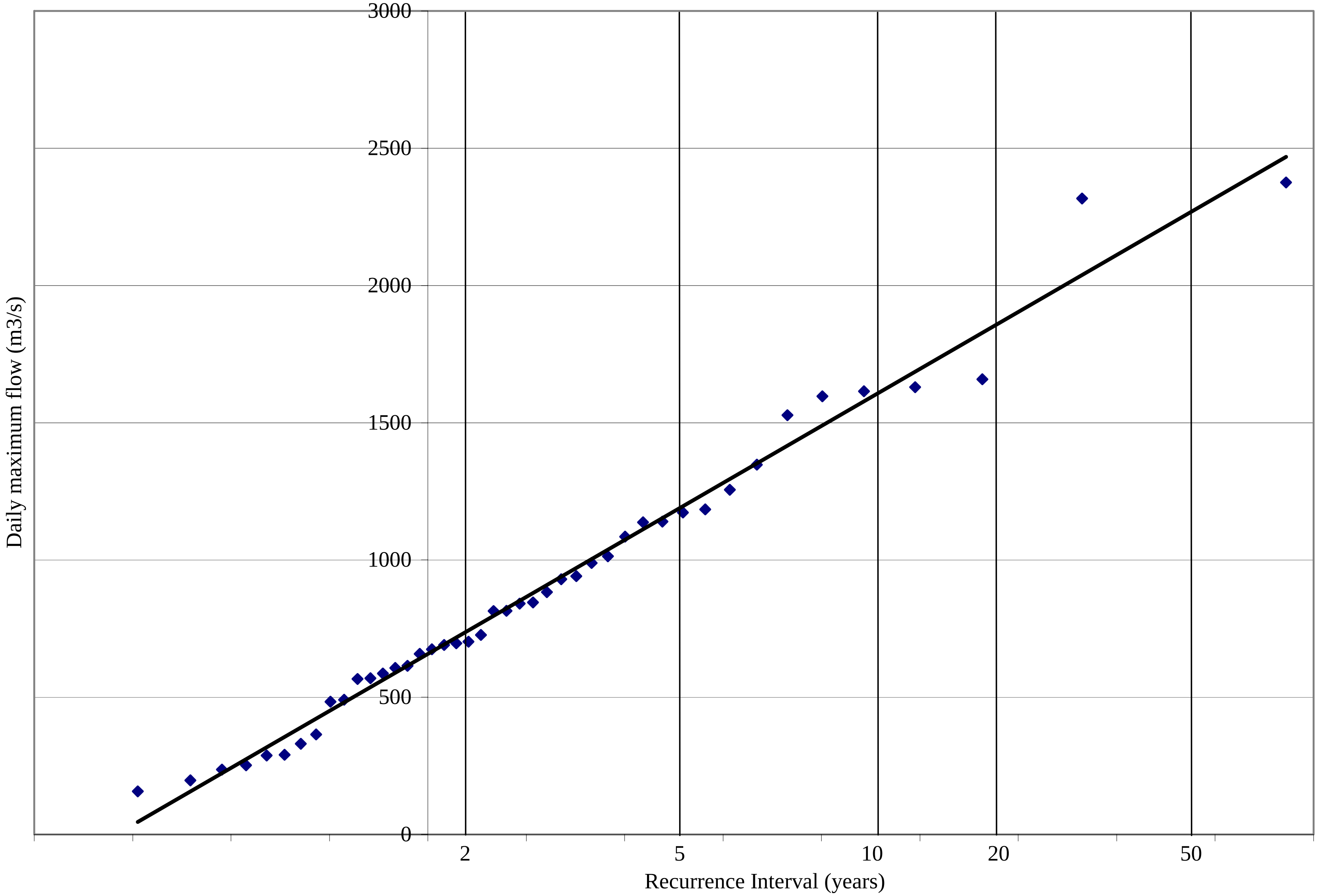


Figure 2-38. Flood frequency curve for annual series of maximum daily runoff from the Revuboe River catchment, based on 1955-2000 time series data.

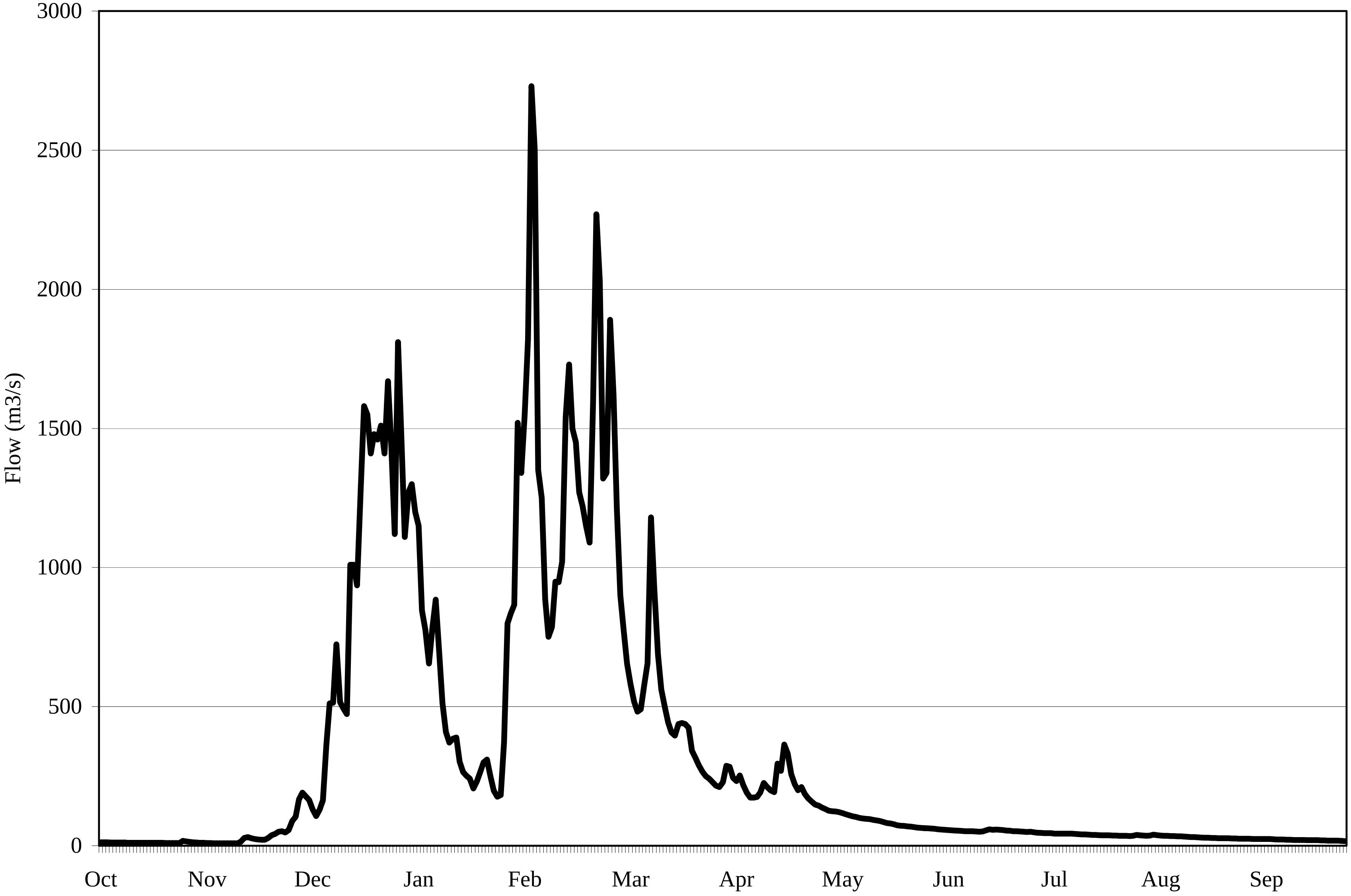


Figure 2-39. Typical hydrograph of daily runoff from the Luenha River catchment (1962/63 hydrological year).

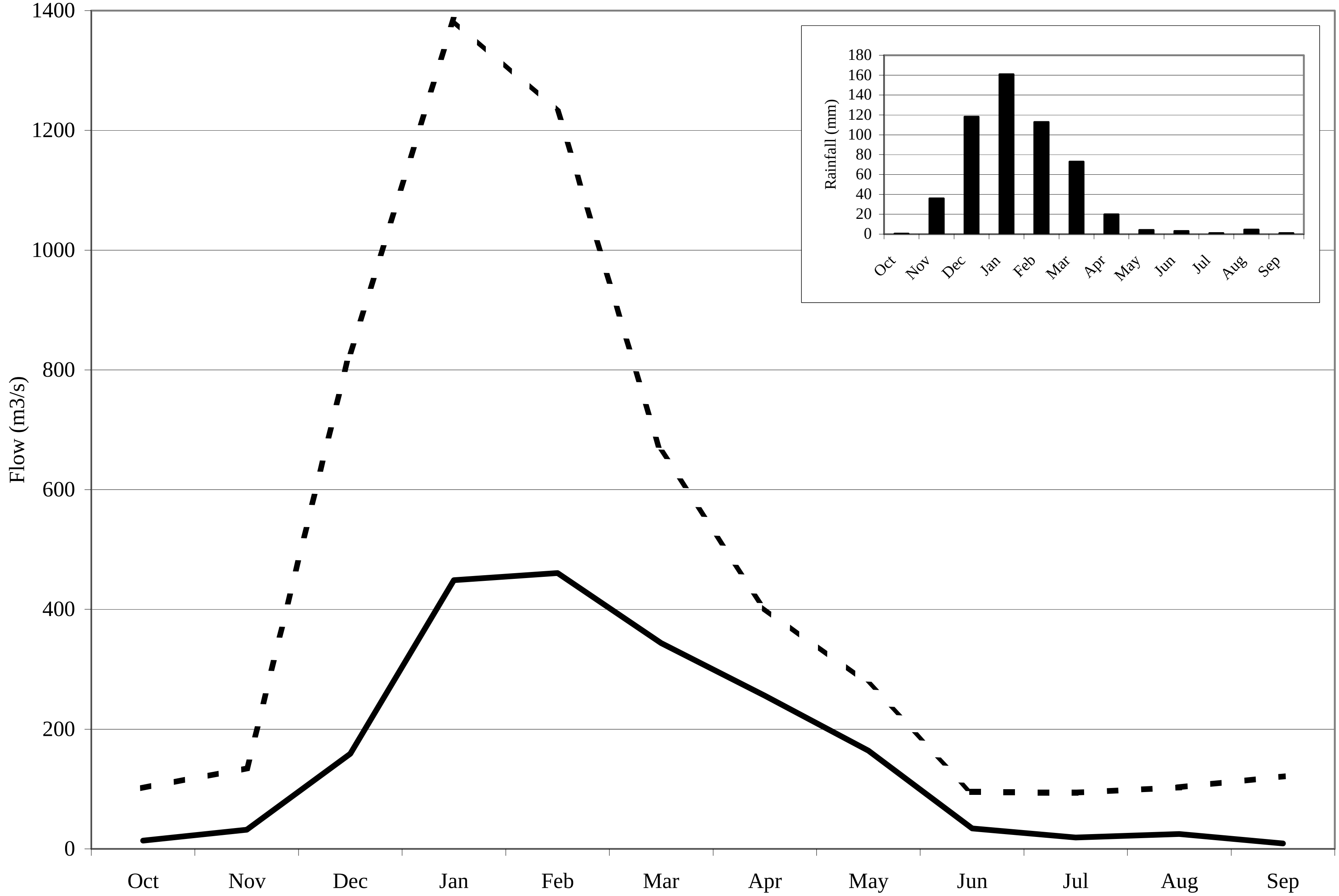


Figure 2-40. Mean monthly rainfall (inset), and hydrographs of mean monthly and mean maximum monthly runoff, for the Luenha catchment, 1960-71.

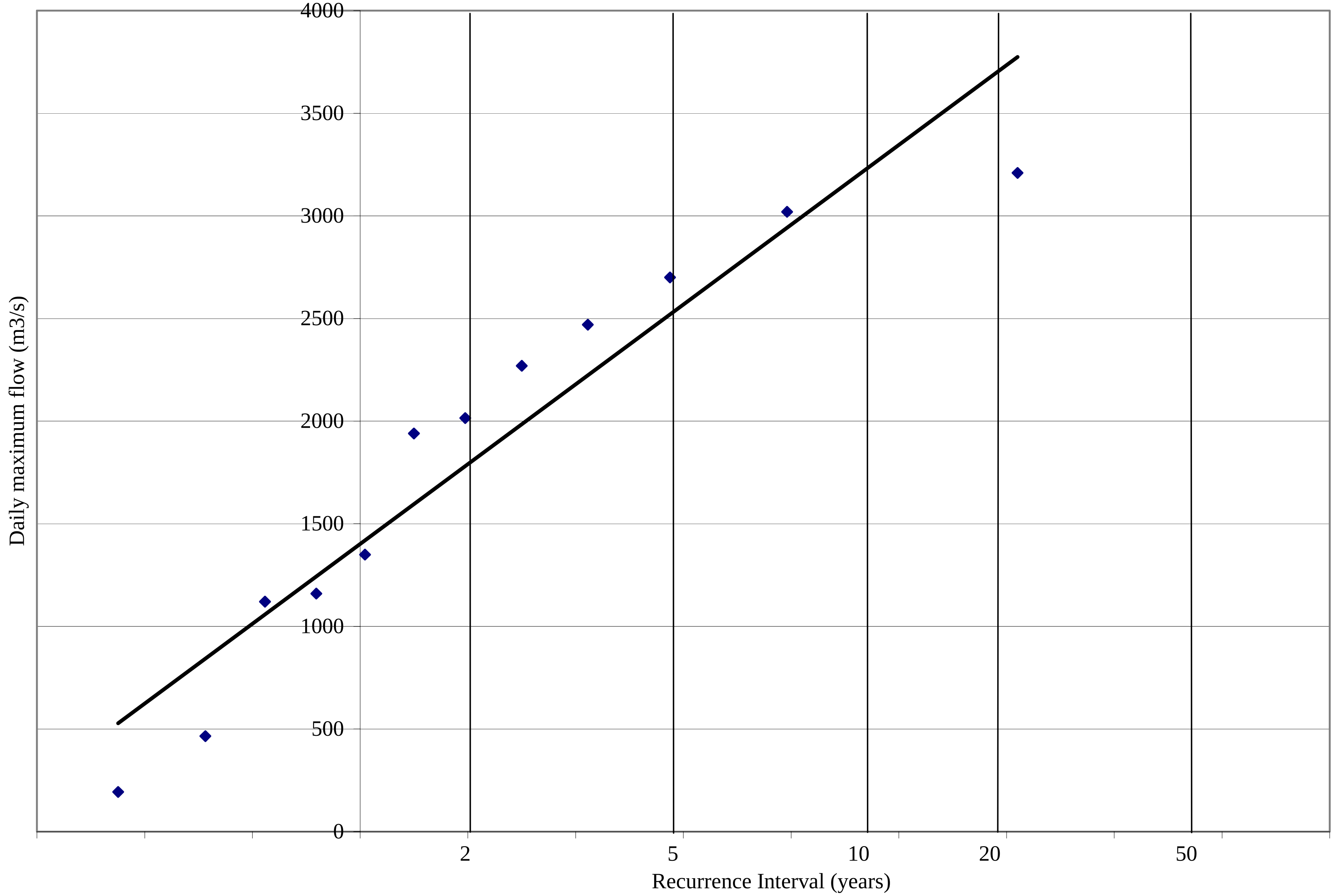


Figure 2-41. Flood frequency curve for annual series of maximum daily runoff from the Luenha River catchment, based on 1960-71 time series data.

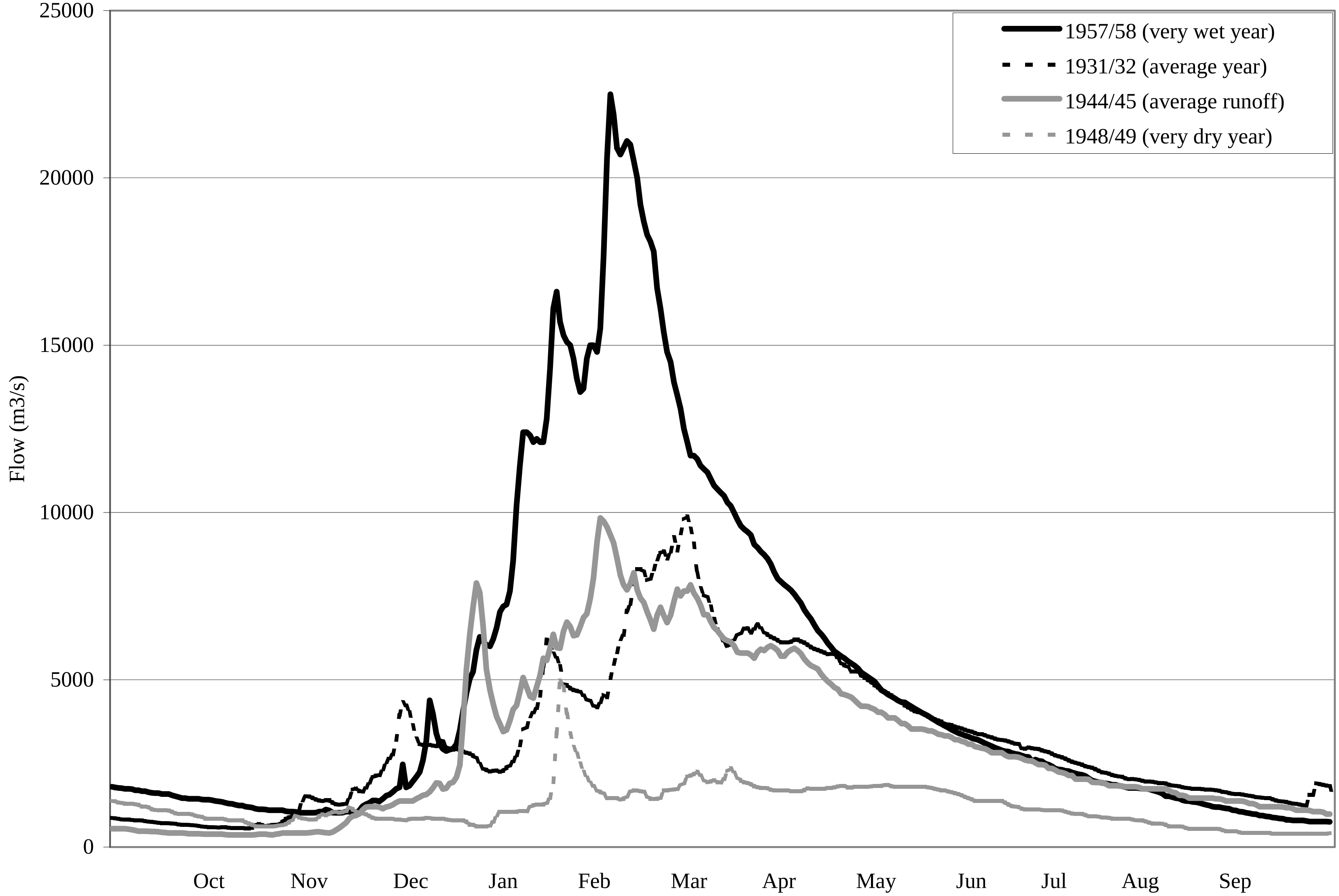


Figure 2-42. Typical hydrographs of average daily flow in the Zambezi River at Muturara prior to the construction of Kariba Reservoir, during years of above-average, average, and below-average runoff.

Figure 2-43. Hydrograph of average daily flow in the Zambezi River at Muturara since the completion of Cahora Bassa Reservoir, 1975-99.

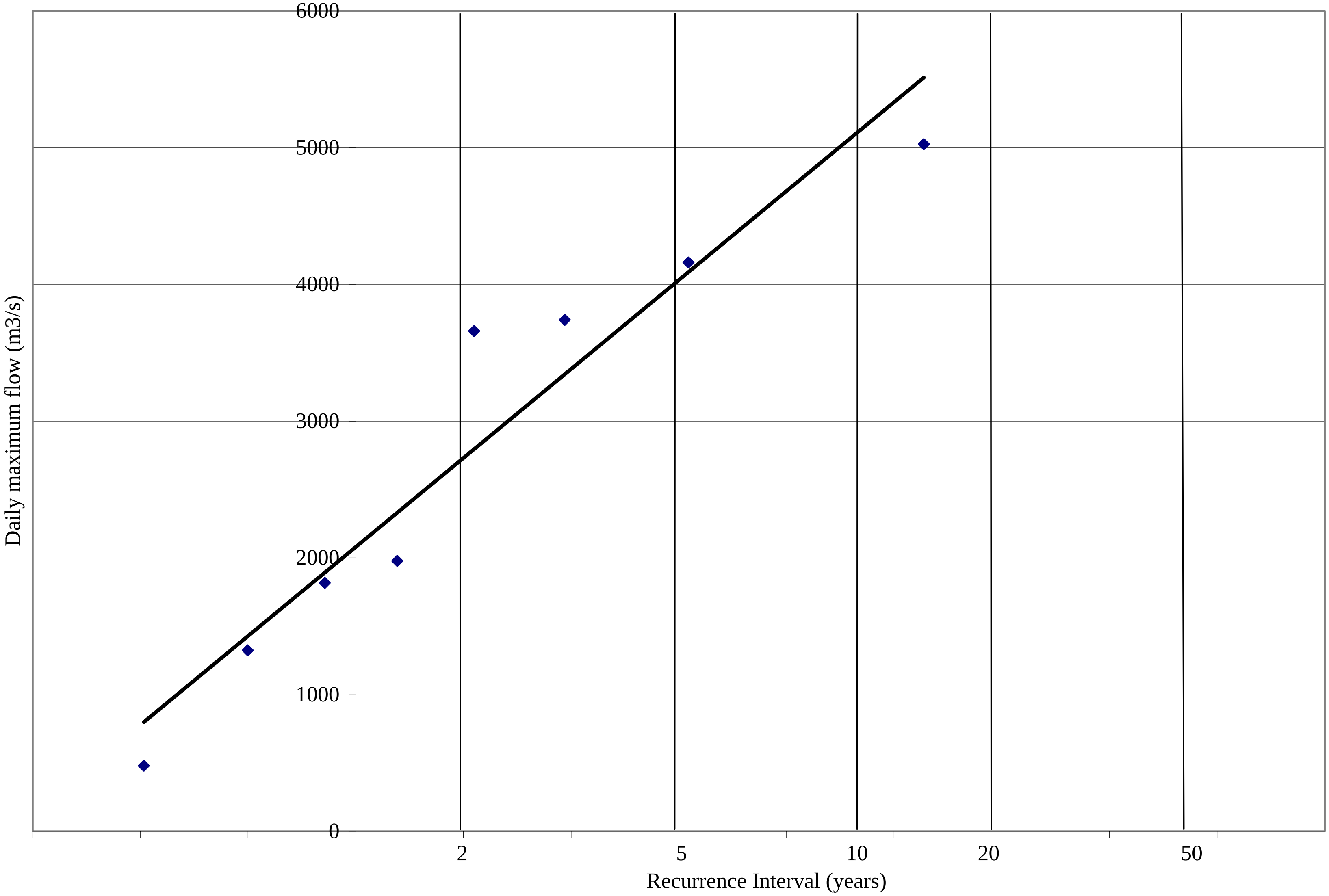


Figure 2-44. Flood frequency curve for annual series of maximum daily runoff from the combined Moravia-Angonia and Manica Plateau tributaries, based on 1960-68 time series data.

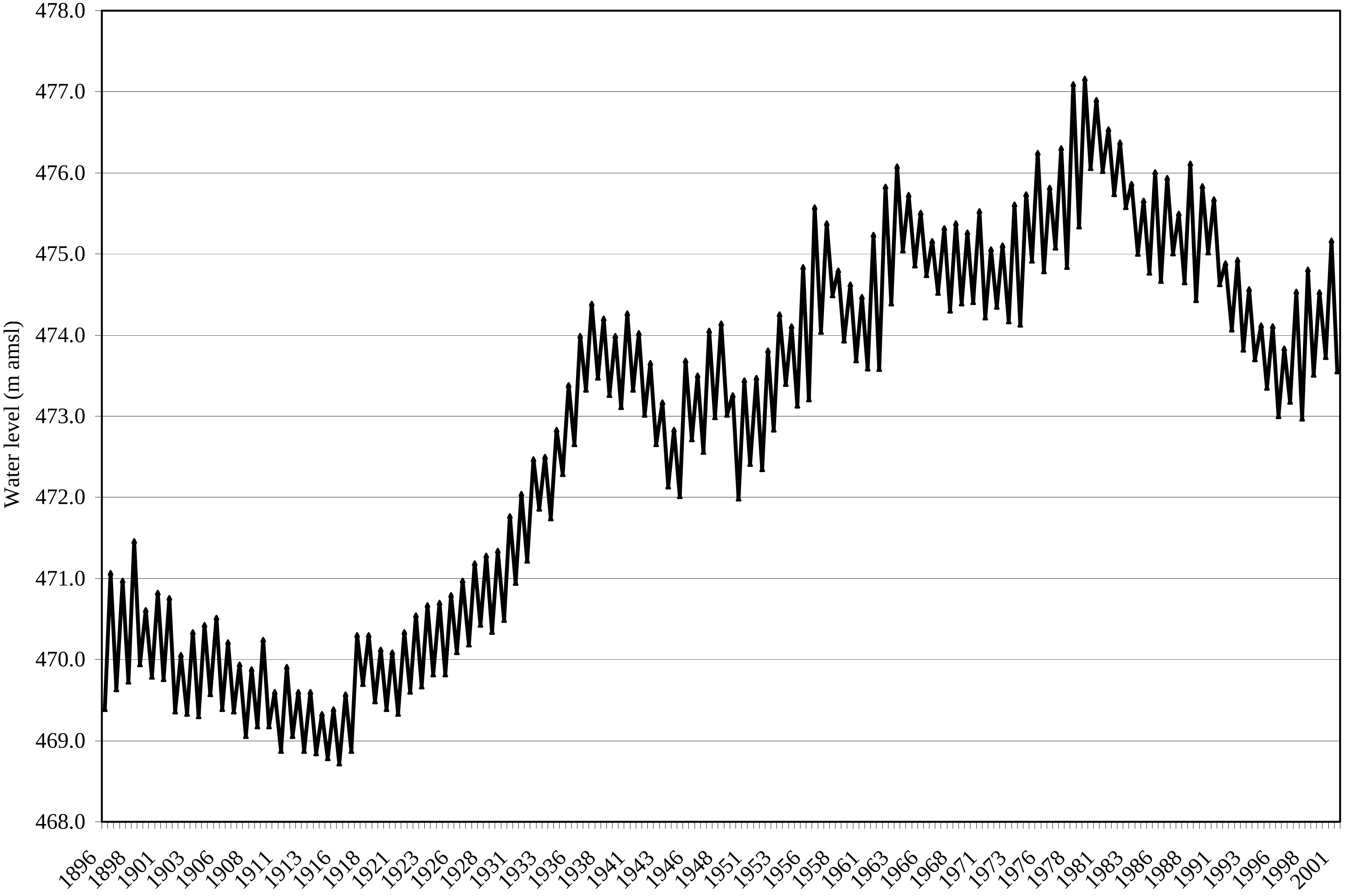


Figure 2-45. Lake Malawi long-term water level fluctuations (annual maximum and minimum, 1896-2001).

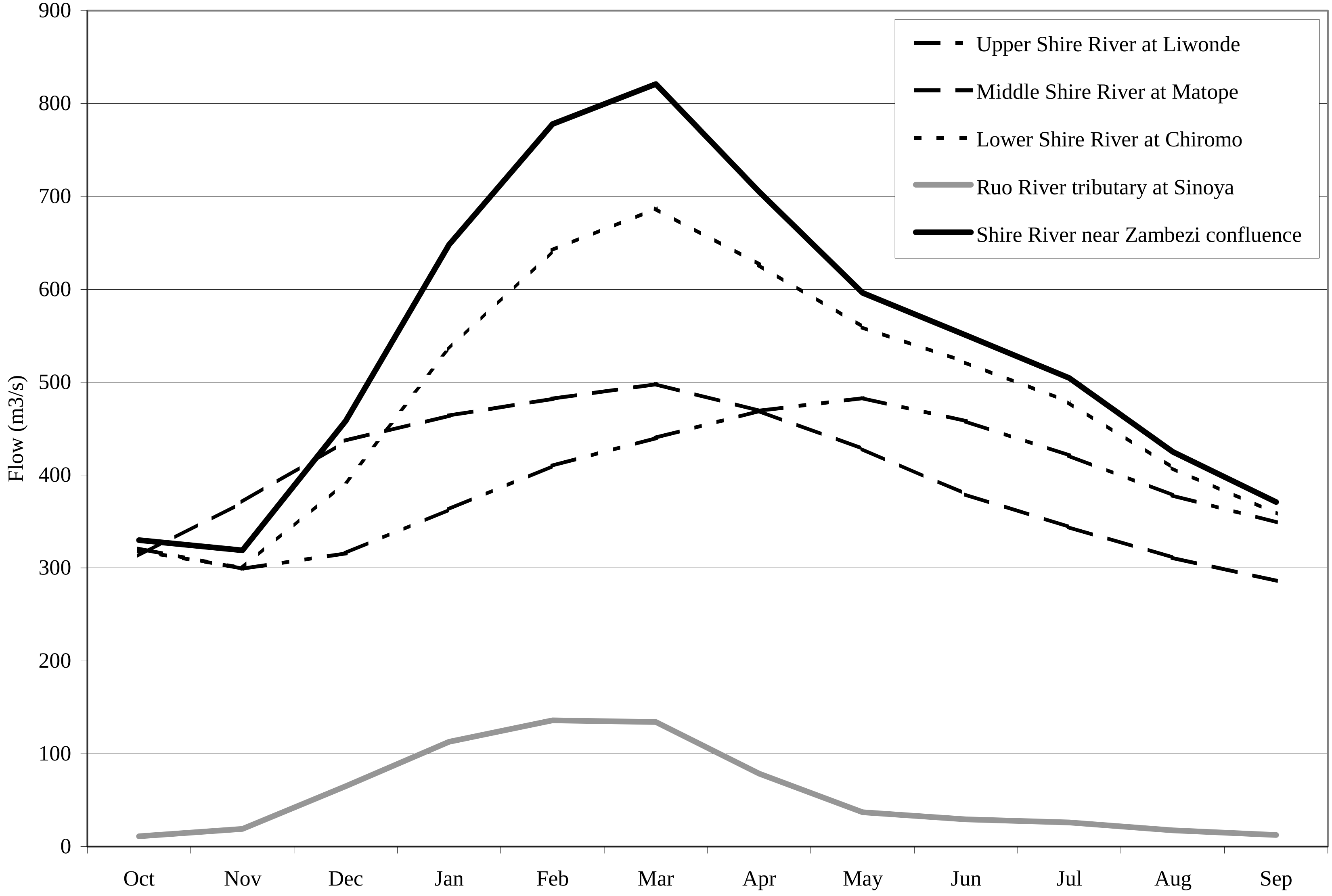


Figure 2-46. Hydrographs of mean monthly runoff from the Shire River Valley, 1952-98, showing flows in the Upper Shire, Middle Shire, and Lower Shire, and contribution from the Ruo River catchment.

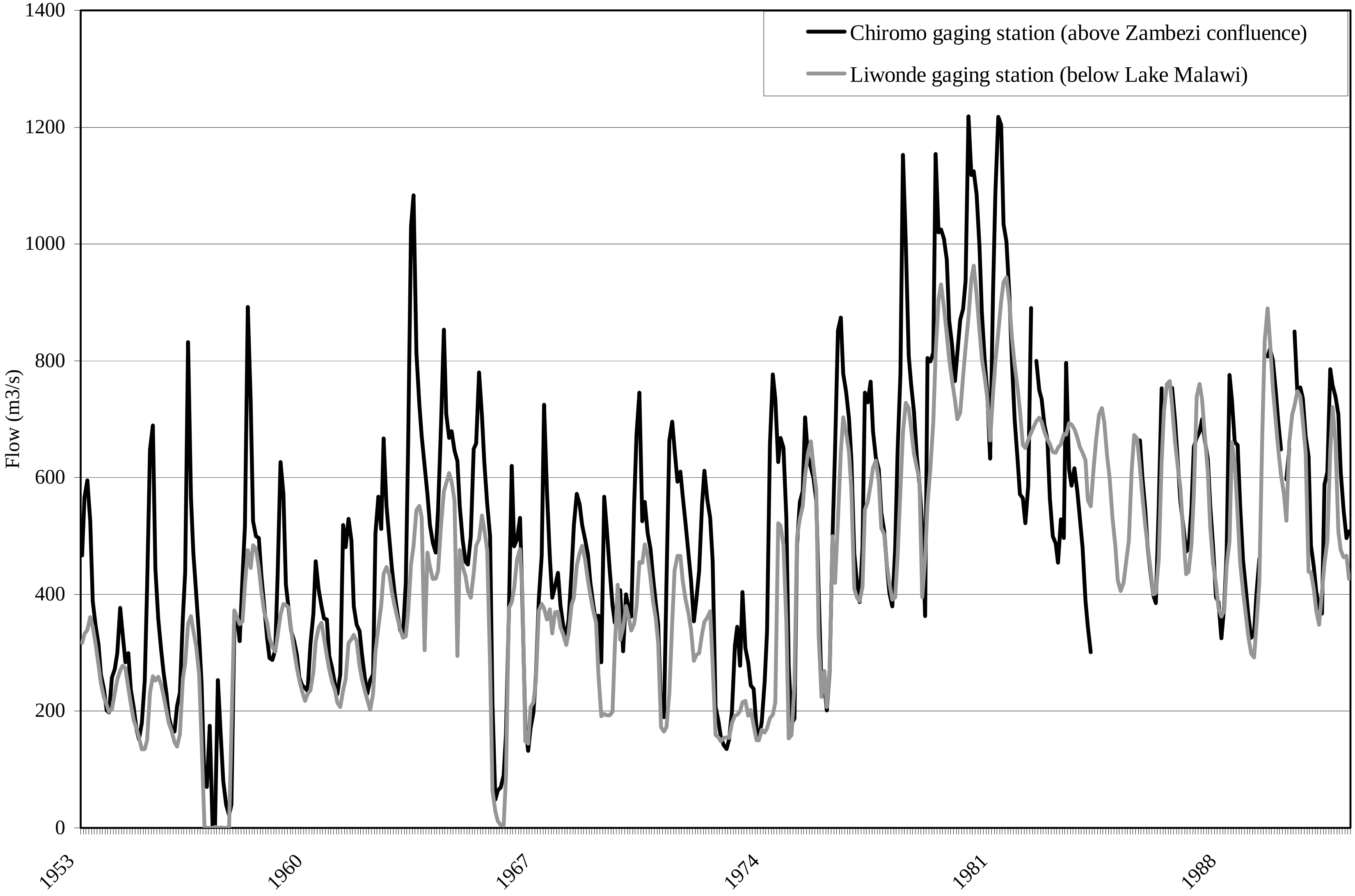


Figure 2-47. Times series of monthly runoff in the Upper and Lower Shire River, showing influence of Lake Malawi outflows on downstream flows.

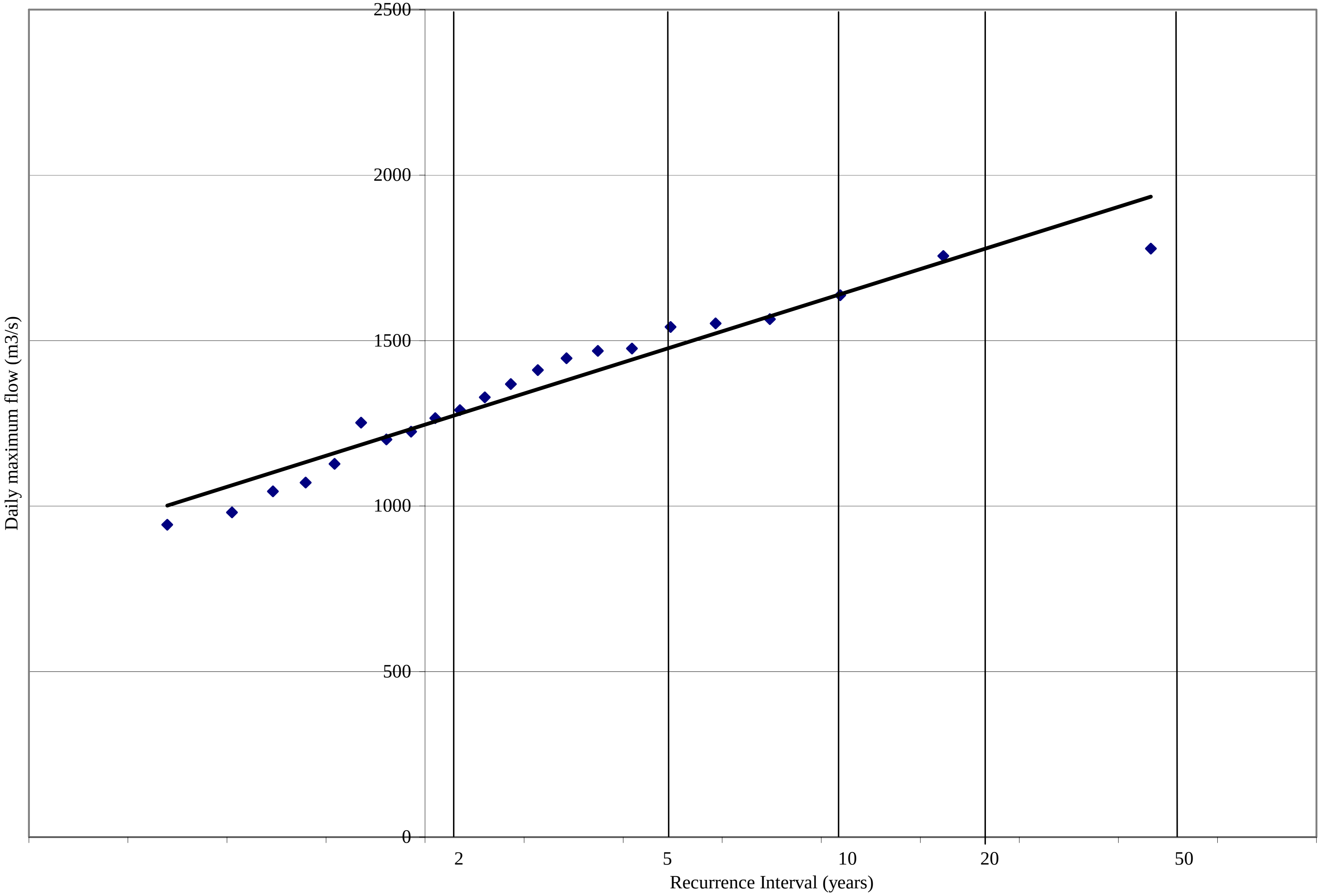


Figure 2-48. Flood frequency curve for annual series of maximum daily runoff from the Shire River catchment, based on 1951-82 time series data.

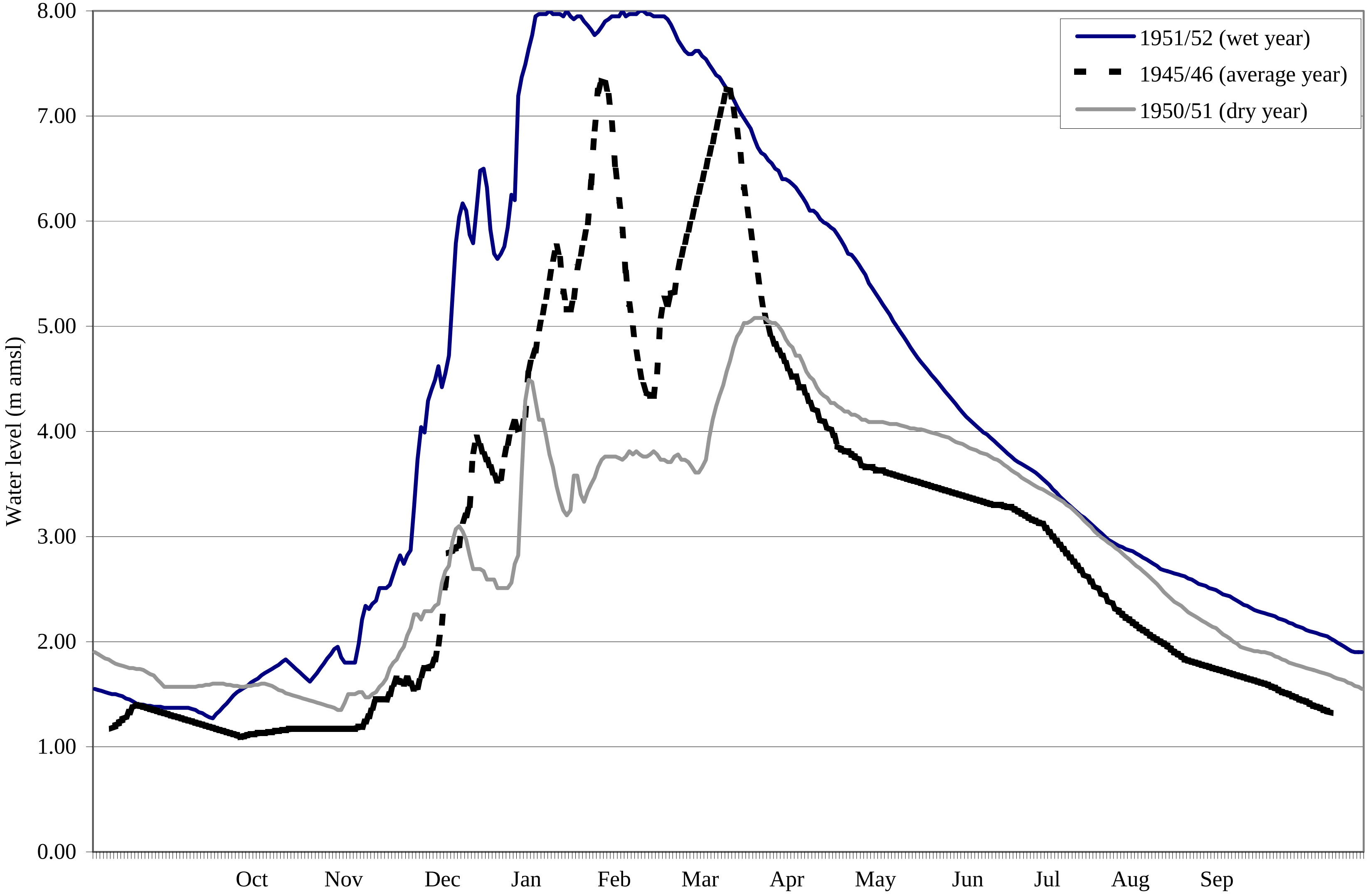


Figure 2-49. Typical hydrographs of average daily water levels at Marromeu gauging station prior to the construction of Kariba Reservoir, comparing water level conditions during years of above-average, average, and below-average annual runoff.

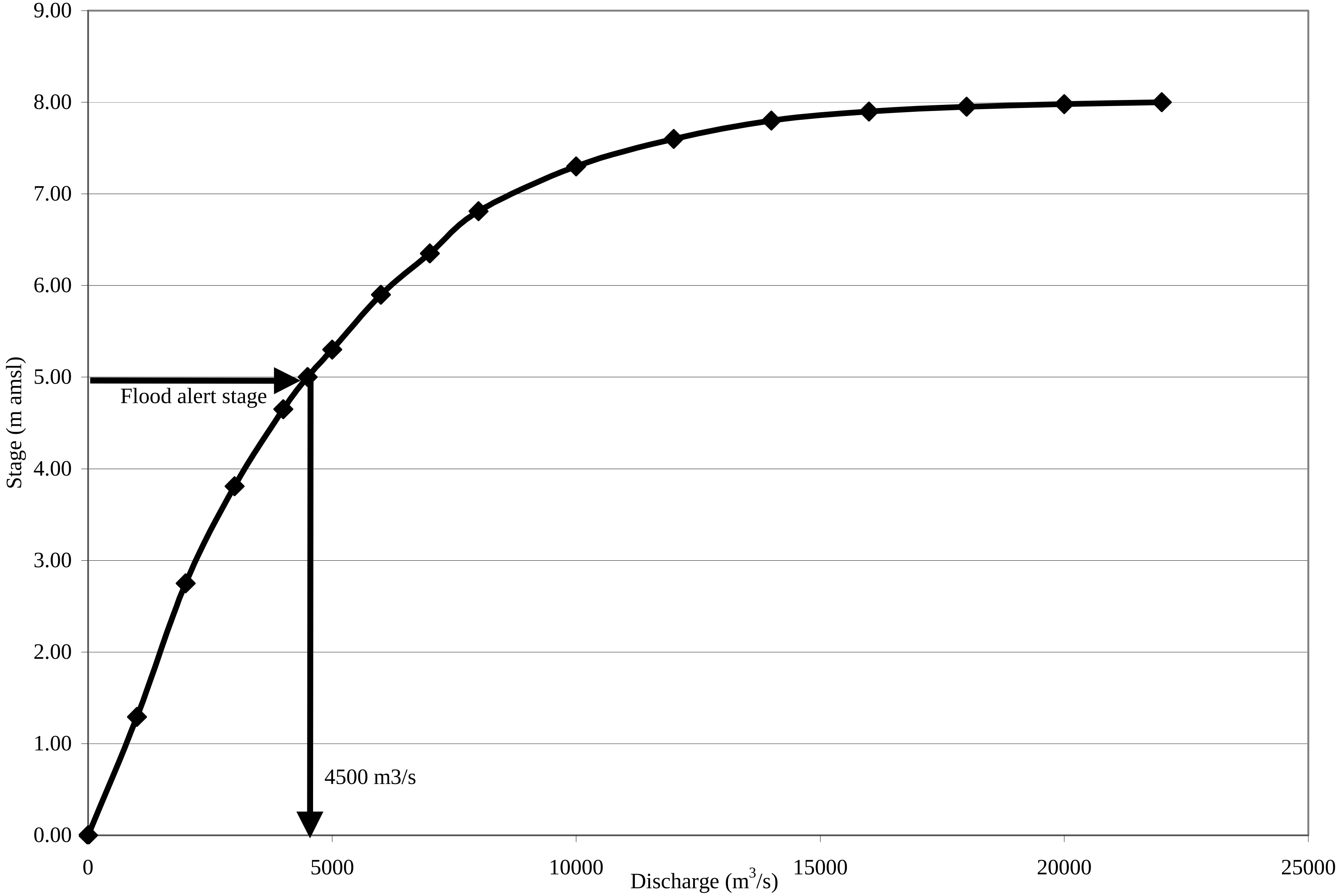


Figure 2-50. Historical stage-discharge rating curve for Marromeu gauging station, Zambezi Delta.

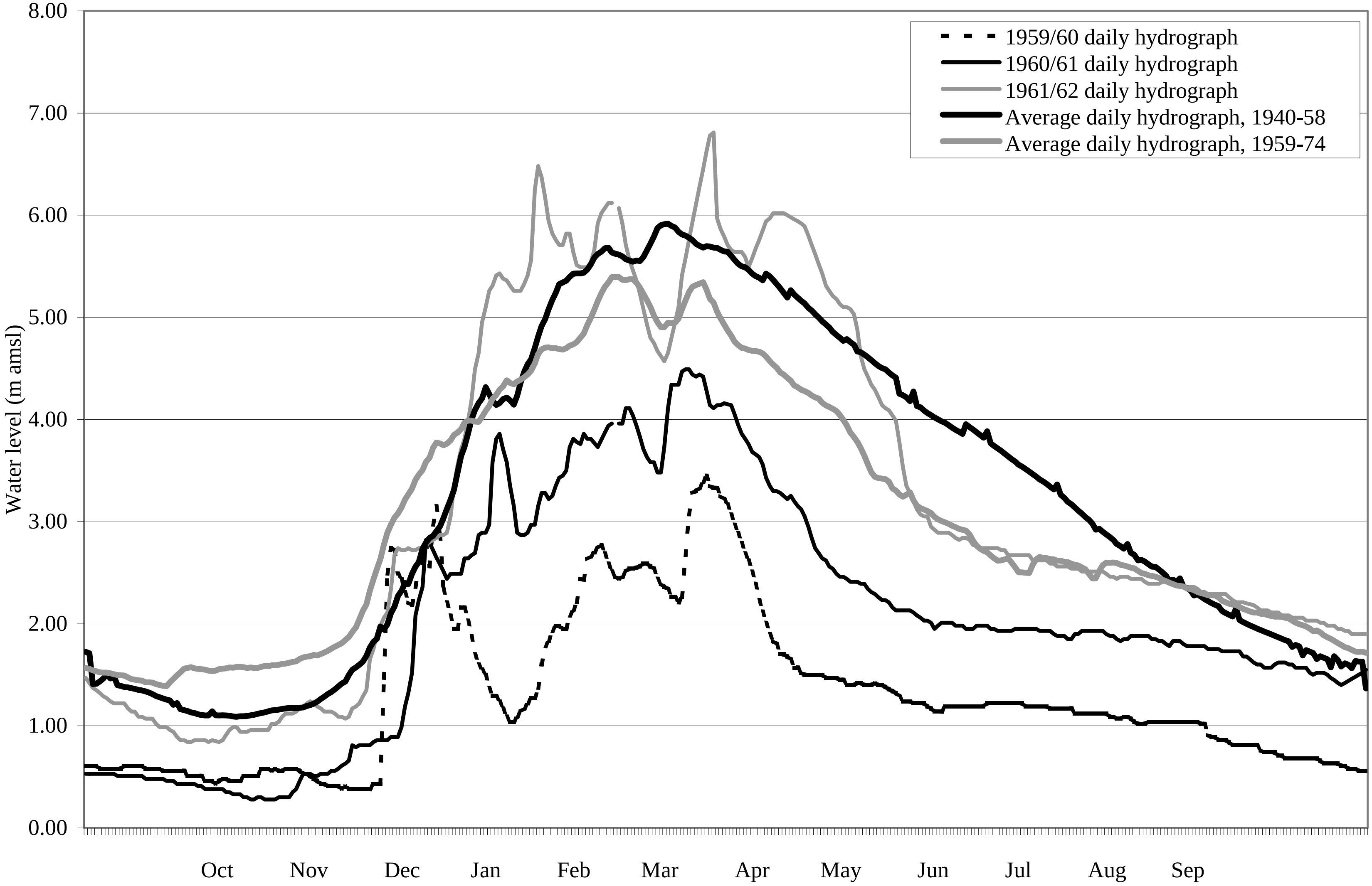


Figure 2-51. Hydrographs of average daily water levels at Marromeu gauging station, comparing water level conditions during the initial three years of filling of Kariba Reservoir with average water levels before and after Kariba regulation.

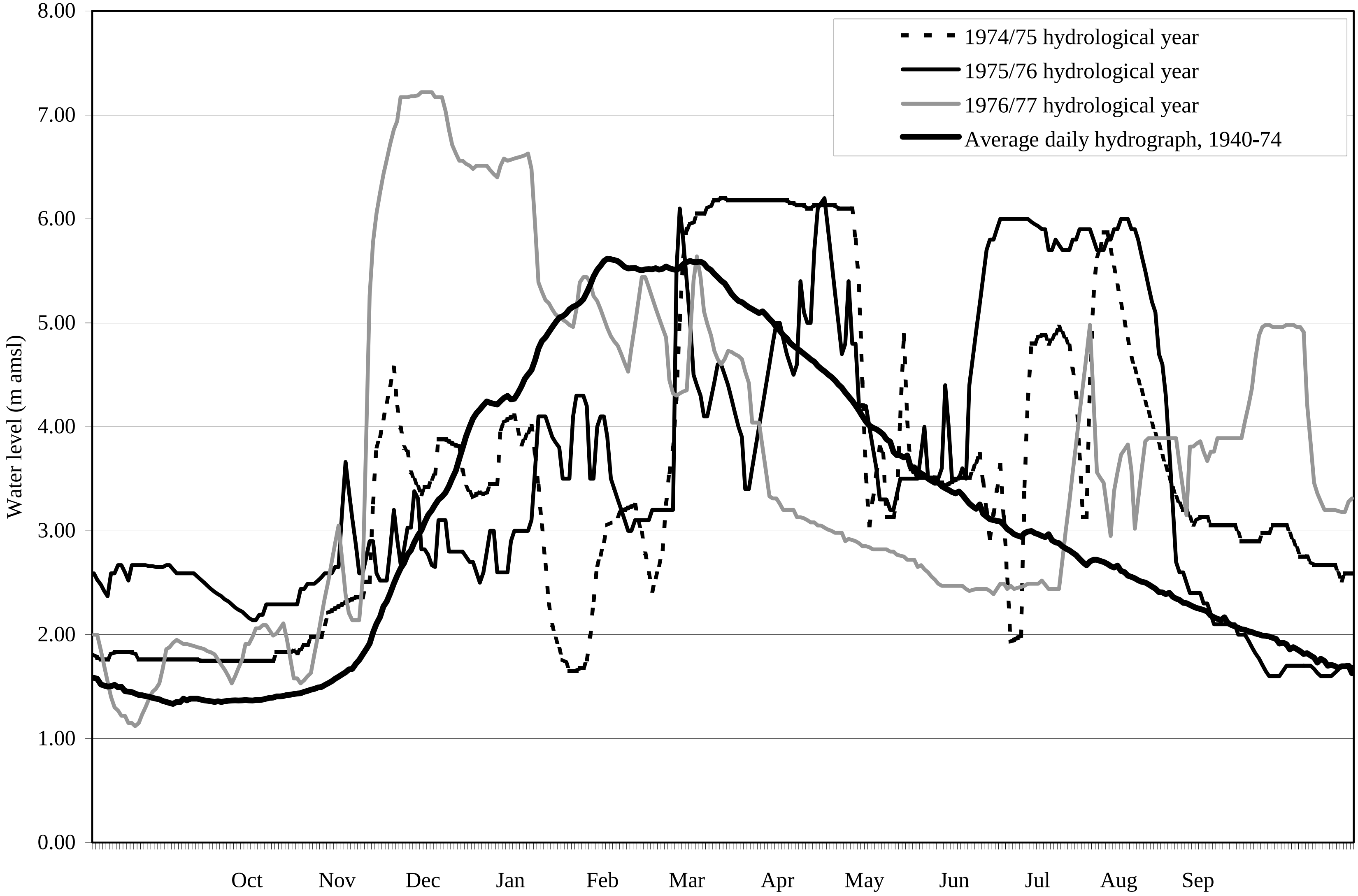


Figure 2-52. Hydrographs of average daily water levels at Marromeu gauging station, comparing water level conditions during the first three years of Cahora Bassa Reservoir operation with historical pre-dam conditions.

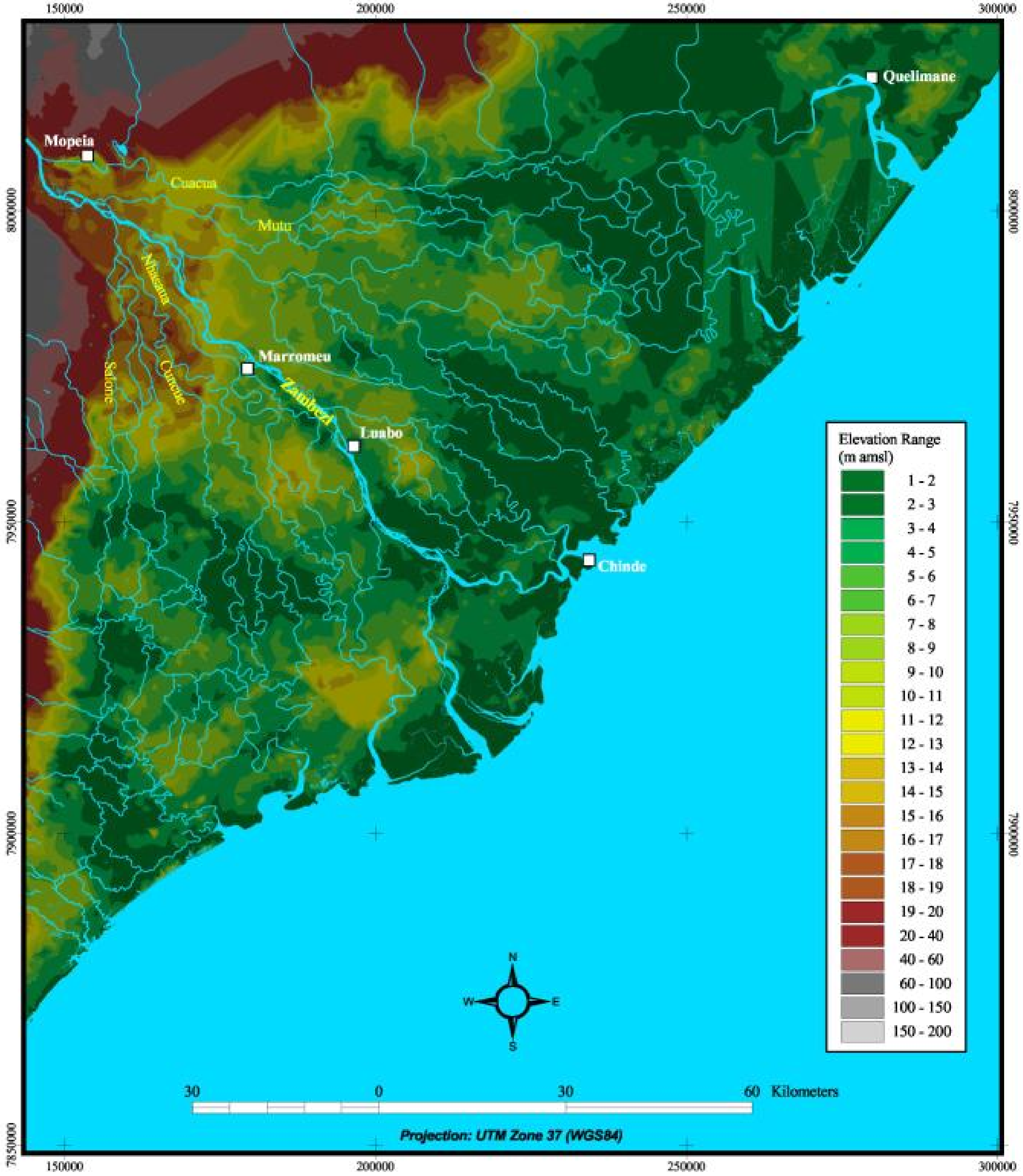


Figure 2-53. Topographic map of the Zambezi Delta showing major distributary channels under historical conditions.

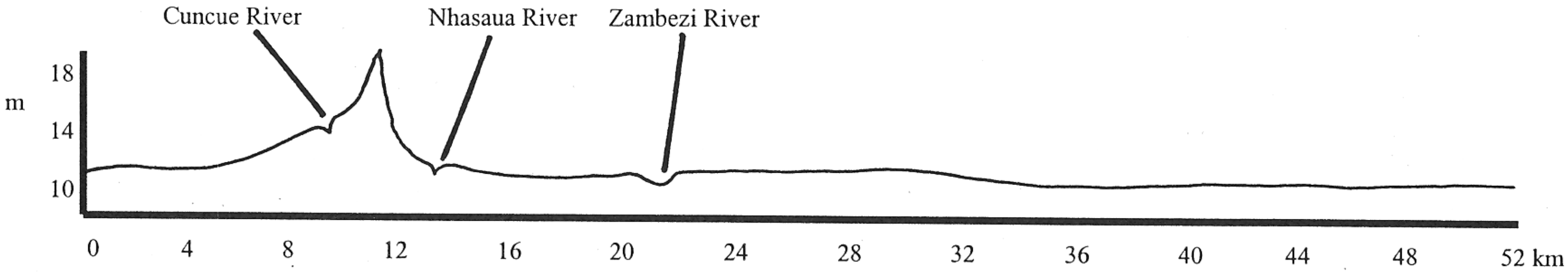


Figure 2-54. Cross-sectional profile of the Zambezi Delta near Marromeu (from Sushka and Napica 1988).

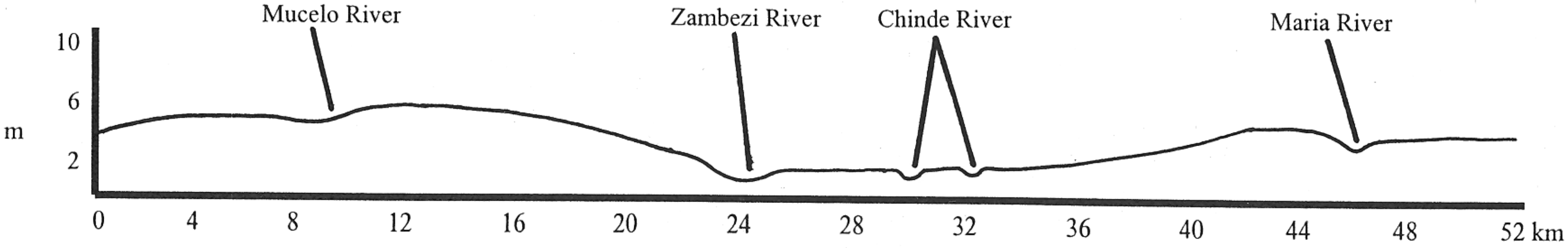


Figure 2-55. Cross-sectional profile of the Zambezi Delta near the Indian Ocean coast (from Sushka and Napica 1988).

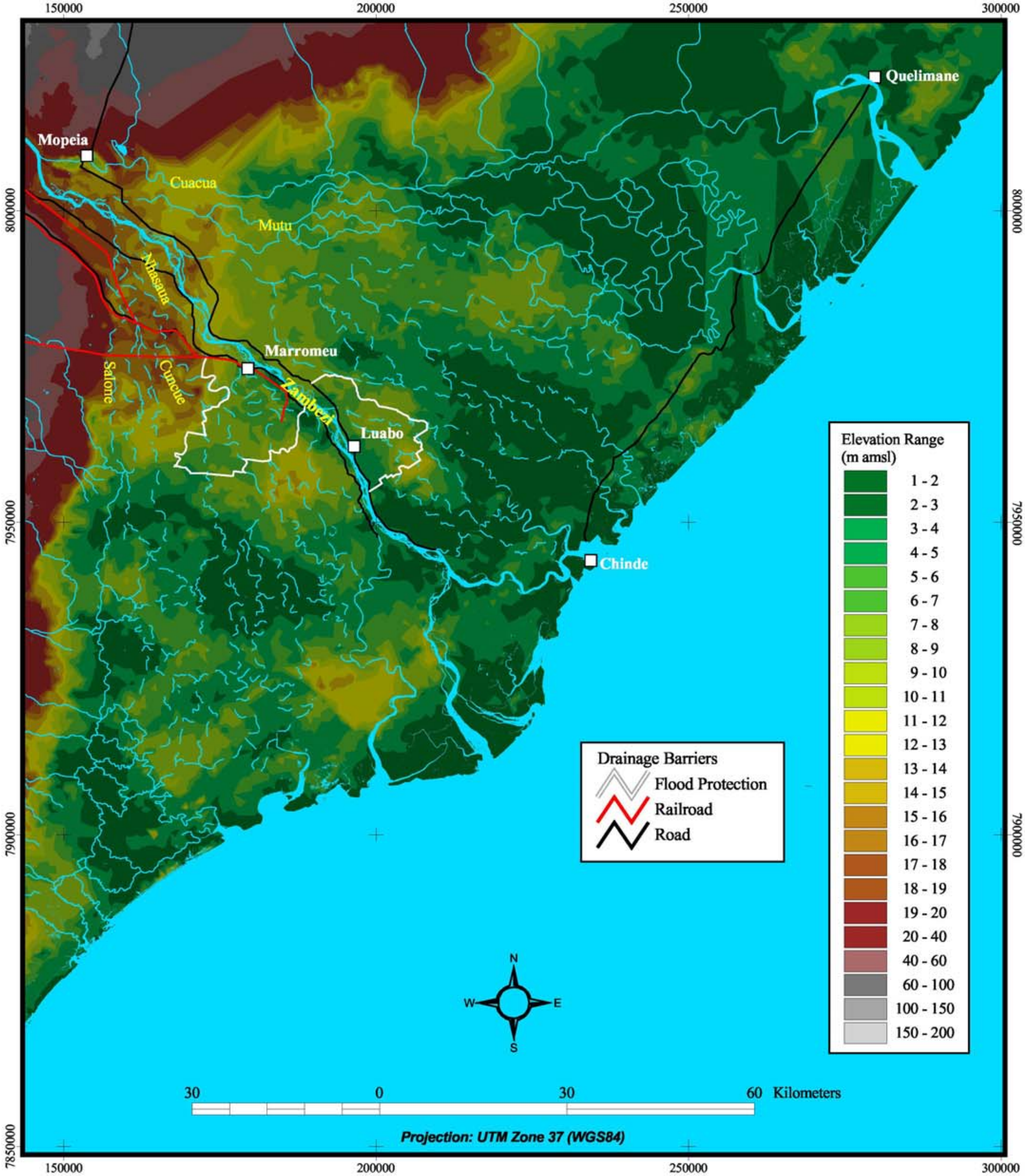
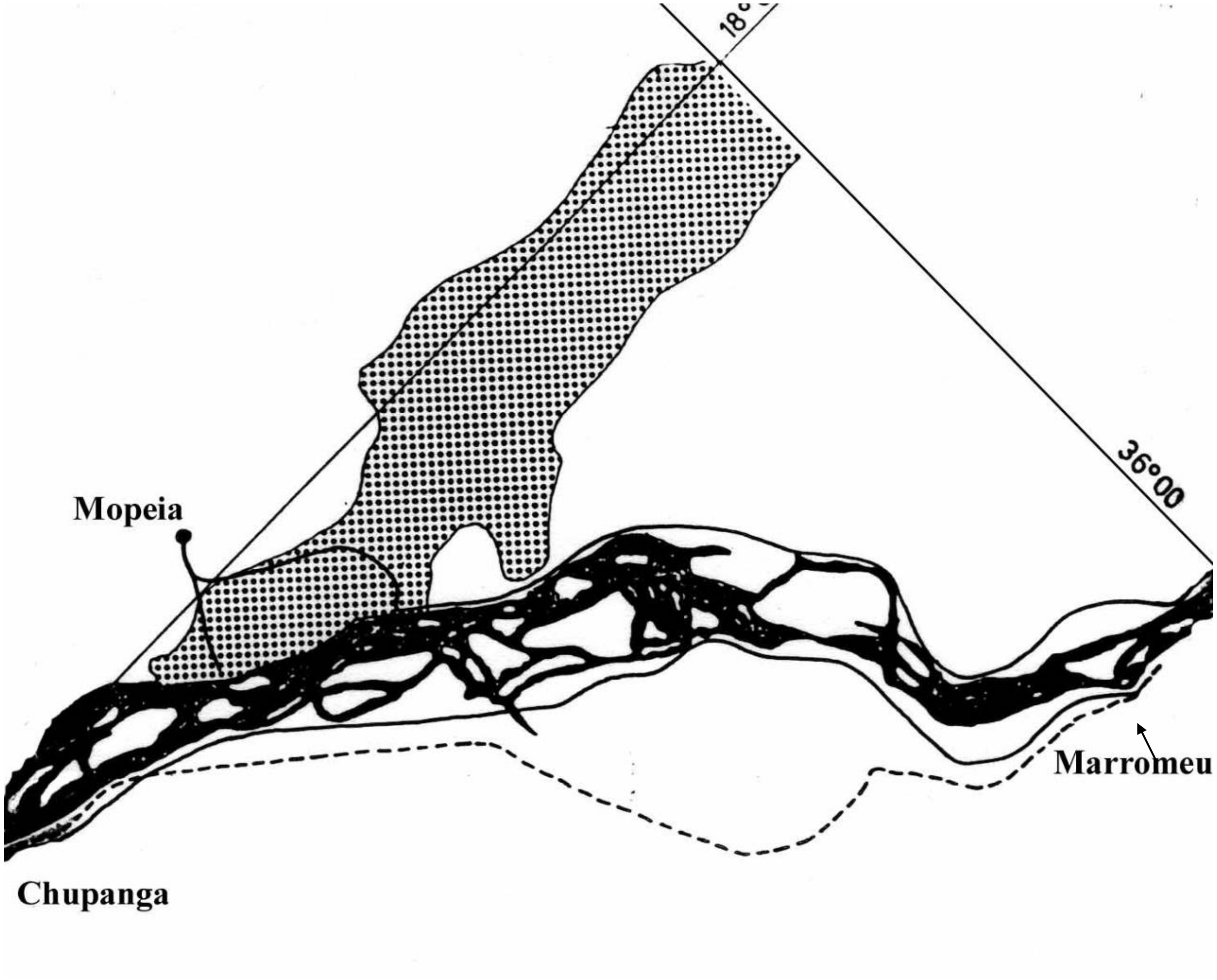


Figure 2-56. Topographic map of the Zambezi Delta showing major distributary channels under current conditions. The dashed lines indicate obstructed waterways.



— Road embankment
…… Railway embankment

Figure 2-57. Extent of inundation (shaded area) in the upper Zambezi Delta when Zambezi discharge reaches 5000 m^3/s (adapted from RPT 1979).

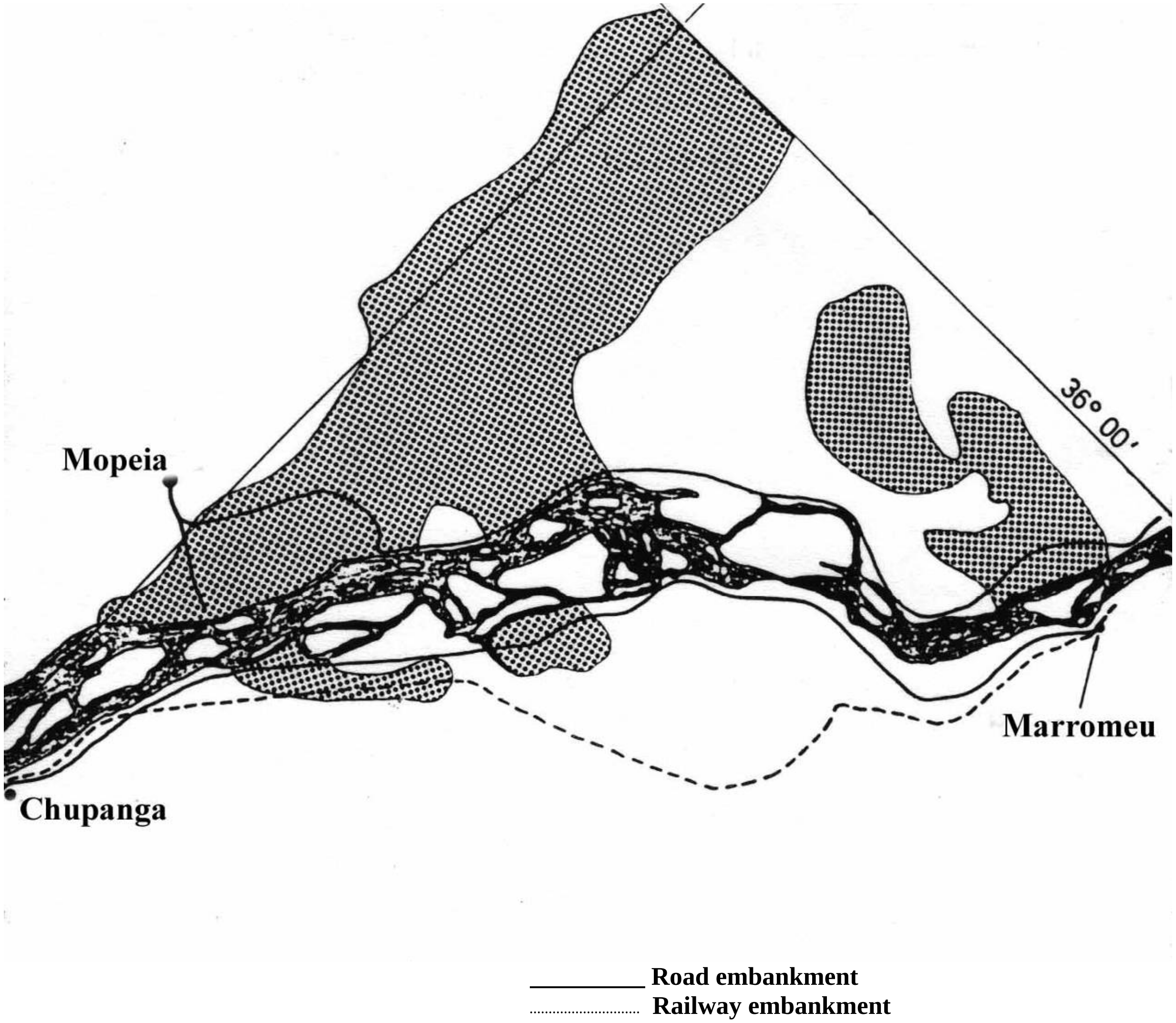
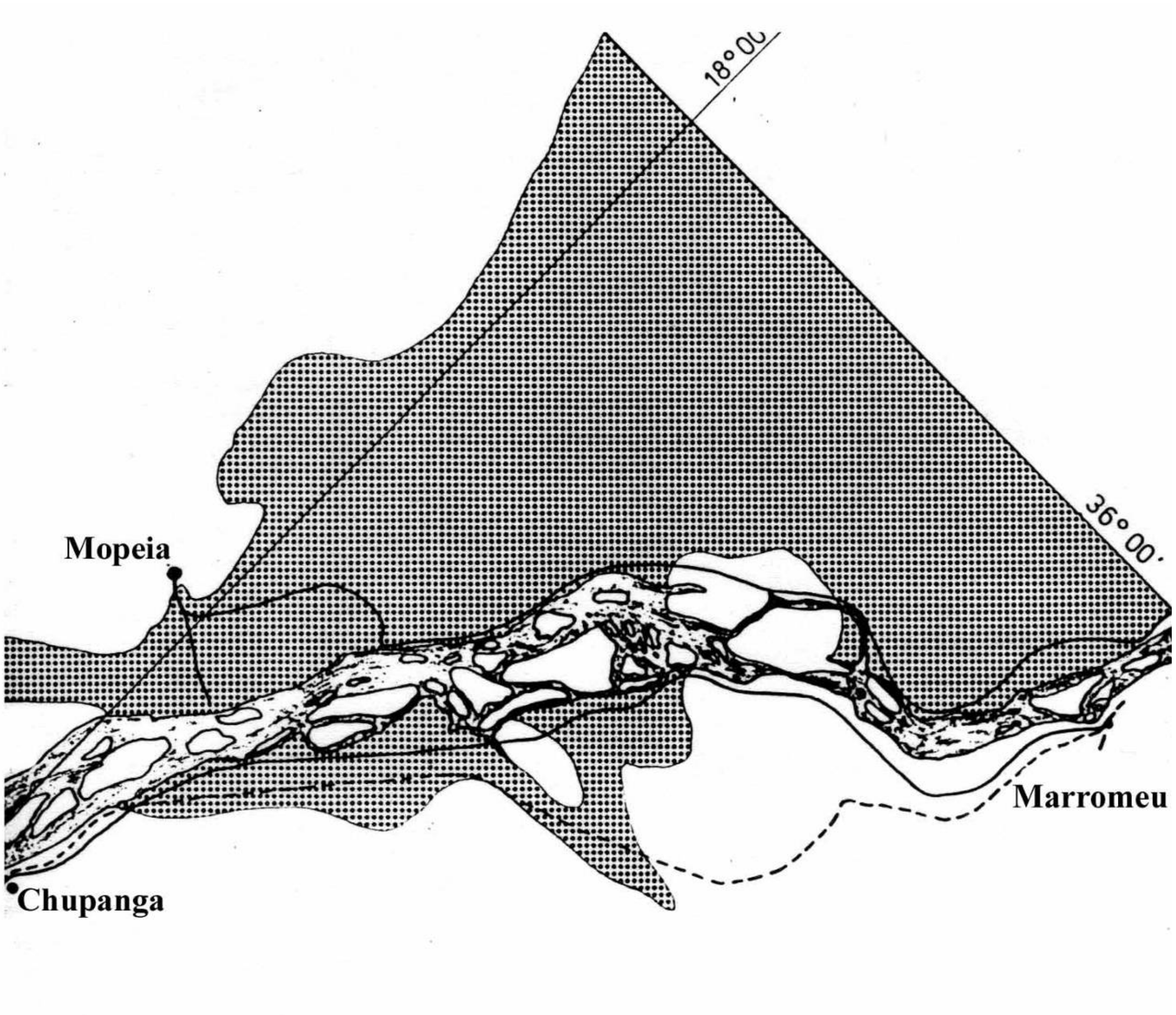


Figure 2-58. Extent of inundation (shaded area) in the upper Zambezi Delta when Zambezi discharge reaches 9000 m^3/s (adapted from RPT 1979).



_________ **Road embankment**

…………………… **Railway embankment**

Figure 2-59. Extent of inundation (shaded area) in the upper Zambezi Delta when Zambezi discharge reaches 13,000 m^3/s (adapted from RPT 1979).

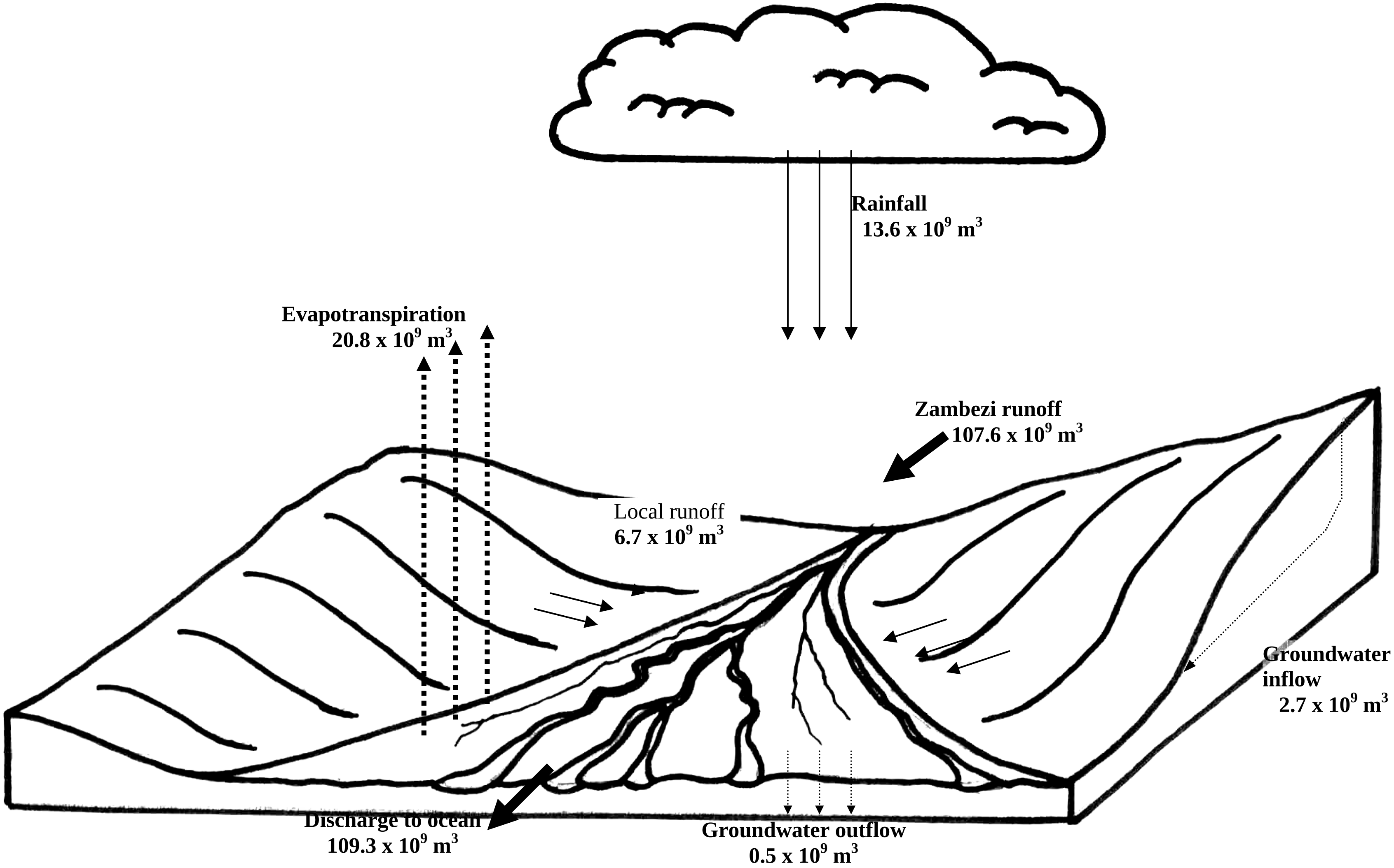


Figure 2-60. Water balance components for the Zambezi Delta under historical conditions (prior to the development of the Zambezi catchment).

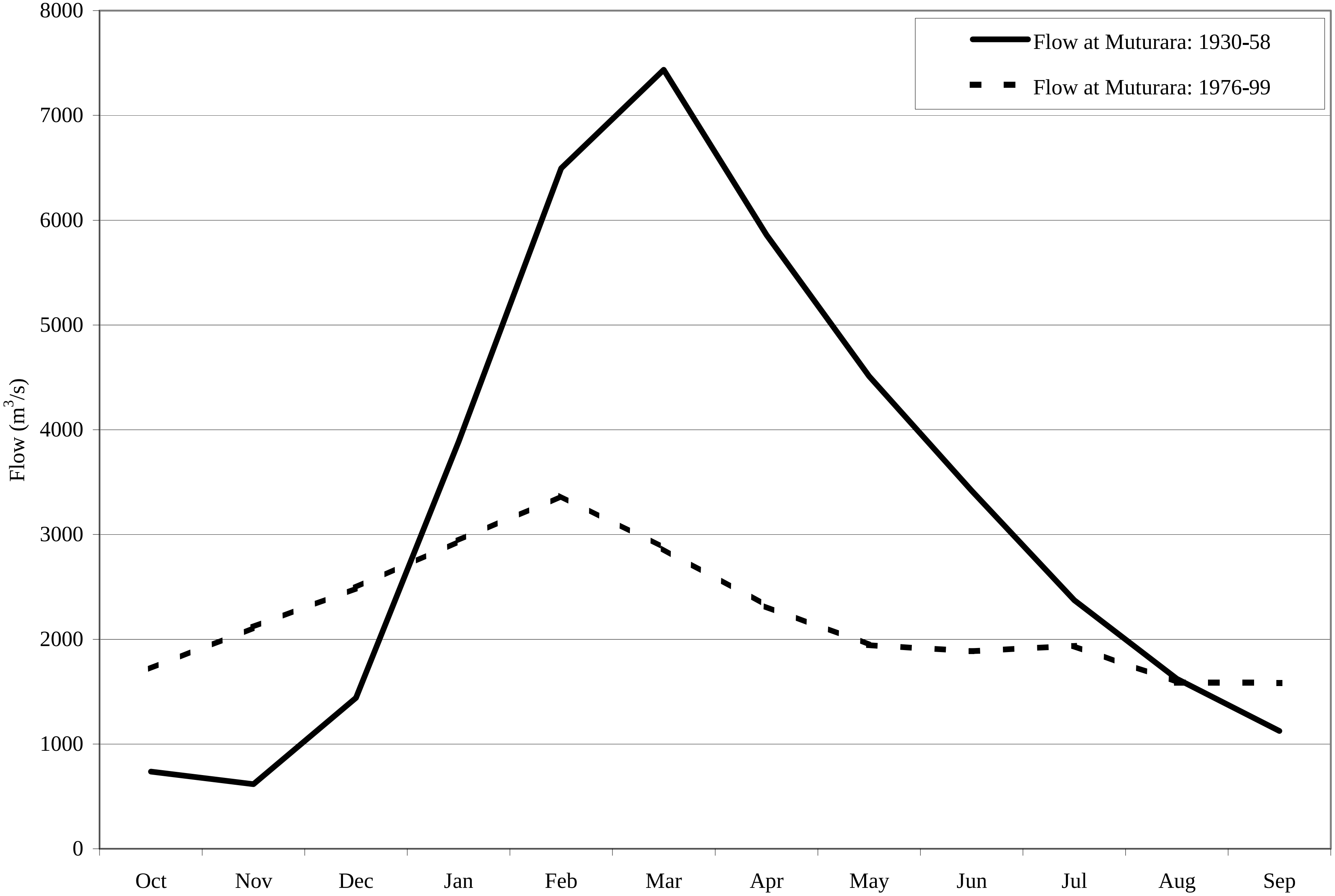


Figure 2-61. A comparison of mean monthly flow values for Zambezi River at Muturara, before construction of Kariba Reservoir (1930-58) and after construction of Cahora Bassa Reservoir (1976-99).

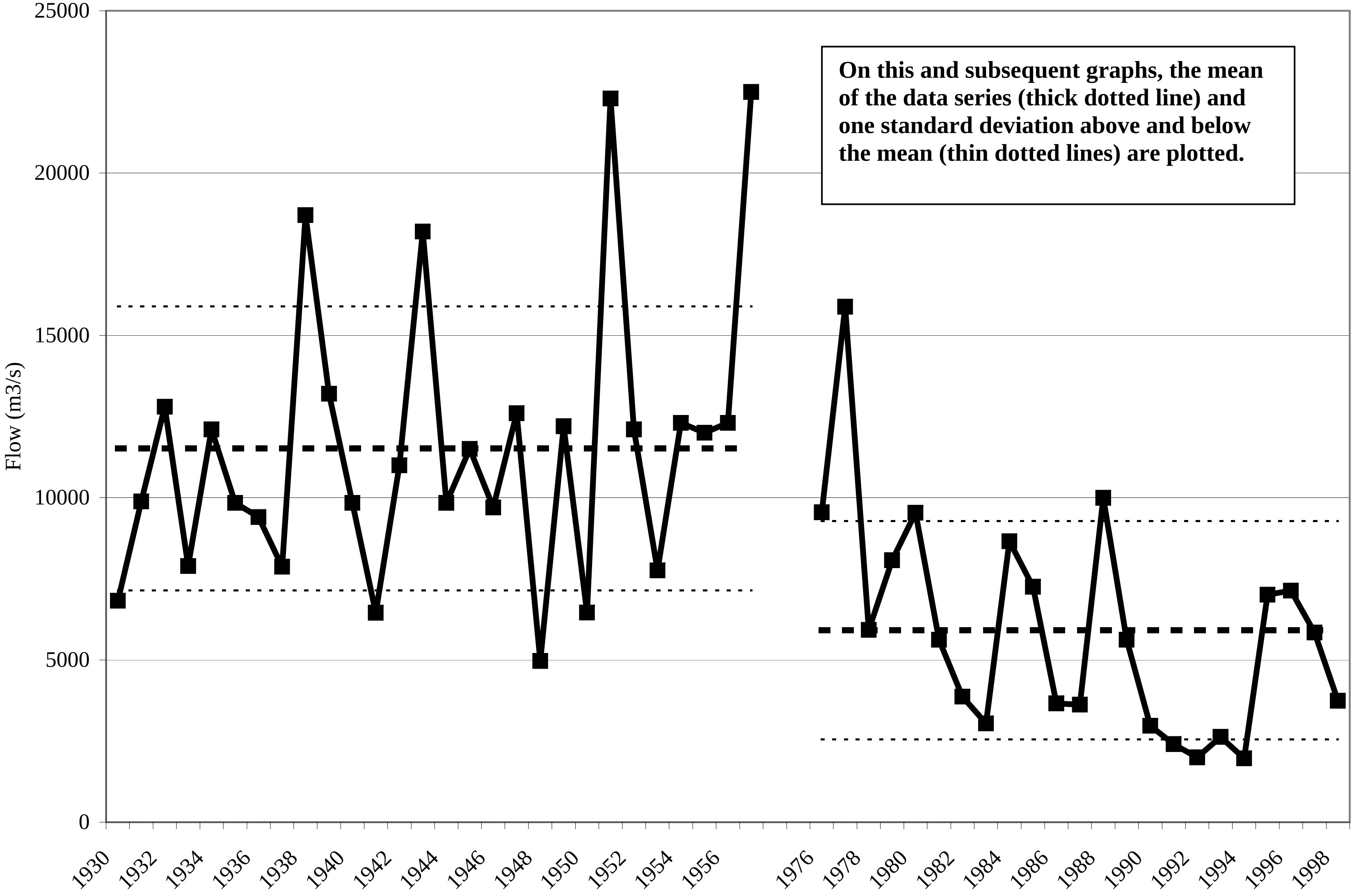


Figure 2-62. A comparison of maximum 1-day discharge values for the Zambezi River at Mutarara, before construction of Kariba Reservoir (1930-58) and after construction of Cahora Bassa Reservoir (1976-99).

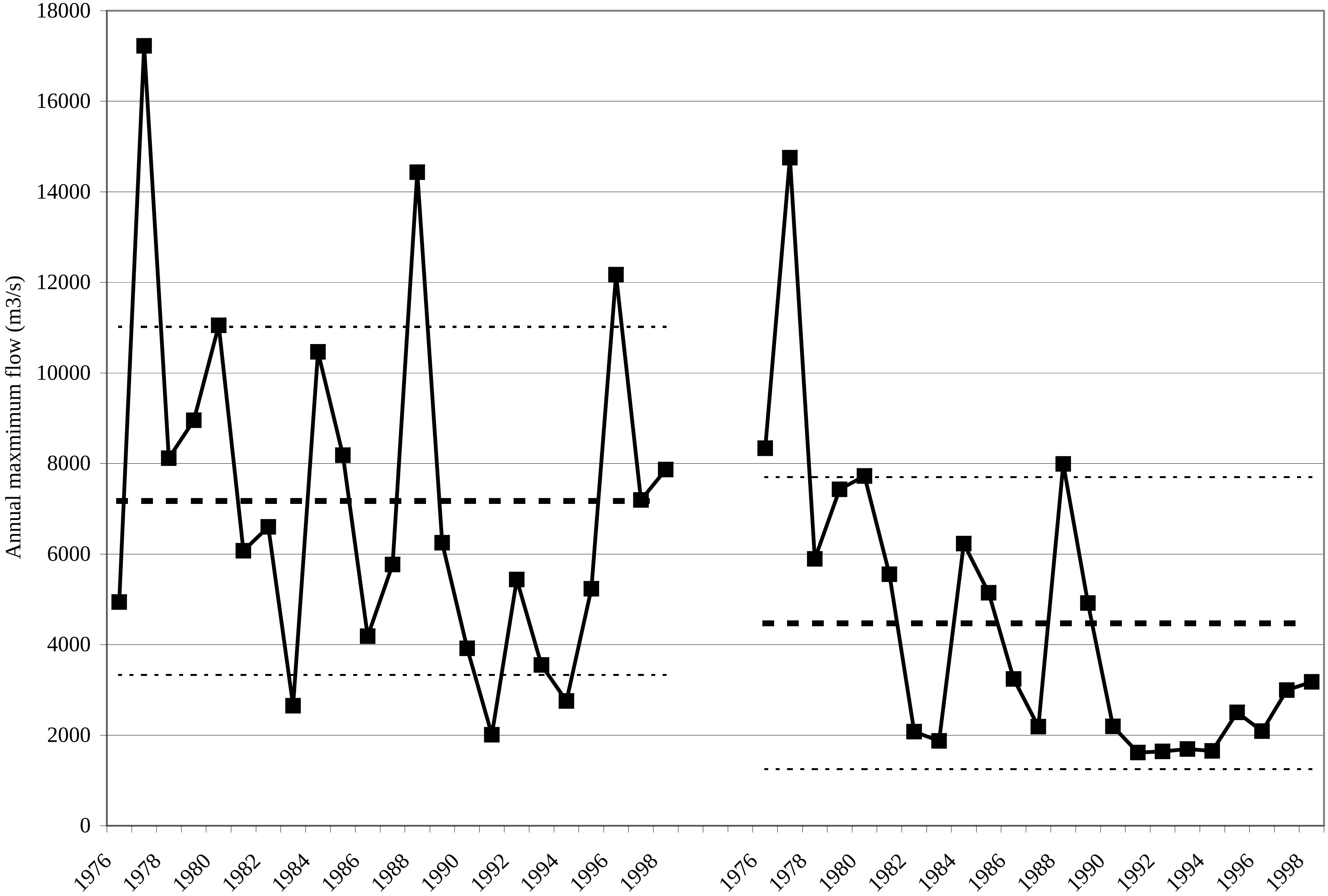


Figure 2-63. A comparison of annual series of maximum 1-day values for inflows and outflows at Cahora Bassa Reservoir.

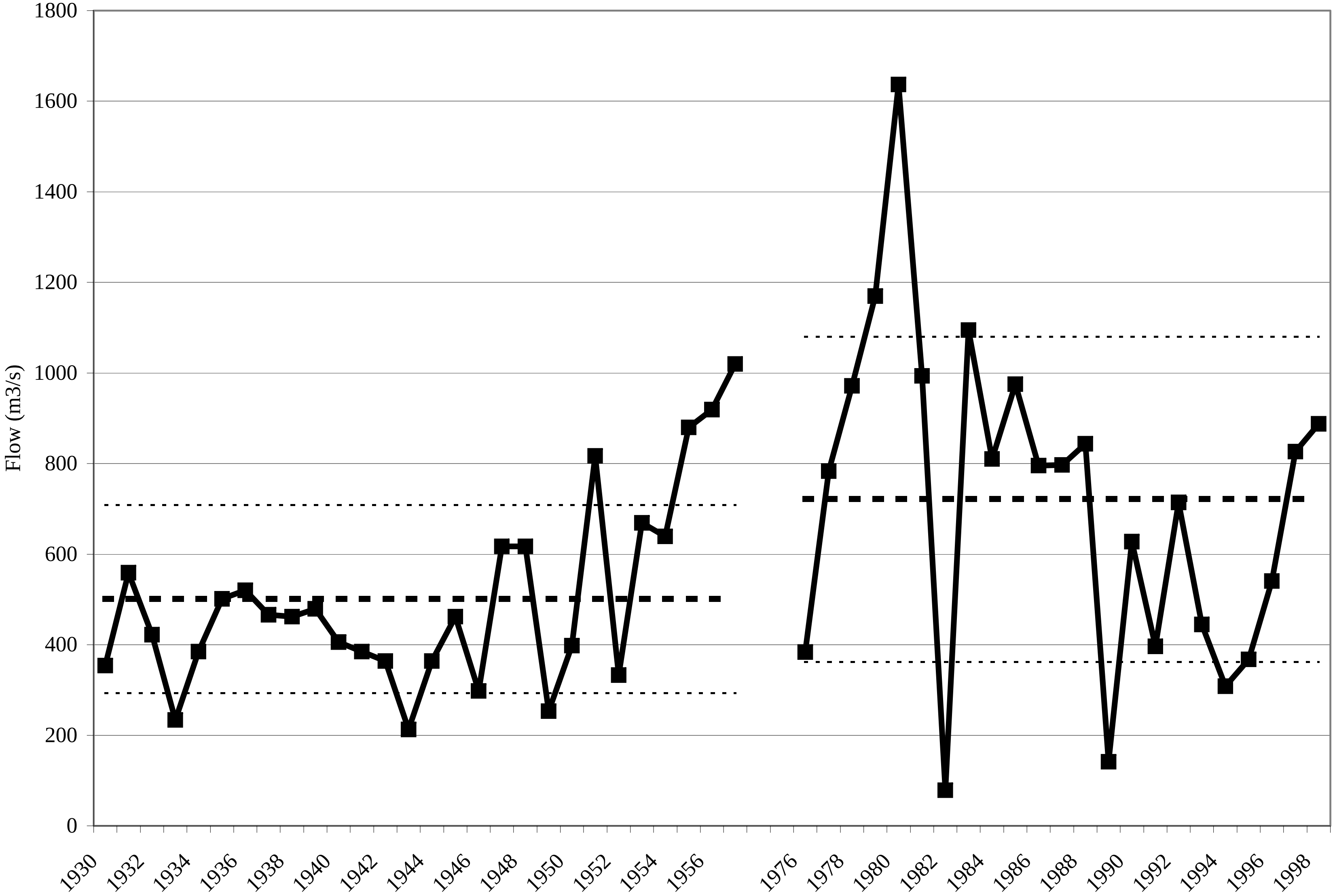


Figure 2-64. A comparison of minimum 1-day discharge values for the Zambezi River at Muturara, before construction of Kariba Reservoir (1930-58) and after construction of Cahora Bassa Reservoir (1976-99).

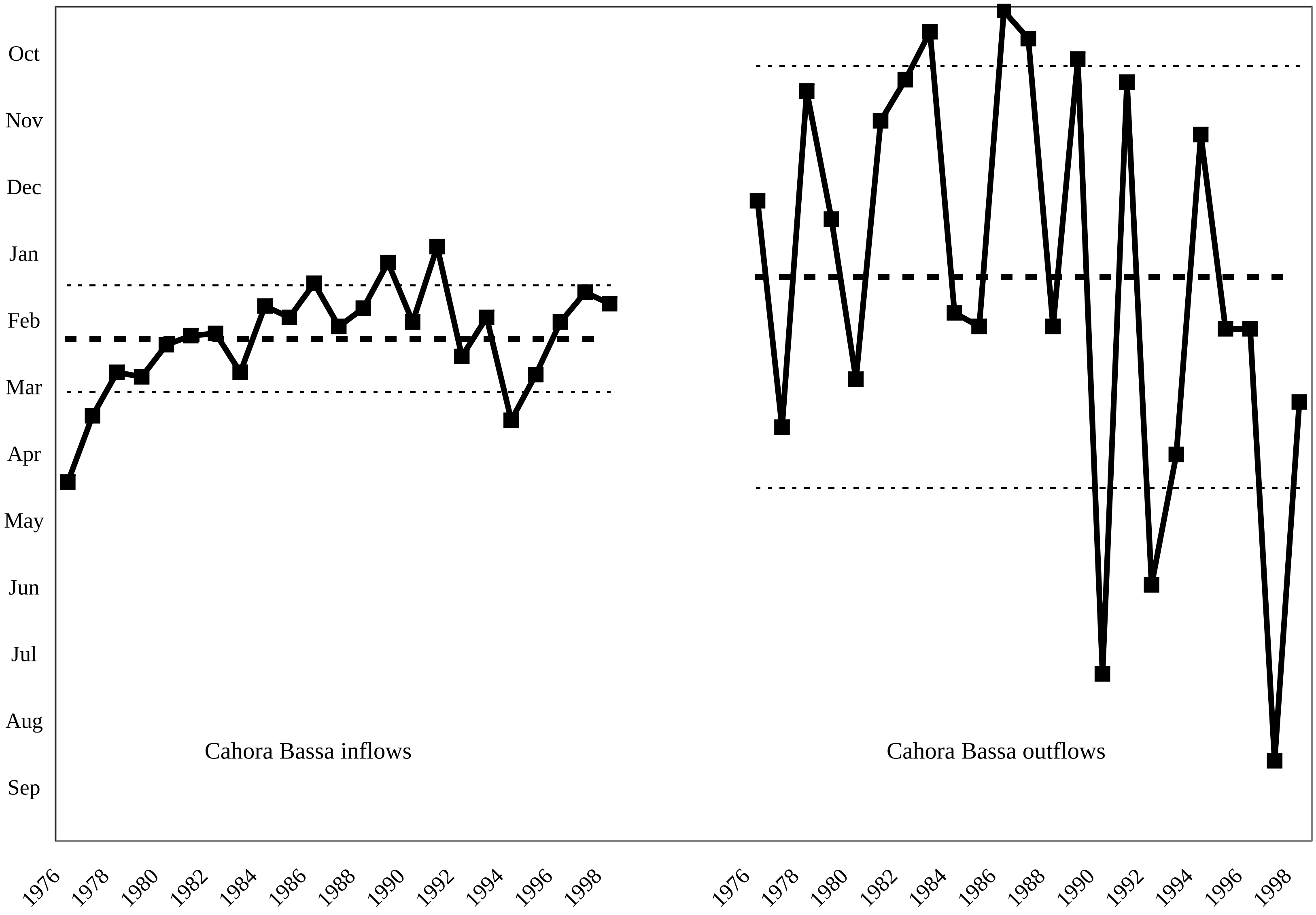


Figure 2-65. A comparison of the annual series of values for the timing of annual maximum 1-day inflows and outflows at Cahora Bassa Reservoir.

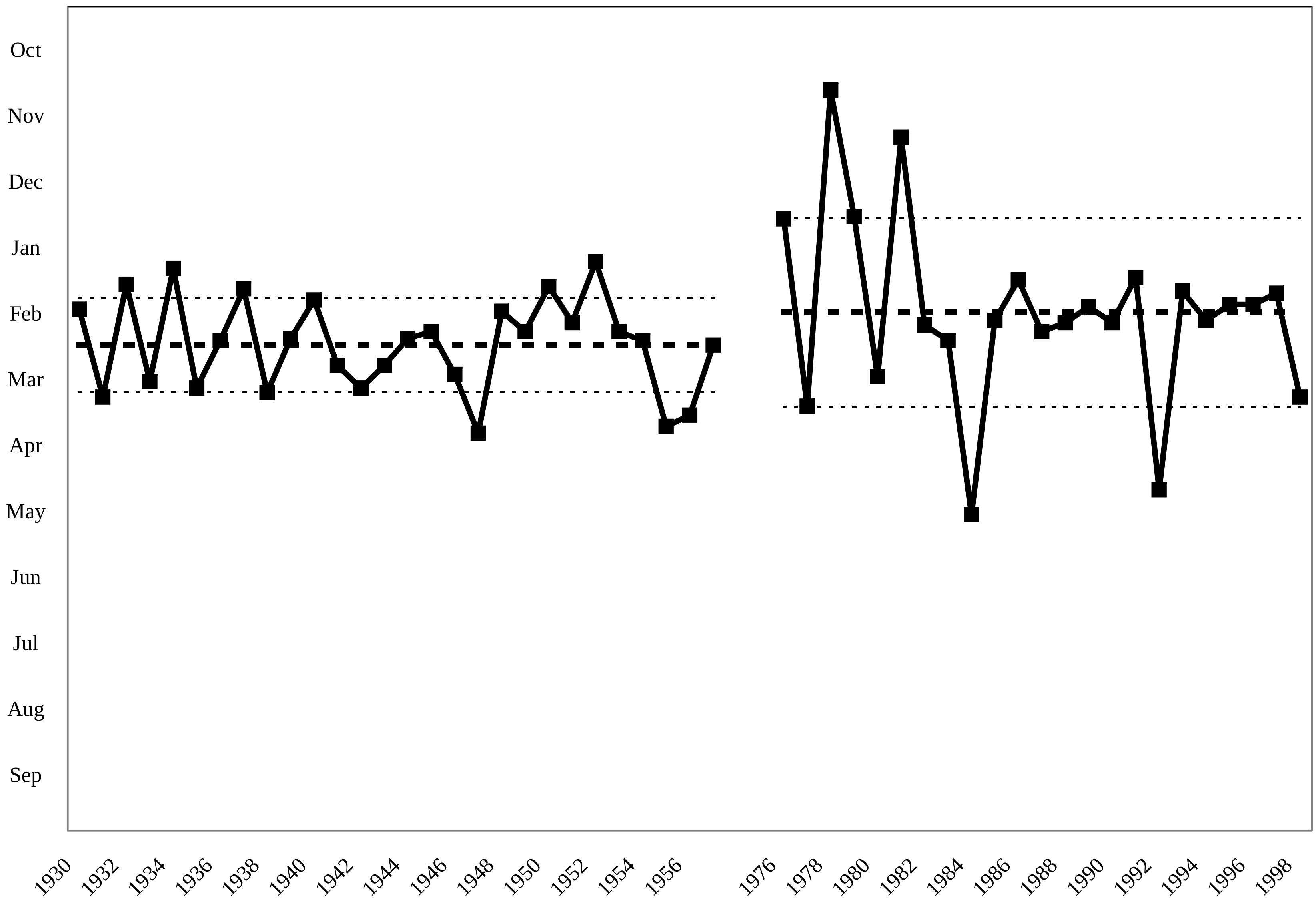


Figure 2-66. A comparison of the annual series of values for the timing of annual maximum 1-day Zambezi River flow at Muturara, before construction of Kariba Reservoir (1930-58) and after construction of Cahora Bassa Reservoir (1976-99).

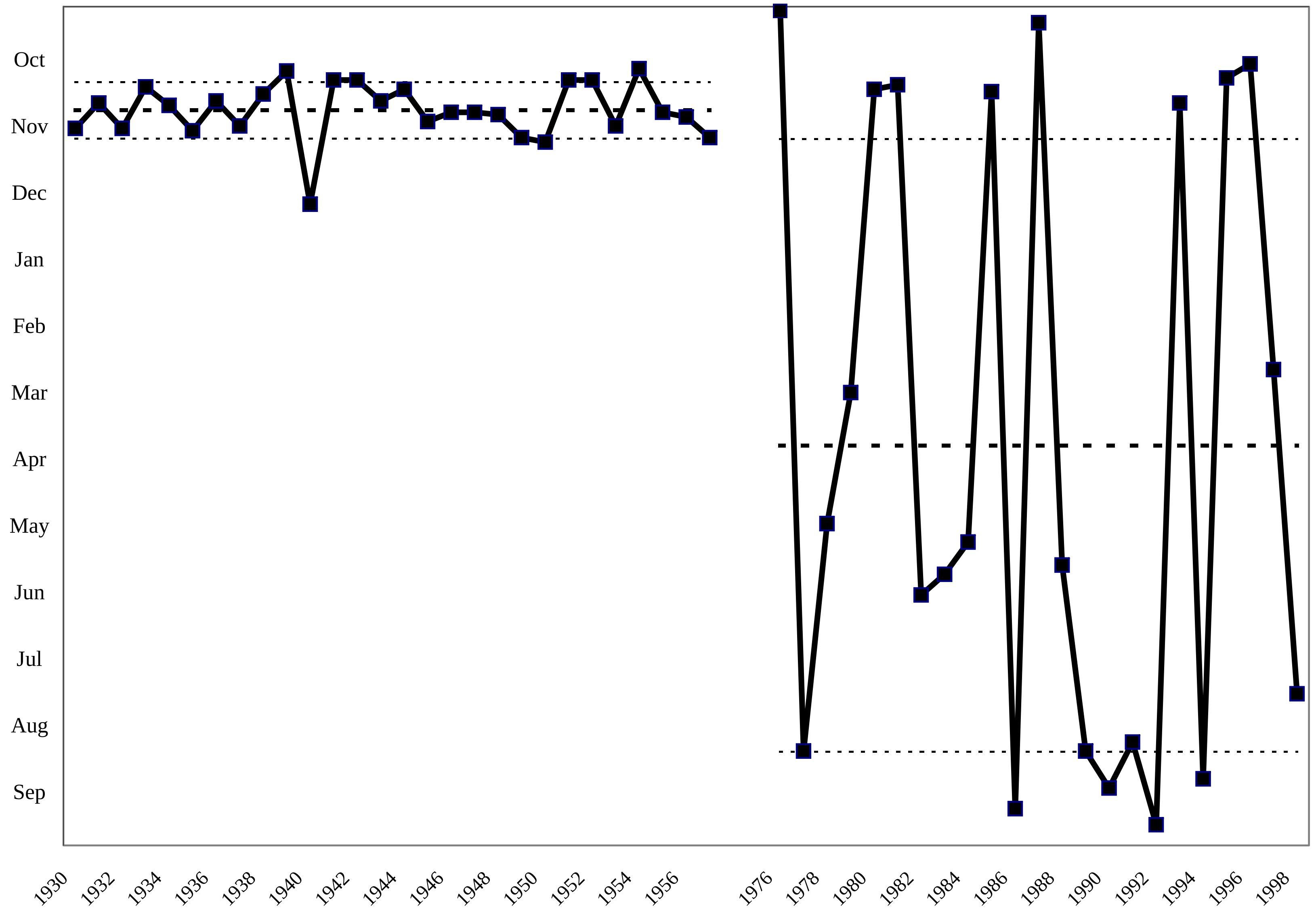


Figure 2-67. A comparison of the annual series of values for the timing of annual minimum 1-day Zambezi River flows at Muturara, before construction of Kariba Reservoir (1930-58) and after construction of Cahora Bassa Reservoir (1976-99).

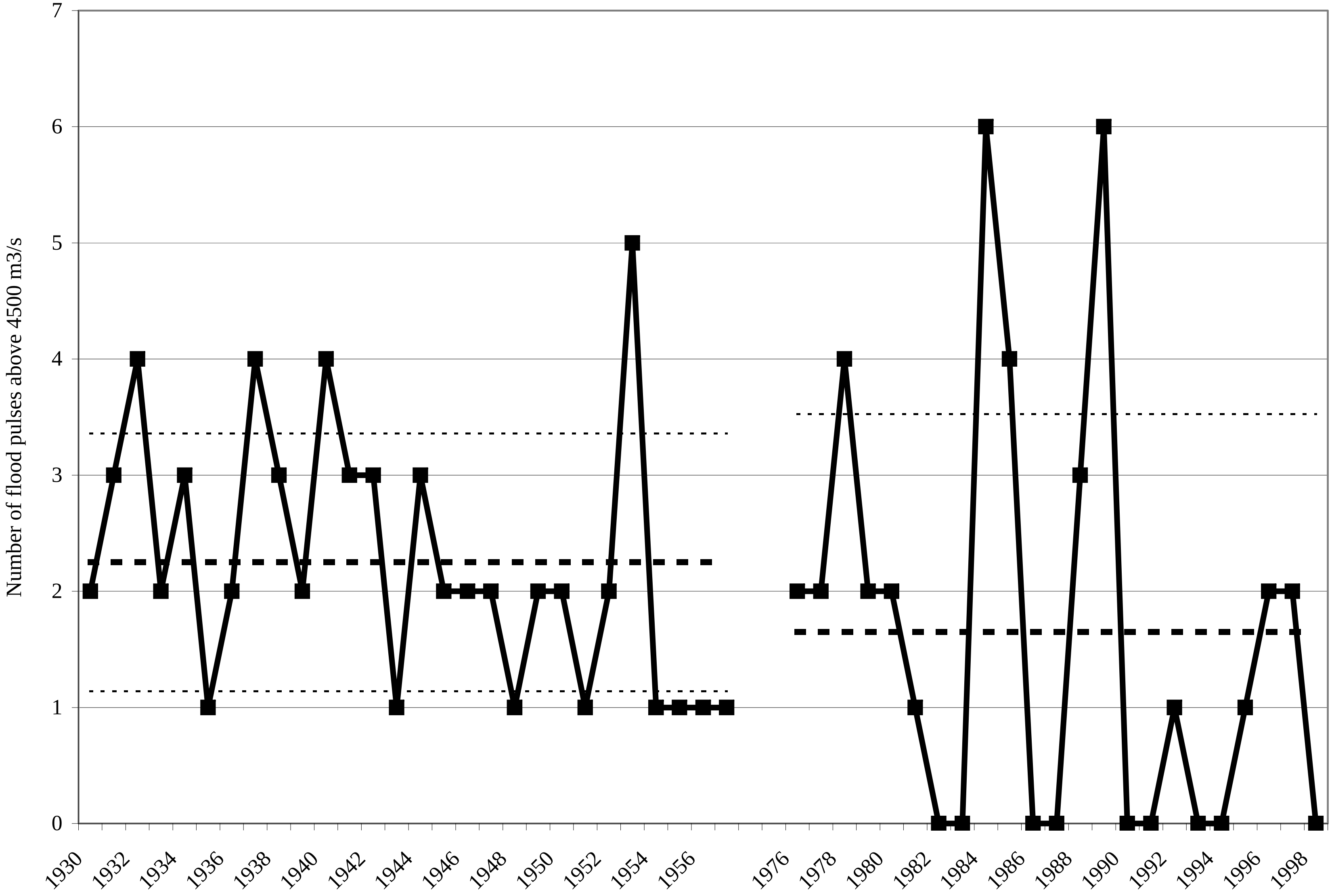


Figure 2-68. A comparison of annual series of annual number of flood pulses above 4500 m3/s for the Zambezi River at Muturara, before construction of Kariba Reservoir (1930-58) and after construction of Cahora Bassa Reservoir (1976-99).

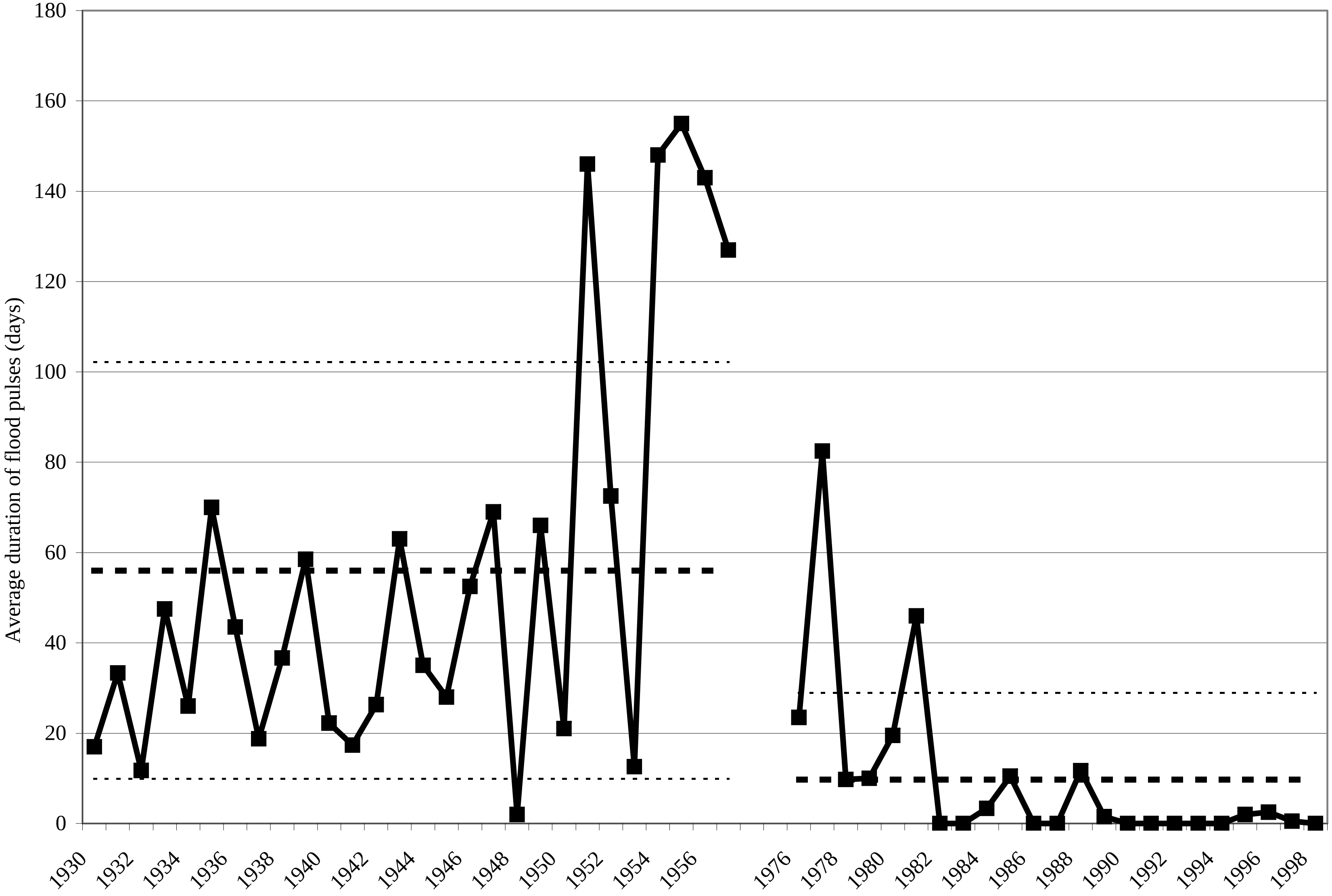


Figure 2-69. A comparison of annual series of annual average duration of high flood pulses above 4500 m3/s for the Zambezi River at Muturara, before construction of Kariba Reservoir (1930-58) and after construction of Cahora Bassa Reservoir (1976-99).

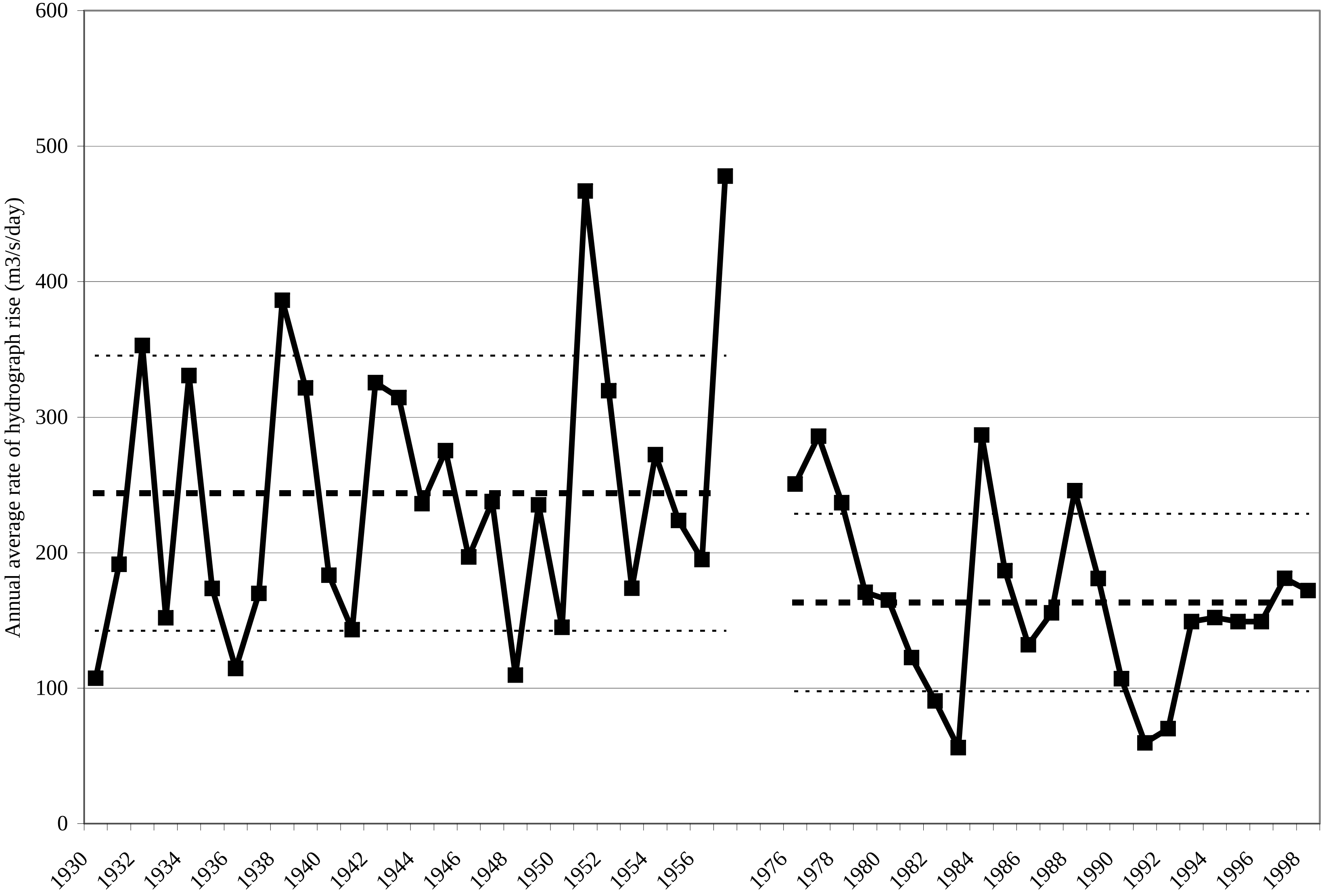


Figure 2-70. A comparison of the annual average rates of hydrograph rise for the Zambezi River at Muturara, before construction of Kariba Reservoir (1930-58) and after construction of Cahora Bassa Reservoir (1976-99).

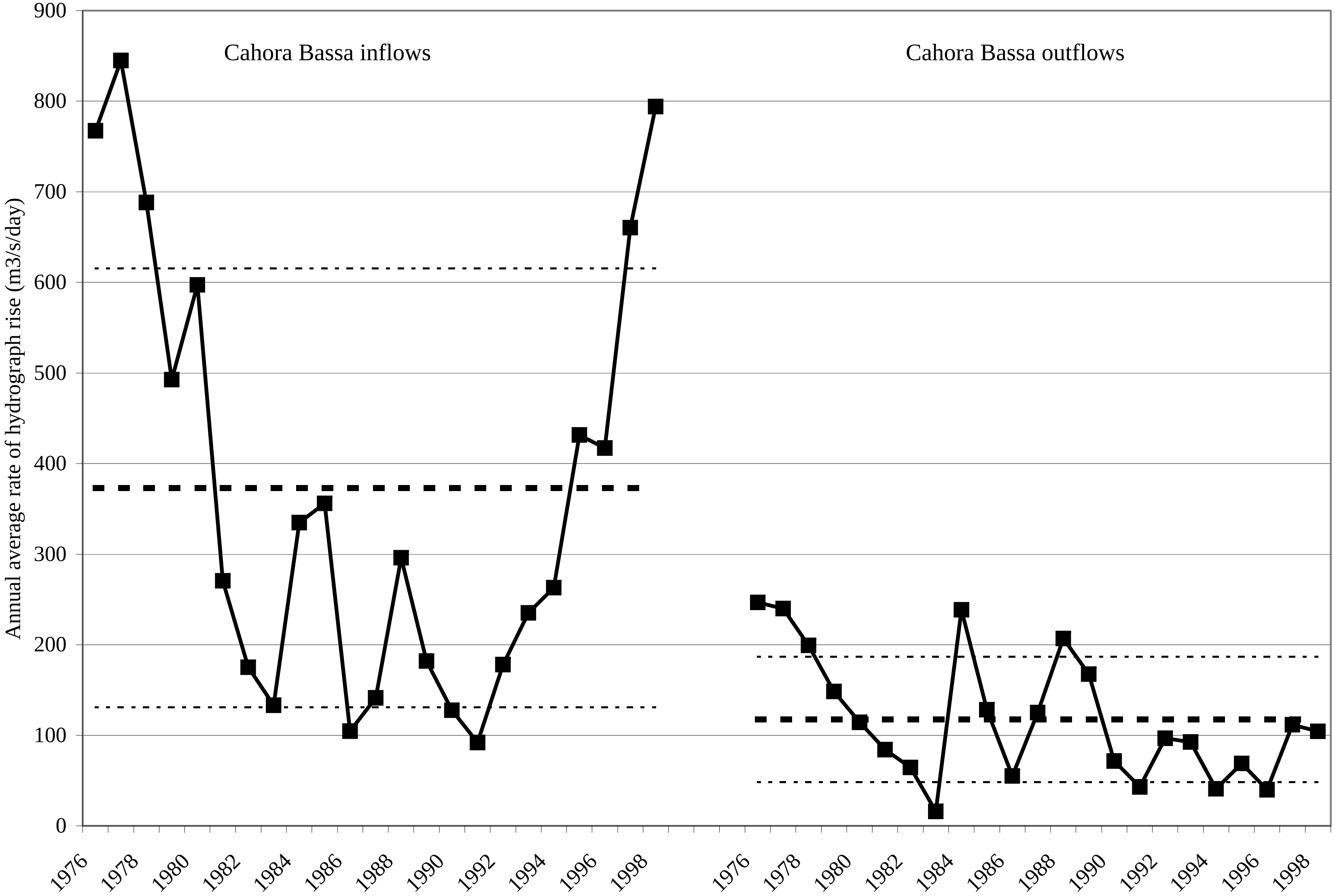


Figure 2-71. A comparison of the annual series of values for annual average rates of hydrograph rise for inflows and outflows at Cahora Bassa Reservoir.

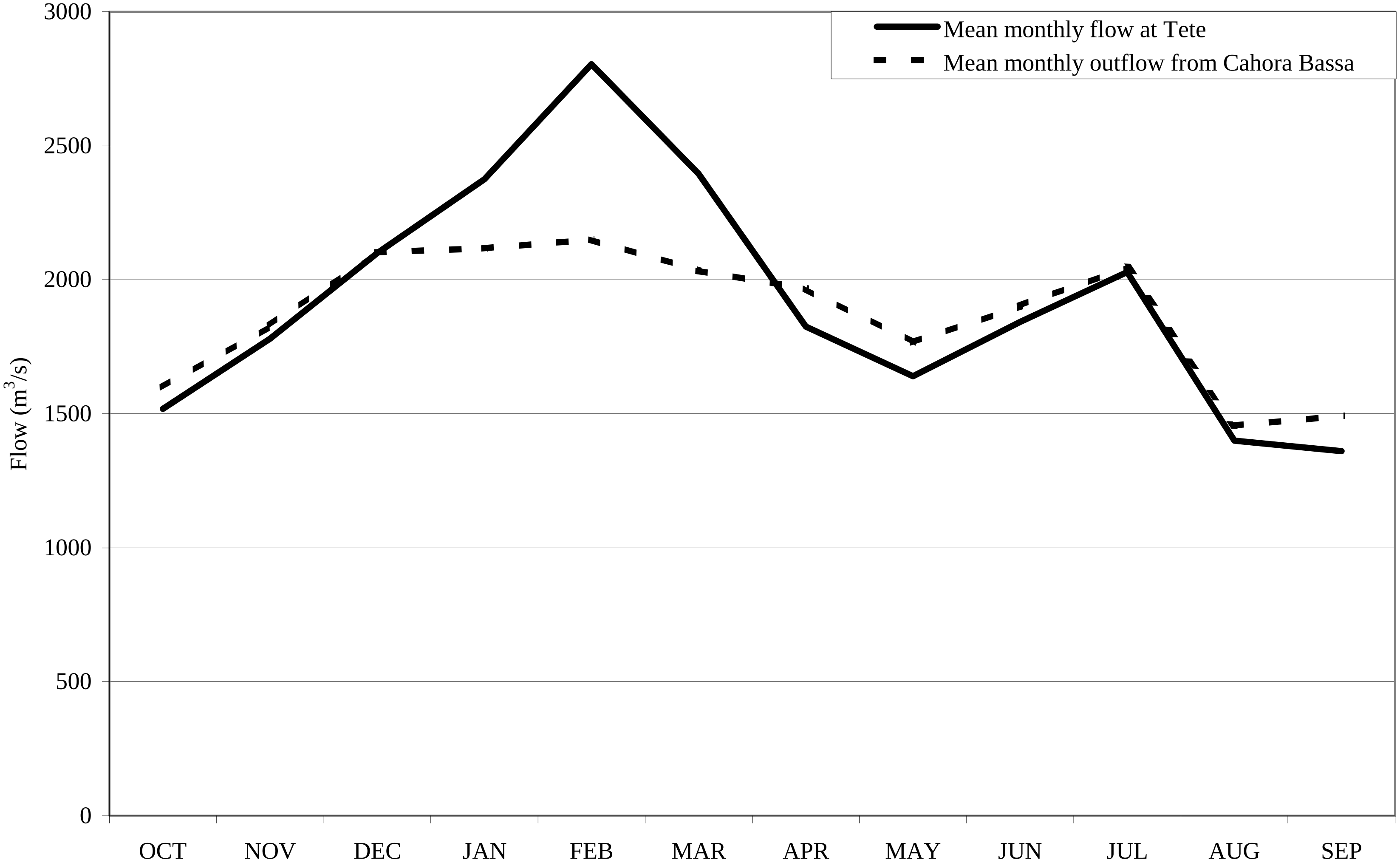


Figure 2-72. Hydrographs of mean monthly flow measured at Tete gauging station, and mean monthly discharge from Cahora Bassa Reservoir, 1974-2000.