Chapter 98

Zambezi River Basin

BY
ANTON J. SCHLEISS AND JOSÉ P. MATOS

ABSTRACT

With a basin covering 1.4 million km², the Zambezi is the fifth largest drainage basin in Africa. Bounded by the 9°S and 21°S parallels, it is home to approximately 30 million people and is officially shared by eight riparian countries. The river stretches over 2600 km across Southern Africa, from Angola in the west to Mozambique in the east, and plays a vital role in the region's cultural identity and economy.

Along the course of the Zambezi River and the main tributaries, a number of relevant features can be highlighted. These include some very large wetland areas and lakes, major dams, and UNESCO World Heritage Sites. A substantial hydropower potential of 13,000 MW, of which only about 5000 MW are currently exploited, coexists with ecologically rich areas, some among them listed as Ramsar Sites.

In recent years, the study of the basin's hydrology has gained relevance as it holds the key to answering concerns of future water availability, survival of riverine natural ecosystems, flood prevention, and the optimization of dam operations. In this chapter, a brief account of the basin is given. Emphasis is placed upon its main features, climate, runoff regime, hydrological studies conducted in the area and the main difficulties they face, and current concerns as well as future challenges related to water resources.

98.1 INTRODUCTION

The Zambezi River Basin is located in Southern Africa and spans from the 9°00'S to 20°30'S latitudes and 18°20'E to 36°25'E longitudes. Covering an area of 1.4 million km², the Zambezi is the fifth largest river basin in Africa. Holding the Continent's fourth place in length, its main stem stretches over 2600 km across Southern Africa, from Angola to Mozambique.

The basin is home to approximately 30 million people and its area is shared by eight riparian countries: Angola (18.5%), Botswana (1.4%), Malawi (8.0%), Mozambique (11.8%), Namibia (1.2%), United Republic of Tanzania (2.0%), Zambia (41.6%), and Zimbabwe (15.6%) (SADC/SARDC et al., 2012). In Fig. 98.1, its geographical location and main features are depicted.

With the tropical rainforests of the Congo to the north and the Kalahari Desert to the south, the basin encompasses humid, semiarid, and arid regions dominated by seasonal rainfall patterns associated with the Inter-Tropical Convergence Zone. Hydrological processes are largely influenced by evaporation. Flows are affected by the presence of large wetlands as well as major lakes and reservoirs.

The major waterbody in the basin is Lake Malawi, being the Kariba and Cahora Bassa artificial reservoirs second to it in terms of volume. Among the basin's wetlands, the Barotse Floodplain, the Kafue Flats, and the Marromeu Complex are worth highlighting.

The river and its main tributaries are vital to the riparian populations from cultural and economic standpoints. They are sources of hydropower, havens of ecological diversity and essential for the region's food security. The basin is rich in terms of natural resources. The main economic activities are fisheries, mining, agriculture, tourism, and manufacturing (The World Bank, 2010).

98.2 PHYSICAL CHARACTERIZATION

The Zambezi River Basin is commonly split into three main regions: the Upper Zambezi (not to be confounded with the homonymous subbasin), the Middle Zambezi, and the Lower Zambezi (Fig. 98.2). The basin hosts remarkable features, including lakes and reservoirs amongst the largest in the World and vast wetlands of high ecological value that cover thousands of square kilometers.

The Upper Zambezi is marked by steep slopes in the northern area and, going south, large wetlands such as the Barotse Floodplain. A distinctive feature of the region is the Chobe-Zambezi confluence, where water can flow both ways. The Middle Zambezi spans between the World-renowned Victoria Falls and the Cahora Bassa reservoir. Two major tributaries of the Zambezi (the Kafue and Luangwa rivers) join it in this region. Kariba Dam and the Kafue hydropower system (Itezhi-Tezhi and Kafue Gorge Dams), as well as the Kafue Flats, are its most noticeable features. The Lower Zambezi is dominated by Lake Malawi and the Cahora Bassa dam and reservoir. In the lowlands, approaching the outlet to Indian Ocean, the Shire Wetlands and the Delta, including the Marromeu Complex, can be found.

Prior to the formation of the modern Zambezi, the Okavango, Upper Zambezi, Kafue, and Luangwa rivers drained into the paleo-Lake Makgadikgadi, approximately located in current-day Kalahari Desert. To the east, the Shire River flowed into the Indian Ocean, having the Lower Zambezi as its tributary. While the Malawi Lake formed as part of the East African Rift Valley (Delvaux, 1995), the Lower Zambezi progressively grew to the west through erosion and, in a process also influenced by tectonism, eventually captured the Luangwa, Kafue, Upper Zambezi, and Chobe rivers, reducing inflows and finally leading to the disappearance of paleo-Lake Makgadikgadi (Moore and Larkin, 2001; Podgorski et al., 2013).

98.3 MAIN FEATURES

98.3.1 Tributaries

The Zambezi is also divided into 13 official subbasins (Fig. 98.2). Although the river gains its strength already at the Upper Zambezi in Angola and Zambia, some tributaries are worth looking into due to their specific hydro-logical behavior.

The Chobe (also named Cuando, Kwando, or Lyanti) is a somewhat par-ticular subbasin. Despite its large area, its influence on the average yearly runoff of the Zambezi is very small, being the flow at the confluence highly dependent on water levels (Matondo and Mortensen, 1998; Euroconsult Mott MacDonald, 2008; The World Bank, 2010). This happens due to the low slope of the main stem of the Chobe River, which makes most of its water disperse within the Linyanti Swamp. The swamp acts as an inland delta only linked to the Zambezi through a narrow strip with another sizeable wetland, the Chobe Swamps, at the confluence.

The Kafue, in Zambia, is among the basin's most studied regions in terms of hydrology and water resources. This owes partly to its large hydropower scheme, comprised of the Itezhi-Tezhi and Kafue Gorge dams, and the

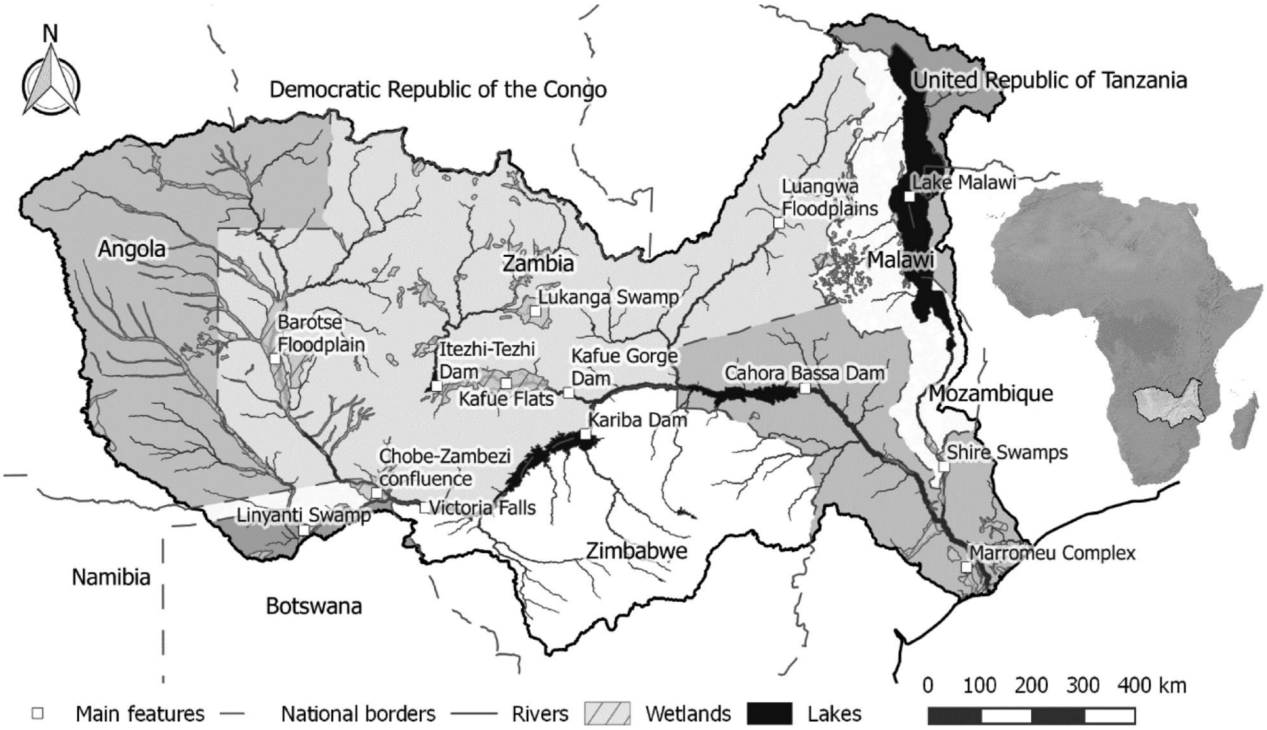


Figure 98.1 Geographical location and some of the main features of the Zambezi River Basin.

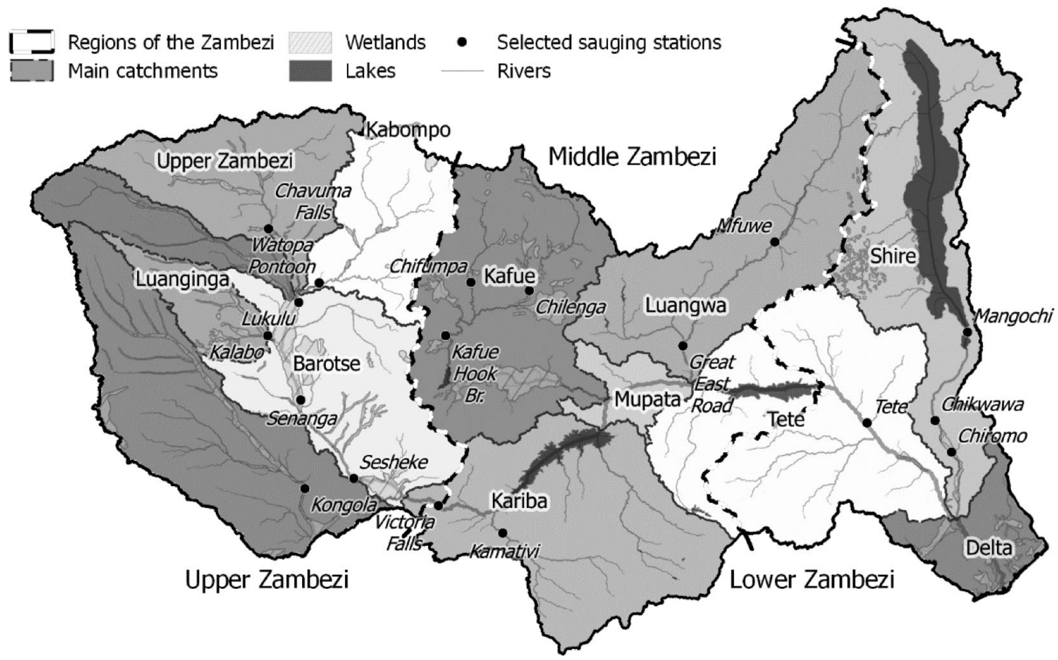


Figure 98.2 Regions of the Zambezi River Basin, official subbasins, and selected gauging stations.

Kafue Flats ecosystem. The hydrological processes in the Kafue Basin are particularly complex with the influence of massive floodplains (the Lukanga Swamp and the Kafue Flats) and the aforementioned dams. The Kafue contributes to approximately 10% of the Zambezi's runoff.

The Luangwa River flows into the Zambezi just upstream of the Cahora Bassa reservoir. Its subbasin presents a relevant hydrologic modeling challenge as it is mostly ungauged, has a small storage volume, and displays fast response times to rainfall events (Meier, 2012). The fast hydrological response often leads to significant high flood peaks that emphasize the importance of the subbasin even beyond its mean contribution of 17% to the Zambezi's runoff.

The Shire River's subbasin is marked by its most prominent feature: Lake Malawi. Receiving a high average annual rainfall, the Shire River accounts for 19% of the basin's runoff. Considerable water losses take place through evaporation from the lake, which averages nearly 290 m^3/s (The World Bank, 2010). Long stretches of wetland areas—the Elephant and Ndinde marshes—that characterize the lower reaches of the Shire down to the confluence with the Zambezi River have the additional effects of decreasing runoff volumes and peak flows.

98.3.2 Main Waterbodies and Hydropower Schemes

The Barotse Floodplain is the largest wetland of the Upper Zambezi. Having a maximum width of over 30 km, the wetland covers an area in excess of 7500 km^2. As a large share of the west portion of the basin, it is underlain by Kalahari sands, which form an enormous groundwater reservoir (Winsemius et al., 2006; Moore et al., 2008; Meier, 2012). The floodplain substantially affects the shape of the annual streamflow hydrographs.

The Chobe-Zambezi confluence wetland does not exert an influence on the Upper Zambezi's hydrographs comparable to that of the Barotse Floodplain. It is interesting due to its complex hydraulics as, depending on water levels, flow from the Chobe River can contribute to the Zambezi, or conversely, a portion of the Zambezi can flow into the Chobe. Yearly average contributions are from the Zambezi into the Chobe and have been assessed to be between 0 and 40 m^3/s (Matondo and Mortensen, 1998; Euroconsult Mott MacDonald, 2008; The World Bank, 2010). Due to this behavior, a reduction of the Zambezi's peak discharges can be observed in the area.

Hundreds of dams exist on the Zambezi River Basin. Among these, the vast majority are small-sized and located in Zimbabwe. Some of the larger infrastructures are worthy of particular mention.

The Kariba dam was completed in 1959. The mean annual runoff in the section of the dam is of about 1300 m^3/s (Meier, 2012). It has a considerable installed capacity of 1450 MW, which equates to a discharge of 1800 m^3/s. Its spillway capacity is close to 9500 m^3/s. With a storage capacity of 180 km^3 (of which about 65 km^3 are active storage) and having a surface area of approximately 5500 km^2, Lake Kariba is among the most important artificial reservoirs in the World, being the largest by volume according to the International Commission on Large Dams. It has large impacts on downstream flows, greatly reducing seasonal variability (Beilfuss and Dos Santos, 2001) and having a key role in flood mitigation in the basin.

The Kafue hydropower scheme, comprised by the Itezhi-Tezhi and Kafue Gorge dams, is unusual. The Kafue Gorge dam, downstream, takes advantage of a large hydraulic head but lacks substantial storage capacity for flow regulation. This storage is provided by the Itezhi-Tezhi reservoir's 6 km^3, 200 km upstream. The Itezhi-Tezhi dam was completed in 1978 and was designed to allow managed releases in order to sustain inflows to Kafue Gorge. The Kafue Gorge reservoir was built in 1972 and its power plant has an installed capacity of 900 MW.

Amidst both dams, the Kafue Flats are affected by the operation of the system. The area is an extensive wetland of high ecological value, 250 km long, and up to 90 km wide, which spreads from Itezhi-Tezhi down to the Kafue Gorge reservoir and covers an area of 6500 km^2. The Kafue River meanders through this extremely flat area with an average slope of 3 cm/km, hence the travel time of the water through the Flats is of about 2 months (Meier, 2012).

The Cahora Bassa dam was completed in 1974 with the primary objective of exporting power to South Africa. It can presently produce up to 2075 MW of electricity, which corresponds to a flow of roughly 2250 m^3/s—very close to the average discharge in its section. The spillway's capacity is of about 14,000 m^3/s. The reservoir lays at the upstream edge of the Lower Zambezi. It has a volume of 60 km^3, with 52 km^3 live storage capacity. Its role in the management of floods is very important, although limited as the dam drains an area of over 1,000,000 km^2.

Lake Malawi, also known as Nyasa or Niassa, is by far the largest waterbody in the basin. Located in the valley of the East African Rift, it has a surface area of 28,000 km^2, a volume of 8000 km^3, and a length of 550 km (Jury and Gwazantini, 2002). Levels are controlled by barrages some kilometers downstream from the outlet, along the Shire River. Hydrologically the lake is remarkable for its sheer size and the unusually high ratio between its surface area and that of the contributing catchment, which is close to one-third.

The Delta is yet another note-worthy reference of the Zambezi. Essential to the Mozambican economy, it is a vast wetland covering a triangular area that stretches 120 km inland and covers a 200 km swath of coastline. Part of it is the Marromeu Complex, an 11,000 km^2 area of economic, social, and ecological relevance. The impacts of the large dams on the Delta have for long been a motive of study and debate (Beilfuss, 2001; Beilfuss and Brown, 2006; Ronco, 2008).

Besides the three mentioned hydropower schemes, other major investments have been proposed within the basin and are being actively studied; among these stand the Mphanda Nkuwa run-of-river scheme (1500 MW), about 60 km downstream Cahora Bassa (COBA et al., 2011), the Batoka Gorge Dam, just upstream of Kariba (1600 MW), the Kafue Gorge Lower Dam (downstream of Kafue Gorge, 750 MW), the Kariba extension (660 MW) (The World Bank, 2010), and the Cahora Bassa North Bank extension (1250 MW) (NIPPON KOEI UK, 2012).

98.4 CLIMATE

Three distinct seasons can be identified in the Zambezi. A cold dry season with temperatures from 15 to 27°C lasts from May to September. A dry hot season where temperatures reach up to 32°C settles from October to November. From December to April a hot rainy season, characterized by high temperature and high humidity, is observed (Meier, 2012).

The average yearly rainfall over the basin displays a high spatial variability and amounts to about 1000 mm/yr (Fig. 98.3), the basin is prone to higher rainfall rates in the northern regions. In some areas, such as the Upper Zambezi and Lake Malawi, yearly rainfall can add up to as much as 1400 mm/yr, while in the southern part of Zimbabwe it can be as little as 500 mm/yr (The World Bank, 2010). Consequence of a largely semiarid climate, potential evapotranspiration has a key role in the hydrological processes taking place in the basin has been estimated to be between 1560 (Beilfuss, 2012) and 2000 mm/yr (Meier, 2012; Liechti, 2013).

Climate variations are particularly strong in the basin, although difficult to assess. An extensive analysis of Southern African climate revealed variability patterns which translate into mean runoff variations. Associated with these patterns are main periodical components of 80 and 18 years (Liechti, 2013).

According to the Intergovernmental Panel on Climate Change (IPCC) (2001), climate change over the next century will have a very substantial impact on Africa and the Zambezi River Basin in particular, be it in terms of temperature, rainfall, evaporation, or runoff. In fact, based on data by Arnell (1999), the same publication infers that the Zambezi has the worst scenario of decreased precipitation (~15%), increased potential evaporative losses (~15–25%), and diminished runoff (~30–40%).

Based on IPCC findings, that result from the application of global circulation models, and constrained a lack of regionalized estimates, Beilfuss (2012) provides an encompassing overview of how climate change is expected to affect the basin in the future.

98.5 RUNOFF REGIME

Hydrologic processes within the basin are largely conditioned by evaporation. In spite of the 1000 mm average annual rainfall, mean discharges to the Indian Ocean amount to less than 10% of the available water, with estimates ranging from 3250 to 3960 m^3/s (Matondo and Mortensen, 1998; Beilfuss and Brown, 2006; Euroconsult Mott MacDonald, 2008; Tilmant et al., 2010).

Most of the runoff in the Zambezi River Basin is generated in the north, namely in the Upper Zambezi, Kafue, Luangwa, and Shire subbasins (Fig. 98.4). Flood periods following the rainy season vary slightly across the basin, but are generally observed from January to April. The runoff is substantially delayed by wetlands and reservoirs, the latter constituting the largest source of human water consumption by far, estimated from 13 to 17 km^3/yr (Euroconsult Mott MacDonald, 2007; Beck, 2010). Hydrological responses in the basin are heterogeneous as a consequence of rainfall distribution, geology, and land cover, being also substantial variation associated with the seasonal vegetation changes characteristic of arid and semiarid climates.

The runoff is affected by long climate cycles. Referring to the period from 1924 to 2004, Mazvimavi and Wolski (2006) estimated the period of the main runoff cycle to be of 40 years. Although hard to assess quantitatively, the effect of these cycles appears to be substantial. Anecdotally, in the first years of the twentieth century Lake Malawi's level fell below the outlet elevation for a period of several years and, more recently, from 1970 to 2000, the mean flow from the Upper Zambezi region, measured at Victoria Falls, has steadily decreased from 1500 m^3/s to 700 m^3/s, having registered an increase since.

In Fig. 98.5, the hydrographs registered at key gauging stations throughout the basin are synthesized. They are displayed from October to September according to the region's hydrological year. Lukulu drains the Upper Zambezi, Kabompo, and Lungue Bungo subbasins. In light of the area upstream, discharges at Kongola are strikingly low and stable throughout the year, both reflecting the effects of wetland areas in the Chobe subbasin and justifying the small average contribution of the tributary to the Zambezi's runoff. Victoria Falls, downstream of Lukulu, the Barotse Floodplain, and the Chobe Swamps evidences a peak later in the year. Although long series characterizing the tributaries from the south bank of the Zambezi are difficult to obtain, some insight into the hydrological regime in the area can be gained from inspecting records at Kamativi. Despite a moderate yearly contribution to runoff, tribu-taries from the south are very relevant for the management of the Kariba reservoir early in the rainy season. Kafue Hook Bridge drains a substantial part of the Kafue subbasin. Downstream contributions to the Zambezi are, however, substantially altered by the Kafue hydropower system's operation and the Kafue Flats. The Luangwa subbasin evidences a fast hydrological response and is prone to relatively high peak discharges.

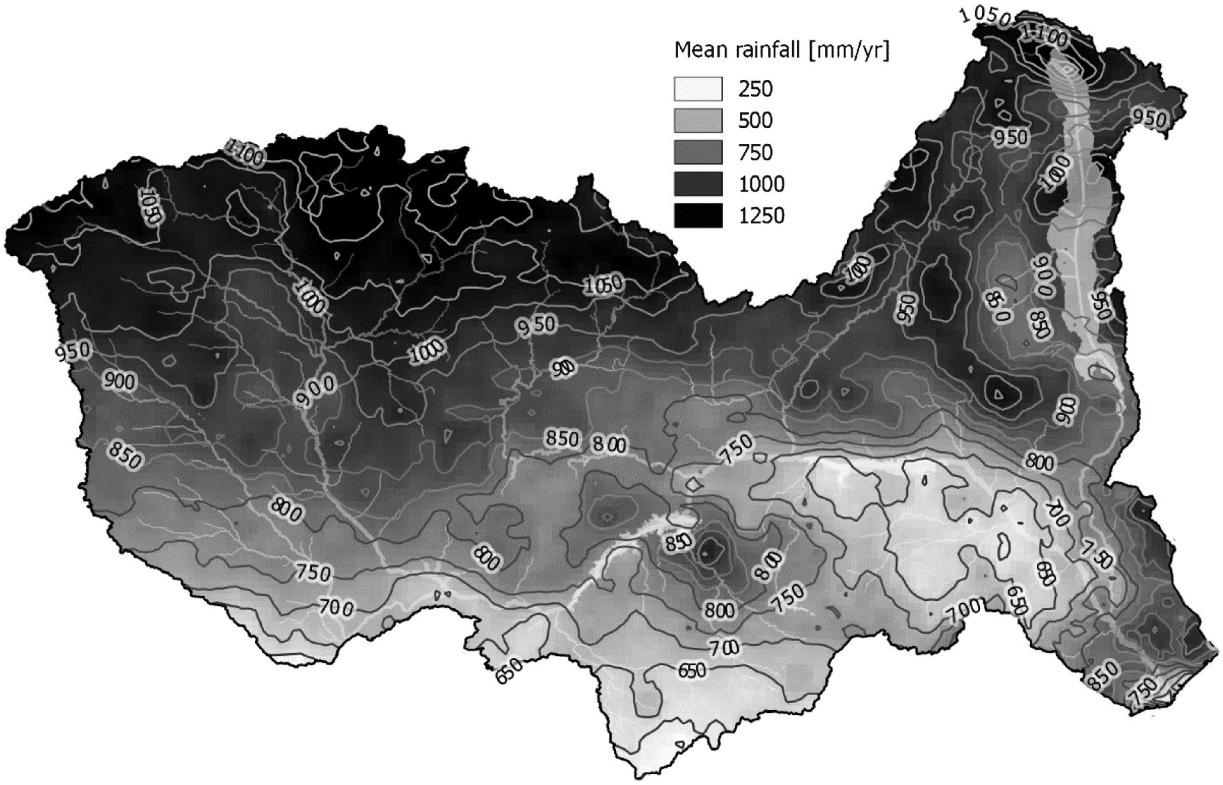
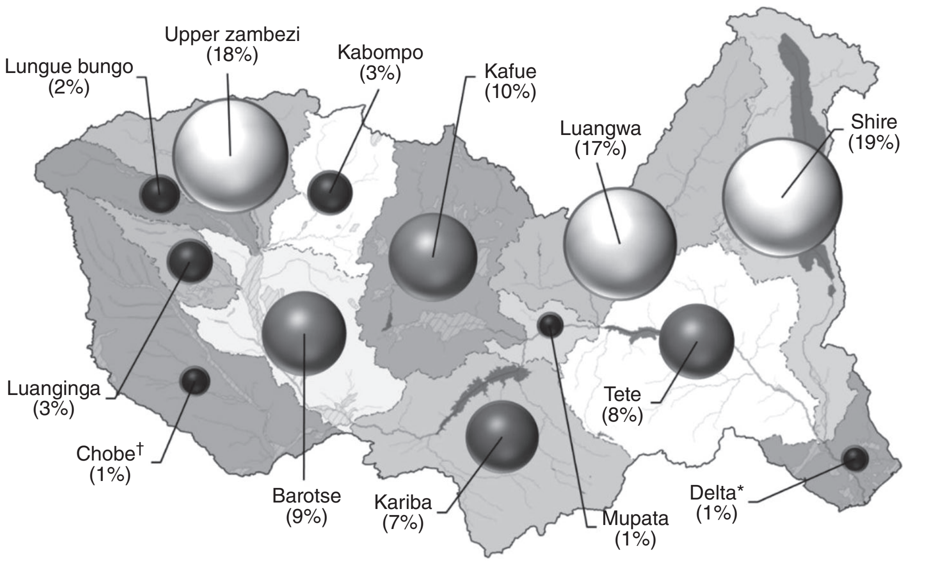


Figure 98.3 Mean annual rainfall estimated from 2001 to 2009 (derived using the NOAA Rainfall Estimate 2, RFE2, satellite product). Contour lines represented according to 50 mm/yr intervals.



* The delineation of the contributing basin to the delta is not agreed upon in the literature due to the complex hydraulics of the region. The contribution to the runoff given here might be an underestimation according to the delineation of the Delta adopted by the source.
† The Chobe subbasin serves both as inlet and outlet of the Zambezi River depending on water levels. Despite a small mean contribution, it seems to have some impact on flood peaks.

Figure 98.4 Contribution of the main subbasins to the mean annual runoff of the Zambezi River. [*Source: Adapted from Euroconsult Mott MacDonald (2008)*]

In Table 98.1, data on the recorded maximum and minimum discharges at several locations within the basin is given (see Fig. 98.2 for reference). Mean discharges were not included due to the difficult interpretation that is owed to the strong climate variations characteristic of the region.

98.6 PAST HYDROLOGICAL STUDIES

Given its size, importance to local populations, and potential—taken in a wide context, from economical to ecological—much remains to be studied in terms of hydrology within the Zambezi River Basin. The conflicts that underpinned the second half of the twentieth century in some countries of the region took their toll on investment in water resources. Recently, the resolution of the armed conflicts in Angola and Mozambique along with an overall more stable and open political phase has spurred renewed international interest in the area.

With goals as distinct as broad future scenario assessments or real-time flood forecasts, past hydrological studies have ranged from simple lumped to complex distributed approaches adopting daily to monthly time steps. Here, emphasis is placed on works with a strong hydrological component and/or whose overview of the Zambezi provides a particularly valuable reference for

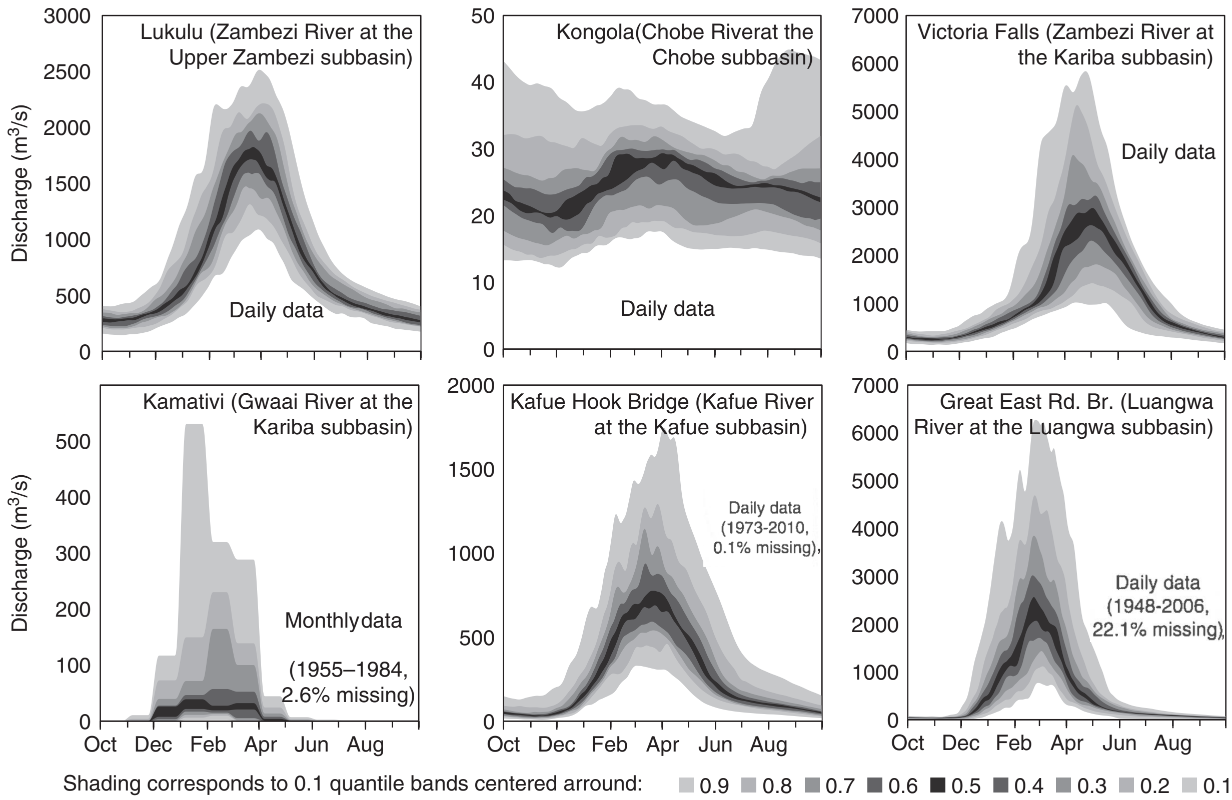


Figure 98.5 Synthesis representation of the hydrographs on record at key points of the basin. Should be interpreted in light of the climate variations during the recorded period. The Kamativi series is downstream of a relatively small area compared to the others and serves as an illustration of tributaries on the south bank of the Zambezi. See Fig. 98.2 for the locations.

hydrological works. Adding to those, there are numerous other sources that focus on environmental issues and are not emphasized in this chapter.

The development of specialized hydrological models has been restricted and mainly undertaken in the scope M.Sc. and Ph.D. researches. Among the latter, Meier (2012) worked on three watersheds: the Upper Zambezi, the Kafue, and the Luangwa, having used remotely sensed soil moisture data and developing a real-time forecasting application based on a conceptual model updated by an Ensemble Kalman Filter. Michailovsky (2013) addressed the issue of insufficient discharge data by resorting to satellite radar altimetry in order to derive discharge estimates at key ungauged locations. With the goal of producing operational reservoir inflows at Kariba and Itezhi-Tezhi, she applied the Soil and Water Assessment Tool (SWAT) model (Neitsch et al., 2011) coupling it to a routing scheme and a custom floodplain representation. Updates were made using an Extended Kalman Filter.

In the works of Liechti (2013) and Matos (2014), the multiple-objective calibration of a daily SWAT model of the basin was endeavored (Liechti et al., 2014). Liechti later used results to evaluate impacts of future scenarios on hydropower production, while Matos invested in the treatment of additional historical data for extended model calibration (Matos et al., 2014) and the development of flow forecasting techniques. Also recently, Kling et al. (2014) calibrated a performing monthly model of the basin in order to assess future scenarios.

More practical efforts have been addressed integrated water resources management issues such as optimizing water allocation, analyzing investment opportunities, future scenarios, or dam operation synchronization. The issue of optimal water allocation has also been addressed (Beck, 2010; Tilmant et al., 2010; King and Brown, 2014). In addition to these, several works dealt with specific areas of the basin. Worthy of reference are the several studies conducted for the Kafue subbasin (DHV, 1980, 2004; Meier, 2012) and the lower Zambezi (Beilfuss, 2001; Govender and Everson, 2005; Beilfuss and Brown, 2006; Ronco, 2008). The effects on wetlands and lakes, as well as their impacts in hydrology and water quality have also been a focus of study. Examples are the works by Zurbrügg (2012), Pettersson (2002), or Kunz (2011).

Of particular interest are the *Multisector investment opportunity analysis* (The World Bank, 2010), *The dam synchronization and flood releases in the Zambezi River Basin project* (SWRSD Zambezi Basin Joint Venture, 2011), and the *Integrated water resources management strategy and implementation plan for the Zambezi River Basin* (Euroconsult Mott MacDonald, 2008) which, albeit being based on simple approaches, provide comprehensive depictions of the present and future situations in the basin.

The expansion of the hydropower sector, the establishment of environmental flows programs, and the development of the mining industry have motivated an acknowledgeable share of the recent water resources studies.

Overall, one of the major concerns among authors is model calibration and validation; a problem mostly bound to short and unevenly spatially distributed discharge time series. In the majority of the models, particularly those developed with research purposes, remote sensing data sources are used extensively. Also striking is the focus of most works, which seems to gravitate toward the large impoundments, major wetlands, and the regions where more data are available, virtually neglecting some other hydrologically relevant areas such as the Luangwa subbasin.

98.7 HYDROLOGICAL DATA

The access to hydrological data throughout the basin is generally troublesome. The relatively low investment that has been made on measurement infrastructure—a legacy of the basin's history—and the lack of a consolidated supranational interlocutor, only recently addressed by the establishment of the permanent office of the Zambezi Watercourse Commission (ZAMCOM), makes the access to existing data a time consuming and intricate process.

The coverage of rain gauge stations is limited and most recent studies have resorted to satellite rainfall estimates as an alternative. Different satellite products vary widely over the region, with the Tropical Rainfall Measurement Mission 3B42 version 7, the NOAA Rainfall Estimate 2.0 and the Global Satellite Mapping of Precipitation (GSMaP) Moving Vector with Kalman filter method (MVK) version 5.222 being acknowledged as the most accurate over the Zambezi (Liechti, 2013; Matos, 2014).

Discharge data are collected by numerous agencies and operators throughout the basin. The Global Runoff Data Centre, not comprehensive in the Zambezi region but still containing an appreciable record of historical discharges, may constitute the most convenient data provider for research

Table 98.1 Maximum and Minimum Discharges on Record at Selected Gauging Stations. Should Be Interpreted in Light of the Climate Variations Observable in the Recorded Period

Name	River	Subbasin	Maximum discharge on record (m^3/s)	Minimum discharge on record (m^3/s)	Period	Missing(%)
Chavuma Falls	Zambezi	Upper Zambezi	7416	24	1959–2008	4.7
Watopa Pontoon	Kabompo	Kabompo	1320	14	1958–2008	3.6
Kalabo	Luanginga	Luanginga	321	5	1958–2005	6.9
Lukulu	Zambezi	Barotse	2726	127	1950–2004	12.4
Senanga	Zambezi	Barotse	3062	253	1947–2004	8.4
Sesheke	Zambezi	Barotse	8135	127	1942–2006	16.2
Kongola	Chobe	Chobe	50	11	1982–2003	0.0
Victoria Falls	Zambezi	Kariba	8204	92	1958–2010	0.0
Kamativi*	Gwaai	Kariba	575	0	1955–1984	–
Chilenga	Kafue	Kafue	1000	7	1973–2010	22.4
Chifumpa	Lunga	Kafue	1412	11	1954–2010	13.6
Kafue Hook Br.	Kafue	Kafue	2629	4	1973–2010	0.0
Mfuwe	Luangwa	Luangwa	1140	–	1978–2006	53.0
Great East Road	Luangwa	Luangwa	11677	–	1948–2006	21.9
Tete†	Zambezi	Tete	16802	221	1960–1990	0.4
Mangochi‡	Shire	Shire	1051	119	1976–2005	11.6
Chikwawa‡	Shire	Shire	1413	115	1980–2009	12.1
Chiromo‡	Shire	Shire	2142	130	1970–2009	6.0

* Based on monthly records.
† Series influenced by the Kariba dam. Series affected substantially by the Cahora Bassa dam (from 1969) and, to lesser extent, by the Itezhi-Tezhi dam (from 1974).
‡ Affected by the controlled levels of Lake Malawi.

purposes. A more recent endeavor, the African Dams Project's Tethys Zambezi hydrology online database, holds a more comprehensive set of records collected from several institutions throughout the basin, but effective protocols for direct data sharing are still to be put in place.

Finally, one of the flagship projects of ZAMCOM is the revival of the Zambezi Water Information System (ZAMWIS), a centralized water resources database for the basin. Although presently in its early stages, once completed ZAMWIS will certainly constitute a valuable repository and source of information on the Zambezi.

98.8 CURRENT CONCERNS AND FUTURE CHALLENGES

The most pressing issues that need addressing in the basin are the management of floods, which carry heavy social and economic costs in the region, the heterogeneity and uneven expansion of water use by the riparian countries—a potential source of future conflicts—and the growing demands on water resources which are increasing the strain imposed on ecologically valuable areas. For the Lower Zambezi in particular, navigability has also been a major concern.

Growing investments on operational flow forecasting, coordinated operation of major hydropower facilities, the definition and development of ecological flows' programs, and the study of transboundary water transfers reflect the highlighted issues.

While an overall basin plan that will guide future water resource development for the benefit of all while protecting the natural systems is needed, it is ZAMCOM's mission to promote a reasonable and equitable development for the Zambezi. As it gains strength, the commission is regarded as a key supporter of efforts that address that need.

In the future it is expected that dam operations will evolve toward increasingly flexible, cooperative, and informed models by virtue of newly developed schemes, powerhouse extensions, higher demands, and the emergence of more competitive power markets in the region. Related to hydropower, a relevant effort is being made by several organizations in order to study and establish environmental flows programs.

In parallel, better management and cooperative development of the basin's water resources could significantly increase agricultural yields and the relatively still moderate water consumption offers many development opportunities for irrigated agriculture.

Technically, hydrological modeling of the basin presents specific difficulties. Perhaps the most relevant are the basin's size and heterogeneity. If, on the one hand, such a large basin has a "smooth" hydrological response where the effects of particular features are averaged out, on the other hand, size and heterogeneity are in the way of a detailed understanding of the hydrological processes taking place. The same attributes put into question the validity of lumped approaches and pose acknowledgeable computational difficulties to distributed models.

Complex hydraulics in some of the basin's wetlands and the predominant semiarid climate should not be neglected as they are related to high transmission losses, higher spatial rainfall variability, and seasonal differences in vegetation cover. The climate variations affecting rainfall and runoff can lead to questions related to model calibration and validation, particularly so in light of the recent history of hydrometric and meteorological measurements in many parts of the basin.

How wetlands that remain largely untouched and are havens for wildlife, as well as human occupied riparian areas can be safeguarded in a future of increasing water demands and an expanding hydropower sector remains an open question, particularly so in the face of the strong climate changes that are expected for the Zambezi River Basin. Although such a question should be posed for every major river basin, it is particularly important for the Zambezi due to the natural resources it still possesses and the scale of changes to come. Added investment in water resources management is needed on the Zambezi, arguably now more than ever, and sound hydrologic science is and will continue to be a stepping stone in order to adequately seize opportunities and meet future challenges.

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