16

The Zambezi: Origins and Legacies of Earth's Oldest River System

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16.1 Introduction

The Zambezi rises with considerable modesty in north-west Zambia from a small spring on the gentle upland of the Southern Equatorial Divide (SED) – the watershed that separates the river from north-west-flowing tributaries of the Congo (Figure 16.1). For some 30 km, the Zambezi headwaters flow to the north, towards the Congo, but then the course swings to the south-west, around a low ridge of Karoo sandstone known as Kalene Hill. This direction is maintained for a further 200 km into Angola before the river finally turns south-eastwards to the Indian Ocean. It is with such indecision that southern Africa's largest river commences its course.

The Zambezi can be divided into three major segments, each having a distinctive geomorphic unity (Wellington 1955). The first of these extends from the headwaters to Victoria Falls; the second from the Falls to the edge of the Mozambique coastal plain, which commences below Cahora Bassa Gorge; while the third comprises the stretch traversing the coastal plain (Figure 16.2). The aim of this chapter is to provide a description of the Zambezi, with particular focus on the contrasting geomorphological character of these three sectors of the river. It will be demonstrated that these differences are not accidental, but closely reflect the evolution of the Zambezi by processes of river piracy over a period extending back to before the disruption of Gondwana around 120 Ma. Summarizing the model of drainage evolution of the Zambezi (Moore and Larkin 2001; Moore et al. 2012), this narrative of the Zambezi's evolution starts at the inauguration of the Proto-Zambezi river (Key et al. 2015).

The evolution of the Zambezi River has repeatedly modified the distribution of riverine plant and animal species. River captures have not only been important in facilitating species dispersions but, particularly over the Neogene, have also led to the disruption of formerly continuous populations, providing a driving force for speciation. Recent cross-disciplinary research has applied estimated evolutionary timings of the divergence between aquatic species to resolve the chronology of major river captures and lake tenures: using the genomic record calibrated with molecular clocks (Cotterill and de Wit 2011; Cotterill et al. 2016).

Parts of the Zambezi have a long history of human occupation, but there are also under-populated areas that represent some of the world's last major remaining wilderness areas, in large measure because of the

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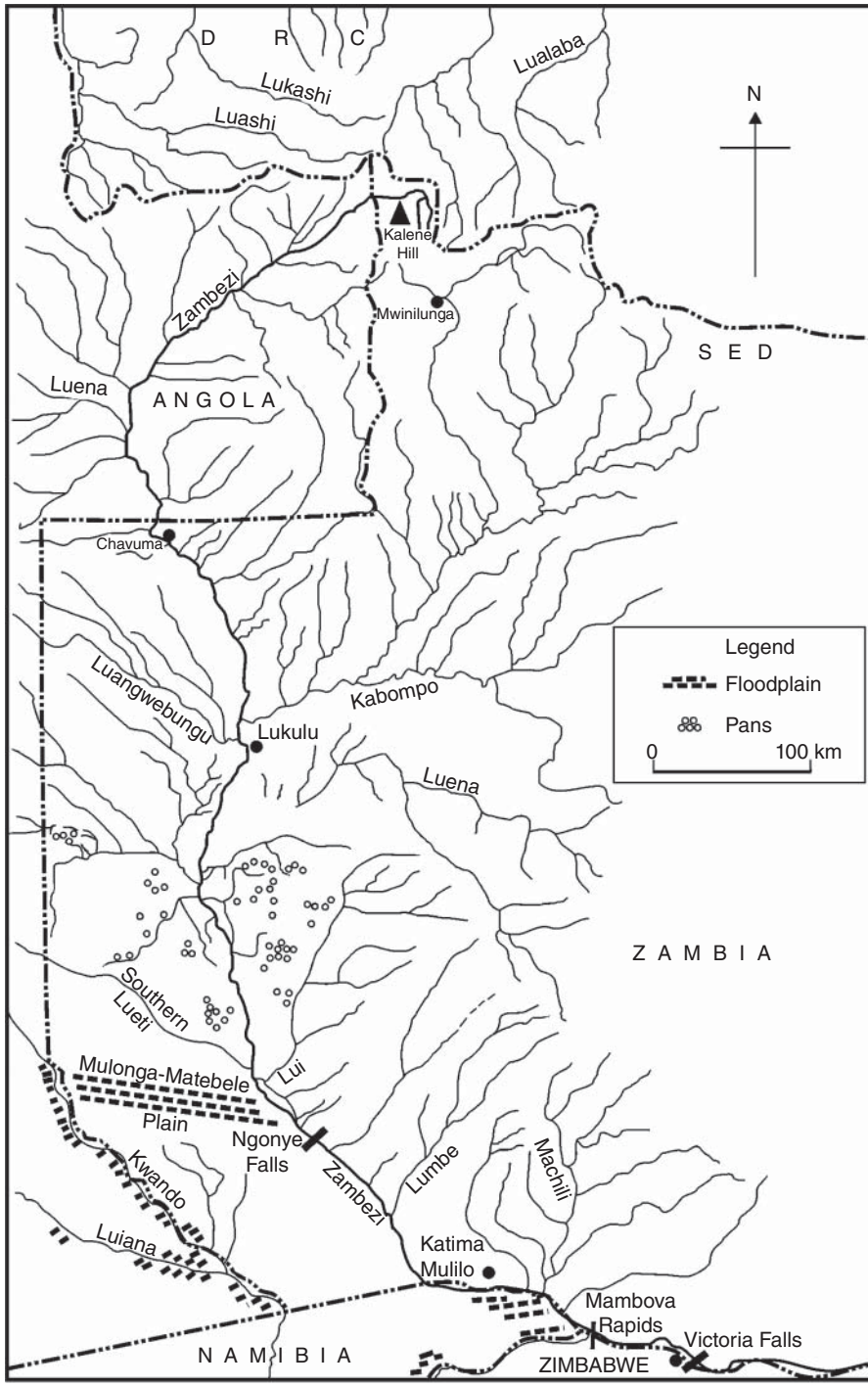


Figure 16.1 The Upper Zambezi system. Triangle shows the position of Kalene Hill. Note that the Southern Equatorial Divide (SED) forms the southern boundary of the Democratic Republic of Congo (DRC) with Angola and Zambia.

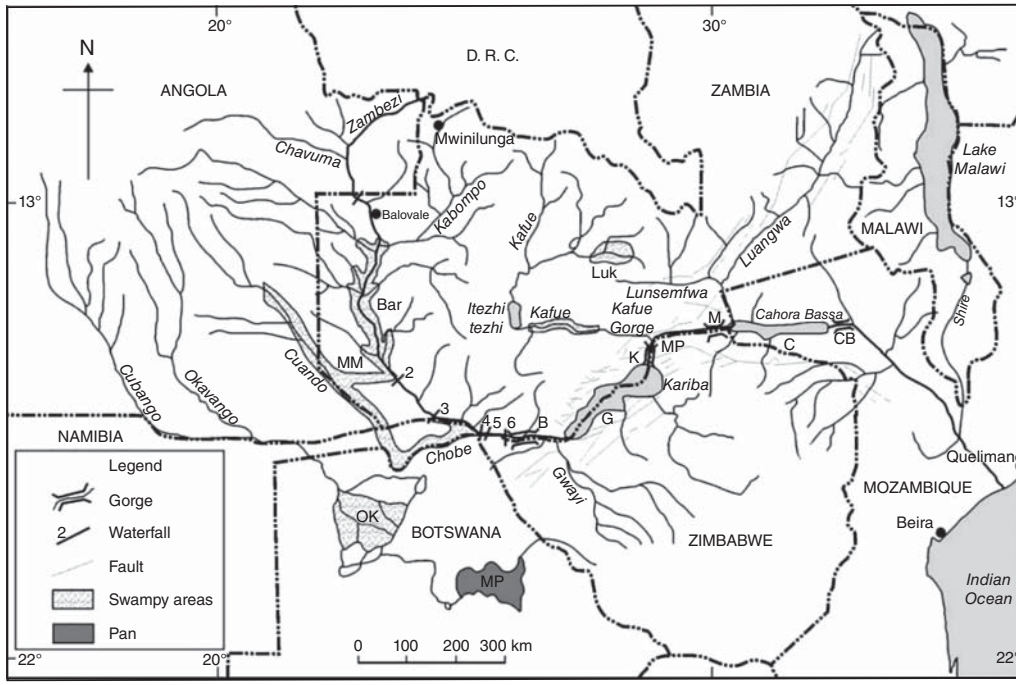


Figure 16.2 The Zambezi drainage system, adapted from Nugent (1990) and large dams. Note that the Linyanti and Chobe floodplains (both marked Chobe in this figure) are shown in detail in Figure 16.14. Rift basins: G, Gwembe Trough (mid-Zambezi Basin); MP, Mana Pools Basin; C, Chicoa or Cahora Bassa Basin. Gorges: B, Batoka Gorge; K, Kariba Gorge; M, Mupata Gorge; CB, Cahora Bassa Gorge. Rapids and Falls: 1, Chavuma; 2, Ngonye Falls; 3, Katima Mulilo; 4, Mambova; 5, Katombora; 6, Victoria Falls. Floodplains: Bar, Barotse floodplain; Luk, Lukanga; MM, Mulonga-Matebele. OK, Okavango Delta. Pans: MP, Makgadikgadi Pans. Source: Adapted from Nugent (1990).

barrier to settlement posed by the tsetse fly. However, measures to control the tsetse fly are progressively reducing this barrier, and these wilderness areas are coming under increasing population pressure. Several large dams, which have been constructed along the Zambezi and its tributaries to provide hydro-electrical power, have had major ecological impacts on the Zambezi system. Additional impoundments that are planned will require that careful management plans be put in place to satisfy the competing demands for the river's finite resources. This in turn demands a refined understanding of the hydrology and ecology of the system. While a detailed overview of these aspects is beyond the scope of this chapter, salient issues will be highlighted.

16.2 The Zambezi River System

The Zambezi River system and the locations of major dams are illustrated in Figure 16.2, while Figure 16.1 shows the major headwater tributaries. The upper reaches of the river are incised into Precambrian basement rocks that form the SED. A little above its confluence with the west bank Lungwebungu tributary, which rises in the Angolan highlands, the Upper Zambezi widens into the Barotse floodplain (Figure 16.3). This is a very low gradient stretch of shallow, languid water, some 180 km in length, and 30 km in maximum width during periods of peak flood, which extends to just above Ngonye Falls (Figure 16.4). Most of this



Figure 16.3 Barotse floodplain. Source: Photograph reprinted with permission from Mike Main.



Figure 16.4 Ngonye Falls. Upper Zambezi. Source: Photograph reprinted with permission from Mike Main.

section of the river traverses unconsolidated sands (loosely referred to as the Kalahari Sand) that cap the Cenozoic Kalahari Formation.

The flats to the east of the Barotse floodplain are marked by a belt of numerous pans, up to 4 km in largest diameter. Some of these are perennially filled with water, while others are fed by springs rising from their margins. A number of lines of pans are also found to the west of the Barotse floodplain, although these are in general much smaller than those fringing the eastern margin. Many of the pans are aligned with shallow grassy valleys, known as dambos, which are bounded by gently sloping, densely vegetated interfluves. The hydrological regime of dambos is characterized by a persistently high water table that produces anaerobic soils, which in turn prohibits tree growth. Perennial water persists in shallow pools, shrouded in tall grass cover, throughout all but the most severe droughts. This makes the dambos the sponges that structure much of the Zambezi catchment. It is in fact hard to locate a minor tributary of the Upper Kafue, Upper Zambezi, or Cuando Rivers whose run-off cannot be attributed to these dambos (White 1976; Skelton 2017; Goyder and Gonçalves 2019). Zambezian grasslands constitute the single largest unit mapped in the Zambezian phytochorion (see Section 16.6), which reflects the spatial dominance of floodplains and dambos (White 1983).

Water flow into the dambos, downslope from the interfluves, has concentrated finer grained minerals into these moist sponges and created clayey soils, enriched in humus derived from the very luxuriant plant growth. The anaerobic grassland associated with dambos and larger floodplains of the Zambezian Plateau is the single most widespread vegetation type in the Upper Zambezi Basin, (White 1976, 1983; Goyder and Gonçalves 2019). The rich soils and availability of water makes the pans and dambos an important focus of agriculture (McFarlane 1995). In terms of both edaphic and ecological criteria, the Upper Zambezi stands apart from the world's rivers because much of its catchment is comprised of dambos.

Below the Ngonye Falls, a little downstream of the southern end of the Barotse Floodplain (Figure 16.4), the gradient of the Zambezi steepens, and the river begins to incise into Karoo-age basalts and sediments that form the sub-Kalahari bedrock, creating a series of rapids. These anticipate the end of the leisurely course of the Upper Zambezi, which terminates abruptly where the river plunges some 100 m along the 1700 m length of the Victoria Falls, or Mosi-a-tunya – The-Smoke-That-Thunders – as they are more aptly known by their vernacular name (Figure 16.5).

Figure 16.6 illustrates the gradient of the section of the Zambezi River above and below Victoria Falls. The 340 km stretch from the Ngonye Falls to Victoria Falls,

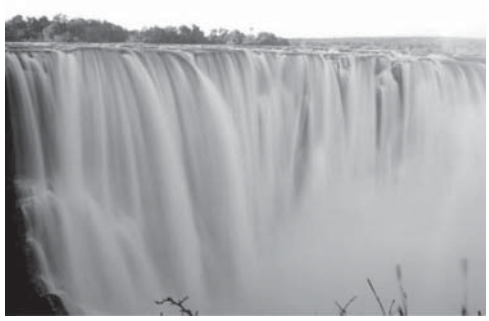


Figure 16.5 Victoria Falls. Source: Photograph reprinted with permission from Mike Main.

which constitutes the lower portion of the Upper Zambezi, has an average gradient of 0.000 24. A second geomorphologically distinct section of the river, designated the Middle Zambezi (Wellington 1955), commences immediately below the falls. Karoo-age basalts and sediments and subordinate Precambrian crystalline basement rocks constitute the bedrock over most of this stretch of the river. It is characterized by a markedly steeper gradient (0.0026) than the section above the falls (Figure 16.6), and initially follows a turbulent course through a series of narrow zigzag gorges before swinging abruptly to the east into the 100 km long Batoka gorge (Figure 16.7). The latter narrows at the Chimamba Rapids, some 30 km further downstream,

> where the whole volume of the great Zambezi converges into a simple pass, only some 50 or 60 feet in width, shuddering, and then plunging for 20 feet in a massive curve that seems in its impact visibly to tear the grim basaltic rocks asunder (and) one learns better than from the feathery spray-fans of the Victoria Falls what force there is in the river and wonders no longer at the profundity of the gorge …
>
> (Lamplugh 1907)

The Chimamba Rapids also mark a sharp break in gradient of the river within the succession of gorges below Victoria Falls (Moore et al. 2012, Figure 16.6).

Below the Batoka Gorge, the Zambezi widens into one of the world's finest wildernesses,

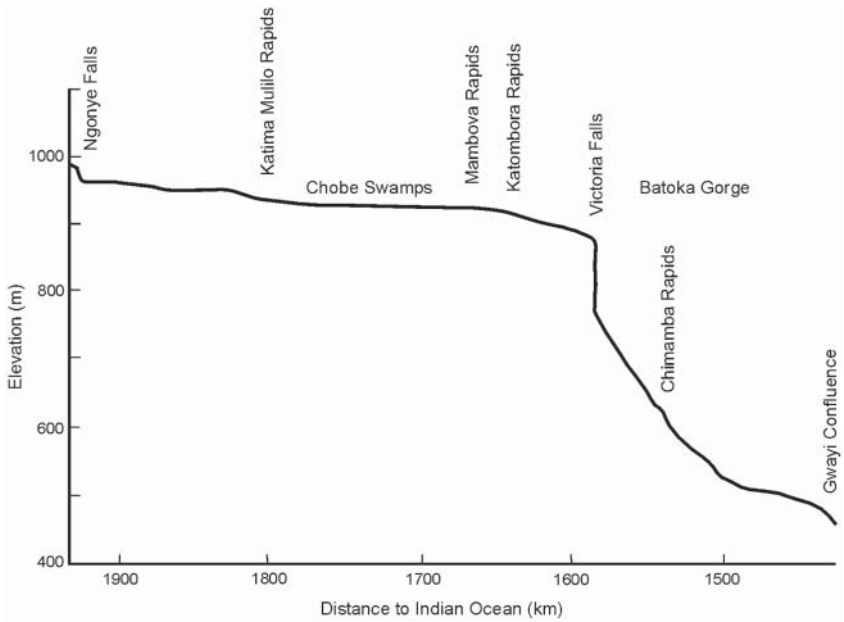


Figure 16.6 Zambezi River profile across the boundary (at Victoria Falls) between the upper and middle sections of the river. Source: Modified after Nugent (1990).

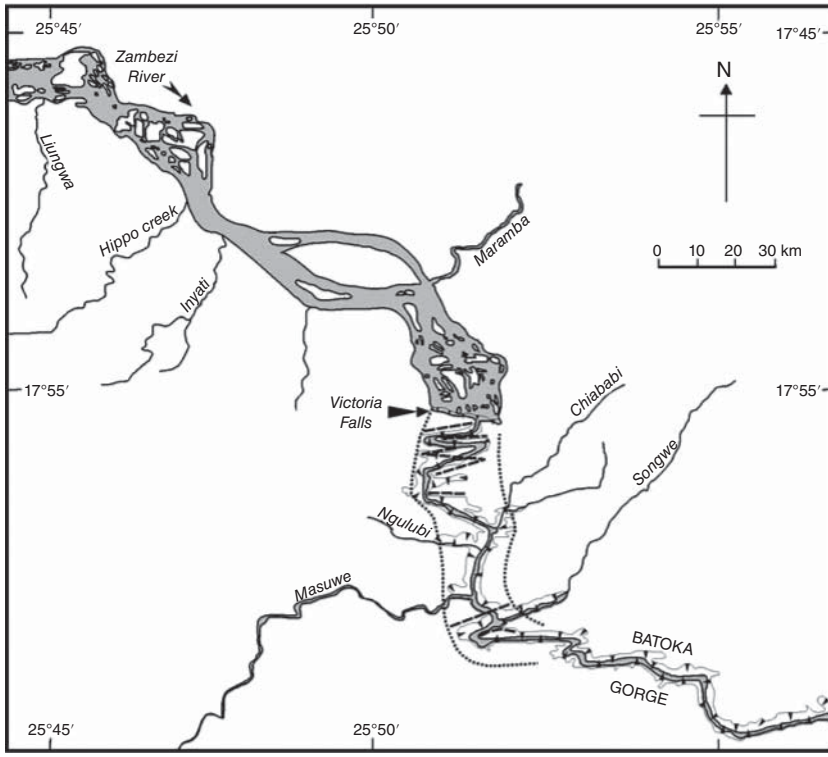


Figure 16.7 Geomorphology of the Zambezi River in the vicinity of Victoria Falls (from 1 : 50 000 topographical sheet 1725D4 (Victoria Falls)). Dashed line on either side of the gorge below the Falls marks a low escarpment, interpreted to represent the original bank of the Zambezi prior to river capture (Wellington 1955). The sharp deflection of the Zambezi from a southerly to an easterly course immediately below the confluence with the Songwe was inferred to mark the capture elbow where the Middle Zambezi beheaded the Upper Zambezi (Wellington 1955). Source: Reproduced from Moore and Larkin (2001), with permission of Geological Society of South Africa.

flowing through a series of broad basins, in places several kilometres in width, and known, in a downstream direction, as the Kariba (or Gwembe), Mana Pools and Chicoa (or Cahora Bassa) basins (Figures 16.2 and 16.8). These are linked by the narrow defiles of the Kariba and Mupata Gorges (Figure 16.9) – not as long or dramatic as the Batoka, but filled by a dark, powerful current, many mysterious eddies, and a haunting, pervasive silence that lingers long after the river enters the broad reaches of the lower basin. Much of the flat valley and steep escarpments in Zambia and Zimbabwe bordering the mid-Zambezi have been set aside as safari and controlled hunting areas. In combination, they stretch from Lake Kariba to the eastern reaches of Lake Cahora Bassa (Figure 16.2). Part of this region, comprising Mana Pools, Sapi, and Chewore, stands out as one of the important remaining wilderness areas in the savannahs of Africa and is appropriately designated as a world heritage site (Frost et al. 2002).

Downstream of the Chicoa Basin, the river flows through one last gorge – the Cahora Bassa, before entering an indolent stretch of the river known as the Lower Zambezi, which traverses the Cretaceous and Cenozoic sedimentary cover of the low-lying (0–400 m) Mozambique coastal plain. The lower reaches of the river, below the Shire confluence (Figure 16.2), forms a huge 100 km long



Figure 16.8 Wide Zambezi at Mana Pools. Source: Photograph reprinted with permission from Mike Main.



Figure 16.10 Zambezi floodplain and delta. Source: Photograph reprinted with permission from Mike Main.



Figure 16.9 Mupata Gorge. Source: Photograph reprinted with permission from Mike Main.

floodplain-delta system of oxbows, swamps, and multichannel meanders (Figure 16.10). The modern river empties into the Indian Ocean between Beira and Quelimane, but abandoned distributary channels of the delta are located along the entire 290 km distance between these two cities. Because of the shallow sloping shelf, this area of the coastline has, at 6.4 m, the highest tidal range on the continent. Given the low-lying hinterland, tides can reach 40–50 km inland. Low-lying ridges, extending parallel to the coast, up to 30 km inland, mark past strandlines associated with former higher sea-level stands (Main 1990). The rich alluvial soils along the river have been utilized for intensive agriculture. On the south bank is the large Marromeu Game Reserve, coastally fringed by extensive mangroves and low-lying dune forest. This was once famous for its large herds of buffalo (*Syncerus caffer*), but the wildlife was severely depleted during the hostilities prior to and immediately after Mozambique independence. The recovery of Mozambique's wildlife is a slow process, but shows signs of some local successes (Holechek and Valdez 2018).

The Zambezi has a number of important tributaries, which constitute major rivers in their own right. The most westerly of these is the Cuando (or Kwando), which follows a south-easterly course as far as the Botswana–Namibia border, where it veers sharply north-eastwards, to link with the Zambezi via the Linyanti-Chobe floodplain (Figure 16.2). The mid-section of the Cuando is a floodplain, comparable with the Barotse floodplain, and linked to the latter by a broad belt of alluvium termed the Mulonga-Matebele

Plain (Figure 16.1), which is subject to flooding in the wet season (Thomas and Shaw 1991).

The Kafue is a north bank tributary with headwaters on the SED. It initially flows in a general southwesterly direction towards the Upper Zambezi; but below the Itezhi thezi scarp, its course veers sharply eastwards in the vicinity of a broad floodplain known as the Kafue Flats. This tributary links with the Mana Pools Basin of the Middle Zambezi below the deeply incised Kafue Gorge (Figure 16.2).

The Luangwa River flows in a general southwesterly direction over most of its length – an unusual orientation for a major tributary of an east-draining river. The course veers sharply to the south-south-east a little above the confluence with the Zambezi in the upper reaches of the Chicoa Basin (Figure 16.2).

The mid-Zambezi has a number of relatively minor south bank tributaries, which rise on the central Zimbabwe divide. Their upper reaches flow in a general northwesterly direction which, like the orientation of the Upper Luangwa, is anomalous for tributaries of a major east-draining river. The major tributary of the Lower Zambezi is the Shire, which flows southwards from its headwaters in Lake Malawi, in Malawi (Figure 16.2).

16.3 Hydrology

The Zambezi is some 2575 km in length from the headwaters to the coastal delta, and has a catchment area of 1.32 million square kilometres that includes portions of eight countries (Nugent 1990). This makes it the largest river in southern Africa, with a cumulative mean annual flow of the main stream and tributaries of approximately 97 km^3 (Table 16.1, Figure 16.11a). This is broadly comparable with the flow of the Nile, but an order of magnitude less than the annual flow of the Congo, which in turn has a mean annual flow that is an order of magnitude less than that of the Amazon.

The hydrology of the Zambezi catchment is determined by the interplay of a variety of factors. The annual variation of rainfall in summer is due to the Intertropical Convergence Zone between the north-east Monsoon and the south-east Trades for the Middle and Lower Zambezi, and the Congo air boundary between the south-west Monsoon and the south-east Trades for the Upper Zambezi. The further south the two boundaries move, the greater the total delivery of rainfall. In winter, these two climatic boundaries move north, resulting in drier conditions across the Zambezi Basin. Rainfall by and large increases from south to north (600–1300 mm), so that the largest contribution to run-off comes from the northern tributaries.

The hydrology of the Zambezi is further influenced by water exploitation by different users, along its main channel and tributaries (Davies 1986; Mendelsohn 2019). The catchment as a whole is relatively undeveloped so that off-take by irrigation, industrial, and domestic users only amounts to some 3% of the total flow of the Zambezi. The use by hydroelectric power, due to the net evaporation from the large reservoirs of Kariba and Cahora Bassa Dams and, to a lesser extent, of the Ithezi thezi and Kafue Gorge Dams, on the Kafue, amounts to just over 5% of the Zambezi flow. However, usage by these sectors is more than offset by the increased runoff due to changes in land use, particularly since the middle of the last century (Davies 1986). Thus, for example, preliminary calculations, based on research by the Wallingford Research Station on Lake Malawi (Price et al. 1998), indicates that increased run-off caused by the clearing of natural forests in the Shire catchment, has meant the level of Lake Malawi in the early 1990s was 1 m higher than it would have been otherwise. Figure 16.11b and Table 16.1 summarize these sector and land use totals, and the resultant mean annual flows are shown in Figure 16.11a.

Mean monthly flows at four different stations (Figure 16.2) on the Upper Zambezi are

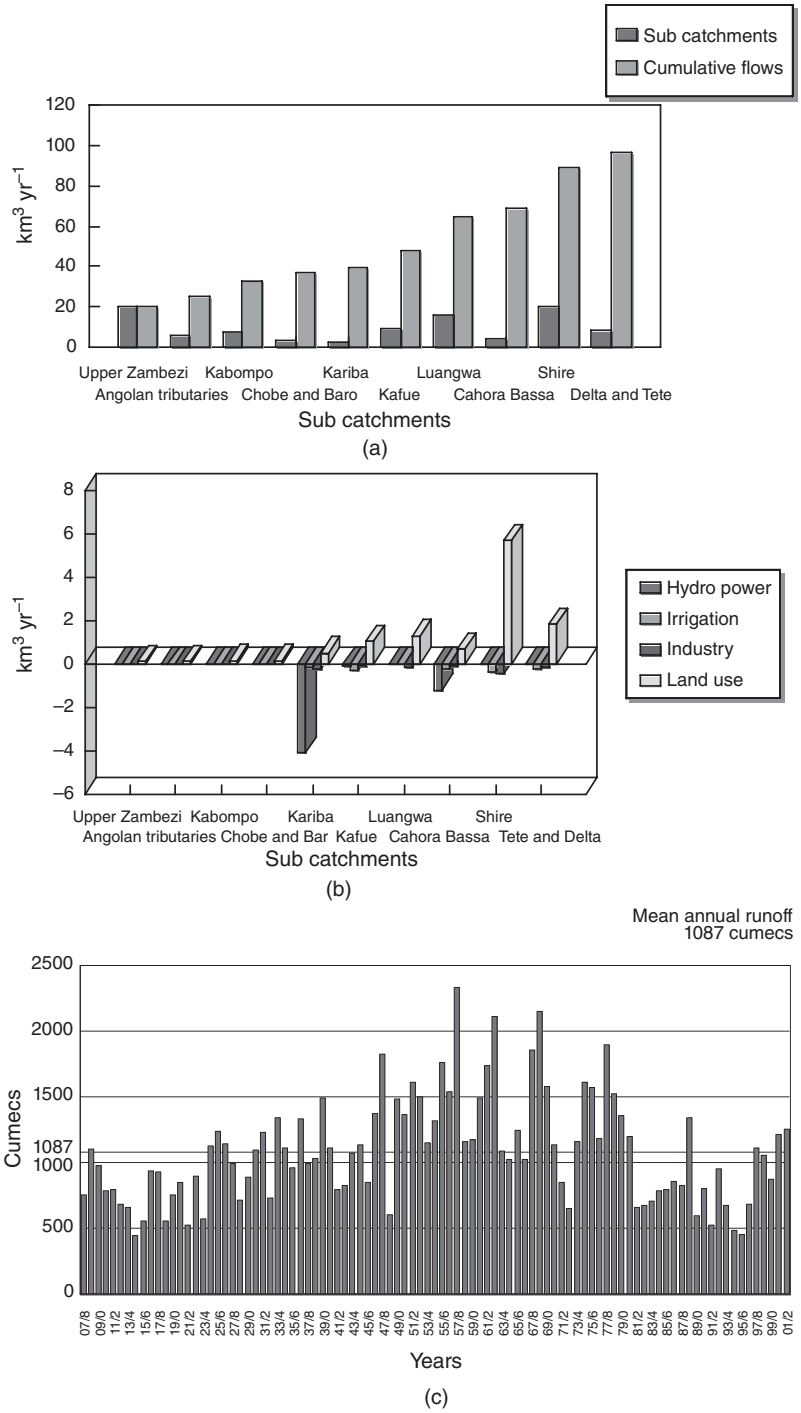


Figure 16.11 (a) Mean and cumulative annual flow of the Zambezi and major tributaries. (b) Utilization of water from the Zambezi and major tributaries. (c) Mean annual flows of the Zambezi River measured at the Victoria Falls station (1907–2002).

Table 16.1 Flow data used in Figure 16.11.

Country	Sub catchment	Hydropower ($km^3\ yr^{-1}$)	Irrigation ($km^3\ yr^{-1}$)	Industry and primary ($km^3\ yr^{-1}$)	Land use change ($km^3\ yr^{-1}$)	1995 yield ($km^3\ yr^{-1}$)	Mean flow ($km^3\ yr^{-1}$)	Place
Angola	Upper Zambezi	0.00	0.00	−0.01	0.12	19.90	19.90	Chavuma
Angola	L.Bungo and Luanginga	0.00	0.00	−0.01	0.09	5.47	25.37	
Zambia	Kabompo	0.00	0.00	0.00	0.13	7.74	33.11	Mongu
Zambia	Barotse and Chobe	0.00	−0.02	−0.04	0.14	3.62	36.73	Victoria Falls
Zimbabwe	Kariba	−4.09	−0.19	−0.23	0.49	2.53	39.26	Kariba Dam
Zambia	Kafue	−0.06	−0.33	−0.13	1.02	8.89	48.15	Mana Pools
Zambia	Luangwa	0.00	−0.03	−0.14	1.29	16.34	64.49	Zumbo
Zim./Moz.	C. Bassa	−1.21	−0.23	−0.12	0.66	4.14	68.63	C. Bassa Dam
Malawi/ Tanzania	L. Malawi and Shire	0.00	−0.41	−0.45	5.70	20.12	95.65	Caia
Moz.	Delta and Tete	0.00	−0.26	−0.16	1.84	8.04	96.79	Sea
	Totals	−5.36	−1.47	−1.29	11.48	96.79		

given in Table 16.2. The annual variation in rainfall between dry winters and wet summers produce high flows in February–April and then progressively lower flows up to a November minimum (Table 16.2). The annual flooding is however buffered by the natural flood regulatory capacity of the floodplains developed on the major headwater tributaries. The most important of these are the Barotse and Chobe floodplains in the upper Zambezi, the Kafue Flats on the Kafue River and Elephant Marsh on the Shire River (Figure 16.2). Flow has been further affected by the construction of major dams (Figure 16.2) on the Zambezi (Kariba and Cahora Bassa) and on the Kafue (Itezhi tezhi and Kafue Gorge).

Records of water level from the hydrological station at Victoria Falls, taken since 1907 are illustrated in Figure 16.11c. These indicate lower than normal years for 1907–1946, above normal for the years 1947–1981, and again below normal for 1982–1997. A major flood of 1958, during the construction of Kariba Dam, followed heavy rains in the upper catchment and also the local catchment below Victoria Falls. A coffer dam was overtopped and a road bridge washed away – at its peak some 9000 $m^3\ s^{-1}$ was passing over the Victoria Falls. In magnitude, it was equivalent to the 1 in 100 year flood, which in turn is roughly half the probable maximum flood of 21 000 $m^3\ s^{-1}$. McCarthy et al. (2000) tentatively interpret the variation in annual flows of the Zambezi to show an apparent oscillation between periods of good years and poor years in an approximately 80 year cycle.

Long-term changes in the Zambezi flow regime are broadly mirrored in the Okavango River. Historical accounts of flooding of the Okavango Delta suggest average to above average outflows for the period 1849–1900, followed by limited outflow with some good

Table 16.2 Zambezi River: mean monthly flows ($m^3\ s^{-1}$).

Station period (month)	Chavuma 1959/1960–2001/2002	Lukulu 1950/1951–2001/2002	Katima Mulilo 1967/1968–2001/2002	Victoria Falls 1951/1952–2001/2002
October	68	271	306	293
November	94	310	320	297
December	228	468	430	438
January	655	803	678	686
February	1411	1294	1211	1184
March	2031	1645	2374	2175
April	1770	1523	3129	3007
May	684	944	2427	2613
June	310	575	1326	1621
July	188	434	691	845
August	124	361	467	519
September	83	306	364	376
Mean annual	637	745	1144	1171

Drainage area: Chavuma (75 500 km^2), Lukulu (206 500 km^2), Katimo Mulilo (337 300 km^2), Victoria Falls (507 200 km^2). See Figure 16.2 for station locations.

years for the period 1900–1951. Outflow from the Delta for the 1960s and 1970s was above normal and the outflow for the 1980s and early 1990s below normal (McCarthy et al. 2000).

16.4 Ecological Impact of Major Dams

The densely vegetated floodplains such as the Barotse (Bulozi) and Chobe (Upper Zambezi) and the Kafue Flats (Figures 16.1 and 16.2), with their shallow gradients, form natural sediment traps that greatly reduce the material supplied to the lower reaches of the river system. Consequently, these floodplains form major wetlands that provide important wildlife refuges, particularly for fish, avifauna, and water-dependent mammals, including hippopotamus, and the lechwe and sitatunga antelopes. Fish migrate into the inundated grasslands of the floodplains during the floods, spawn, and their fry utilize the rich plankton and benthic communities which develop after nutrient release from decomposing organisms drowned by the floodwaters (Cotterill 2005, 2006a). Readily accessible stretches of the Zambezi and major tributaries, including the Angolan rivers and the Barotse floodplain, provide a reliable perennial water source, and are thus an important focus for human settlement and agricultural activity (Davies 1986; Mendelsohn 2019).

Human demands on the Zambezi's headwaters are burgeoning (Mendelsohn 2019), endorsing recent attention to secure the ecological integrity of the source lakes feeding the Angolan tributaries (Skelton 2017, 2019). Beginning with the Kariba project in the late 1950s, there have been marked changes to the ecology and utilization of the Zambezi River system as a result of the construction of several major dams, such as Kariba (Figure 16.12) and Cahora Bassa on the middle Zambezi, and the Itezhi tezhi and Kafue Gorge Dams on the Kafue (Figure 16.2). Flooding of approximately 5500 km^2 of the Gwembe trough inundated all riparian habitats and a significant expanses

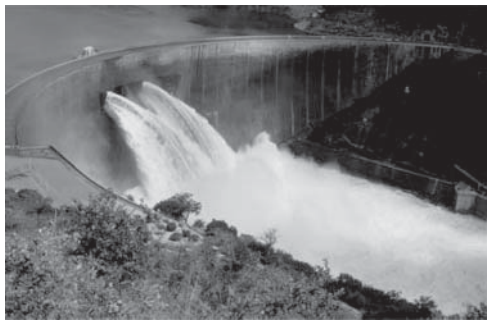


Figure 16.12 Wall of the Kariba Dam. Source: Photograph reprinted with permission from Mike Main.

of mopane and jesse (muchese) thickets. Concerns persist over impacts of the modified flooding regime on the riparian ecology (including local economies) downstream of the Cahora Bassa and Kariba gorges (Davies 1986). Ecology studies of the Mana Pools floodplains have invoked a combination of factors, which drive ongoing changes in vegetation and dependent mammal populations. It is argued the loss of the annual floods since construction of Lake Kariba (notably the Barotse Flood that peaks in the Mid-Zambezi in April–May) means sediments are no longer replenished to downstream habitats. This is hypothesized to impact negatively on vegetation recruitment, and thus dependent consumers (e.g. Ncube et al. 2013).

However, following Jackson (1961), Dunham (1989) pointed out the flooding regime of the mid-Zambezi (pre-impoundment) comprised the distinct 'local' and regional 'Barotse' floods. Local traditional people distinguished these as the local, muddy *Murorwe* from the mainstream, and cleaner *Gumbura*, respectively; the recorded volume of the highest *Gumbura* exceeded the local *Murorwe* by up to seven times. Nevertheless, a total of only three pre-impoundment inundations, downstream of the Kariba, are documented through the twentieth century (Nugent 1986). Dunham (1989) reported a local *Murorwe* flood still occurs in the Mana region, when flow of south-bank tributaries (including the Rukomechi River) backs up against their terminus of the Zambezi at its high stands. Break out of these smaller channels floods the Zambezi's margins, but these events are contingent on above-average heavy rainfall over the southern escarpments.

The dams constructed on the Zambezi and major tributaries have had a major impact on the economy of the region, including benefits to tourism on the lakes. Thus, they represent an important source of hydroelectricity for the whole subcontinent, where there is a rapidly rising demand for power. The introduction of the Lake Tanganyika sardine *Limnothrissa miodon* (colloquially known as 'kapenta') into Lake Kariba in 1967 has formed the basis of an important fishing industry. Against all expectations, this fish survived discharge via the Kariba turbines and sluice gates, as well as a journey of several hundred kilometres to colonize Cahora Bassa, where it now also forms the basis of an important fishing industry (Davies 1986; Jackson 2000). The large dams have also become the focus of an important tourist industry.

Nevertheless, these economic benefits have come at considerable human and ecological costs. The construction of Lake Kariba led to the displacement of about 50 000 members of the Tonga tribe which had inhabited the area since about 1100 CE, while about 25 000 people were relocated as a result of the construction of Cahora Bassa. These displacements have led to serious community disturbances, major psychological upsets, and emotional problems in the attempt to adapt to new terrain and a new way of life, and bitterness and resentment that rankles to this day (Davies 1986).

Both the Kariba and Cahora Bassa Dams were constructed within Karoo-age rift zones (Scholz et al. 1976; Broderick 1990). Scholz et al. (1976) noted that during the period 1969–1973, over 100 seismic events with magnitudes equal to or greater than 2.0 were recorded in the Kariba basin, and concluded that these could not be explained only in terms water loading linked to filling of the

dam. Rather, they concluded, 'the reservoir impoundment simply enhanced the seismicity in an already active zone'. It can only be hoped that the dam construction was sufficiently robust to withstand the ongoing seismicity, as collapse would be disastrous for the low-lying ecosystems downstream, including the World Heritage Site of Mana Pools, and especially the Mozambique coastal plain surrounding the lower reaches of the Zambezi.

The dams have also had severe ecological impacts on the major floodplains, as a result of the reduction of the supply of water and sediment. The resultant contraction of these wetlands impacts particularly on fish, avifauna, and water-dependent antelope species, and are only marginally offset by the added wetlands of the lake shallows (Davies 1986). This is well illustrated by the collapse in numbers of the semi-aquatic Kafue lechwe (*Kobus kafuensis*), which is endemic to the Kafue flats, following construction of the Itezhi-tezhi Dam. Today, this species is confined to a fragment of the former range, with a decline from an estimated population of 350 000 at the turn of the twentieth century to less than 30 000 today (Cotterill 2005). It has also been estimated that the closure of Cahora Bassa led to a 70% reduction of the supply of sediment to the lower reaches of the river, and that this could lead to severe erosion of the Zambezi Delta, threatening both agricultural activity and the important Marromeu wilderness area. During the annual floods prior to construction of the dams, the drowned grasslands of the delta were protected from overgrazing, and thus able to regenerate. The virtual elimination of the natural flooding regime has disturbed this important ecological dynamic. It may also be responsible for the present marked die-off of the coastal mangroves, and the catastrophic decline of the coastal shrimp-fishing industry (Davies 1986). The latter author notes that a major problem in quantifying the ecological effects of the construction of the major dams was the lack of baseline environmental data prior to their construction.

Despite these concerns related to the construction of large dams on the Zambezi and tributaries, on 23 July 2018, the Governments of Zimbabwe and Zambia agreed in principle to the construction of a further major dam, located some 47 km below Victoria Falls, within the Batoka Gorge (see Figure 16.7). This has a planned power generation capacity of 1600 MW, which may be increased to 3000 MW. With an envisaged wall height of 176 m, the full supply water level would be 757 m asl, resulting in a dam with an area of 23 km^2, and extending upstream to the Second Gorge below Victoria Falls. Quite apart from the aesthetic impact on the Victoria Falls World Heritage Site, this would destroy one of the world's finest stretches of white water rafting below Victoria Falls, with potentially negative impacts on a flourishing tourism industry, and local employment. It has, however, been suggested, using a variety of climatic modelling scenarios, that both the power generating capacity and the financial return from dam construction could be very adversely affected by future climate change (Harrison and Whittington 2002). Moreover, the Batoka gorges are located within a seismically active zone extending south-west into the Makgadikgadi Rift Zone (Eckardt et al. 2016). It remains to be seen whether dam construction will actually proceed, given these economic considerations and the likely environmental lobbying.

16.5 Evolution of the Zambezi River System

It has long been appreciated that the configuration of the Zambezi and tributaries has evolved over time, and that the modern course of the river reflects the interplay of a complex history of geomorphic events. Our understanding of these evolutionary processes rests, in large measure, on remarkably perceptive early pioneering work of du Toit (1927, 1933), Dixey (1945), Wellington (1955), Bond (1963) and Grove (1969); and more recent

studies by Cooke (1980) and Thomas and Shaw (1991). This section briefly reviews some of the broader lines of evidence for the initiation and subsequent geomorphic evolution of the Zambezi system.

Major changes in the geometry of the Zambezi River system are indicated by the following lines of evidence:

1. The sharp changes in direction of the courses of the Cuando, Kafue, and Luangwa (Figure 16.2) strongly suggest capture elbows.
2. The upper Luangwa drains to the south-west, while south bank tributaries of the Zambezi, which rise on the central Zimbabwe divide, drain to the north-west (Figure 16.2). Moore and Moore (2006) noted that these orientations are most unusual for tributaries of a major east-flowing river, and suggest that these drainage lines were originally in accord with a west-flowing, Karoo age (Permian-Triassic) fluvial system. Palaeocurrent directions in fluvial Triassic (Karoo) sediments in the Zambezi valley indicate westerly sediment transport directions (Oesterlen and Millsteed 1994; Shoko 1998), consistent with this interpretation. The origins of this early west-draining Proto-Zambezi drainage system has recently been reviewed by Key et al. (2015) – see below.
3. The sedimentary sequence on the Mozambique plain between Maputo and Beira, and offshore deposits to the east of this plain (Dingle et al. 1983) reflect changes in sediment supply by the major eastward-draining southern African rivers, and provides a timescale for dating important river captures (Moore and Larkin 2001).
4. Much of the western portion of Africa between the Orange River and the Congo is blanketed by a veneer of upper Cretaceous to Pleistocene sediments of the Kalahari Formation (Figure 16.13b). Isopach studies of these sediments have identified a number of deep pre-Kalahari valleys, which are inferred to mark the position of former drainage lines (Moore and Larkin 2001).
5. The occurrence of a high proportion (41%) of fish species common to the middle Zambezi and Limpopo Rivers indicates that they have been linked at some stage. The native fish fauna of the Upper Kafue (a tributary of the Middle Zambezi) is very similar to the Upper Zambezi, only less speciose (Skelton 2019). Of the 64 species of fishes then known to occur in the Upper Kafue, only two are absent from the Upper Zambezi (Gaigher and Pott 1973; Bowmaker et al. 1978; Skelton 1993, 1994). This biogeographic pattern points to a former link between the Kafue and Upper Zambezi, and is reinforced by estimates of Mid-Pleistocene genetic divergence between indicator species (Cotterill and de Wit 2011). Paired populations of riverine plant species on the Zambezi and Limpopo (Moore 1988) could also be explained by a former link between these two rivers.

Summarizing several lines of evidence, including these discussed above, Moore and Larkin (2001) postulated the following broad sequence of evolutionary changes in the Zambezi River system.

In the early Cretaceous, following the opening of the Atlantic Ocean at approximately 120 Ma, the Cubango-Okavango, Cuando, and Upper Zambezi were the major south-east-flowing headwaters of the Palaeo-Limpopo River system (Figure 16.13a). The Upper Zambezi was probably linked to the Limpopo via the Shashe River, which is over 1 km in width near the confluence of the latter two rivers, indicating a marked overfit with the ephemeral modern flow regime.

The Kafue was originally a major south-west-flowing east bank tributary of the Upper Zambezi. The Chambeshi, whose headwaters included rivers that are today part of the upper Congo system, originally formed the upper reaches of the Palaeo-Kafue. This former extensive Chambeshi-Kafue drainage line is

designated the Palaeo-Chambeshi (Cotterill 2006a). The sharp change in course of the modern Kafue, where it enters the western end of the Kafue Flats (Figure 16.2), is interpreted as a capture elbow (Dixey 1945; Bond 1963). The earlier course of the lower Kafue is marked by a 2 km wide wind gap in the modern divide with the Zambezi at the western end of the Kafue Flats, and a belt of alluvium, underlain by coarse, current-bedded fluvial gravels, between the Kafue Flats and the Machili Flats (Dixey 1945; Thomas and Shaw 1991). The location of the original course of the lower Kafue via the Machili Flats is shown in Figure 16.13c and the Digital Elevation Model (DEM) image presented in Figure 16.14. This image clearly illustrates how the alluvium associated with the Machili Flats extends north-east across the line of the Upper Zambezi into northern Botswana (Moore et al. 2012).

Moore and Larkin (2001) inferred that the Luangwa originally continued on the southwesterly course of the upper reaches of the river, via the fault-bound Gwembe Basin. A deep pre-Kalahari valley, which straddles the Botswana–Zimbabwe border and located on a projection of this southwesterly line, was interpreted to be a relict of the original Luangwa–Gwembe course. This is consistent with the suggestion by Moore and Moore (2006) that the Luangwa, which is floored by Karoo sediments, is a relict tributary of a former west-flowing Karoo-age drainage system that pre-dated the break-up of Gondwana.

Key et al. (2015) synthesized new evidence to constrain a minimum age of the inception of this Proto-Zambezi River in the Late Palaeozoic (~290 Ma). Its eastern headwaters drained the remnants of the vast north–south oriented Trans-Gondwana Mountain Range, which formerly straddled modern Mozambique. The main channels of the Proto-Zambezi exploited the Dwyka glacial rift-valleys (Late Carboniferous – Early Permian) ultimately inherited by the modern Mid-Zambezi and Luangwa Rivers. The inception of the Proto-Zambezi to at least 290 Ma contrasts against the maximum age of ~260 Ma of the Proto-Mississippi and Mississippi Rivers, which Potter and Hamblin (2006) had ranked as one of the world's oldest persistent drainage systems. In terms of the model presented by Key et al. (2015), the Luangwa would have maintained its southwest-flowing course from the initiation of the Zambezi river system to the present, making it the world's oldest extant drainage line.

The initiation of the early post-Gondwana drainage system in south-central Africa, described above, can be understood in terms of the model proposed by Cox (1989). He envisaged that doming of the subcontinent occurred over major mantle plumes (the Paraná and Karoo plumes) linked to the disruption of Gondwana, and considered responsible for triggering the eruption of the Karoo and Etendeka flood basalts in the east and west of the subcontinent, respectively. Cox (1989) envisaged that the elevated ground over the plumes in turn, provided the headwaters for a new post-Gondwana drainage system (Figure 16.13a). Moore and Blenkinsop (2002) demonstrated that there was a major reorganization of the drainage system on the subcontinent immediately prior to or at the time of disruption of Gondwana, consistent with Cox's proposal. It should be noted, however, that there is currently considerable debate surrounding the existence of mantle plumes and their putative geological impacts. Rift-flank uplift associated with the disruption of Gondwana provides a potential alternative explanation to the plume model to account for a major reorganization of the former Gondwana drainage system.

Irrespective of whether the initiation of the post-Gondwana drainage system is ascribed to the impact of a plume, or simply rift-flank uplift, the opening of the Indian Ocean between ~180 and 150 Ma would be expected to have enhanced the former west-flowing Gondwana drainage system, including the Proto-Zambezi. However, the configuration of the earliest post-Gondwana drainage network

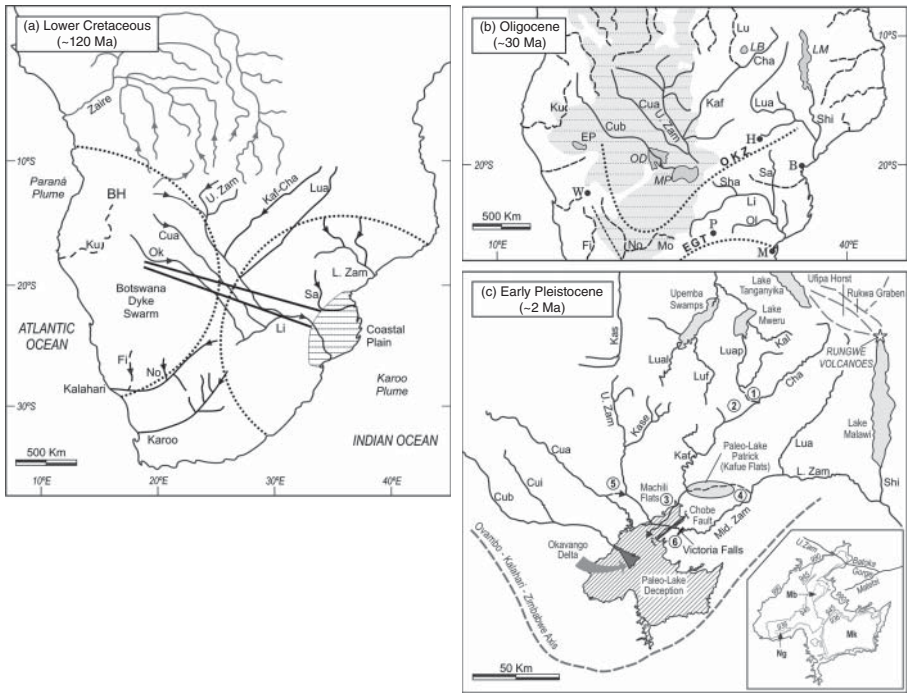


Figure 16.13 (a) Early Cretaceous drainage system in south-central Africa based on reconstructions by de Wit (1999) and Moore and Larkin (2001). Faint lines, modern drainage lines; heavy lines, reconstructed drainage lines for period; Dotted lines show the inferred extent of the areas affected by updoming by the Karoo and Paraná Plumes, respectively. Source: Modified from Cox (1989). Abbreviations for Figure 16.13a–c. Cities: B, Beira; H, Harare; M, Maputo; P, Pretoria; W, Windhoek. Rivers and Pans: BH, Bié Highlands; Cha, Chambeshi; Cua, Cuando; Cub, Cubango; Cui, Cuito; EP, Etosha Pans; Fi, Fish; Kaf, Kafue; Kal, Kalungwishi; Kas, Kasai; Kase, Kasempa; Ku, Kunene; LB, Lake Bangweulu; Li, Limpopo; LM, Lake Malawi; Lu, Luapula; Lua, Luangwa; Lual, Lualaba; Luf, Lufira; L. Zam, Lower Zambezi; Mo, Molopo; MP, Makgadikgadi Pans; No, Nosib; Ok: Cubango-Okavango; OD, Okavango Delta; Ol, Olifants; Sa, Save; Sha, Shashe; Shi, Shire; U. Zam, Upper Zambezi. (b) Oligocene drainage reconstruction (Moore and Larkin 2001). Pale grey tone shows the distribution of the Kalahari Group sediments. Source: After Haddon (2000). Dashed lines, modern drainage lines; heavy lines, reconstructed drainage lines for period; OKZ, Ovambo–Kalahari–Zimbabwe flexure axis. Source: After Moore (1999). Grey tone shows modern distribution of Kalahari Formation sediments. Late Palaeogene flexuring along the OKZ Axis severed the link between the Limpopo and Cubango-Okavango, Cuando and Upper Zambezi–Luangwa–Kafue. As a consequence, the latter three rivers developed into a major endoreic system, which terminated in the Kalahari Basin, and contributed to deposition of the Kalahari Formation sediments. Headward erosion of the lower Zambezi, initiated by crustal flexuring along the OKZ axis, resulted in the capture of the Luangwa. The resultant lowering of the Luangwa base level, coupled with increased flow in the Lower Zambezi, initiated headward erosion towards the point of capture, and incision of the Cahora Bassa Gorge. Continued headward erosion of the Lower Zambezi led successively to capture of the Mana Pools Basin and the Gwembe Trough (location of Lake Kariba). These captures in turn initiated incision of the Mupata and Kariba Gorges, respectively (see Figure 16.2 for localities). Source: Reproduced from Moore and Blenkinsop (2002), with permission from Geological Society of South Africa. (b) Source: Reproduced from Moore and Larkin (2001), with permission of Geological Society of South Africa. (c) Drainage system which sustained the early Pleistocene palaeo-lake in the Makgadikgadi basin, with a shoreline at ~995 m, and designated Palaeo-lake Deception (PLD). Source: McFarlane and Eckardt (2006). © 2006, Botswana Society. 1. Modern link between the upper Chambeshi and Luapala (a Congo tributary); 2. Early Pleistocene link between the upper Chambeshi and the upper Kafue; 3. Early Pleistocene link between the Kafue and PLD; 4. Modern link between the upper Kafue and middle Zambezi; 5. Former link between the Cuando and upper Zambezi via the Mulonga-Matebele plain – see Figure 16.1. The age of this link is uncertain; 6. Victoria Falls. Overflow from PLD exploiting topographic lows would have drained into the middle Zambezi, initiating headward erosion to incise the Batoka Gorge, and ultimately, formation of Victoria Falls.

is poorly constrained, because much of the area which it would have traversed is obscured by a cover of the Cenozoic Kalahari Formation (Figure 16.13b).

Moore and Blenkinsop (2002) ascribed the initiation of an early Cretaceous proto-Zambezi-Limpopo drainage towards the Indian Ocean (Figure 16.13a) to updoming of the subcontinent over Paraná plume, which post-dated the ~180 Ma Karoo plume. The rectilinear pattern of this early river system, with parallel south-east and south-west trending river courses (Figure 16.13a), points to an important structural influence, superimposed on the primary role of the mantle plumes in determining the post-Gondwana drainage system.

The major Early Cretaceous Zambezi-Limpopo River system entered the Mozambique coastal plain via a line of crustal weakness that was exploited by a major west–north–west trending dyke swarm. Reeves (1978) proposed that the dyke swarm was emplaced into the failed arm of a triple junction associated with the disruption of Gondwana. The exit of the Save River to the Mozambique coastal plain was also closely linked to the line of crustal weakness exploited by the dyke swarm (Moore and Blenkinsop 2002). During the Early Cretaceous, the Lower Zambezi constituted a subsidiary coastal drainage system with the Shire as a major north bank tributary. Geophysical evidence (Nairn et al. 1991) shows that the Lower Zambezi course is controlled by major rift faulting. This reconstruction of the proto-Zambezi River system is consistent with the view expressed by Potter (1978) that rifts control the location of long-lived drainages (Key et al. 2015).

The palaeo-Limpopo drainage system was disrupted (Figure 16.13b) by late-Palaeogene crustal flexuring of the sub-continent along an arcuate line termed the Okavango–Kalahari–Zimbabwe (OKZ) Axis by Moore (1999) (modified after the Kalahari–Rhodesian Axis of du Toit 1933). Uplift along this flexure severed the link between the Lower Limpopo and the former south-east-flowing headwater tributaries. These tributaries, including the Zambezi, now became a senile endoreic drainage system that supplied sediment to the inland Kalahari Basin (Figure 16.13b). The subtle, yet profound, control of the OKZ Axis over the regional drainage has been demonstrated by atypical profiles of ephemeral and fossil drainage networks across the southern Kalahari Basin. The concave-up long profiles of the majority of these arid river channels (revealed by precise mapping) are attributed to epeirogenic flexure (Nash and Eckardt 2016).

The Late Palaeogene flexure along the OKZ Axis was responsible for the rejuvenation of the coastal Lower Zambezi, initiating aggressive headward erosion, and ultimately the capture of the Palaeo-Luangwa (Figure 16.13b). The sharp change in the course of the latter from southwesterly to south–southeasterly, just above the modern confluence with the Zambezi (Figure 16.2) is interpreted as a capture elbow. The timing of this capture is not well constrained, but Moore and Larkin (2001) tentatively suggest an Oligocene age in order to account for the thick sedimentary sequence of this vintage on the Mozambique coastal margin. The lowering of the Luangwa base level following this capture, coupled with increased flow in the lower Zambezi, would have accelerated the process of headward erosion. This led to the deep incision of the Cahora Bassa Gorge, to link the Lower and Middle Zambezi River systems (Key et al. 2015).

Continued headward erosion of the rejuvenated, and now predatory Zambezi River, led to successive captures of the Mana Pools and Gwembe Basin during the Neogene. These captures were achieved via the successive incision of the Mupata and Kariba Gorges (Figure 16.2). The resultant lowering of the base level of the Middle Zambezi caused the reversal in flow of this section of the river,

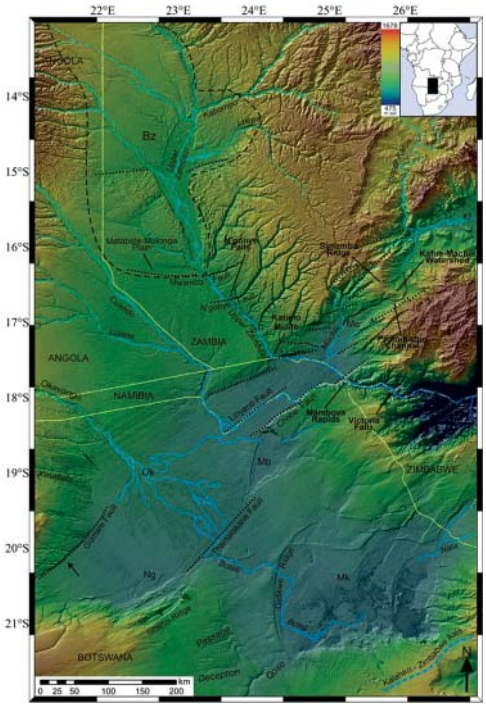


Figure 16.14 Digital elevation model (DEM) covering the upper Zambezi to the deeply incised Batoka Gorge immediately below Victoria Falls, and the Makgadikgadi basin (in the south of the image). The NE–SW oriented valley between the Upper Kafue and the Machili Flats is interpreted to represent the wind gap marking the abandoned channel of the Kafue when it was a north bank tributary of the Upper Zambezi. Note the marked faulting (dotted lines), linked to propagation of the East African Rift System into northern Botswana (see Figure 16.15a). Dashed line (NW of image) delineates the approximate extent of a major lake, designated Palaeo-Lake Bulozi, which developed on the upper Zambezi in the middle Pleistocene. Source: Moore et al. (2012). © 2012, Geological Society of South Africa. Bz,Palaeo-Lake Bulozi; Mb, Mababe Depression; Mc, Macili Graben; Mk, Makgadikgadi Pans; Ng, Lake Ngami; Ok, Okavango Delta.

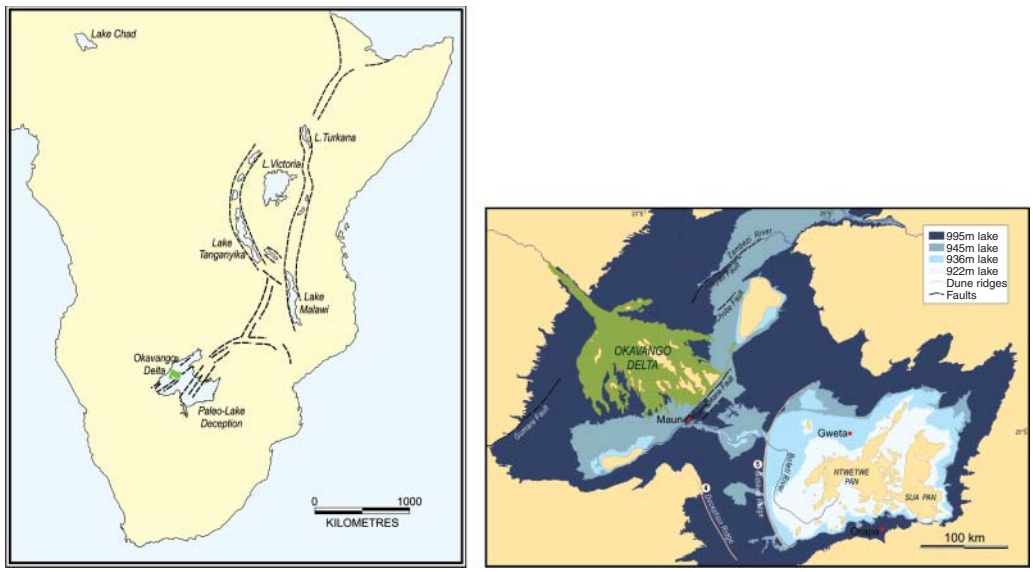
which previously flowed to the south-west (see above, Key et al. 2015).

Until relatively recently, the Middle-Lower and the Upper Zambezi were separate, isolated river systems. Early models to explain the amalgamation of these two stretches into the modern Zambezi generally invoked variants of headward erosion of the middle Zambezi or tributaries. Thus, Wellington (1955) suggested that the sharp change in direction of the modern river from a southerly to an easterly course just below the confluence of the north bank Songwe tributary represented a capture elbow (Figure 16.7).

The comprehensive drainage model of Moore et al. (2012) was summarized by Moore (2017). This model reconstructs how the linking of the two sections of the Zambezi was related to the development of a mega-lake, designated Palaeo-Lake Deception (PLD) (McFarlane and Eckardt 2006), within the Makgadikgadi basin on the Kalahari Plateau (Figure 16.13c). The Ntwetwe and Sowa Pans, together referred to as the Makgadikgadi Pans, are the modern desiccated relics of this major inland lake, which formed as a result of the propagation of the East African rift system (EARS) to the south-west into what is present-day northern Botswana (Figure 16.15a). At its greatest extent, bounded at a contour at ~995 m, PLD would have covered an area of 170 000 km^2, drowning the lower sections of the Upper Zambezi (McFarlane and Eckardt 2006) (Figure 16.15b). It is estimated that this major lake was initiated at approximately 2 Ma (Moore et al. 2012), although this date is not tightly constrained. The widespread structural control over these successive impoundments is represented in the numerous NE–SW trending faults across northern Botswana, which are partially obscured by recent sediments (Eckardt et al. 2016). A recent synthesis of structural and geophysical evidence confirms late Neogene rifting along the western faults of the Luangwa graben, which uplifted the Muchinga Escarpment and the Mporokoso plateau to its north; it is considered coeval with the formation of the Upper Kafue-Congo watershed. This evidence adds further support for the south-west extension of the EARS though the Kafue Flats and Machili basin into the Okavango-Makagdikgadi basins (Daly et al. 2020).

At the time of the initiation of PLD, bounded by the 995 m elevation contour, the Upper Chambeshi and Kafue Rivers formed a single drainage line, the Palaeo-Chambeshi, linked with the Upper Zambezi. This was the dominant river network sustaining the lake (Figure 16.13c). This former extensive drainage line would have flowed into the Makgadikgadi basin, debouching across the Machili Flats to sustain PLD. This major drainage line was disrupted by diversion of the Upper Chambeshi into the Luapula River, which resulted in a major decrease of the inflow and contraction of the palaeo-lake to a lower (945 m) shoreline, covering an area of some 65 000 km^2, similar to that of modern Lake Victoria (Figure 16.15b). Severance of the link between the Kafue and the Upper Zambezi and diversion of the former river to link with the middle Zambezi (Figure 16.13c) resulted in a further drop in water supply, and contraction of the lake to a 936 m shoreline. Subsequent further reductions in flow into the lake, linked to drainage reorganizations, resulted in its ultimate desiccation (Moore et al. 2012).

Compared to the skirting hinterland, the modern anomalously high rainfall over Lake Victoria provides an extant model for the local climatic forcing over a massive inland lake, maintained by evaporation off this large body of water. The resultant rainfall over the lake exceeds the local evaporation rates, such that a net surplus input sustains the lake at its lowest topographic level, where it overflows into the White Nile. A similar water balance likely maintained the extensive Makgadikgadi lake systems bounded by the 945 and 995 m shorelines, with outflow focused on the lowest point in the surrounding topography (Moore et al. 2012). It is suggested that, ultimately, overtopping from the Makgadikgadi lake was channelled into a mid-Zambezi tributary as the major effluent channel (Moore 2017). Because of the marked difference in elevation (which is 400–500 m) between the lake and the middle Zambezi, and marked increase in flow, this would have triggered rapid headward erosion



(a) (b)

Figure 16.15 (a) Location of the palaeo-lake of the Makgadikgadi basin in relation to the East African Rift System, which propagated to the south-west. (b) Areas covered by palaeo-lakes in the Makgadikgadi basin bounded by progressively lower shorelines. Sua and Ntwetwe Pans are the modern desiccated relics of this former extensive lake system.

by the middle Zambezi and incision of the Batoka Gorge.

Between the modern falls and the Songwe confluence, the Zambezi flows through a zigzag series of narrow gorges with either east-north-easterly or west-north-westerly orientations. The northern edges of these gorges are interpreted to represent earlier positions of the falls, controlled by faults and fracture lines (Wellington 1955). The Devil's cataract, on the western edge of the modern line of the falls is generally considered to mark the point where a new line of falls will develop.

The timing of the establishment of the link between the Upper- and Mid-Zambezi is not tightly constrained. However, Derricourt (1976) notes that high-level gravels, now isolated from 110 to >250 m above the Zambezi, were laid down by the river before and during the upstream migration of the falls (Clark 1950). Gravels above the eastern end of the Western Batoka Gorge are tentatively ascribed an Early Pleistocene age, suggesting that the capture was of a similar vintage. This evidence accords well with the inferred Early Pleistocene age for the initiation of the Makgadikgadi Lake system (Moore et al. 2012).

The Early Pleistocene capture of the Upper Zambezi by the Middle Zambezi was followed by a complex series of drainage reorganizations on the Kalahari Plateau, including and beyond the point where the boundaries of Botswana, Zimbabwe, Zambia, and Namibia meet (locally termed the Four Corners Area). The low relief of the area (an undulating plain generally between 900 and 1100 m in altitude), coupled with tectonic activity along faults with a north-east–south-west orientation (e.g. Chobe and Linyanti Faults; Figure 16.14), transverse to the major drainage lines (Reeves 1972), played a major role in these changes to the drainage system.

Uplift along the Linyanti Fault (Figures 16.2 and 16.14) diverted the Cuando from a former south-easterly course (across northern Botswana) to the north-east to link with the Zambezi via the Linyanti-Chobe floodplain. Similarly, uplift along the Chobe Fault (Figure 16.14) initiated sedimentation by the Zambezi, lowering the grade of the river, and leading to the development of the Chobe floodplain. The younger sediment associated with these floodplains overlie earlier deposits that extend north-east, via the Machili Basin towards the Kafue Flats, and south-west into northern Botswana beneath the modern alluvial deposits of the Okavango Delta.

To the north-east of the Machili Flats, the sharp change of the course of the Kafue from southerly to easterly immediately upstream of the Kafue Flats (Figure 16.2) was interpreted to be a capture elbow (Dixey 1945; Bond 1963) where the upper reaches of the river were captured by a north bank tributary of the Middle Zambezi. Headward erosion of the latter is logically ascribed to the lowering of base level of the Middle Zambezi following capture of the Mana Pools Basin by the Lower Zambezi. The deep Kafue Gorge, a little above the confluence with the Middle Zambezi, would reflect accelerated erosion associated with this base level lowering, coupled with the enhanced flow resulting from the capture of the headwaters. Although the timing of the capture is not well constrained, recent fieldwork has identified a lacustrine sequence of carbonate sediments that reflect the former existence of a major lake (designated Lake Patrick, Figure 16.13c), with an estimated former area of 17 000 km^2, that covered most of the Kafue Flats during early to mid-Pleistocene times (Simms 2000). More fieldwork is required to refine our understanding of the origin and duration of Lake Patrick. However, it may have been initiated by faulting across the Palaeo-Kafue that severed the former link to the Upper Zambezi. If so, the Kafue Flats floodplain is the relict of this lake, which would have been drained following capture by a Middle Zambezi tributary. Lake Patrick, and the later Kafue Flats floodplain are thus interpreted to reflect the early stages of river piracy in an area of low relief before the upper sections of the river had graded to

the lowered base level. The evidence therefore tentatively suggests a mid-Pleistocene age for beheading of the Upper Kafue and subsequent capture by the Middle Zambezi (Moore et al. 2012).

North-east of the Kafue headwaters, the Chambeshi River follows a south-westerly course before swinging sharply to the north, becoming the Luapala – a headwater tributary of the Congo River (Figure 16.13c). This sharp change in course suggests a capture elbow, and that the Chambeshi originally constituted the headwaters of the Kafue (Figure 16.13c). As yet, it is not possible to date this capture with direct geomorphological evidence, but its disruption is constrained in the Early Pleistocene, based on genetic evidence (discussed below) including closely related species of lechwe antelopes, and fishes (Cotterill and de Wit 2011; Goodier et al. 2011; Cotterill et al. 2016).

Williams (1986) suggested that the formation of the Barotse floodplain was linked to tectonic uplift, which formed the Bulozi graben (Cotterill 2006a; Moore et al. 2012) and recent geophysical and structural evidence supports recent incipient rifting that is also expressed in the Kabompo and Luansanza Rift rifts, due east of the Bulozi rift (Daly et al. 2020). While the precise nature of this uplift is not well understood, many of the east bank Zambezi tributaries in the south of the floodplain (Figure 16.1) exhibit remarkably linear north-east–south-west courses, parallel to the major faults to the south. This suggests that the Barotse floodplain developed as a result of a lowering of the gradient caused by faulting across the line of the Upper Zambezi, coupled with the resultant sedimentation (Moore et al. 2012). Clark (1950) describes a ferricrete bar with embedded Middle Stone Age (MSA) lithic artefacts on the Zambezi riverbed above Ngonye Falls (Figure 16.2). This attests to a period of sub-aerial exposure, pointing to impoundment of the river above the falls, designated Palaeo-Lake Bulozi (Moore et al. 2012, Figure 16.14). A minimum age of 300 000 years on early MSA tools (Barham and Smart 1996; McBrearty and Brooks 2000) indurated in the ferricrete likely underestimates timing of the impoundment of the Palaeo-Lake Bulozi maintained by the Upper Zambezi (Cotterill 2006a; Moore et al. 2012). The resultant decrease in river gradient would, in turn, have lowered base-levels of the Upper Zambezi tributaries. Because of the low relief of the area, this would have disrupted these drainages, with lines of dambos and pans marking their original courses.

The Cuando floodplain probably has a tectonic origin similar to that suggested for the Barotse floodplain. The Cuando and Barotse floodplains are linked via the Mulongo-Matebele plain (Figures 16.1 and 16.13c), which, from DEM images, appears to be an abandoned channel that originally linked the upper Cuando and the upper Zambezi. This interpretation is supported by the identification of basal Kalahari diamond-bearing gravels underlying the Mulonga-Matabele floodplain (Motapa Diamond Inc., press release, 2005). The tenure of this former link and timing of abandonment is poorly constrained at present (Moore et al. 2012). Wellington (1955) noted that outflow from the Okavango into the Linyanti (lower Cuando), and thence into the Zambezi, sometimes occurs via the Selinda spillway (Figure 16.14). He interprets this to reflect the incipient stages of capture of the Okavango by the Zambezi.

Patterns in distributions of certain fishes in the modern Zambezi testify to the radical changes in the landscape that forged its modern configuration. This geophysical evolution simultaneously enriched its biota. An excellent example is seen in the tigerfishes, *Hydrocynus vittatus* species complex, among the most charismatic of African fishes. These ferocious predators are widely distributed through many of the continent's tropical freshwaters (Figure 16.16). The earliest fossil teeth of *Hydrocynus* are recorded from scattered Eocene beds in southern Namibia and North Africa (Pickford 2018). A Pan-African

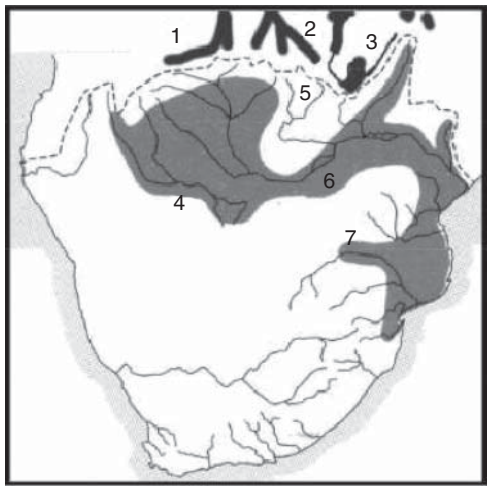


Figure 16.16 Distribution of the tigerfish (*Hydrocynus vittatus* species complex). Dark grey: tributaries of the Congo River (1, Kasai; 2, Lufira; 3, Upper Chambeshi-Luapula). Lighter grey: drainages south of the Southern Equatorial Divide (4, Okavango; 5, Kafue; 6, Zambezi; 7, Limpopo). Source: Modified from Moore et al. (2012).

phylogeographical study (Goodier 2010; Goodier et al. 2011) compared mtDNA sequence data of 10 living species. The results constrained the Early Neogene origin of extant tigerfishes in the Congo basin, which seeded dispersals of ancestral *Hydrocynus* on to the Tanzanian plateau, and then south-west across the wetland archipelago of the Kalahari Plateau. Subsequently, speciation of *H. vittatus* in the Upper Zambezi-Cubango system coincided with the Early Pleistocene breakup of the first-order tributaries of the Palaeo-Chambeshi, which also isolated endemic populations of tigerfishes in the Lufubu River, and Lakes Bangweulu and Mweru, respectively. In the Mid-Pleistocene, this population of *H. vittatus* seeded a northward dispersal out of the Upper Zambezi, into the Congo Basin, which most likely coincided with the capture of a major Upper Zambezi headwater by the Kasai, a north-flowing Congo tributary. Most recently, in the Late Pleistocene, tigerfishes dispersed downstream, via the Batoka gorges – east and then south – as far as southern Mozambique, and Mpumalanga and Kwa-Zulu-Natal in South Africa (Goodier 2010; Goodier et al. 2011).

Recent research has mapped out the southern extent of the Lower Kalahari Aquifer (LKA) straddling the eastern Caprivi Region and north-east Botswana, where it is maintained within a succession of alluvial and lacustrine sediments. Its origins appear to predate the incremental rifting that formed the Makgadikgadi palaeo-lakes, whose sediments overlie older fluvio-deltaic sediments. Robust dates on the original inception of this vast reservoir of fossil groundwater are challenging to constrain, but the tenure of the LKA substantially exceeds 100 ka (Bäumle et al. 2019).

The congruence of formative events with changes to the major rivers highlights, and indeed reinforces, our insights into recent geomorphological evolution of the Zambezi and neighbouring drainage. These movements of tigerfishes have, nonetheless, been contained downstream of distinct waterfalls; and two conspicuous gaps in their modern distribution (Figure 16.16) are especially interesting. Tigerfishes are absent from the Shire River (and thus Lake Malawi) above the Shire Falls. Dispersals through the Zambezi have been contained downstream of a similar physical barrier in the Kafue Gorge, which prevents tigerfishes form reinvading the Upper Kafue system, where an isolated population of *Hydrocynus* had gone extinct in the Proto-Kafue basin (Goodier 2010; Goodier et al. 2011).

16.6 Drainage Evolution and Speciation

The Zambezian region, and in particular the Upper Zambezi Basin, hosts a rich flora and fauna, making the area one of the world's 'hotspots' in terms of biodiversity and endemic species (White 1965, 1983). This diversity is in turn a reflection of pulses of speciation and the evolution of many endemic organisms in

the roughly 5 million years since the end of the Miocene. Examples of the rich biota of the Upper Zambezi are presented below, and the factors responsible for driving speciation are then considered. These underline the close link between evolutionary and geological processes.

The Upper Zambezi Basin lies in the centre of the Zambezian phytochorion (centre of plant endemism). At 3.77 million square kilometres, this phytochorion is the largest of all of Africa's nine principal centres of plant evolution. Its significance is exemplified in the occurrence of 53% endemic species of flowering plants in a total flora of no less than 8500 species (White 1983). The headwaters of the Upper Zambezi lie within Africa's richest region of flowering plants – the Katanga-Bemba region of the Zambezian phytochorion. The magnitude of this richness can be gauged by the statistic of at least 180 endemic species of flowering plants recorded only in the degree square in which the Upper Kafue River rises (12°S; 29°E). This zone of uniqueness extends along the SED (Figures 16.1 and 16.2): from north-east Angola across the source of the Zambezi in the Ikelenge pedicle (the narrow, north-oriented finger of land in the extreme north-west of Zambia) through Katanga and northern Zambia, and east to Lakes Tanganyika and Malawi (Linder 2001). No less than 3000 species of flowering plants have been recorded within this Katanga–Bemba region (Malaisse 1997).

The dambos associated with the Upper Zambezi have been a focus of major speciation, with an abundance of cryptophytic plants – or geoxylic suffrutices – aptly named underground trees because almost all the trunk and stems of these plants are buried. No less than 102 species in 55 genera of 30 families have been recorded in catchments of the Upper Zambezi, especially on the Kalahari sands. The closest relatives to many of these cyptophytes are large savannah trees. In fact besides their very different growth forms, these pairs of species (one a large tree, the other an inconspicuous suffrutex) are often very difficult to tell apart (White 1976; Zigelski et al. 2019).

This richness of endemic plants in the Zambezian region is complemented in the fauna. This can be seen in better-studied insect groups, especially the Lepidoptera. Beautiful butterflies of the genus *Charaxes* (Nymphalidae) include endemic species whose larvae feed on Zambezian plants such as *Brachystegia* (Henning 1988). The Upper Zambezian headwaters are further characterized by a notable richness in fishes, dragonflies, and reptiles, as well as certain mammals and birds. Thus, several birds are restricted to the dambos and floodplains of the Upper Zambezi. These include three species of longclaw (Fulleborn's, Grimwood's, and Rosy-chested); White-throated francolin (*Peliperdix albogularis meinertzhageni*) endemic to the wide dambos of the Upper Zambezi and eastern Angola; and several cryptic species of passerine birds – especially cisticolas, including the aptly named Dambo Cisticola (Cotterill 2006b). Another interesting example of speciation is the explosive evolution of molerats, revealed by recent research across western and central Zambia, with no less than 17 different chromosome forms, comprising six recognized species (van Daele et al. 2004). The most charismatic of the mammals is the puku (*Kobus vardonii*). The range of this dambo specialist is centred on the Zambezian region.

The endemism is further illustrated by the fragmented distributions of five isolated species of lechwe across south-central Africa. These semi-aquatic antelope are respectively endemic to Bangweulu (Black lechwe, *Kobus smithemani*), Kafue Flats (Kafue lechwe, *Kobus leche kafuensis*), with the apparently more widely distributed Red lechwe (*K. leche*) in the Okavango-Linyanti and Upper Zambezi floodplains. Roberts' lechwe (*Kobus robertsi*) occurred in floodplains of the Kalungwishi and Luongo Rivers between Lakes Bangweulu and Mweru, but is now extinct. The recently described Upemba lechwe (*Kobusanselli*)

(Cotterill 2005) endemic to the Kamalondo depression (in the Upemba swamps of the Democratic Republic of Congo, over 300 km north of the SED) is especially interesting, because its distribution indicates former links with rivers across a much wider area. Equally interesting, is an isolated population of lechwes in central Angola, on the northern side of the SED in swamps in the headwaters of the Cuanza and Luando Rivers, which eventually flow into the Atlantic Ocean. These lechwes have therefore speciated across an archipelago of wetlands represented today across the upper Congo, Okavango, and Upper Zambezi drainage systems (Cotterill 2004, 2005, 2006a).

Several determinants can be singled out for not only just a high richness of species but also evolution of so many endemics, especially in the sub-regions (Barotse and Katanga-Bemba) within the Zambezi Basin. One has involved vicissitudes in climate, which especially through the Pleistocene, caused habitats to expand and contract sequentially. Evidence for these climatic fluctuations comes from major east–west *alab* dunes in south-western Zambia, north-western Zimbabwe, and straddling the northern border between Botswana and Namibia. These dunes reflect at least three different episodes when the climate was considerably more arid than at present (Lancaster 2000). During Pleistocene inter-glacials, moist evergreen forests, rich in Guineo-Congolian plants were widespread. Fragments of these forests are today restricted to headwaters of the Zambezi and Congo Rivers and along the plateau ridges. This interplay between alternating expansions and contractions of evergreen forest versus savannahs invokes responses to switches in Plio-Pleistocene climates. This climatic forcing accounts for many, but not all, speciation events (Cotterill 2011).

The formation and then fragmentation of wetlands by river piracy, particularly during the Pleistocene, has been an equally significant agent of pulses of speciation. Drainage evolution of the Palaeo-Chambeshi system has been invoked as the primary cause of the recent evolution of the molerats (van Daele et al. 2004; Cotterill and de Wit 2011). The influence of river piracy is particularly well illustrated by speciation of the Lechwe antelopes. Originally, ancestral lechwe populations would have occurred more widely along the Okavango, Upper Zambezi, and Palaeo-Chambeshi catchments. There is strong evidence for the last-mentioned formerly draining much of Katanga and north-east Zambia and linked with the Kafue, although it is now part of the Congo Basin (Figure 16.13c). Contiguous habitat of these widely distributed aquatic antelopes was fragmented subsequently by late Plio-Pleistocene river piracy, leading to speciation in discrete wetlands (Cotterill 2004, 2005). The isolated lechwe population in central Angola, discussed previously, is plausibly explained by headwater capture of originally south-flowing drainages by the Cuanza River. Genetic studies reveal these different lineages of antelopes became isolated in the Middle Pleistocene, and thus refine our understanding of wetlands established after river piracy events (Cotterill 2006a; Cotterill and de Wit 2011).

The speciation of birds and plants endemic to dambos suggests that these habitats in Barotseland may have been important refuges during Pleistocene interpluvials when the surrounding vegetation was much more arid. Many of the larger moisture dependent savannah trees (e.g. *Parinari* and *Syzygium*) would have retreated far north as components of mesic savannahs. The dominant vegetation across the Zambezian plateau in arid interpluvials was likely similar to the central Kalahari today, with arid adapted trees in valleys and grassy dunes (Barham 2000). The current co-existence of *Parinari capensis* and *Parinari curatellifolia* along dambo margins in south-central Africa represents a remarkable circumstance that provides a snapshot of species' contractions and dispersions in the dynamics of palaeoenvironment.

The dramatic radiation of geoxylic suffrutices, or 'under-ground trees' across the Upper Zambezi valley (the area known as Barotseland) has been ascribed to the interplay between several factors (Zigelski et al. 2019). White (1976) notes that their characteristic habit is seasonally waterlogged anaerobic grassland, mostly on extremely oligotrophic (nutrient-poor) Kalahari sands. This habitat forms as a result of the high water table in summer and is particularly characteristic of the edges of the dambos that fringe the Upper Zambezi. Large trees are unsuited to this environment as their roots do not survive in waterlogged anaerobic conditions. White (1976) suggests that it was these inhospitable conditions that provided the trigger for large woodland tree species to adopt the suffretex growth form, leading to speciation. He inferred that such speciation appears recent, most likely Pleistocene, and that this pulse of diversification 'merely sharpened the edges of taxa which began their differentiation a very long time before' (White 1976, p. 67).

White (1976) however noted that such evolution is unlikely to have taken place by woodland tree species invading the dambos under stable conditions – they would simply not survive to colonize such an inhospitable environment. Rather, the more likely scenario has entailed gradual evolution of suffretex adaptations by these plants to correspondingly slow changes in their environments. So it appears that these Zambezian suffrutices tracked formation of the dambos. White (1976) further suggested that the latter in turn formed in response to the effects of tectonism in an area of low relief. This prescient suggestion is consistent with the proposed evolution of the Barotse floodplain and associated dambos by faulting across the line of the river, as discussed above. The resulting lowering of river gradients in turn initiated high summer water tables. The geoxylic suffrutices of the Barotseland area thus provide a fine illustration of geological processes driving speciation.

16.7 Cultural and Economic Aspects

Early Stone Age (ESA) artefacts recovered along the course of the Zambezi and its tributaries (Dixey 1945; Clark 1950; Derricourt 1976; Barham and Mitchell 2008) attest to lengthy human occupation of the Zambezi Basin. It has been suggested that in the Plio-Pleistocene, the mosaic of woodlands and dambos on the Zambezian plateau would have provided a suitable habitat for hominins that, despite the present lack of fossil remains, may have flourished in this area (Moore et al. 2012). The underground forests of cryptophytes would have been a most reliable food resource for hominins with requisite knowledge: a widespread and abundant source of carbohydrates (especially starch) in Zambezian dambos that extends into woodlands on Kalahari sand. Indeed, today, the San hunter-gatherers possess an intimate and indeed encyclopaedic knowledge of a wealth of edible plants, including these particular cryptophytes. Acknowledgement of the potentially important role of the Zambezian region in human evolution places some ecogeographical objectivity to dominant entrenched views of hominin evolution. These focus on South and East Africa, with special devotion to the 'East side story' founded in the abundant fossil deposits of the East African Rift (O'Brien and Peters 1999).

Today, human economics and culture are intimately linked to the changing character and seasonal cycles of the Zambezi. This is strikingly exemplified on the Barotse floodplain of western Zambia, which is home to the Lozi, who have their origins in the great Lunda-Luba Empire of the Congo Basin and probably arrived in these parts in the late seventeenth century. Comparative isolation allowed them to develop instruments of government that helped the nation exist as a political entity for more than 200 years and to have survived 40 years of domination by a migrant Sotho group, in the nineteenth century. Historically, the Lozi witnessed the first

tentative steps of foreigners crossing the continent: Arab traders from Zanzibar, Mambaris (slavers) from what would become Angola, and Livingstone's double crossing of the continent in the late 1850s.

Inasmuch as people are shaped by the land in which they live, so the life and lore of the Lozi reflects the annual surges of the Zambezi's waters. Each year, high rainfall on the watershed impels the Zambezi to rise above its low banks and to begin its inundation of the great plains of western Zambia. Grasses, stimulated by the abundance of moisture, put on a sustained spurt of growth, which outpaces the rising flood. In this way a carpet of green shades the entire plain, sometimes standing a metre or more above it, creating the illusion of limitless meadow. The Lozi, who are pastoralists and agriculturalists, move ahead of the waters to the higher land that demarcates the eastern edge of the floodplains and return with their cattle and hoes when the waters recede. Centuries have shaped an elaborate and extremely colourful ceremony that marks these events.

Kuomboka is the annual ceremonial departure of the Lozi king and his counsellors from the flooded plains to the dry mainland. It symbolizes the king's leadership and the loyalty of his people and recognizes the dominating role of the annual flood in the lives of the Lozi. The move by boat is from the island of Lealui over 10 km from the mainland at Mongu. Royalty travel in splendid barges poled by bare-chested Indunas. The inhabitants, forbidden to leave before the king, follow in numerous smaller vessels.

To announce Kuomboka, the Maoma, or royal drums, are sounded a day or two before and, being heard from 15 km, echo through the night in dramatic style. Kuomboka itself is an unforgettable spectacle with reds, black, white, and greens swirling in a kaleidoscope of dizzying, merging colours. Fleets of wooden canoes, the stately passage of Nalikwanda and Notila (the royal barges), the swift and sleek 'spy boats' that quest for passage and safety ahead of the procession all add to an extraordinary sight, unchanged since long before colonial times. One hundred and twenty men pole the great barge on which the royal orchestra, composed of drums and Lozi xylophones, fills the air with a deep and throbbing rhythm. It is an occasion of splendour, of colour, but, above all, a celebration of seasonable pulse of the river itself.

16.8 Conclusion

The readily accessible stretches of the Zambezi and its major tributaries provide a reliable perennial water source and thus an important focus of human settlement. Demands from humans have increased, and now increasingly determine the future of the flow regimes, and the riparian neighbourhood of the Zambezi. Less and less of its course escapes these demands and growing impacts. The first really major perturbation was the construction of the Kariba and Cahora Bassa Dams, creating two major man-made lakes. Two more – at Batoka and Mupata – are planned.

The major theme running through this chapter is the intimate link between geological, ecological, and evolutionary processes, which have shaped the Zambezi River since its Gondwana origins over 280 Ma. A clear understanding of these interwoven threads is critical to developing management plans for the Zambezi system as a whole. The large areas set aside as wilderness areas in the mid-Zambezi are coming under increasing pressure – from poaching, demands of tourism and, in accessible areas, demands for agricultural land. The war waged over several decades against the tsetse fly has greatly reduced this natural barrier to settlement of wild areas, as exemplified in the Dande, Sebungwe, and Urungwe catchments of the mid-Zambezi in northern Zimbabwe. The widespread use of persistent pesticides in exterminating the tsetse fly has also conferred expensive environmental impacts (Douthwaite and Tingle 1994). These impacts are compounded by the spread of rural subsistence agriculture across large areas of previously sparsely populated semi-arid savannah following elimination of the tsetse fly (du Toit and Cumming 1999). These

pressures require a balancing of aesthetic and economic concerns with ecological and geological constraints.

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References

Barham, L. (2000). The palaeobiogeography of central Africa. In: *The Middle Stone Age of Zambia, South Central Africa* (ed. L. Barham), 223–236. Bristol: Western Academic and Specialist Press.

Barham, L. and Mitchell, P. (2008). *First Africans: African Archaeology from the Earliest Tool Makers to Most Recent Foragers (Cambridge World Archaeology)*. Cambridge University Press.

Barham, L.S. and Smart, P.L. (1996). An early date for the Middle Stone Age of central Zambia. *Journal of Human Evolution* 30: 287–290.

Bäumle, R., Himmelsbach, T., and Noell, U. (2019). Hydrogeology and geochemistry of a tectonically controlled, deep-seated and semi-fossil aquifer in the Zambezi region (Namibia). *Hydrogeology Journal* 27: 885–914.

Bond, G. (1963). Pleistocene environments in southern Africa. In: *African Ecology and Human Evolution* (eds. F.C. Howell and F. Bouliere), 308–334. Chicago: Viking Fund Publications in Anthropology/Aldine.

Bowmaker, A.P., Jackson, P.N., and Jubb, R.A. (1978). Freshwater fishes. In: *Biogeography and Ecology of Southern Africa* (ed. M.J.A. Werger), 1181–1230. The Hague: W.H. Junk.

Broderick, T.J. (1990). An interpretation of the geology of the Cabora Bassa basin, mid-Zambezi Valley. *Annals of the Zimbabwe Geological Survey* XIV (1988–1989): 1–11.

Clark, J.D. (1950). *The Stone Age Cultures of Northern Rhodesia*. Claremont: Southern African Archaeological Society.

Cooke, H.J. (1980). Landform evolution in the context of climatic change and neo-tectonism in the middle Kalahari of northern central Botswana. *Transactions of the Institute of British Geographers* 5: 80–99.

Cotterill, F.P.D. (2004). Drainage evolution in south-central Africa and vicariant speciation in swamp-dwelling weaver birds and swamp flycatchers. *The Honeyguide* 25 (1): 7–25.

Cotterill, F.P.D. (2005). The Upemba Lechwe, *Kobus anselli*: an antelope new to science emphasizes the conservation importance of Katanga (south-central Africa). *Journal of Zoology* (London) 265: 113–132.

Cotterill, F.P.D. (2006a). The evolutionary history and taxonomy of the *Kobus leche* species complex of south-central Africa in the context of Palaeo-drainage dynamics. PhD thesis. University of Stellenbosch.

Cotterill, F.P.D. (2006b). Taxonomic status and conservation importance of the avifauna of Katanga (southeast Congo Basin) and its environs. *The Ostruch* 77: 1–21.

Cotterill, F.P.D. (2011). Biogeographical overview of the Lunda region. In: *Rapid Biodiversity Assessment of the Carumbo Lagoon Area, Lunda Norte, Angola. Expedition Report* (ed. B.J. Huntley), 76–99. Republic of Angola. Part II,: Department of Environment.

Cotterill, F.P.D. and de Wit, M.J. (2011). Geoecodynamics and the Kalahari Epeirogeny: linking its genomic record, tree of life and palimpsest into a unified narrative of landscape evolution. *South African Journal of Geology* 114: 489–514.

Cotterill, F.P.D., Nagy, B., Watters, B., and Bellstedt, D.U. (2016). Tracking Quaternary and Neogene landscape evolution through the geoecodynamics of fishes: unique proxy of

tenures and mode of Africa's dambos and depocentres. *Quaternary International* 404 (2016): 174–213.

Cox, K.G. (1989). The role of mantle plumes in the development of continental drainage patterns. *Nature* 342: 873–876.

van Daele, P.A.A.G., Dammann, P., Meier, J.L. et al. (2004). Chromosomal diversity in mole-rats of the genus *Cryptomys* (Rodentia: Bathyergidae) from the Zambezian region: with descriptions of new karyotypes. *Journal of Zoology* (London) 264: 317–326.

Daly, M.C., Green, P., Watts, A.B. et al. (2020). Tectonics and landscape of the Central African Plateau, and their implications for a propagating Southwestern Rift in Africa. *Geochemistry, Geophysics, Geosystems* https://doi.org/10.1029/2019GC008746.

Davies, B.R. (1986). The Zambezi River system. In: *The Ecology of River Systems* (eds. B.R. Davies and K.F. Walker), 225–267. Dordrecht: Dr W. Junk.

Derricourt, R.M. (1976). Retrogression rate of the Victoria Falls and the Batoka Gorge. *Nature* 264: 23–25.

Dingle, R.V., Siesser, W.G., and Newton, A.R. (1983). *Mesozoic and Tertiary Geology of Southern Africa*. Rotterdam: A.A. Balkema. 375 pp.

Dixey, F. (1945). The geomorphology of Northern Rhodesia. *Proceeding Transactions of the Geological Society of South Africa* 47: 9–45.

Douthwaite, R.J. and Tingle, C.C.D. (1994). *DDT in the Tropics: The Impact on Wildlife in Zimbabwe of Ground-Spraying for Tsetse Fly Control*. Chatham: Natural Resources Institute.

Dunham, K.M. (1989). Vegetation-environment relations of a Middle Zambezi floodplain. *Vegetatio* 82: 13–24.

Eckardt, F.D., Cotterill, F.P.D., Flügel, T.J. et al. (2016). Mapping the surface geomorphology of the Makgadikgadi Rift Zone (MRZ). *Quaternary International* 404: 115–120.

Frost, P.H., Timberlake, J.R., and Chidumayo, E. (2002). Miombo-mopane woodlands and grasslands. In: *Wilderness: Earth's Last Wild Places* (ed. P. Robles Gil), 182–204. Washington, D.C.: Cemex Conservation International.

Gaigher, I.G. and Pott, R.M.C. (1973). Distribution of fishes in southern Africa. *South African Journal of Science* 69: 25–27.

Goodier, S.A.M. (2010). Evolution of the African tigerfish (Genus *Hydrocynus*): insights into drainage evolution. MSc thesis. University of Cape Town.

Goodier, S.A.M., Cotterill, F.P.D., O'Ryan, C. et al. (2011). Phylogeny of African Tigerfish (genus *Hydrocynus*) reveals palaeogeographic signatures of linked Neogene geotectonic events. *PLoS One* 6 (12): e28775. https://doi.org/10.1371/journal.pone.0028775.

Goyder, D.I. and Gonçalves, F.M.P. (2019). The flora of Angola: collectors, richness and endemism. In: *Biodiversity of Angola* (eds. B.J. Huntley, V. Russo, F. Lages and N. Ferrand), 79–96. Springer Open. https://doi.org/10.1007/978-3-030-03083-4_6.

Grove, A.T. (1969). Landforms and climatic change in the Kalahari and Ngamiland. *The Geographical Journal* 135: 191–212.

Haddon, I.G. (2000). Kalahari Group sediments. In: *The Cenozoic of Southern Africa, Oxford Monographs on Geology and Geophysics*, vol. 40 (eds. T.C. Partridge and R.R. Maud), 173–182. Oxford University Press.

Harrison, G.P. and Whittington, H.W. (2002). Susceptibility of the Batoka Gorge hydroelectric scheme to climate change. *Journal of Hydrology* 264: 230–241.

Henning, S.P. (1988). *The Charaxinae Butterflies of Africa*. Aloe Books/Frandsen.

Holechek, J. and Valdez, R. (2018). Wildlife conservation on the rangelands of eastern and southern Africa: past, present, and future. *Rangeland Ecology & Management* 71: 245–258.

Jackson, P.B.N. (1961). *The Fish of the Middle Zambesi*. Trustees of the National Museums of Southern Rhodesia.

Jackson, P.N.B. (2000). Freshwater fishery research organisations in central and eastern

Africa: a personal reflection. *Transactions of the Royal Society of South Africa* 55: 1–81.

Key, R.M., Cotterill, F.P.D., and Moore, A.E. (2015). The Zambezi River: an archive of tectonic events linked to the amalgamation and disruption of Gondwana and subsequent evolution of the African Plate. *South African Journal of Geology* 118: 425–438. https://doi.org/10.2113/gssajg.118.4.425.

Lamplugh, G.W. (1907). Geology of the Zambezi basin around Batoka Gorge. *Quarterly Journal of the Geological Society* 63: 150.

Lancaster, N. (2000). Eolian deposits. In: *The Cenozoic of Southern Africa*, Oxford Monographs on Geology and Geophysics, vol. 40 (eds. T.C. Partridge and R.R. Maud), 73–87. Oxford University Press.

Linder, H.P. (2001). Plant diversity and endemism in sub-Saharan tropical Africa. *Journal of Biogeography* 28: 169–182.

Main, M. (1990). *Zambezi. Journey of a River*. Southern Book Publishers. 313 pp.

Malaisse, F. (1997). *Se Nourrir en Forêt Claire Africaine: Approache écologique et nutrionnelle*. Gembloux: Presses Agronomiques de Gembloux.

McBrearty, S. and Brooks, A.S. (2000). The revolution that wasn't: a new interpretation of the origin of modern human behaviour. *Journal of Human Evolution* 39: 453–563.

McCarthy, T.S., Cooper, G.J.R., Tyson, P.D., and Ellery, W.N. (2000). Seasonal flooding in the Okavango Delta, Botswana – recent history and future prospects. *South African Journal of Science* 96: 25–33.

McFarlane, M.J. (1995). Pans and Dambos of Western Province, Zambia. Backstopping mission, 15–30 August 1995. Department of Agriculture, Ministry of Agriculture, Food and Fisheries, Mongu, Western Province, Zambia. Open File Report.

McFarlane, M.J. and Eckardt, F.D. (2006). Lake deception: a new Makgadikgadi palaeolake. *Botswana Notes and Records* 38: 195–201.

Mendelsohn, J. (2019). Landscape changes in Angola. In: *Biodiversity of Angola* (eds. B.J. Huntley, V. Russo, F. Lages and N. Ferrand), 123–137. Springer Open. https://doi.org/10.1007/978-3-030-03083-4_6.

Moore, A.E. (1988). Plant distribution and the evolution of the major river systems in southern Africa. *South African Journal of Geology* 91: 346–349.

Moore, A.E. (1999). A reappraisal of epeirogenic flexure axes in southern Africa. *South African Journal of Geology* 102: 363–376.

Moore, A.E. (2017). The Victoria Falls and gorges – landscape of the angels. In: *Africa's Top Geological Sites* (eds. C. Ahhhaeusser, M. Viljoen and R. Viljoen), 16–20. Struik Nature.

Moore, A.E. and Blenkinsop, T. (2002). The role of mantle plumes in the development of continental-scale drainage patters: the South African example revisited. *South African Journal of Geology* 105: 353–360.

Moore, A.E. and Larkin, P.A. (2001). Drainage evolution in south-central Africa since the break-up of Gondwana. *South African Journal of Geology* 104: 47–68.

Moore, A.E. and Moore, J.M. (2006). A glacial ancestry for the diamondiferous gravels at Somabula, central Zimbabwe. *South African Journal of Geology* 109: 625–636.

Moore, A.E., Cotterill, F.P.D., and Eckardt, F.D. (2012). The evolution and ages of Makgadikgadi palaeo-lakes: consilient evidence from Kalahari drainage evolution, south-central Africa. *South African Journal of Geology* 115: 385–413.

Nairn, A.E.M., Lerche, I., and Lliffe, J.E. (1991). Geology, basin analysis, and hydrocarbon potential of Mocambique and the Mocambique Channel. *Earth-Science Reviews* 30: 81–124.

Nash, D. and Eckardt, F.D. (2016). Drainage development, neotectonics and base-level change in the Kalahari Desert, southern Africa. *South African Geographical Journal* 98: 308–320.

Ncube, S., Beevers, L., and Hes, E.M. (2013). The interactions of the flow regime and the terrestrial ecology of the Mana floodplains in

the middle Zambezi river basin. *Ecohydrology* 6: 554–566.

Nugent, C. (1986). Historical changes in the behaviour of the Zambezi river at Nyamuomba. *Zimbabwe Science News* 20 (9): 121–131.

Nugent, C. (1990). The Zambezi River: tectonism, climatic change and drainage evolution. *Palaeogeography, Palaeoclimatology, Palaeoecology* 78: 55–69.

O'Brien, E.M. and Peters, C.R. (1999). Landforms, climate eco-geographic mosaics, and the potential for hominid diversity in Pliocene Africa. In: *African Biogeography, Climate Change, and Human Evolution* (eds. T.G. Bromage and F. Schrenk), 115–137. Oxford: Oxford University Press.

Oesterlen, P.M. and Millsteed, B.D. (1994). Lithostratigraphy, palaeontology, and sedimentary environments of the western Cabora Bassa Basin, Lower Zambezi Valley, Zimbabwe. *South African Journal of Geology* 97: 205–224.

Pickford, M. (2018). Freshwater aquatic and aquaphile vertebrates from Black Crow (Ypresian/Lutetian, Namibia) and their palaeoenvironmental significance. *Communications of the Geological Survey of Namibia* 18: 26–37.

Potter, P.E. (1978). Significance and origin of big rivers. *Journal of Geology* 86: 13–33.

Potter, P.E. and Hamblin, W.K. (2006). *Big Rivers Worldwide*, vol. 48, 1–78. USA: *Brigham Young University Geology Studies*.

Price, D.J., Calder, I.R., and Hall, R.I. (1998). *Water Balance of African Lakes*. Wallingford: Institute of Hydrology. 72 pp.

Reeves, C.V. (1972). Rifting in the Kalahari? *Nature* 237: 95–96.

Reeves, C.V. (1978). A failed Gondwana spreading axis in southern Africa. *Nature* 273: 222–223.

Scholz, C.H., Koczynski, T.A., and Hutchins, D.G. (1976). Evidence for incipient rifting in southern Africa. *Geophysical Journal Astronomical Society* 44: 135–144.

Shoko, D.S.M. (1998). The tectono-sedimentary relationships within the Cabora Bassa basin, Zambezi Rift, with special emphasis on the Dande Sandstone Formation. PhD thesis. University Zimbabwe. 312 pp. plus appendices.

Simms, M.F. (2000). Appendix A. Preliminary report on Lake Patrick. In: *Middle Stone Age of Africa* (ed. L. Barham), 275–280. Bristol: Western Academic and Specialist Press.

Skelton, P.H. (1993). *A Complete Guide to the Freshwater Fishes of Southern Africa*. Harare: Tutorial Press. 388 pp.

Skelton, P.H. (1994). Diversity and distribution of freshwater fishes in east and southern Africa. *Annals Museum Central Zoology* 275: 95–113.

Skelton, P. (2017). The National Geographic Okavango Wilderness Project – An adventurous trail of discovery. *Saving Freshwater Fishes and Habitats*. Newsletter of the IUCN SSC/WI Freshwater Fish Specialist Group, 21, 14, 21–24.

Skelton, P. (2019). The freshwater fishes of Angola. In: *Biodiversity of Angola* (eds. B.J. Huntley, V. Russo, F. Lages and N. Ferrand), 207–242. Springer Open. https://doi.org/10.1007/978-3-030-03083-4_6.

Thomas, D.S.G. and Shaw, P.A. (1991). *The Kalahari Environment*. Cambridge: Cambridge University Press. 284 pp.

du Toit, A.L. (1927). The Kalahari. *South African Journal of Science* 24: 88–101.

du Toit, A.L. (1933). Crustal movements as a factor in the evolution of South Africa. *South African Geographical Journal* 16: 3–20.

du Toit, J.T. and Cumming, D.H.M. (1999). Functional significance of ungulate diversity in African savannas and the ecological implications of the spread of pastoralism. *Biodiversity and Conservation* 8: 1643–1661.

Wellington, J.H. (1955). *Southern Africa – A Geographic Study, Volume 1: Physical Geography*. Cambridge: Cambridge University Press. 528 pp.

White, F. (1965). The savannah woodlands of the Zambezian and Sudanian domains: an ecological and phytogeographical comparison. *Webbia* 19: 651–681.

White, F. (1976). The underground forests of Africa: a preliminary review. *Singapore Gardeners Bulletin* 24: 57–71.

White, F. (1983). *The Vegetation of Africa: A Descriptive Memoir to Accompany the UNESCO/AETFAT/UNSO Vegetation Map of Africa*. Paris: UNESCO.

Williams, G.J. (1986). A preliminary Landsat interpretation of the relict landforms of western Zambia. In: *Geographical Perspectives on Development in Southern Africa* (eds. G.J. Williams and A.P. Wood), 23–33. Queensland: Commonwealth Geographical Bureau/James Cooke University.

de Wit, M.C.J. (1999). Post-Gondwana drainage and the development of diamond placers in western South Africa. *Economic Geology* 94: 721–740.

Zigelski, P., Gomes, A., and Finckh, M. (2019). Suffrutex dominated ecosystems in Angola. In: *Biodiversity of Angola* (eds. B.J. Huntley, V. Russo, F. Lagese and N. Ferrand), 109–121. Springer Open. https://doi.org/10.1007/978-3-030-03083-4_6.