15

The Zambezi River

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15.1 INTRODUCTION

The Zambezi rises with considerable modesty in north-west Zambia from a small spring on the gentle upland of the Southern Equatorial Divide – the watershed that separates the river from north-west-flowing tributaries of the Congo (Figure 15.1). 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 geomorphological 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 15.2). 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.

The evolution of the Zambezi River has had a major influence on the distribution of riverine plant and animal species. River captures have not only been important in facilitating species dispersions but, particularly in the Plio-Pleistocene, have also led to the disruption of formerly continuous populations, providing a driving force for speciation. Dating the timing of species divergence, using genetic markers, offers the potential to refine our understanding of the chronology of major river captures.

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

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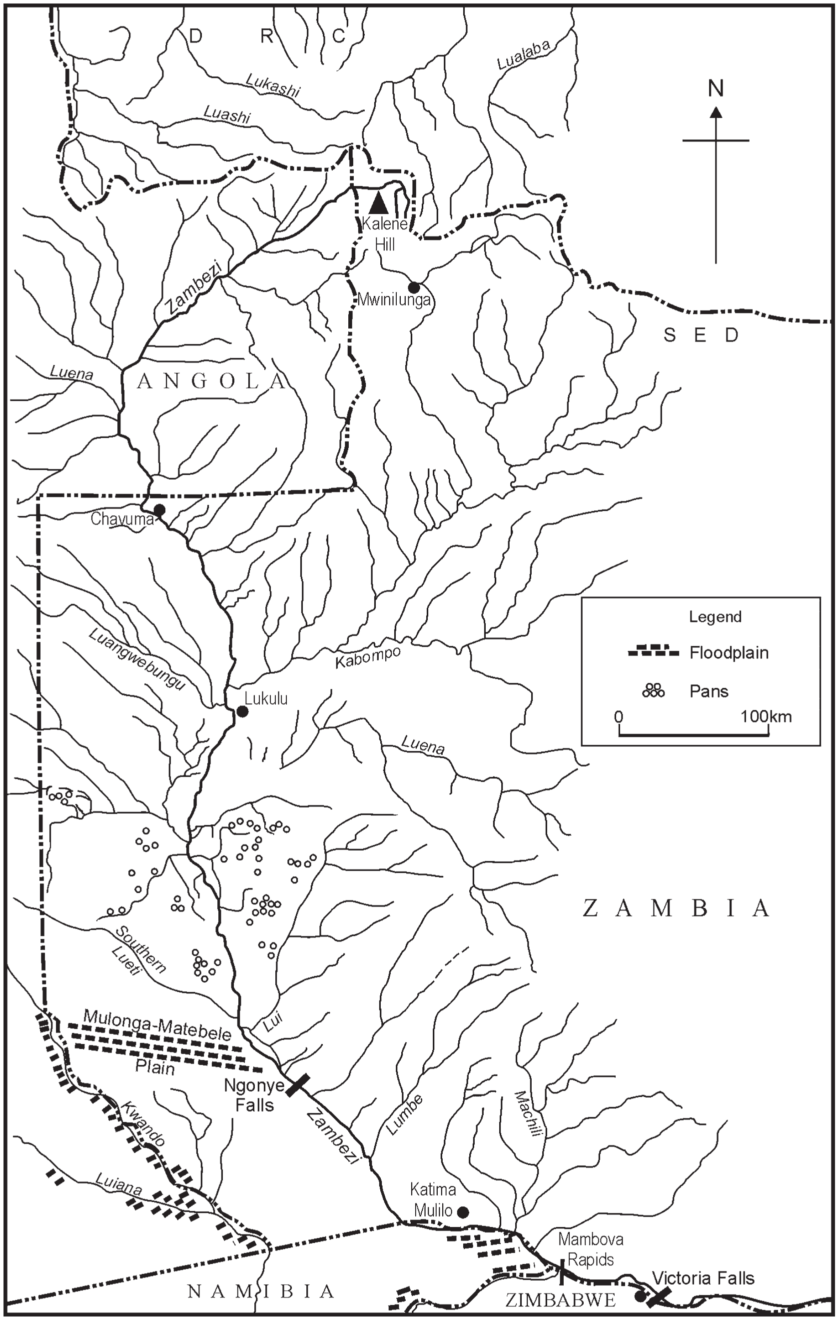

Figure 15.1 The Upper Zambezi system. Triangle shows the position of Kalene Hill. Note that the Southern Equatorial Divide (SED) forms the southern boundary of the Democratic Republic of Congo (DRC) with Angola and Zambia

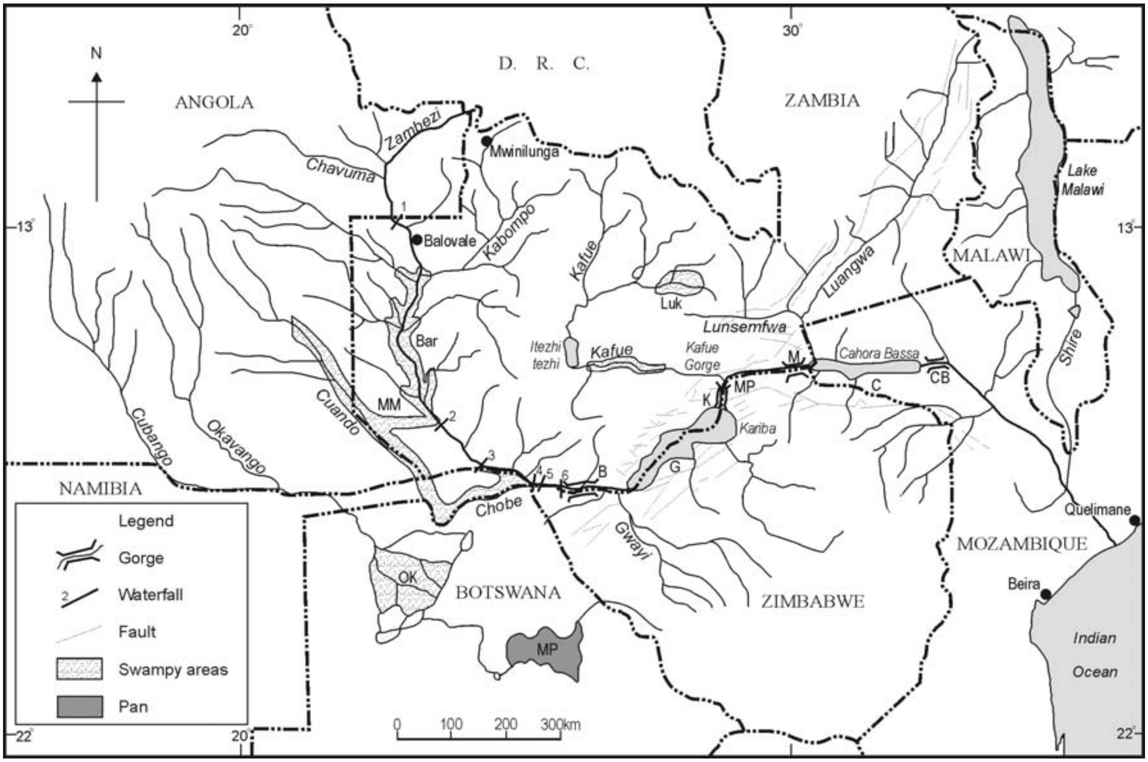

Figure 15.2 The Zambezi drainage system, adapted from Nugent (1990) and large dams. Note that the Linyanti and Chobe floodplains (both marked Chobe in this figure) are shown in detail in Figure 15.14. Rift basins: G, Gwembe Trough (mid-Zambezi Basin); MP, Mana Pools Basin; C, Chicoa or Cahora Bassa Basin. 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

15.2 THE ZAMBEZI RIVER SYSTEM

The Zambezi River system and the locations of major dams are illustrated in Figure 15.2, while Figure 15.1 shows the major headwater tributaries. The upper reaches of the river are incised into Precambrian basement rocks that form the South Equatorial Divide. A little above the confluence with the west bank Lungwebungu tributary, which rises in the Angolan highlands, the Upper Zambezi widens into the Barotse floodplain (Figure 15.3). 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 15.4). Most of this section of the river traverses unconsolidated sands (loosely referred to as the Kalahari Sand) that cap the Tertiary-age Kalahari Formation.

Figure 15.3 Barotse floodplain. Photograph reprinted with permission from Mike Main

Figure 15.4 Ngonye Falls. Upper Zambezi. Photograph reprinted with permission from Mike Main

Figure 15.5 Victoria Falls. Photograph reprinted with permission from Mike Main

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 runoff cannot be attributed to these dambos (White, 1976). Zambezian grasslands constitute the single largest unit mapped in the Zambezian phytochorion (see Section 15.6), 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). 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 15.4), 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 15.5).

Figure 15.6 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, which constitutes the lower portion of the Upper Zambezi, has an average gradient of 0.00024. 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 15.6), 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 15.7). 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)

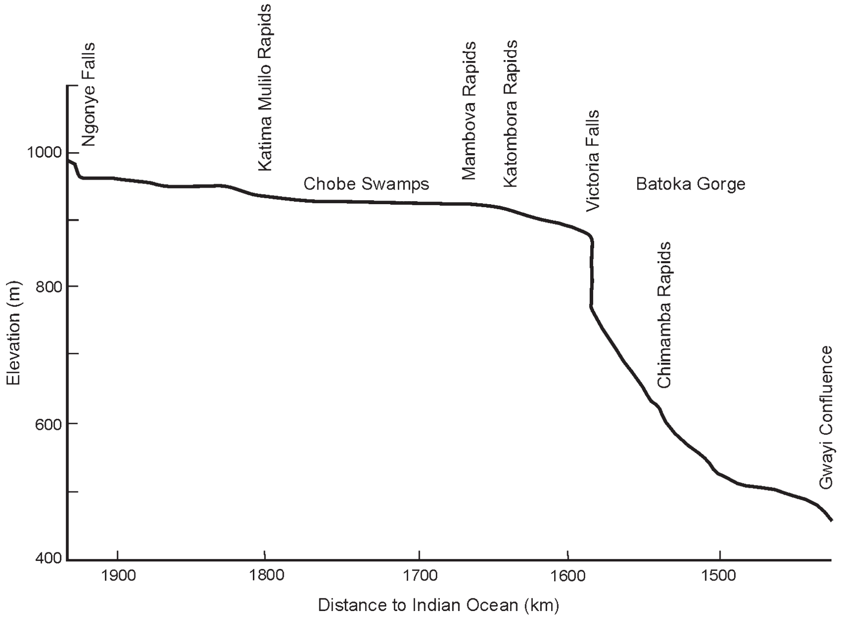

Figure 15.6 Zambezi River profile across the boundary between the upper and middle sections of the river (modified after Nugent, 1990)

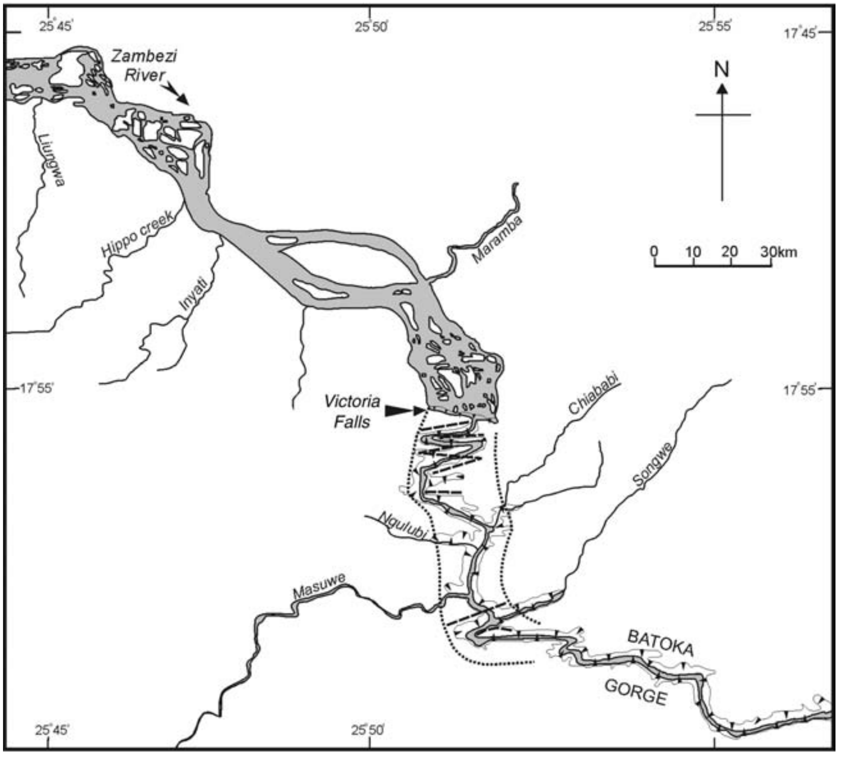

Figure 15.7 Geomorphology of the Zambezi River in the vicinity of Victoria Falls (from 1:50 000 topographical sheet 1725D4 (Victoria Falls). Dashed line on either side of the gorge below the Falls marks a low escarpment, interpreted to represent the original bank of the Zambezi prior to river capture (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). Reproduced from South African Journal of Geology, Vol. 104, Moore A.E., Larkin P.A., Drainage evolution in south-central Africa since the break-up of Gondwana, pp. 47–68, 2001, with permission of Geological Society of South Africa

The Chimamba Rapids also mark a sharp break in gradient of the river within the succession of gorges below Victoria Falls (Figure 15.6).

Below the Batoka Gorge, the Zambezi widens into one of the world's finest wildernesses, flowing through a series of broad basins, in places several kilometers in width, and known, in a downstream direction, as the Kariba (or Gwembe), Mana Pools and Chicoa (or Cahora Bassa) basins (Figures 15.2 and 15.8). These are linked by the narrow defiles of the Kariba and Mupata Gorges (Figure 15.9) – 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 15.2). Part of this region, comprising Mana Pools, Sapi and Chewore, stands out as one of the important remaining wilderness areas in the savannas 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 Tertiary sedimentary cover of the low-lying (0–400 m) Mozambique coastal plain. The lower reaches of the river, below the Shire confluence (Figure 15.2), forms a huge 100 km long floodplain-delta system of oxbows, swamps, and multichannel meanders (Figure 15.10). 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

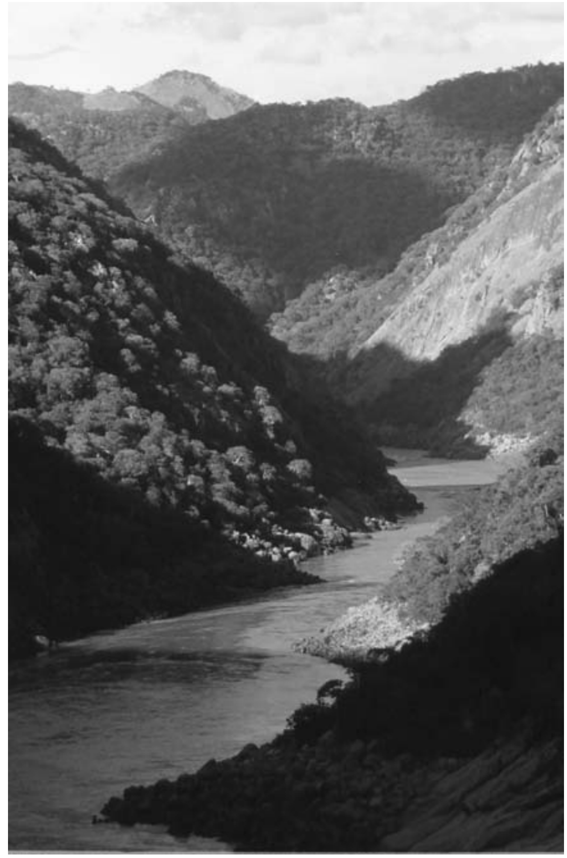

Figure 15.9. Mupata Gorge. Photograph reprinted with permission from Mike Main

Figure 15.8 Wide Zambezi at Mana Pools. Photograph reprinted with permission from Mike Main

Figure 15.10 Zambezi floodplain and delta. Photograph reprinted with permission from Mike Main

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.

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 northeastwards, to link with the Zambezi via the Linyanti-Chobe floodplain (Figure 15.2). 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 15.1), which is subject to flooding in the wet season (Thomas and Shaw, 1991).

The Kafue is a north bank tributary with headwaters on the Southern Equatorial Divide. It initially flows in a general southwesterly direction towards the Upper Zambezi, but the 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 15.2).

The Luangwa River flows in a general south-westerly 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 15.2).

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 north-westerly direction that, 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 15.2).

15.3 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 km^2 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 15.1, Figure 15.11a). This is broadly comparable with the flow of the Nile, but an order of magnitude less than the

Table 15.1 Flow data used in Figure 15.11

Country	Sub catchment	Hydropower (km^3 year^{-1})	Irrigation (km^3 year^{-1})	Industry and primary (km^3 year^{-1})	Land use change (km^3 year^{-1})	1995 yield (km^3 year^{-1})	Mean flow (km^3 year^{-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		

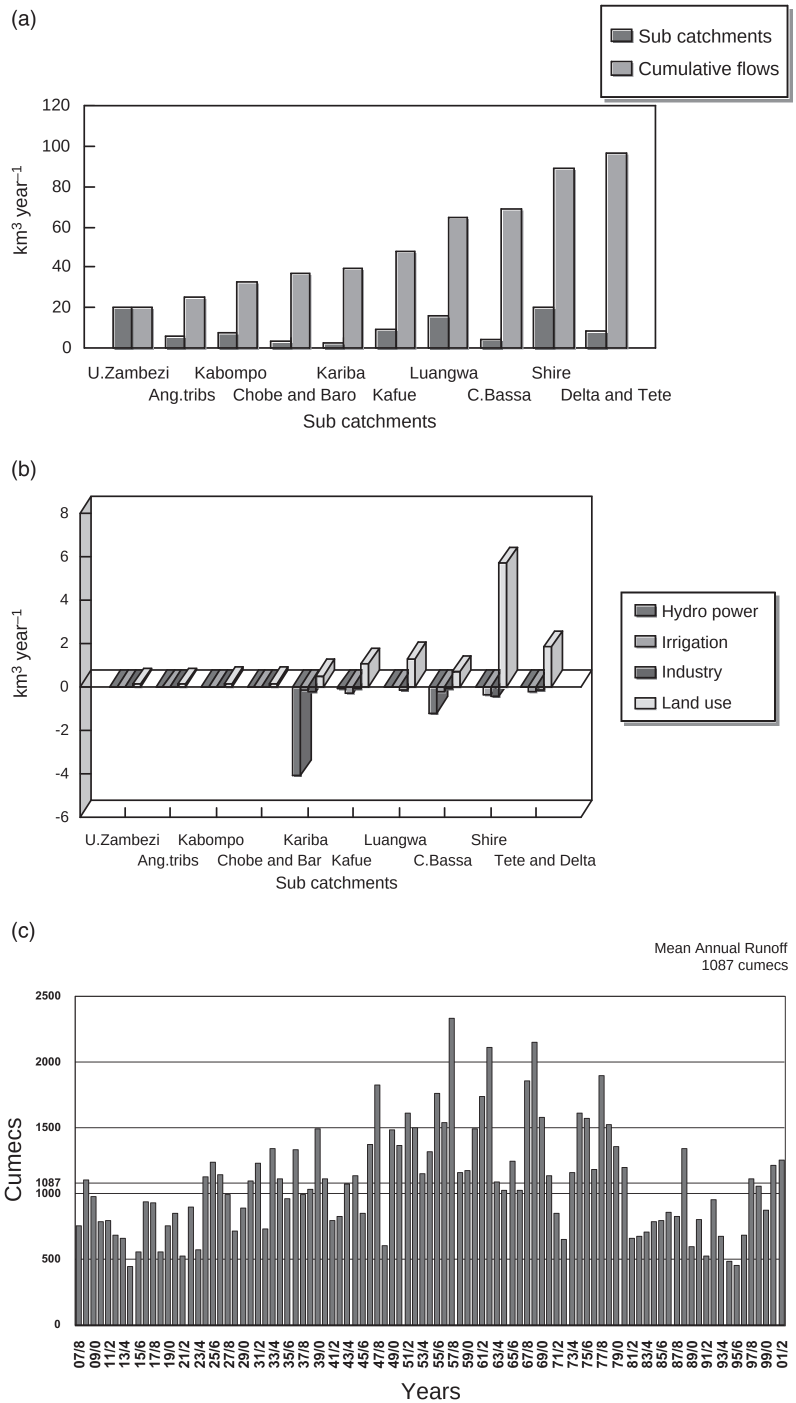

Figure 15.11 (a) Mean and cumulative annual flow of the Zambezi and major tributaries. (b) Utilization of water from the Zambezi and major tributaries. (c) Mean annual flows of the Zambezi River measured at the Victoria Falls station (1907–2002)

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 runoff comes from the northern tributaries.

The hydrology of the Zambezi is further influenced by water exploitation by different users. 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 Kafue Gorge Dam, 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 runoff 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 15.11b and Table 15.1 summarize these sector and land use totals, and the resultant mean annual flows are shown in Figure 15.11a.

Mean monthly flows at four different stations (Figure 15.2) on the Upper Zambezi are given in Table 15.2. 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 15.2). 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 15.2). Flow has been further affected by the construction of major dams (Figure 15.2) 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 15.11c. 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 $m^3 s^{-1}$ were 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

Table 15.2 Zambezi River: mean monthly flows ($m^3 s^{-1}$)

Station Period (years)	Chavuma 1959/60–2001/02	Lukulu 1950/51–2001/02	Katima Mulilo 1967/68–2001/02	Victoria Falls 1951/52–2001/02
Oct.	68	271	306	293
Nov.	94	310	320	297
Dec.	228	468	430	438
Jan.	655	803	678	686
Feb.	1411	1294	1211	1184
Mar.	2031	1645	2374	2175
Apr.	1770	1523	3129	3007
May.	684	944	2427	2613
Jun.	310	575	1326	1621
Jul.	188	434	691	845
Aug.	124	361	467	519
Sep.	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 15.2 for station locations.

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 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).

15.4 ECOLOGICAL IMPACT OF MAJOR DAMS

The densely vegetated floodplains such as the Barotse and Chobe (Upper Zambezi) and the Kafue Flats (Figures 15.1 and 15.2), with their shallow gradients, form natural sediment traps that greatly reduce the material supplied to the lower reaches of the river system. These floodplains as a consequence 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. Readily accessible stretches of the Zambezi and major tributaries, such as the Barotse floodplain, provide a reliable perennial water source, and are thus an important focus for human settlement and agricultural activity (Davies, 1986).

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 15.12) and Cahora Bassa on the middle Zambezi, and the Itezhi tezhi and Kafue Gorge Dams on the Kafue (Figure 15.2). These impoundments had a major impact on the economy of the region. 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 colonise 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.

Figure 15.12 Wall of the Kariba Dam. Photograph reprinted with permission from Mike Main

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 AD, 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).

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 that 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.

15.5 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), and Bond (1963); 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 15.2) 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 15.2). Moore *et al.* (2007) note 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 fluvial system. Palaeocurrent directions in fluvial Triassic (Karoo) sediments in the Zambezi valley indicate westerly sediment transport directions (Oesterlen and Milsteed, 1994; Shoko, 1998), consistent with this interpretation.
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 sediments of upper Cretaceous to Tertiary age (Figure 15.13). 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.
5. The occurrence of a high proportion (41%) of fish species common to the middle Zambezi and Limpopo Rivers (see Figure 15.13e for location of the latter drainage) 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. Of the 64 species of fishes recorded in the Upper Kafue, only two are absent from the Upper Zambezi (Gaigher and Pott, 1973; Bowmaker *et al.*, 1978; Skelton, 1993, 1994). This points to a former link between the Kafue and Upper Zambezi. 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.

Based on lines of evidence such as those summarized 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 Okavango, Cuando and Upper Zambezi were the major south-east-flowing headwaters of the Palaeo-Limpopo River system (Figure 15.13a). 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 southwest-flowing east bank tributary of the Upper Zambezi. The Palaeo-Chambeshi, whose headwaters included rivers that are today part of the upper Congo system, formed the upper reaches of the palaeo-Kafue. The sharp change in course of the modern Kafue, where it enters the western end of the Kafue Flats, (Figure 15.2) is interpreted as a capture elbow (Dixey, 1945; Bond, 1963). The former 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 Basin (Dixey, 1945; Thomas and Shaw, 1991). The location of the Machili River and Basin is shown in Figures 15.1 and 15.14. The Digital Elevation Model (DEM) image presented in Figure 15.15 clearly illustrates how the alluvium associated with the Machili Basin extends northeast across the line of the Upper Zambezi into northern Botswana.

Moore and Larkin (2001) inferred that the Luangwa originally continued on the southwesterly course of the

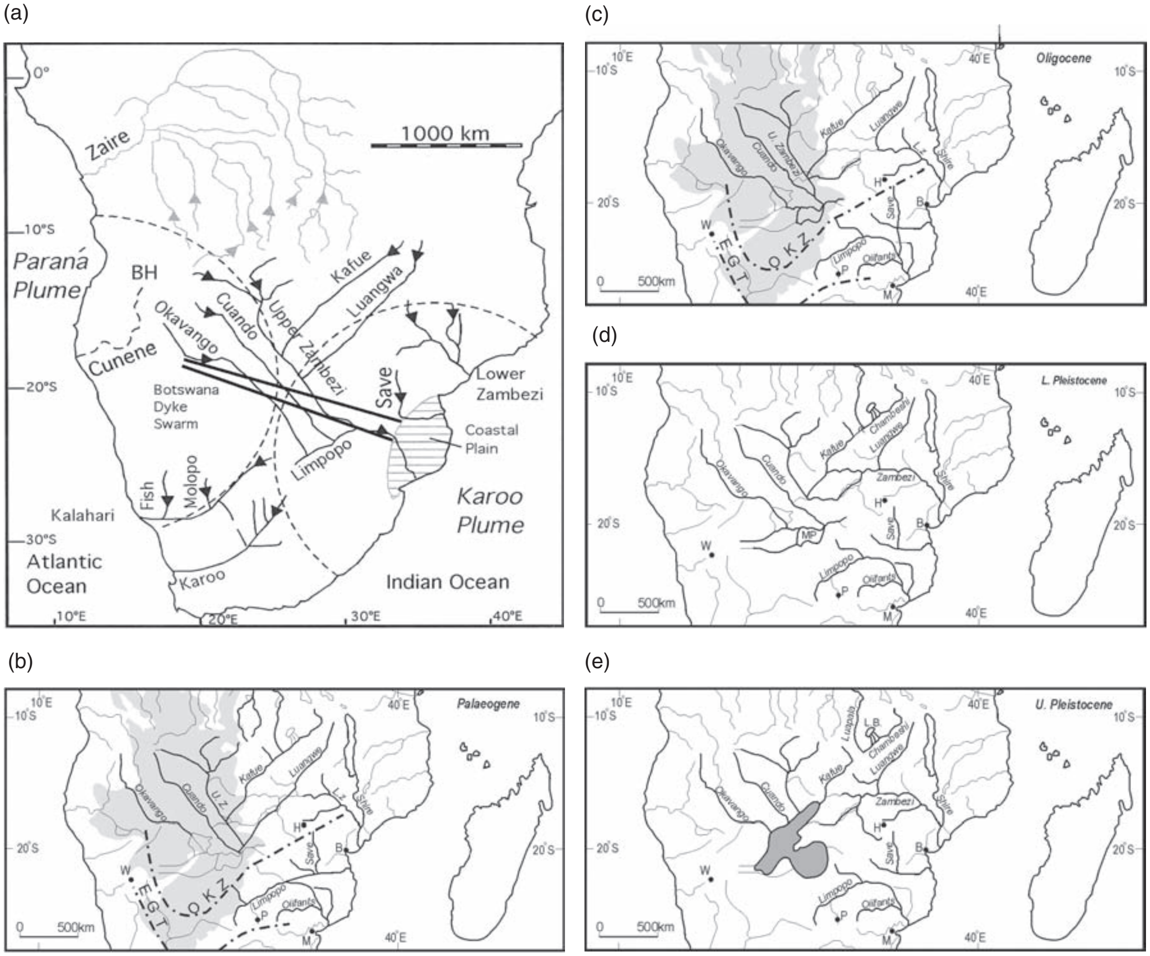

Figure 15.13 (a) Drainage system in south-central Africa based on reconstructions by de Wit (1999) and Moore and Larkin (2001). Dotted lines show the inferred extent of the areas affected by updoming by the Karoo and Paraná Plumes, respectively (after Cox, 1989). (b) Faint lines, modern drainage lines; heavy lines, reconstructed drainage lines for period; LZ, Lower Zambezi; OKZ, Ovambo-Kalahari-Zimbabwe flexure axis (after Moore, 1999). City locations as follows: B, Beira; H, Harare; M, Maputo; P, Pretoria; W, Windhoek. Grey tone shows modern distribution of Kalahari Group sediments. End-Cretaceous to early Tertiary flexuring across the OKZ Axis severed the link between the Limpopo and Cubango-Okavango, Cuando and Upper Zambezi–Luangwa–Kafue. During the Palaeocene and Eocene, the latter three rivers formed a major endoreic system, which terminated in the Kalahari Basin, and contributed to deposition of the Kalahari Group sediments. Lower Palaeogene isopachs on the Mozambique margin (Dingle *et al*., 1983) indicate southward displacement of the mouth of the Shire. (c) Abbreviations as for (b). Headward erosion of the lower Zambezi, inititated 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. (d) MP, Makgadikgadi Pans. Other abbreviations as for (b). 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. Incision of the Batoka Gorge was initiated once the Middle Zambezi beheaded the Upper Zambezi in the Early Pleistocene. (e) Grey tone shows Lake Palaeo-Makgadikgadi. LB, Lake Bangweulu; other abbreviations as for (b). Displacement along the major north-east-trending Linyanti and Chobe Faults temporarily severs the link between the Upper and Middle Zambezi, and diverts the flow of the Kafue and Zambezi into Lake Palaeo-Makgadikgadi, which filled to the 945 m shoreline level. Diversion of the headwaters of these rivers is reflected by a break in erosion in the Batoka Gorge. The timing of diversion of the Upper Zambezi into Lake Palaeo-Makgadikgadi cannot be accurately dated, but is estimated to be Early Pleistocene (Cotterill, 2006a). (a) Reproduced from South African Journal of Geology, Vol. 105, Moore A., Blenkinsop T., The role of mantle plumes in the development of continental-scale drainage patterns: The southern African example revisited, pp. 353–360, 2002, with permission from Geological Society of South Africa. (b–e) Reproduced from South African Journal of Geology, Vol. 104, Moore A.E. Larkin P.A., Drainage evolution in south-central Africa since the break-up of Gondwana, pp. 47–68, 2001, with permission of Geological Society of South Africa

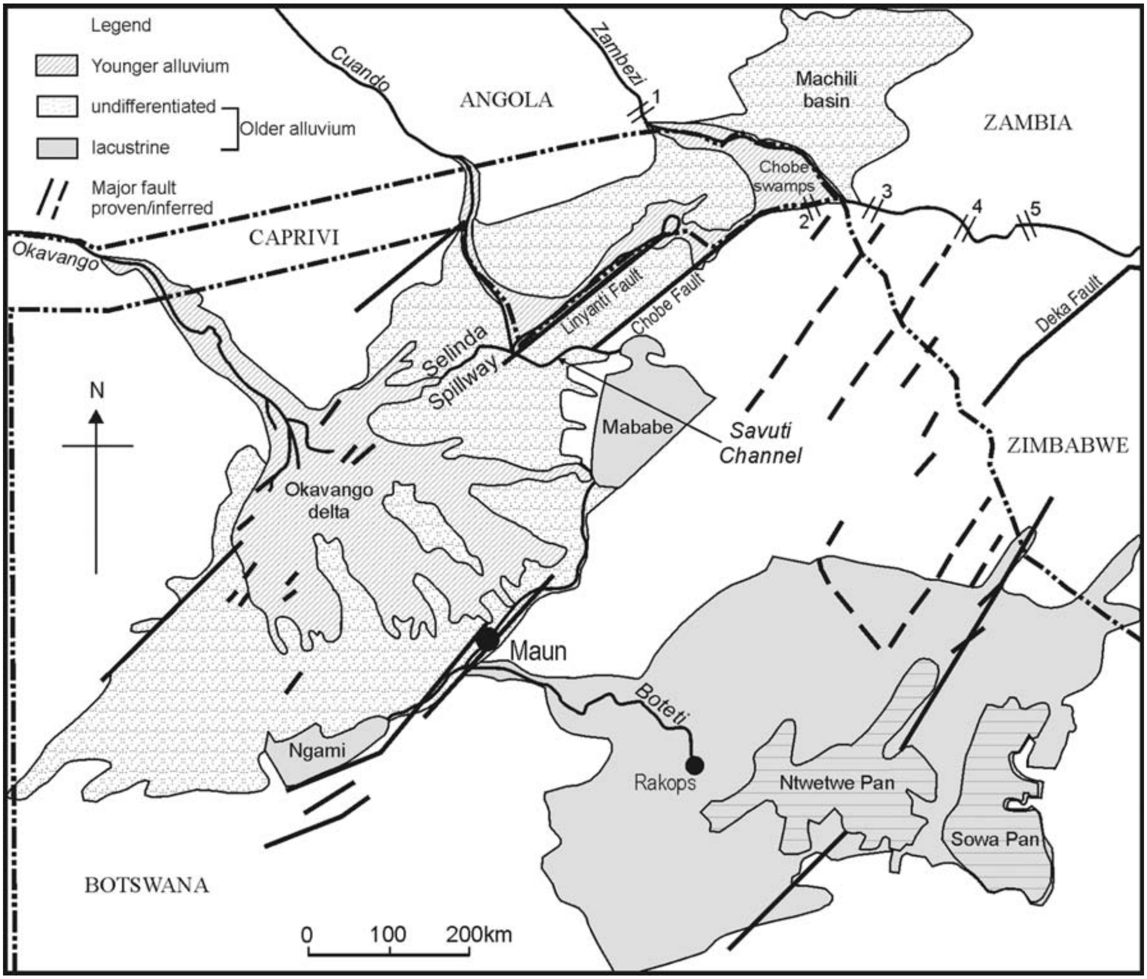

Figure 15.14 The distribution of alluvial and lacustrine sediments in north-eastern Botswana and southern Zambia. The alluvium of the Machili Basin probably extends further to the north-east as far as the Kafue Flats (Thomas and Shaw, 1991). Limits of the older alluvium reflect the approximate extent of Lake Makgadikgadi associated with the 945 m shoreline. This comprised two subsidiary basins, linked via a narrow neck along the Boteti River valley (Thomas and Shaw, 1991). Note that the south-west–north-east trending basin, which was subsequently partially covered by the Okavango Delta, is strongly fault-controlled. The younger alluvium (horizontal lining) is associated with the floodplain of the Okavango Delta and the fault-bound Linyanti and Chobe floodplains. Numbers 1–5 denote positions of rapids and falls: 1, Katima Mulilo; 2, Mambova; 3, Katombora; 4, Victoria Falls; 5, Chimamba Rapids. Reproduced from South African Journal of Geology, Vol. 104, Moore A.E., Larkin P.A., Drainage evolution in south-central Africa since the break-up of Gondwana, pp. 47–68, 2001, with permission of Geological Society of South Africa

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 *et al.* (2007) that the Luangwa, which is floored by Karoo sediments, is a relict of a Karoo-age drainage system that pre-dated the break-up of Gondwana.

The major lower 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

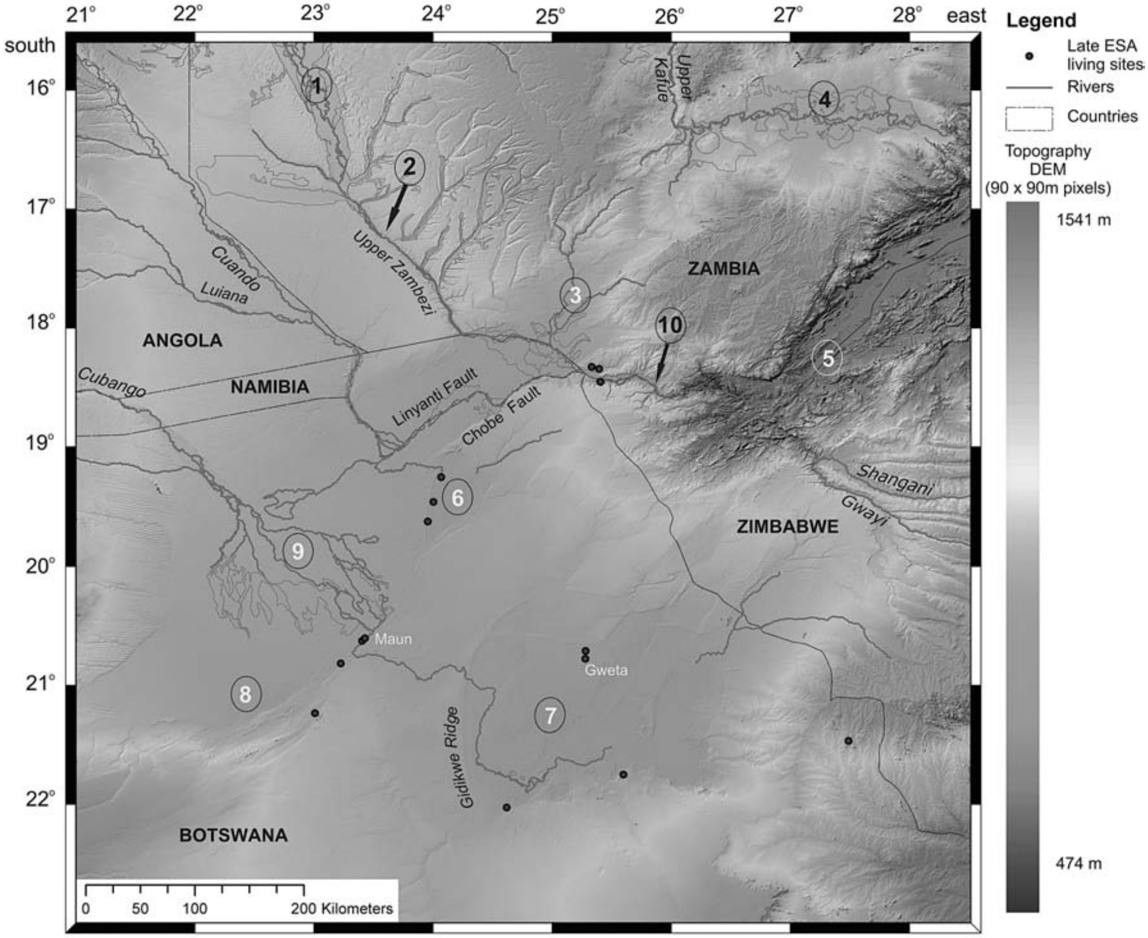

Figure 15.15 (See also colour plates.) DEM image illustrating the subdued topography extending from the Machili Flats, across the line of the Upper Zambezi River, south-west into the area formerly covered by the greater Palaeo-Lake Makgadkigadi. This reflects alluvium supplied by the upper Chambeshi-Kafue system, which was formerly linked to the Upper Zambezi via the Machili Flats. Locations: 1, Barotse Floodplain; 2, Ngonye (Sioma) Falls; 3, Machili Flats; 4, Kafue Flats, formerly occupied by Pleistocene Lake Patrick; 5, Gwembe Trough (Lake Kariba); 6, Mababe depression, 7, Makgadikgadi depression; 8, Ngami depression; 9, Okavango Delta; 10, Victoria Falls. Early Stone Age (ESA) living sites (Robbins and Murphy, 1998; McFarlane and Segadika, 2001) in the Makgadikgadi Basin depicted by circles

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 lower 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.

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 subcon-

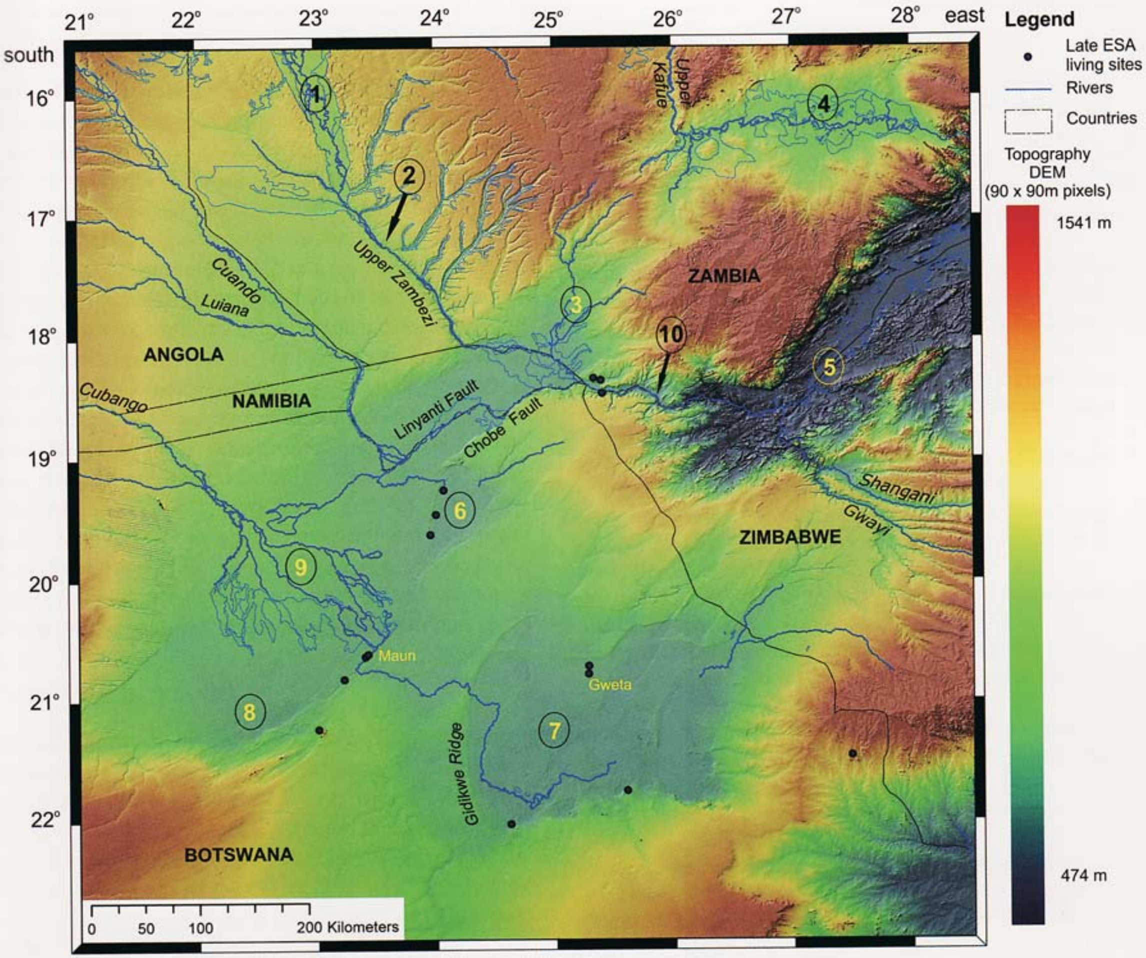

Figure 15.15 DEM image illustrating the subdued topography extending from the Machili Flats, across the line of the Upper Zambezi River, south-west into the area formerly covered by the greater Palaeo-Lake Makgadkigadi. This reflects alluvium supplied by the upper Chambeshi-Kafue system, which was formerly linked to the Upper Zambezi via the Machili Flats. Locations: 1, Barotse Floodplain; 2, Ngonye (Sioma) Falls; 3, Machili Flats; 4, Kafue Flats, formerly occupied by Pleistocene Lake Patrick; 5, Gwembe Trough (Lake Kariba); 6, Mababe depression, 7, Makgadikgadi depression; 8, Ngami depression; 9, Okavango Delta; 10, Victoria Falls. Early Stone Age (ESA) living sites (Robbins and Murphy, 1998; McFarlane and Segadika, 2001) in the Makgadikgadi Basin depicted by circles

tinent, respectively. The elevated ground over the plumes in turn, provided the headwaters for a new post-Gondwana drainage system. 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. They ascribed the initiation of an early Cretaceous proto-Zambezi-Limpopo drainage towards the Indian Ocean (Figure 15.13a) 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 15.13a), points to an important structural influence, superimposed on the primary role of the mantle plumes in determining the post-Gondwana drainage system.

The palaeo-Limpopo drainage system was disrupted (Figure 15.13b) by end-Cretaceous to early Tertiary crustal flexuring of the subcontinent 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 15.13b).

The lower Tertiary 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 15.13c). The sharp change in course of the latter from south-westerly to south-south-easterly, just above the modern confluence with the Zambezi (Figure 15.2) 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.

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. The resultant lowering of the base level of the Middle Zambezi caused the reversal in flow of this section of the river, which previously flowed to the south-west.

Ultimately headward erosion cut across the line of the Upper Zambezi diverting the flow of this river from the endoreic Kalahari Basin into the Middle Zambezi, to re-establish the link to the Indian Ocean (Figure 15.13d). This capture thus provided the link between the gentle-gradient upper and steeper middle sections of the river. The result was a major lowering of the base level of the Upper Zambezi, and a dramatic increase in flow to the middle and lower sections of the river. This triggered rapid headward erosion by the Middle Zambezi into the Karoo-age Batoka basalts, probably strongly influenced by east–west structural controls, and incision of the deep, 101 km length of the Batoka Gorge. Wellington (1955) suggests that the capture elbow is marked by the point where the Zambezi swings from a southerly to easterly flow direction immediately below the confluence with the Songwe, and some 10 km below the modern line of Victoria Falls (Figure 15.7). 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 capture of the Upper Zambezi is not well constrained. However, Derricourt (1976) notes that high level gravels, now isolated from 110 m 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 Batoka Gorge are tentatively ascribed a lower Pleistocene age, suggesting that the capture was of a similar vintage.

Following the early Pleistocene capture of the Upper Zambezi by the Middle Zambezi, there was a complex series of drainage reorganizations in the area surrounding 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 (Figure 15.7), transverse to the major drainage lines (Reeves, 1972), played a major role in these changes to the drainage system.

Evidence for these changes comes from fossil lacustrine deposits and landforms in northern Botswana (Figure 15.14). The Ntwetwe and Sowa Pans (together referred to as the Makgadikgadi Pans) are relics of a major lake, enclosed at the 945 m level by a variety of fossil shoreline features. The lacustrine deposits associated with the

Makgadikgadi Pans are linked, via the Boteti River, to an extensive fault-bound south-west–north-east stretch of alluvium, which extends across the Zambezi River into the Machili Basin, to the western edge of the Kafue Flats. The alluvium associated with the Machili Basin that stretches across the Zambezi is illustrated in the DEM image shown in Figure 15.15.

These alluvial deposits provide evidence for a former major inland lake, termed Lake Palaeo-Makgadikgadi (Thomas and Shaw, 1991), with a surface area of the order of 120 000 km^2 (Figures 15.13e and 15.14). Grove (1969) calculated that it is not possible to account for the existence of a lake of such proportions by any realistic increase in precipitation. He demonstrated rather, that a body of water of this size could only be maintained by inflow from the Zambezi River. The implication is that the Zambezi was at some stage diverted from its modern course to the south-west, into northern Botswana. A ferricrete bar across the Zambezi, just above Victoria Falls (Clark, 1950), attests to an episode of sub-aerial exposure of the river bed, consistent with this interpretation. The extension of the alluvium into the Machili Basin and to the Kafue flats (Figures 15.14 and 15.15) suggests that the Kafue may have also emptied into this major lake. A less extensive lake (Lake Caprivi) is recorded by fossil shorelines at the 936 m level associated with the Mababe and Ngami depressions (Shaw and Thomas, 1988). These authors suggest that this lake post-dated the Lake Palaeo-Makgadikgadi at the 945 m level, although it also required inflow from the Zambezi. They note that fossil shorelines on the Makgadikgadi Pan at elevations of 920 m and 912 m may have been maintained by overflow from Lake Caprivi via the Boteti.

Dating of the 945 m lake level, and thus the timing of the diversion of the Zambezi into northern Botswana, is not well constrained. ^{14}C ages for shells and calcretes associated with the 945 m shoreline range from 10 000 to 50 000 years BP – the upper limit of the dating technique (Thomas and Shaw, 1991). Unfortunately, the significance of these ages is difficult to interpret, as calcretes often reflect multiple episodes of carbonate precipitation. McFarlane and Segadika (2001) describe an archaeological site with Early Stone Age (ESA) tools on the floor of the Makgadikgadi Pans between the 945 and 920 m shoreline levels. These Acheulian artifacts require that the lake is at least earlier than the end of the ESA, now considered to be at least 300 ka – and likely to be even older (Barham and Smart, 1996; McBrearty and Brooks, 2000). An older age for palaeo-lake Makgadikgadi would be consistent with evidence from the Batoka Gorge presented by Derricourt (1976). He suggested that the break in river profile at the Chimamba Rapids, 40.71 km downstream of the Victoria Falls, reflects a mid-Pleistocene break in the erosion. Diversion of the Zambezi into the Makgadikgadi Pans in northern Botswana could account for this break in erosion. It would also explain the sub-aerial formation of the ferricrete on the floor of the Zambezi above Victoria Falls. This in turn requires that the point of diversion of the river into northern Botswana was upstream of the Falls. Recent reappraisal of these events reveals the ferricrete and Chimamba rapids testify to not one, but two, discrete breaks in erosion of the Batoka gorge, which concur with the complex history of tenures of successive palaeolakes in northeast Botswana (Cotterill, 2006a; Cotterill and Moore, in preparation).

The exact mechanism responsible for diverting the Zambezi into northern Botswana is not well understood, but probably involved an interplay between tectonic movement associated with the Chobe Fault, which crosses the line of the Zambezi upstream of Victoria Falls (Figure 15.14), and sedimentation in the Chobe floodplain. Present day seismic activity in northern Botswana (Reeves, 1972), with epicentres defining a north-east–south-west swath, broadly parallel to the fault lines, in northern Botswana, indicates that they are still active.

Uplift along the Linyanti Fault (Figure 15.14) 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 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 southwest into northern Botswana beneath the modern alluvial deposits of the Okavango Delta.

The sharp change of the course of the Kafue to the east in the area of the Kafue Flats is 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), 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 probably a 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.

The Chambeshi River, to the north-east of the Kafue headwaters, follows a south-westerly course before swinging sharply to the north, becoming the Luapala – a headwater tributary of the Congo River (Figure 15.13e). This sharp change in course suggests a capture elbow, and that the Chambeshi originally constituted the headwaters of the Kafue (Figure 15.13c). As yet, it is not possible to date this capture with any confidence, but the relative timing is discussed ahead in relation to the dispersal and modern distribution of closely related species of lechwe antelopes, and of the tigerfish (*Hydrocynus vittatus*).

Williams (1986) suggested that the formation of the Barotse floodplain was linked to tectonic uplift. 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 15.1) 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. Clark (1950) describes a ferricrete bar with embedded Middle Stone Age (MSA) lithic artifacts on the Zambezi riverbed above Ngonye Falls. This attests to a period of sub-aerial exposure, pointing to impoundment of the river above the falls. 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 the impoundment. 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 Matebele-Mulongo plain (Figure 15.1), which, from DEM images, appears to be an abandoned channel that originally linked the upper Cuando and the upper Zambezi. Wellington (1955) notes that outflow from the Okavango into the Linyanti (lower Cuando), and thence into the Zambezi, sometimes occurs via the Selinda spillway (Figure 15.14). 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 the tigerfish, *H. vittatus*, which is among the most charismatic of African fishes. Adapted to tropical conditions, this ferocious predator is widely distributed through much of the continent's freshwaters (Figure 15.16). The species is believed to have originated in the Congo Basin; and thereafter it dispersed through south-central Africa southwards as far as southern Mozambique, and Mpumalanga and Kwa-Zulu-Natal in South Africa. Bell-Cross (1965) hypothesized that the most likely dispersal route out of the Congo Basin was into Upper Zambezi headwaters from the Kasai. This occurred only after the Kasai, a north-flowing Congo tributary, captured an easterly flowing headwater of the Upper Zambezi. Thereafter tigerfish dispersed far and wide south of the Southern Equatorial Divide.

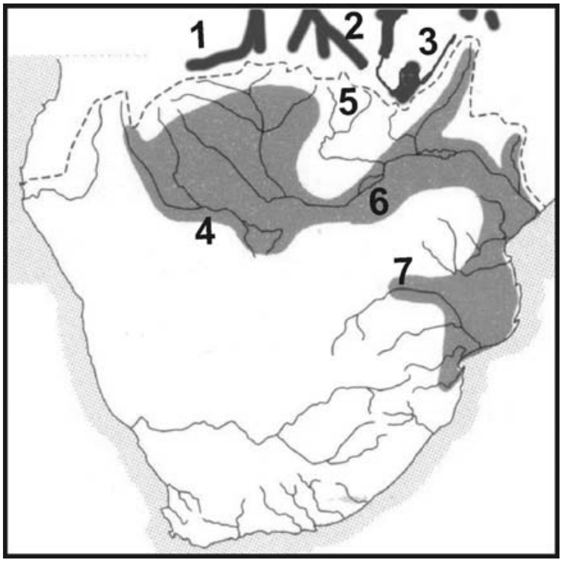

Figure 15.16 Distribution of the tigerfish (*Hydrocynus vittatus*). Dark grey: tributaries of the Congo River (1, Kasai; 2, Lufira; 3, Upper Chambeshi-Luapula). Lighter grey: drainages south of the Southern Equatorial Divide (4, Okavango; 5, Kafue; 6, Zambezi; 7, Limpopo)

Their movements have, nonetheless, been contained downstream of distinct waterfalls; and two conspicuous gaps in their modern distribution (Figure 15.16) are especially interesting. These highlight, and indeed reinforce, our insights into recent geomorphological evolution of the Zambezi and neighbouring drainage. Tigerfish are absent from the Shire River (and thus Lake Malawi) above the Shire Falls. A similar physical barrier in the Kafue Gorge, has prevented its invasion of the Upper Kafue system (Jubb, 1952; Skelton, 1994). Yet, the occurrence of tigerfish in adjacent Katanga and northern Zambia (especially the Lufira, Chambeshi, Luapula and Upper Lualaba Rivers) points to invasion of the Zambezi, only after the Chambeshi had become a Congo tributary; and equally when the Upper Kafue no longer flowed south-west and had been pirated by the Middle Zambezi creating the Kafue Gorge. We can conclude that the Kasai beheaded an Upper Zambezi tributary geologically recently. Clearly, it has followed on the breakup of the Palaeo-Chambeshi system. Therefore, the invasions by tigerfish (and several other Congo fish species) into the Upper Zambezi and adjacent rivers on the south-central African plateau occurred relatively recently in the Pleistocene (Cotterill, 2006a).

15.6 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 km^2, 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 Southern Equatorial Divide (Figures 15.1 and 15.2): 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 savanna 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).

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 is 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 (*Pediperdix 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 vardoni*). 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, *K. kafuensis*), with the apparently more widely distributed Red lechwe (*K. leche*) in the Okavango-Linyanti and Upper Zambezi floodplains. Roberts' lechwe (*K. robertsi*) occurred in floodplains of the Kalungwishi and Luongo Rivers between Lakes Bangweulu and Mweru, but is now extinct. The recently described Upemba lechwe (*K. anselli*) (Cotterill, 2005) endemic to the Kamalondo depression (in the Upemba swamps of the Democratic Republic of Congo, over 300 km north of the Southern Equatorial Divide) 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 Southern Equatorial Divide 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 in across the upper Congo, Okavango and Upper Zambezi drainage systems (Cotterill, 2004, 2005).

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 subregions (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 interglacials, 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 history of expansion and contraction of evergreen forest in response to climatic change accounts for some of the speciation, but not all.

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). 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 (Figure 15.13d), although it is now part of the Congo Basin (Figure 15.13e). 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. Generic studies, soon to be formally published, reveal these different lineages of antelopes were first isolated in the Middle Pleistocene, and thus refine the dating of river piracy events (Cotterill, 2006a).

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 savanna trees (e.g. *Parinari* and *Syzygium*) would have retreated far north as components of mesic savannas. 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 coexistence of *Parinari capensis* and *P. 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 'underground trees' across the Upper Zambezi valley (the area known as Barotseland) has been ascribed to the interplay of a number of factors. White (1976) notes that their characteristic habit is seasonally waterlogged anerobic 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: 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 in an earlier section. 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.

15.7 CULTURAL AND ECONOMIC ASPECTS

ESA artifacts recovered along the course of the Zambezi and its tributaries (Dixey, 1945; Clark, 1950; Derricourt, 1976) 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. 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 encylopaedic 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.

15.8 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 manmade lakes. Two more – at Batoka and Mupata – are planned.

The major theme running though this chapter is the intimate link between geological, ecological, and evolutionary processes. 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 savanna 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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