THE ZAMBEZI RIVER AT MANA

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The Zambezi River downstream of Kariba was disrupted by the building of Kariba Dam in the late 1950's. The effects of the dam have been minor compared with the enormous changes which took place following the capture of the upper catchment, which occurred at the end of the Middle Pleistocene, about 125 000 years ago. Following both events the river adapted to change by finding a new equilibrium, in which streamflow and channel sediment reached a new stable balance.

This paper examines the streamflow of the Zambezi and how it was changed by Kariba Dam. It looks at the movement of sediment within the river, how this forms islands and terraces and how the system evolved since the Pleistocene capture of the upper catchment. Finally the channel changes that followed damming at Kariba are examined and the present stability of the system is briefly considered.

Hydrology

Hydrographs record the discharge of the Zambezi before and since the building of Kariba Dam. The natural (pre-dam) streamflow is illustrated in Fig. 1 at two points along the river. At Victoria Falls, the annual rise and fall of the river forms a smooth curve, rising to a single peak between March and May. The smoothness of the curve results from extensive flatlands upstream in Barotseland and the Chobe Swamps. High summer rainfall in northwestern Zambia and eastern Angola causes the Zambezi to overtop its banks and innundate extensive lowlands, known as *bulozi,* in the Western Province of Zambia. The Barotse Plain, which forms a major part of this *bulozi,* stores some nine cubic kilometres of water in this way during an average flood. This water is gradually released back into the Zambezi as the flood subsides. The Barotse Plain delays the annual flood on the Zambezi by some six weeks.

The Zambezi's flood is further delayed at Kazungula, where flood waters back up the Chobe River to innundate extensive swamps on the eastern Caprivi Strip. The Barotse Plain and the Chobe Swamps buffer flow along the river, smoothing out surges caused by individual rainstorms in the catchment. Another important effect of these flatlands is to remove most of the sediment from the water. As the annual flood innundates these regions, silt and clay particles come out of suspension and are deposited. River water downstream of Kazungula is thus very clean.

Streamflow at Kariba prior to the building of the dam is illustrated (Fig. 1b) by the hydrograph at Nyamuomba, at the downstream end of Kariba Gorge. The annual flood from the Upper Catchment used to reach Nyamuomba about five days after passing over the Victoria Falls. Superimposed on the rising limb of this event were a series of brief but often intense flood peaks. These peaks represent flash floods resulting from rain storms over Kariba's lower catchment, between the two guaging stations. Most of the lower catchment drains the Sebungwe region of Zimbabwe, where rivers such as the *Sanyati*, the *Sengwa* and the *Gwayi* respond quickly to local rains to give flood peaks lasting only a few days. These floods reached the Zambezi during the time of maximum local rainfall (roughly December to March) and generally used to precede the main, upper catchment flood. Since they drain areas of moderate relief and are not impeded by swamps, lower catchment floods used to carry a high sediment load into the Zambezi.

Streamflow on the Zambezi was changed when the dam was closed at Kariba on 2nd December 1958. The hydrograph at Kariba (Fig. 2a) illustrates the new pattern that developed. Floods from the upper catchment were absorbed by Lake Kariba and the water passed through Kariba reflects the way the dam was operated to generate hydro-electric power. Note that for much of the time during the period illustrated in Fig. 2a the flow was between about 500 and 700 cumec. This represents the "base flow" of water passed through Kariba's turbines and rose from about 300 cumec in the early 1960's to some 1 000 cumec by the mid 1980's, reflecting increases in installed generating capacity and electricity demand over this period. At times when water levels on the lake reached critical limits, CAPCO spilled water via some of the six floodgates set in the dam wall. Each floodgate spills approximately 1 500 cumec and the effect is well illustrated in 1968, when first one, then two, then three floodgates were opened.

Small variations in flow are apparent on a weekly cycle and reflect a comparatively low demand for electricity at weekends. There is also a small diurnal variation in flow resulting from a daytime peak in industrial demand for electricity, an evening peak in domestic demand and relatively low demand in the early hours of each morning. This variation is not illustrated in Fig. 2, which is plotted from mean daily flow data.

An estimate of discharge at Mana is given in Fig. 2b, which is plotted as the sum of Kariba streamflow and Kafue streamflow measured at the downstream end of the Kafue Flats. These two stations measure streamflow from about 98% of the catchment at Mana. The unguaged, unregulated tributaries which join the Zambezi downstream of Kariba and Kafue Gorge dams provide an insignificant water input but the only remaining sediment input to the

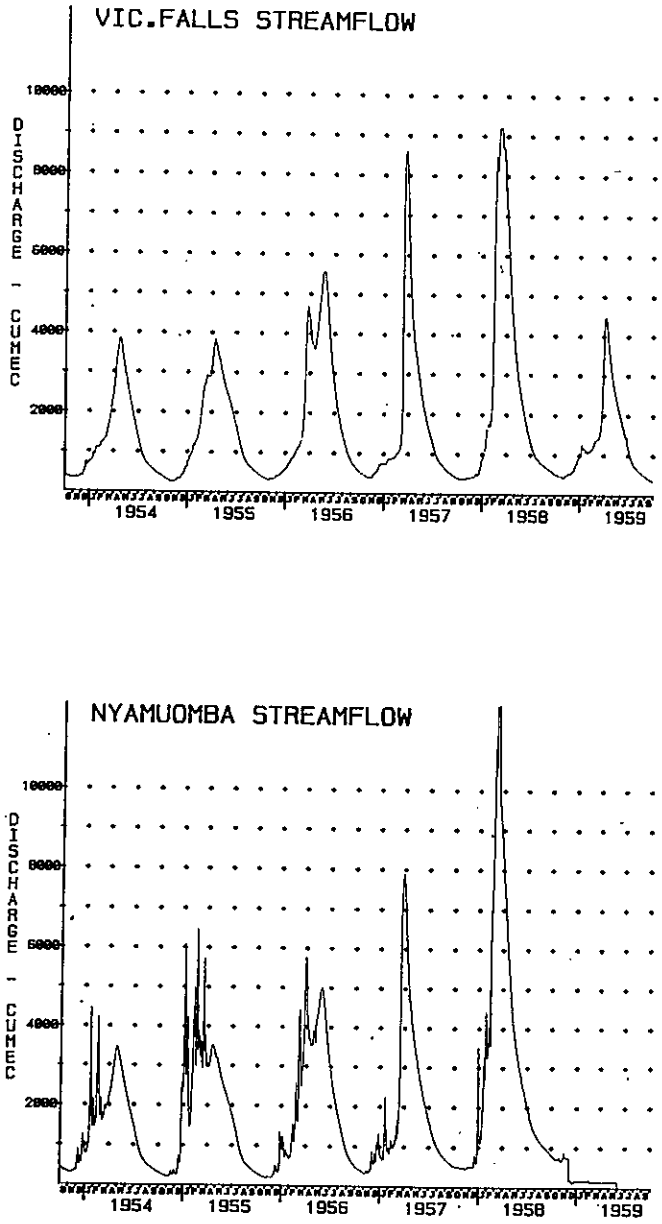

Fig. 1 The natural streamflow regime of the Zambezi River during the five years leading up to the closure of Kariba Dam. Cumec = cubic metres per second. The record flood at Victoria Falls, in March 1958, coincided with high lower catchment runoff and was gauged at Nyamuomba at 15 200 cumec.

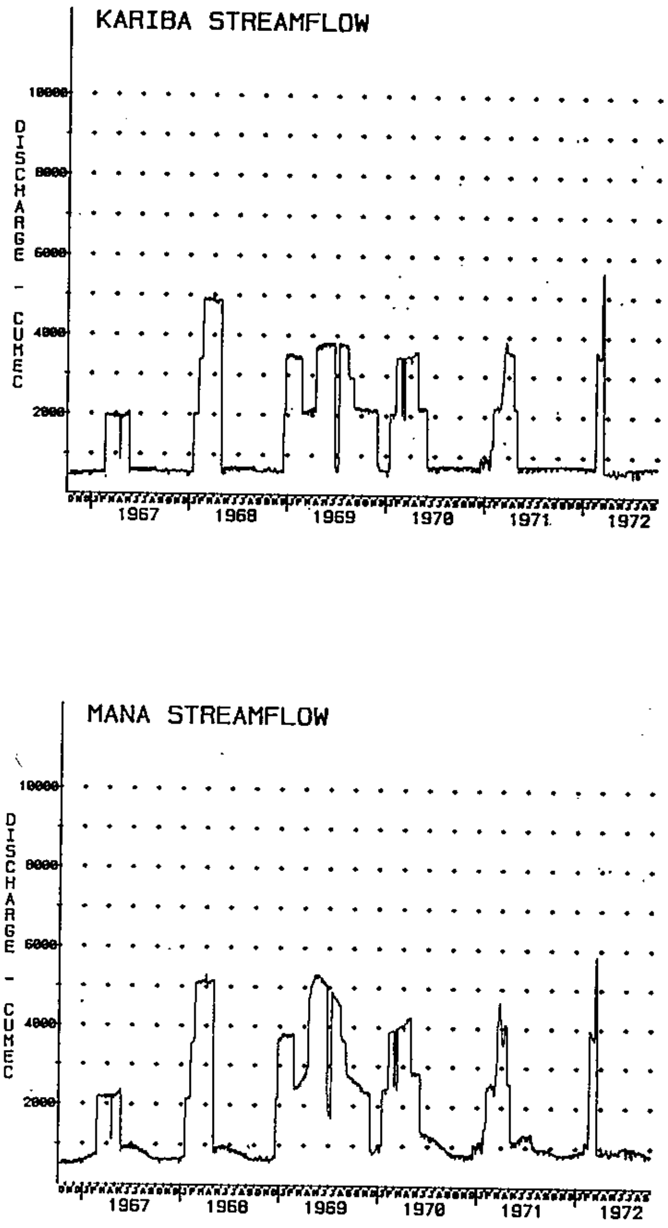

Fig. 2. Streamflow at Kariba dam and downstream. Mana streamflow is synthesised from Kariba and Kafue data.

system. Notice how the Kafue caused variation in the flow at Mana on an annual cycle, even after the Kafue Gorge Dam was closed in 1970.

The Evolution of the Zambezi

The Zambezi River downstream of Lake Kariba can best be understood as the product of an event which occurred during the Pleistocene and probably in the order of 125 000 years ago, the capture of the upper catchment. Prior to capture, the Zambezi was divided into two rivers. The Upper Zambezi flowed southwards into the Kalahari and ended in a huge lake which, at its maximum extent, covered the Makgadikgadi Pans complex, the Okavango Delta and the Chobe Swamps areas. The Middle Zambezi must have had its source on the basalt plateau upstream of Victoria Falls, before flowing into the ancient rift of the Gwembe Trough.

River capture occurred when the Upper Zambezi breached its watershed at Katembora, 15 km downstream of Kasungula and started to flow into Gwembe. The mechanism of this capture has not been proven but both earth movements and climatic change probably played a part. This part of the Zambezi's course crosses the geological lineament that is expressed to the northeast as the Gwembe Trough and to the southwest as the Passarge Basin, filled by up to 10 km depth of Karroo and Kalahari Group sediments of the Central Kalahari. The Victoria Falls zone was the site of east-west trending strike-slip movement which may have accounted for the huge thickness of Karroo basalt, known to extend for more than 1 000 km below the plateau surface. Strike-slip movement has occurred since the basalt was extruded and may well have lowered the watershed around Katembora.

During the Pleistocene (roughly the last two million years) the earth's climate has undergone several periods of cooling, expressed in high latitudes as ice ages. As ice sheets advanced and retreated over Europe and America, the global climate was altered such that southern Africa experienced periods of intense aridity, alternating with periods when the rainfall was significantly higher than at present. During the last of these "pluvials", the lake which formed the end sink of the Zambezi, Chobe and Okavango Rivers must have risen to its highest recorded stand, 945 m above sea level.

As the watershed was being lowered, it was just a matter of time before a high lake stand during a pluvial breached it at its lowest point, the saddle between the hills at Katembora. Once the lake had started to overflow, the waters probably cut relatively rapidly into the basalt to create the gap and rapids at Katembora and initiate a permanent link between the Upper and Middle Zambezi.

The capture of the upper catchment had a massive effect of the trough tract of the Zambezi downstream of Batoka Gorge. Once Lake Palaeo-Makgadikgadi had been drained, streamflow at Kariba must have been six or seven times its pre-capture value. This huge increase in water discharge was accompanied by little or no increase in the discharge of sediment. The sediment laden lower catchment waters were thus diluted by clean water from the upper catchment and the river started to degrade, cutting downwards into its alluvial bed.

Degradation resulting from river capture is recorded in two main ways on the Zambezi. At the end of Kariba Gorge the former bed of the river is marked by a terrace, forming a surface some 30 m above the present channel. The terrace seems to have been preserved because the river at this point cut down relatively rapidly through its alluvial bed to the underlying Karoo sediments which effectively fixed its course and prevented lateral migration.

At Mana the river appears to have been relatively free to cut laterally into its banks and the high terrace has not been preserved. The former (pre-capture) bed of the river in the Mana area is marked by a ridge of rounded and poorly sorted grit to cobble size alluvium some 5 km to 6 km south and east of the present channel and about 50 m above it. This "Stoney Ridge" contains pebbles of jasperlite which fix the provenance (source) of the alluvium to the catchment of the Mid Zambezi. Jasperlites are not carried by any of the tributary streams which meet the Zambezi downstream of Kariba. There are also numerous agates among the stones which must have been eroded from basalt extruded at the end of the Karoo and effectively fix the minimum age of the alluvium. The deposit is post-Karoo Zambezi alluvium and demonstrates that the Zambezi once flowed along a more southerly and higher course than it does today.

River capture effected in this manner, by a lake overtopping its watershed and flowing into an existing river system, is recorded for Pleistocene Lake Bonneville which once occupied a large part of the Great Salt Lake Basin in western U.S.A. Having overtopped its watershed at Red Rock Pass, Lake Bonneville drained rapidly into the Snake River system in a massive flood that apparantly lasted some six weeks. Peak discharge during this event is calculated to have been of the order of 400 000 cumec, about three times the mean discharge of the Amazon River. Large rounded boulders now litter the Snake River Plain as relics of this catastrophe.

The capture of the Upper Zambezi does not appear to have been as sudden or as violent and nowhere in the catchment are alluvial clasts found that are much bigger than cobble grade. There are, however, two lines of evidence which suggest that the alluvium of Stoney Ridge may represent a catastrophic deposit which resulted from the capture event. Deposits of pre-capture alluvium are exposed in many of the river cliffs cut by the Zambezi's tributaries. These contain pebble beds which are typically a few centimetres thick, separated by a few metres of sandy and silty material. In contrast, the alluvium of Stoney Ridge is composed of several metres of principally cobble and pebble sized stones, containing little material finer than grit.

The clast composition of Stoney Ridge is also different from that of the alluvium which preceded it. Whereas the older alluvium contains only rare agates, the deposits of Stoney Ridge contain this material in abundance. Since the major source of agates is from the Karoo basalt of Batoka

Gorge and the plateau above it, river capture can be expected to have increased the relative abundance of agates in the system. Stoney Ridge therefore probably represents a catastrophic deposit, laid down by the flood which accompanied river capture, immediately prior to the degradation which cut the Zambezi down to its present level.

The south bank of the Zambezi at the upstream end of Mana Pools National Park is shown in Fig. 3. In the southeast of the photograph, Kalahari sands support a dense community of mixed layer dry forest, popularly known as jesse bush. Northwest of the jesse, the Stoney Ridge is covered by *Colophospermum mopani*. Mopani also grows on the sodic and often saline clays which extend from the Stoney Ridge to the margin of the recent alluvial terraces. The Zambezi appears to have traversed this zone as it migrated laterally towards its present position without leaving any obvious alluvial deposits. The transition from the mopani vegetation of the sodic clays to the riverine vegetation of the alluvial terraces shows up clearly on Fig. 3. North of this boundary the soils are alluvial and of the same type that are currently being deposited by the river. The start of the alluvial terraces is marked on the main access road to Nyamepi Camp by the abandoned channel at Long Pool.

The Channel, The Terraces and The Pools

The Zambezi River at Mana includes many islands which give the channel a braided appearance. The islands and the Zimbabwean bank are typically formed of sandy alluvium overlain by a layer of clays and silts. The sands often display sedimentary structures such as cross-bedding, which show that they were deposited by the active channel. The height of this alluvium above the present river level suggests that it was deposited during floods, when the water level was raised. The upper, fine-grained layer represents overbank deposits, laid on top of established islands or terraces during flooding.

An aerial view of the river (Fig. 3) illustrates a marked tendency for islands to be deposited adjacent to the Zimbabwean bank, with the main deep water channel on the Zambian side. Smaller channels, typically up to 100 m wide, separate the islands from the Zimbabwean bank. The islands can be seen as the most recent additions of land in the process that formed the alluvial terraces at Mana. In time, the small channels separating the islands from the mainland are cut off and become pools. The island is thus joined to the mainland and becomes a terrace.

Several stages in this process can be distinguished on Fig. 3. Near the centre of this stretch of river lies a sandy island (marked I), separated from the south bank by a continuous channel some 100 m wide. Upstream of this lies another island (II) which is mainly vegetated. The channel separating this island from the mainland has been partially filled in. In the area III, around the confluence of the Rukomeshe River with the Zambezi, several pools cut the recent terrace and record the final stage in the process. The older pools on the alluvial terrace behind Nyamepi Camp at Mana formed in the same way. They now lie several kilometres from the river bank which has built out by this amount since the pools were formed.

This pattern of islands and small channels fringing terraces and pools is typical of the Zimbabwean bank within Mana Pools National Park. It records the lateral migration of the channel into the north bank. Although Recent alluvial terraces exist in several places on the Zambian side, most of the northern margin of the channel consists of a sub-vertical river cliff, formed of partially consolidated alluvium and rising some 5 to 10 m above river level.

The reasons for this assymetry are not entirely clear but are probably related to the structure of the underlying bedrock. The Zambezi River at this point is flowing through a rift valley. During rifting of the type experienced in this part of the valley, both the underlying basement rock and the sediment infill within the rift are often tilted towards the bounding escarpment. This phenomenon, known as roll over, has probably caused the sediments of the Karoo System on the northern margin of the rift to dip towards the Zambian escarpment. Once the river has eroded down to a resistant strata, it tends to follow this layer rather than cut through it. During a flood, when much of the alluvium is swept from the river bed, the channel cross-section becomes assymetrical. There is then a greater tendency for erosion to occur down dip, on the margin adjacent to the deep water channel. During the subsequent period of low flow, there is a greater tendency for deposition to occur on the shallower, up-dip margin.

The process of terrace formation at Mana is different from that which has operated on other rivers in the southern African region, such as the Vaal of South Africa. Successive wet and dry periods during the Pleistocene alternately aggraded and degraded the bed of the Vaal, to create a series of stepped terraces rising several metres above the present river bed. This has not occurred on the Zambezi because, although Pleistocene climatic cycles undoubtedly affected its catchment, the major degradation caused by river capture was too severe to allow aggradation to occur. Thus the Recent terraces at Mana are all set at virtually the same level. The numerous terrace steps that are crossed along the main access road to Nyamepi Camp do not reflect different heights of the terrace surfaces, but rather the tendency of the surfaces to slope away from the river, as a result of levee development adjacent to the former river positions.

The effects of Kariba

The dam at Kariba affected the river channel downstream in two main ways. It changed the river flow regime and it massively reduced the supply of sediment. The responses of rivers to impoundment schemes have been studied extensively and the responses of the Zambezi are not typical of those experienced worldwide. Rivers downstream of dams generally degrade their beds due to reduction in the supply of sediment. They also tend to narrow their channels since the peak flow events, which would otherwise have promoted channel widening, are

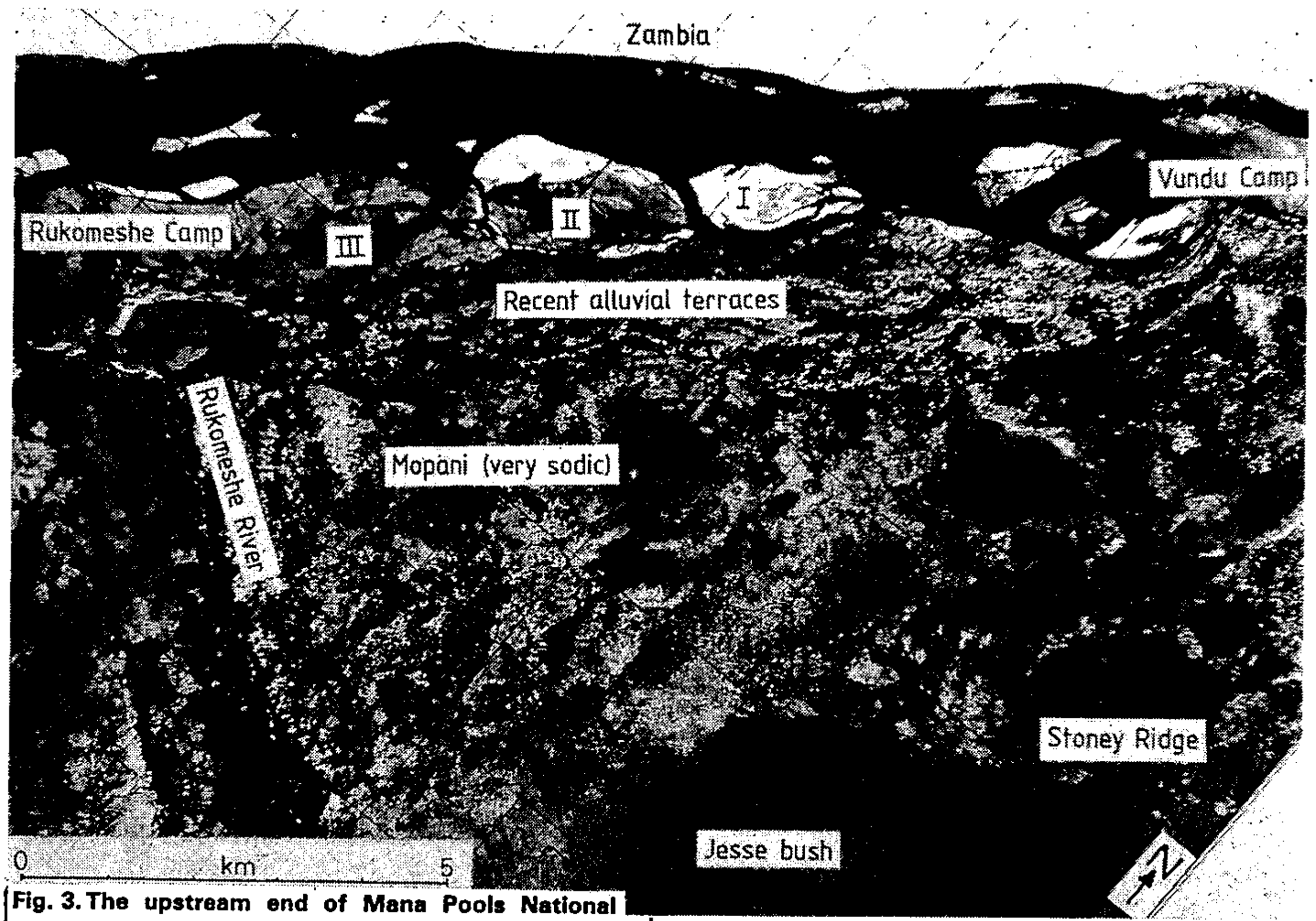

Fig. 3. The upstream end of Mana Pools National Park, taken from orthophoto map No. 1529 C3B, illustrates the evolution of the Zambezi River at Mana (see text). The orthophoto is reproduced by permission of the Surveyor General, copyright reserved.

absorbed by the dam.

The Zambezi has degraded its bed somewhat. Alluvial tracts between Kariba Gorge and Chirundu seem to have been lowered by about 2 m, about half the average degradation experienced below dams in the U.S.A. This limited degradation may be due to the fact that the Zambezi was already degraded, following the capture of the upper catchment. Although the river bed is typically formed of mobile alluvium, it is controlled by bars of hard rock which cross the channel at certain points. One such control point can be seen on Fig. 3 at Vundu Camp. Rapid degradation can only occur between these controlled reaches.

The Zambezi downstream of Kariba has experienced major widening. Between Kariba and Mupata gorges, a river distance of 160 km, the channel has widened by an average of 200 m since Kariba Dam was built. Study of aerial photographs taken at different times has shown that this amount of vegetated land has been lost from both banks and islands in the channel. Widening has affected some stretches more than others and the alluvial stretch at Mana, from Vundu Camp to G Camp downstream of the Sapi, widened by some 300 m over the same period. Although widening is not typical of rivers worldwide, the same problem is reported from below impoundment schemes on many of the large rivers of China, suggesting that widening may be a phenomenon specific to large rivers.

Since Kariba Dam was built, flood gates have been opened repeatedly (Fig. 2a). These artificial floods undoubtedly promoted erosion and much of the widening of the channel occurred during these times. During the six years since June 1981, no flood gates have been opened and the channel has changed very little over this period. This implies that a constant base flow of about 1 000 cumec fed through the turbines provides artificially stable conditions in which little river bank erosion can occur. Since the installed generating capacity of the dam now approaches the maximum that the river's available discharge can reliably produce, it is likely that floodgates will have to be opened far less frequently in the future than they have done in the past. Severe bank erosion and channel widening may well prove to be a problem of the past and the Zambezi should be able to experience long periods of stability in the years to come.