HISTORICAL CHANGES IN THE BEHAVIOUR OF THE ZAMBEZI RIVER AT NYAMUOMBA

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Our understanding of the Zambezi River is hampered by an incomplete written history. Early European explorers often recorded isolated details and National Parks personnel such as Hughes have recorded elements of the oral tradition of the inhabitants. In more recent years, records of river discharge and aerial photography have been collected which could provide valuable insight into river processes before and since damming at Kariba. Streamflow data was collected both upstream and downstream of Kariba for at least a decade prior to damming in 1958. Some of the data is presented here to illustrate the very different natures of the upper and lower catchment flow regimes and the resulting pre-dam discharge. Analysis of anomalies within the flow record are interpreted to reveal the river's grade prior to damming and the degradation of the channel that has followed.

Introduction

Nyamuomba is the point where the Zambezi River leaves Kariba Gorge. It lies at the junction of escarpment paragneisses of the Makuti-Rushinga group and valley floor sediments of the Karroo group (Figure 1). The Zambezi River at this point widens from 150m at the end of the gorge to 1 km at the upstream end of Nyamuomba Island, just 1.2 km downstream.

This site was gauged by the Ministry of Water Development between July 1949 and May 1959. The record has been extended back to October 1947 by correlation with Chirundu data to produce a streamflow record covering the 11 years prior to the final closure of Kariba Dam, on December 2nd 1958 (Figure 4). The discharge at Nyamuomba is compared with the dis-

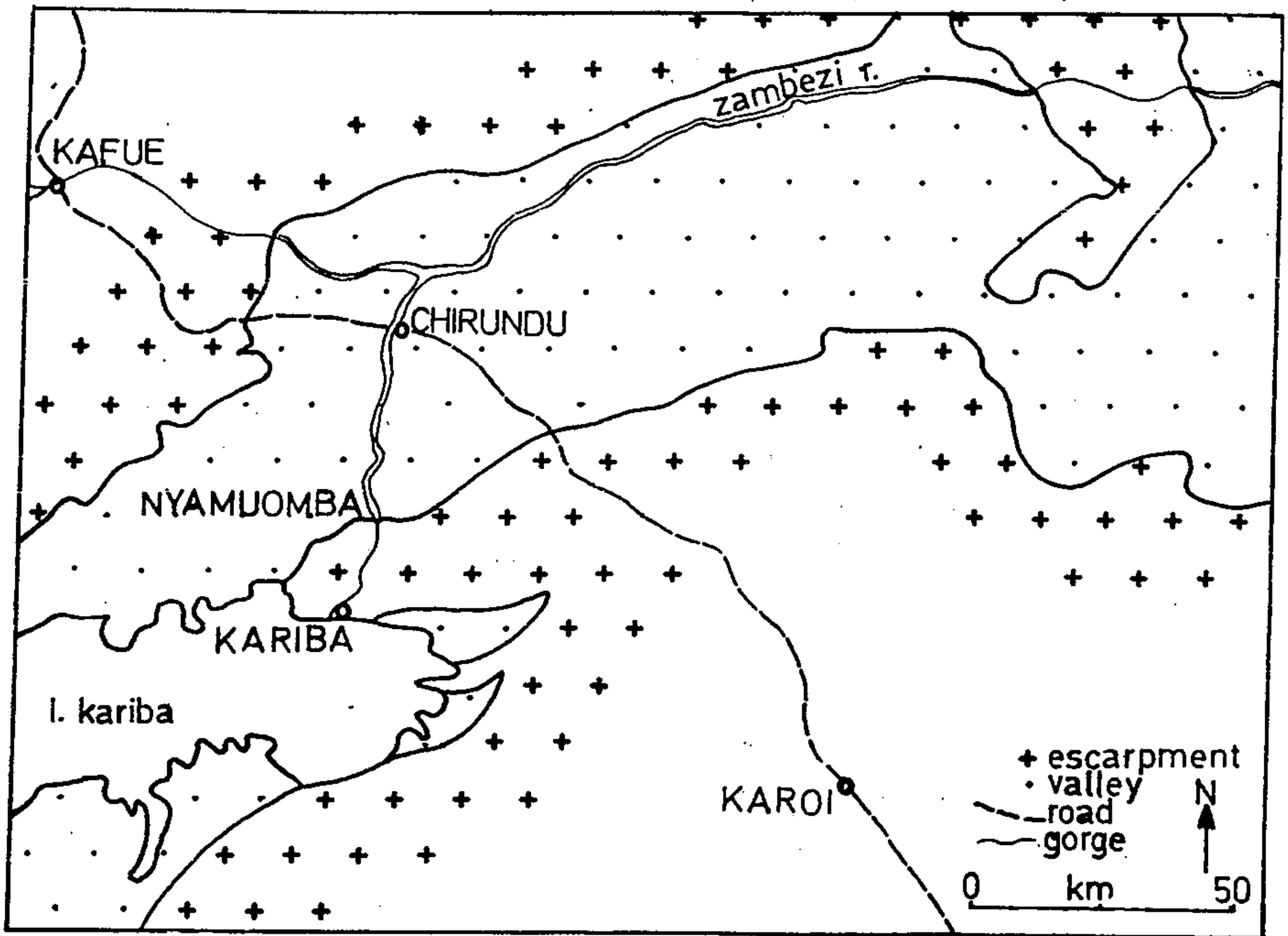


Figure 1: Location map. Source: Geological map of the Federation of Rhodesia and Nyasaland (1961).

charge at Victoria Falls (Figure 3) to show the effect on the hydrology of the Zambezi of Kariba's lower catchment (i.e. tributaries entering the Zambezi below Victoria Falls). Change in the morphology of the river channel at Nyamuomba before and since the construction of Kariba Dam is inferred from comparison of the hydrographs and from the change in the stage/discharge relationship between 1958 and 1985.

Streamflow records

The discharge at a particular point on a river can be estimated from the level of the water surface. It is clear that when a river is in flood and carrying a high discharge, the water level, known as the stage, will be high. Low discharge will be represented by a low stage. In order to estimate discharge, the relationship with water level must first be established.

Linsley et al (1949) describe the process of constructing a *rating curve* to estimate the discharge (Q) from the level of the water's surface. The discharge is calculated at various stages using the formula $Q = A V$, where A is the cross-sectional area of the channel and V is the mean water velocity. The cross-sectional area can be estimated by measuring water depth at several places across the channel. The mean water velocity is more difficult to measure as velocity varies with depth and distance across the channel. The cross-section must be divided into several sub-sections and the velocity measured in each using a current meter lowered into the water.

This rather lengthy calibration process must be repeated at several stages of the river in order to evaluate the range of discharges associated with a range of water levels. Stage is plotted against discharge and the points interpolated to produce the rating curve. This was done by the Ministry of Water Development at Nyamuomba in 1958 (Figure 6) and the water levels which were recorded between 1949 and 1959 have been converted to discharges. Discharges have been estimated in this way at three main points along the Zambezi River in Zimbabwe, at Victoria Falls, Nyamuomba and Chirundu.

1. *Victoria Falls* (1924/25 to present).

Water levels have been recorded since 1907 but the early records are regarded as unreliable. Streamflow has been measured at three places just upstream of the Falls: Victoria Falls Pumphouse, Victoria Falls Bigtree and Livingstone Pumphouse on the north bank. Records from the three stations are well correlated with each other and this data is the most reliable and extensive record of streamflow available for the Zambezi.

1. *Nyamuomba* (1949 to 1959).

Streamflow was measured at the end of the Kariba gorge at Nyamuomba (Kariba 3 records) and within the gorge (Kariba 2 and 3a). Records for sites 2 and 3a are incomplete so site 3, and the exit of Kariba gorge, provides the most complete record of streamflow in this area. Since the tributaries which enter the Zambezi within Kariba Gorge are small (total catchment = 200 km^2.), the Nyamuomba records can be regarded as representing the discharge at Kariba.

3. *Chirundu* (1937-1939 and 1945-1960).

Water levels were recorded at the bridge. Unfortunately, the sandy nature of the river bed in this area has meant that the rating curve for Chirundu was always unstable. Hence the records are considered unreliable. Although the Chirundu data could be correlated with data upstream to generate a synthesised record, this is not attempted here.

There have been two attempts to synthesise lower catchment streamflow data. The first was by England (1949) during the planning stage of Kariba Dam, using lower catchment rainfall records. A more detailed consideration of catchment characteristics was carried out by CAPCO (1981) in order to help with dam management. Lower catchment streamflow from 1924 was synthesised as monthly totals. The short term flood events are thus averaged out and CAPCO's figures do not give a realistic picture of brief runoff events.

Modification of Zambezi streamflow by the lower catchment

At Kazungula, 72 kms upstream of Victoria Falls, the Zambezi is joined by the Chobe River. Together, these two great river systems drain some 500 000 square km of rather subdued relief in Western Zambia and Eastern Angola (Figure 2). Along several stretches, both rivers pass through swampy areas, known as *bulozi* in Zambia. Floods from the upper catchment are largely absorbed by these swamps, which release much of this stored water during the falling stages. The result can be seen on the Victoria Falls hydrograph (Figure 3) which generally forms a smooth curve, rising annually around the beginning of each year, normally to a single peak between February and May. A very different pattern is exhibited at Nyamuomba (Figure 4). Although the dry season (roughly May to November) usually exhibits a smooth hydrograph which parallels that for Victoria Falls quite well; the rainy season is characterised by a series of jagged peaks, representing floods within the lower catchment. Although these floods were often very intense events, they were characteristically of short duration, subsiding within a few days.

The floods which arrived at Nyamuomba prior to Kariba Dam were thus of two types. The gradual annual rise and fall of the river resulting from drainage of the upper catchment and, superimposed on the rising limb of this event, a series of flash floods from the lower catchment.

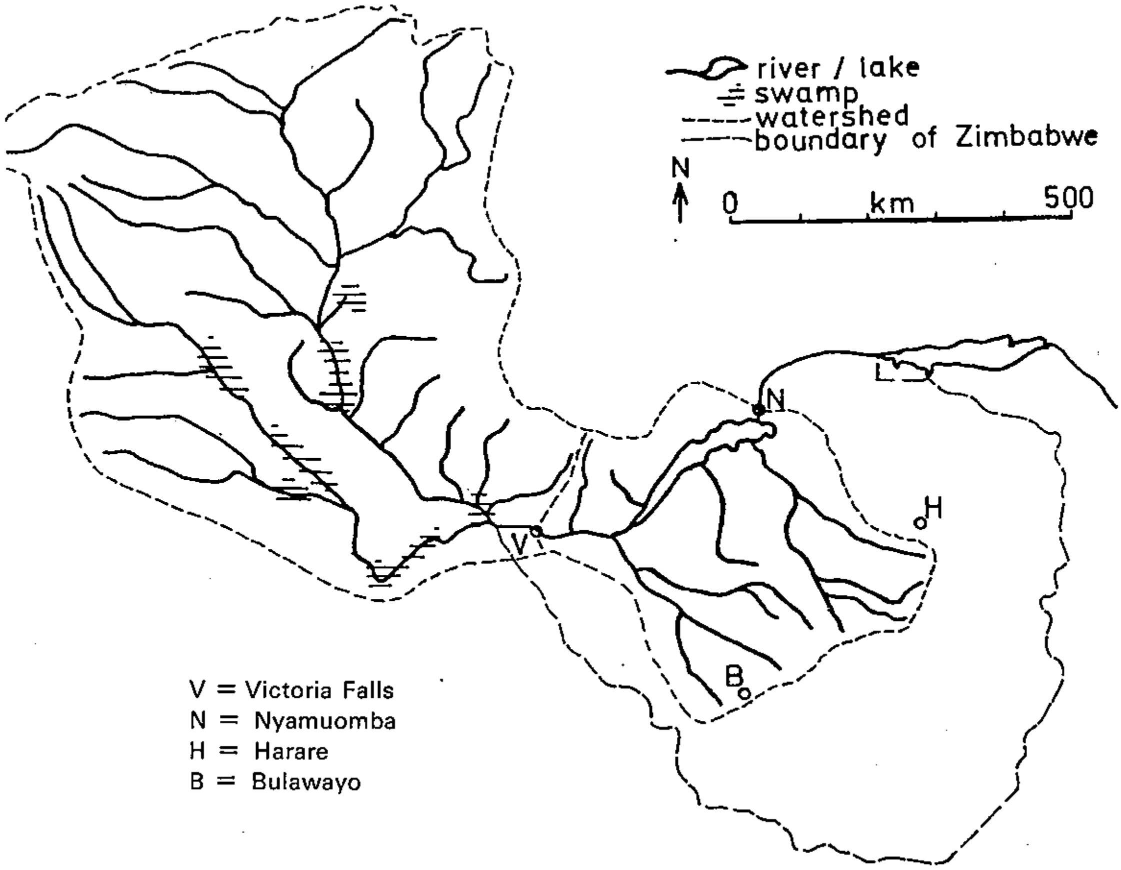


Figure 2: The catchment of Victoria Falls and Nyamuomba. Source: New Oxford Atlas, O.U.P.

As well as differing in frequency and intensity, the lower and upper catchment floods also exhibited significant differences of water quality. Upper catchment waters, having passed through the Chobe and Barotse swamps, had their sediment load filtered out and were very clean. Lower catchment waters, carried through the Sebungwe by sandy rivers such as the Sanyati, the Sengwa and the Gwaai had a high sediment load. So different were the upper and lower catchment floods that local people called them by different names. The dirty, lower catchment flood waters which normally arrived first were known as *Gumbura,* while *Murorwe* referred to the cleaner, more regular flood from Chobe, Barotse and beyond.

For much of the year there was no lower catchment runoff. All the tributaries which join the Zambezi between Victoria Falls and Nyamuomba were ephemeral and dried up for several months between about April and the first rains, in November or December. During this time the only movement along the water courses would be the slow percolation through the bed of sandy streams.

This situation is illustrated by Figure 5, the apparent lower catchment hydrograph calculated as Nyamuomba discharge minus Victoria Falls discharge. The time lag for water passing between the Falls and Nyamuomba has been found as the best fit between the two hydrographs during the dry season and is 4.8 days (see figure 7). The wet season portions of the hydrographs cannot be compared as lower catchment floods confuse the fit. The data has therefore been offset by five days, Victoria Falls data for May 1st has been subtracted from Nyamuomba data for May 6th etc. It is likely that the rising limb of the flood has a rather shorter lag time associated with it. Since the Victoria Falls hydrograph forms a smooth curve, small errors in lag time would not significantly alter the apparent lower catchment hydrograph.

Figure 5 illustrates several interesting features of the lower catchment. The flashy nature of the lower catchment flow regime has already been commented on. Although the upper catchment is more than three times its size and *Murorwe* discharged seven times more water than *Gumbura* over this eleven year period, the

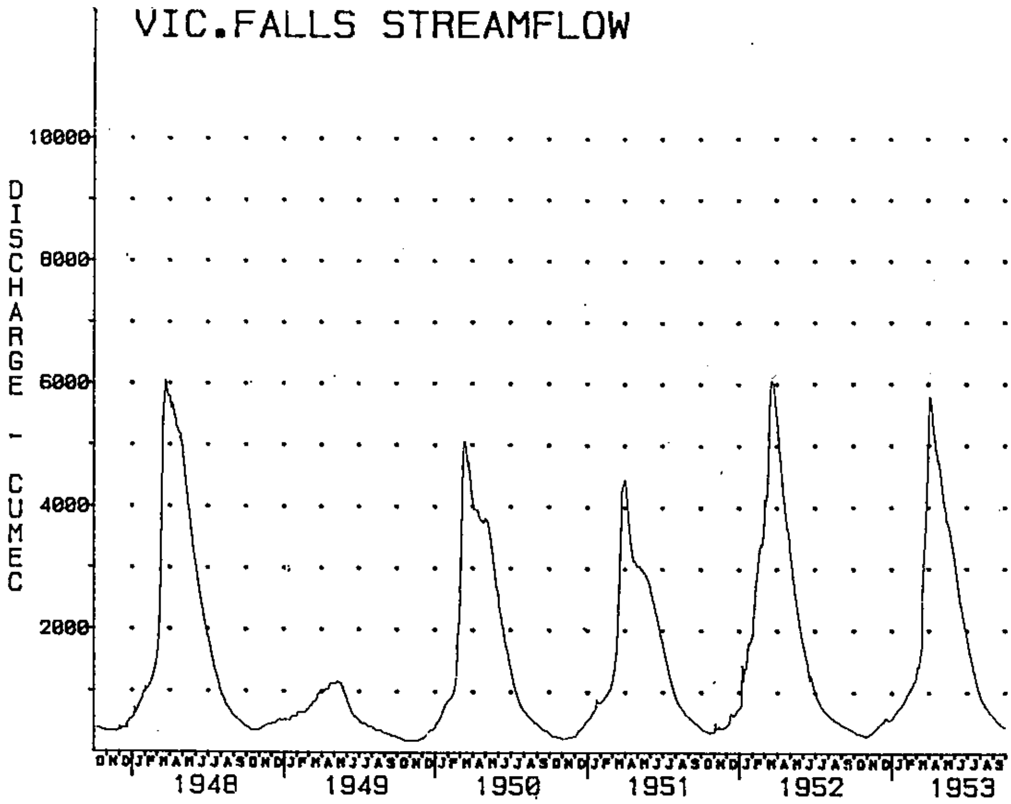


Figure 3: Victoria Falls streamflow, hydrological years 1947/48 to 1958/59.

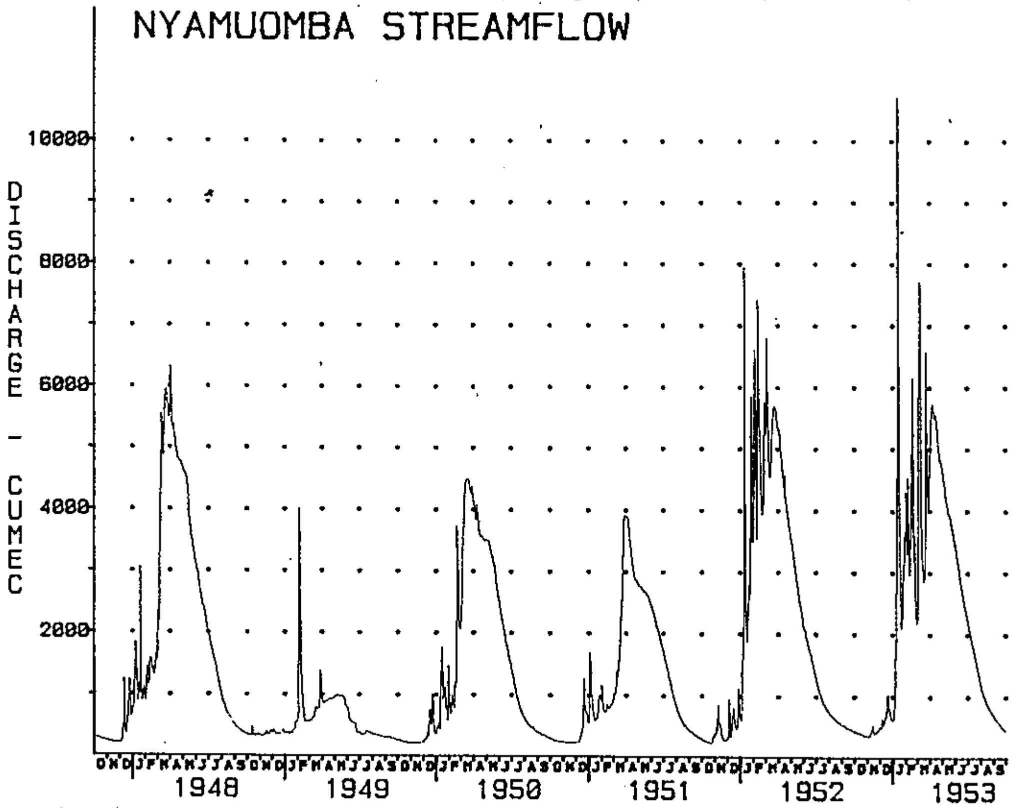
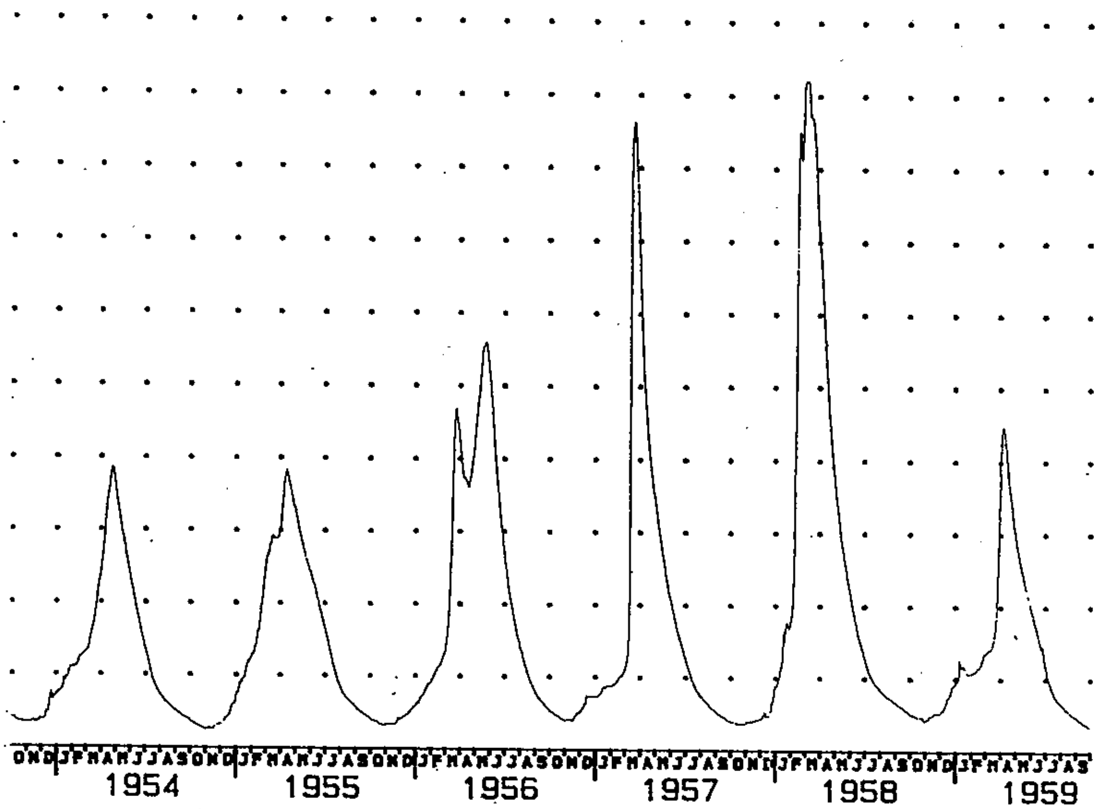


Figure 4: Nyamuomba streamflow, 1947/48 to March 1959. Note the final closure of Kariba (2.12.58). Records are missing from 16.1.50 to 15.2.50 due to the tragic death of the site engineer, Mr. Bellamy and his four staff following a landslide which flattened their camp at the end of the gorge. This period has been filled in using data from the Chirundu



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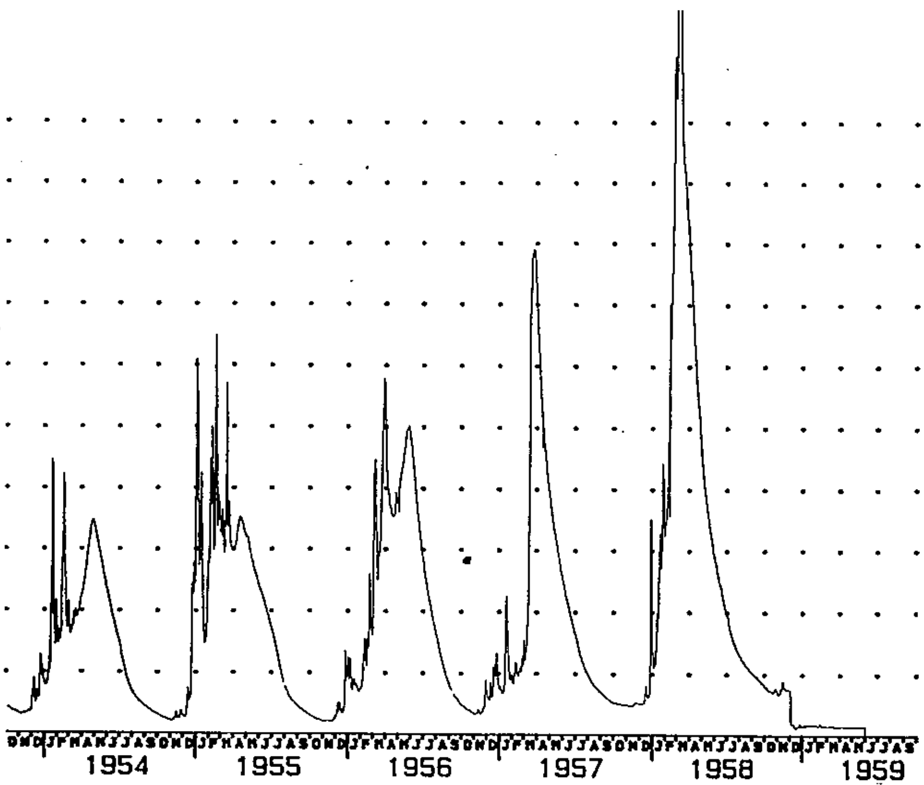

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lower catchment has produced the greater (if briefer) flood, during January 1953. At its peak, this event was discharging 10% more water than the record 1958 peak at Victoria Falls.

It is rare for *Murorwe* to coincide with a major lower catchment outburst and characteristically peaks after *Gumbura* is over. The 1958 flood season is the only one of eleven considered here, when major floods from both catchments coincided to produce a really major event downstream.

Downstream effects

The relationship between water level and discharge at Nyamuomba cannot be used to predict water levels downstream. The wide, shallow nature of the alluvial channel below Kariba Gorge, bounded by low river terraces, would not allow the flood to rise as high as it does within the gorge where the waters are confined laterally.

The riverbank downstream of Kariba Gorge is typically arranged in a series of alluvial terraces. The lower terraces, found adjacent to the channel, support a community of grasses, whereas the older, higher terraces are wooded. The question of the frequency with which these higher terraces were innundated by the annual Zambezi flood was investigated by Hughes, in the late 1960's, during a series of interviews with the people who had lived in the valley below Kariba. According to his informants, only three exceptional floods were recalled in the Mana and Chewore areas and these were estimated to have occurred in 1916, 1934 and 1957. Du Toit (1983) feels that these exceptional events resulted from the lower and upper catchment floods coinciding; a late *Gumbura* or an early

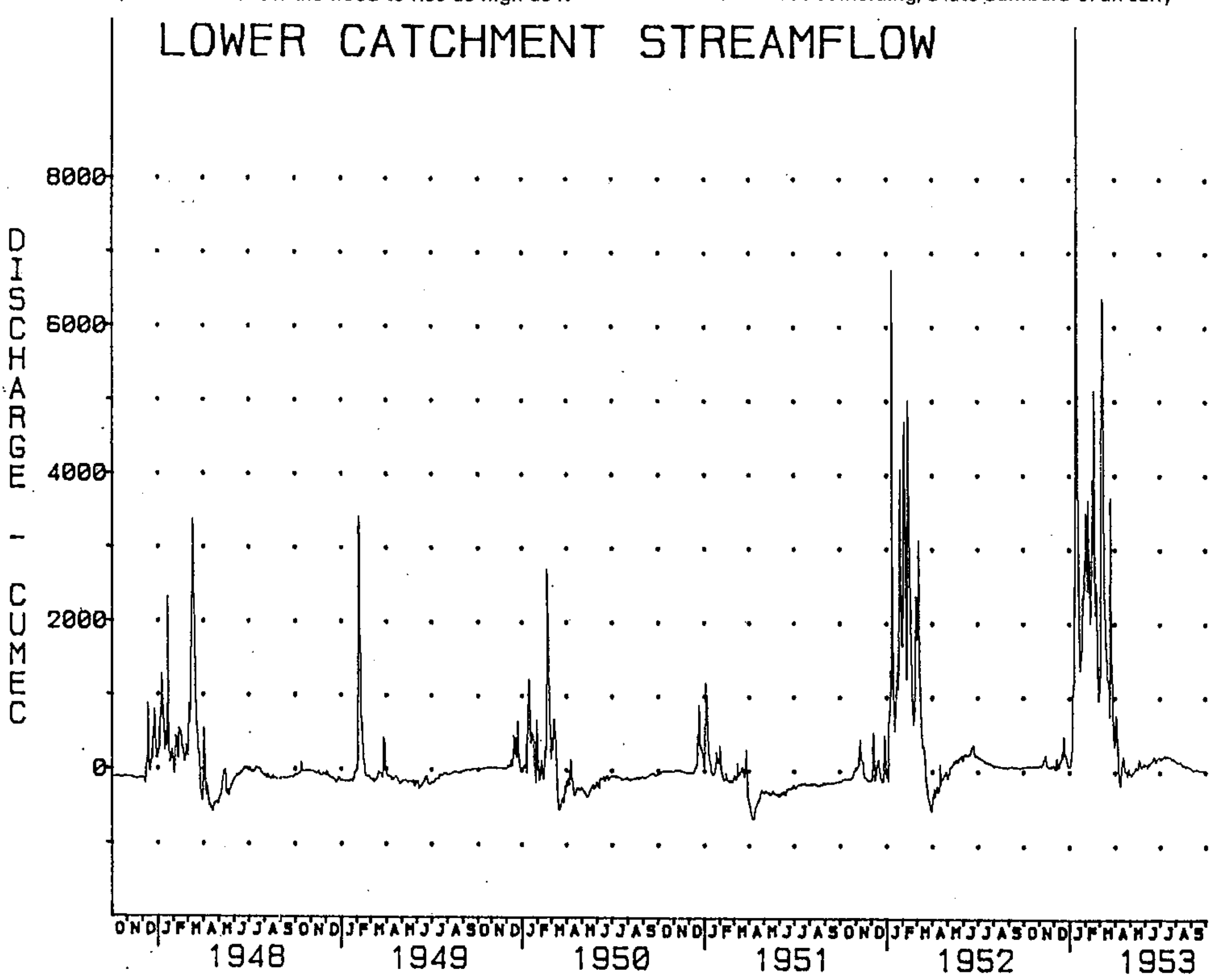


Figure 5: Apparent lower catchment hydrograph (Nyamuomba discharge minus Victoria Falls discharge), 1947/48 to 1957/58. Records are offset by five days to account for the time lag between the two stations.

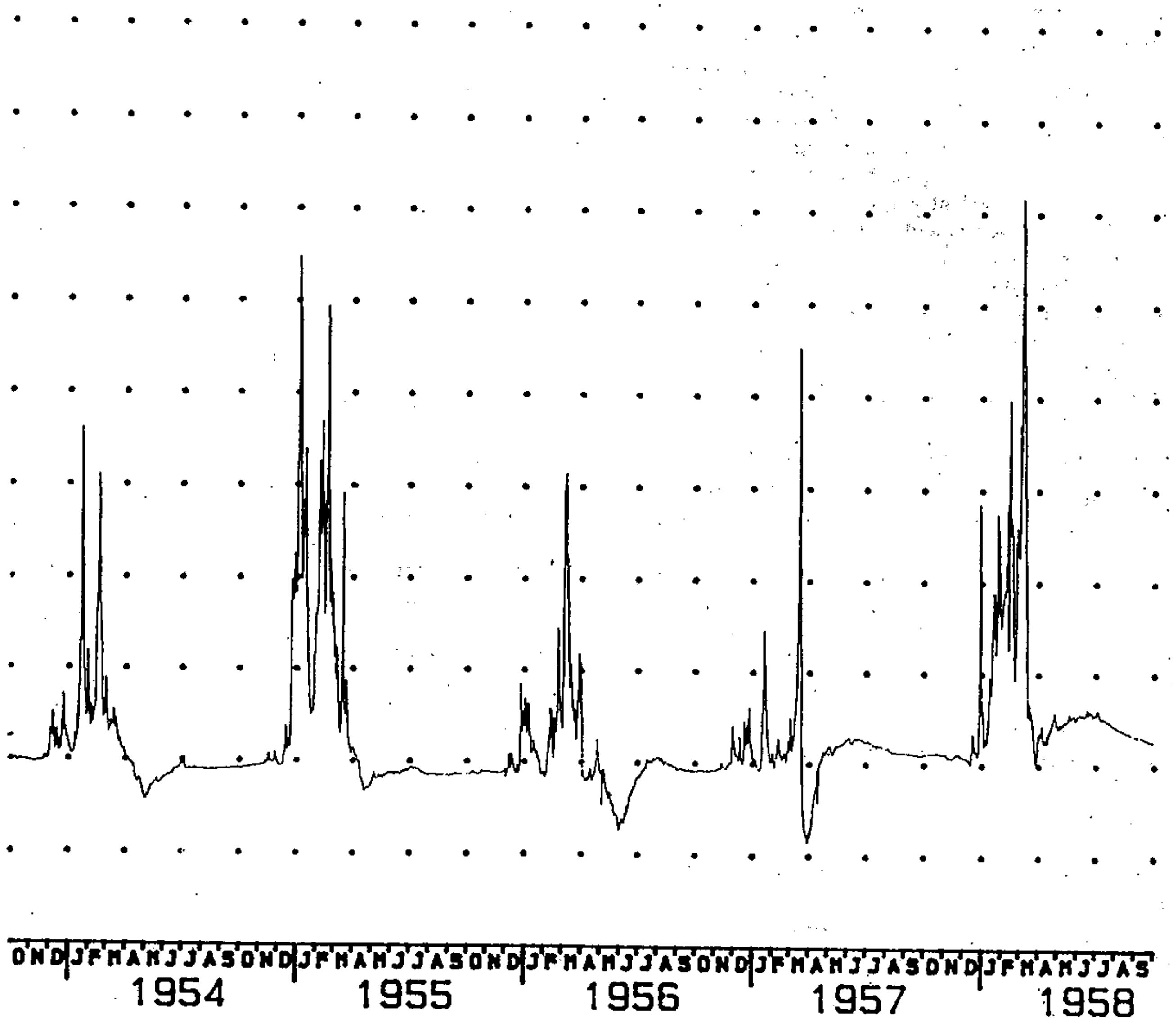
Murorwe or both. This contention is borne out by the streamflow data for the last of these reported floods which shows that record floods at Victoria Falls in 1958 were boosted from a peak of 9200 cumec (cubic metres per second) to 15200 cumec at Nyamuomba. This is surely the event remembered by the local people as the flood of 1957 and recorded by Hughes.

No attempt has been made to construct a rating curve for Mana, which in any case would change with the frequent changes in the channel morphology recorded in this area. It should be noted that brief floods, such as that of January 1953 would have been buffered to some extent by the terraces themselves as their porous, sandy alluvium absorbed water into the banks. A more prolonged upper catchment flood, having saturated the banks, would cause the water to rise higher.

Stability of the rating curve

The apparent lower catchment hydrograph (Figure 5) is clearly in error. For long periods during the dry season the curve falls below zero, suggesting a negative contribution of streamflow from the lower catchment. This is not possible as streamflow can only be positive or (possibly) zero. These "errors" in the hydrograph, which often persist for several months, probably result from perturbations of the rating curve relationship and may provide a clue to changes in the form and dynamic response of the Zambezi river channel.

The relationship between river stage and discharge can be disrupted in a number of ways. Since discharge is the product of cross-sectional area and water velocity, a change in either of these alters the relationship expressed by the rating curve. An increase in water



velocity could be precipitated by a reduction in bed roughness, wetted perimeter or sinuosity or an increase in the slope of the channel. This would reduce the stage for any given discharge or rather, since discharge is estimated from stage, increase the discharge represented by each stage. An increase in the cross-sectional area of the channel could result from erosion of the banks or degradation of the bed and would also mean that more water was being passed through at each river stage. Similarly a reduction in either cross-sectional area or water velocity has the effect of reducing the stage associated with each discharge.

A change in water velocity will have occurred as part of the complex response of the Zambezi to damming at Kariba and may also have occurred during the eleven year period prior to this in response to changes in the Upper Catchment (Inst. of Hydrology, 1981). River channels characteristically respond to changes in their water or sediment discharge by changes in grade (Machin, 1948; Lane, 1955). A stable rating curve indicates that the river is at grade, that is, in approximate equilibrium between channel morphology, hydrology and sediment throughput. An aggrading river is depositing material on its bed and building up an alluvial sedimentary sequence. In such a case, the bed and hence the water level at a given discharge is being raised. The discharge calculated from the rating curve would become gradually greater than the true discharge. Channel degradation puts the rating curve in error in the opposite sense as the rating curve starts to underestimate the discharge. In this way, changes in the stage/discharge relationship can reveal the direction and approximate magnitude of grade changes.

Channel degradation since damming at Kariba

The effects of Kariba dam on the channel morphology at Nyamuomba are expressed through the changes in hydrology and sedimentology imposed by the dam. There have been numerous studies of alluvial channels below dams. Petts (1979) reported a variable response of river channels below 14 British dams. He found that bed armouring (the development of an erosion-resistant layer of stones on the bed) occurred in most cases but that "where armouring does occur, degradation will persist until the reduction of slope and the increase of channel bed roughness reduce the velocity below the threshold for sediment transport" (p. 333). Leopold *et al.* (1964) report American examples of rivers degrading at rates exceeding 15 cm per year. Williams & Wolman (1984) analysed data on alluvial channels downstream of 21 dams, mainly in the Midwestern U.S.A. and describe an average of total degradation immediately downstream of the dams of 4 m, reducing to an average of 1 m at a distance of 100 km downstream. Makkaveyev (1972) reporting on the downstream effects of the water impoundment projects in the U.S.S.R., described the

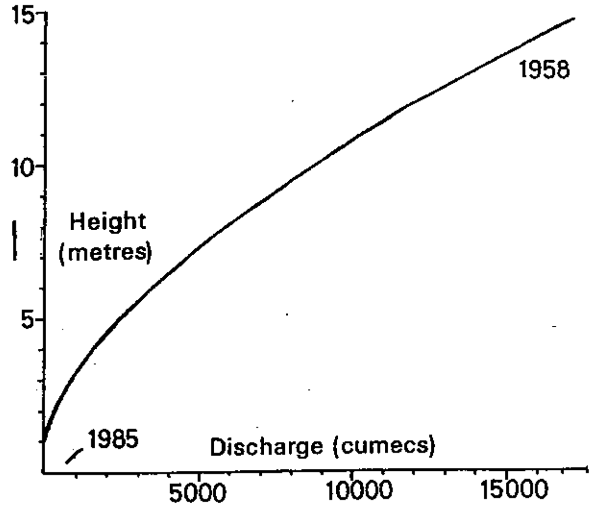


Figure 6: Nyamuomba rating curves, 1958 and 1985. (1 cumec = 1 cubic metre per second). Heights are expressed above an arbitary datum, set at 407.73 metres A.S.L. Note how stages recorded in 1985 are universally lower than those recorded in 1958. This lowering results in part from channel degradation (see text).

same general trend. Chien (1985) summarises the Chinese experience on rivers with a discharge and channel morphology comparable with those of the Zambezi. In all cases where dam management caused sediment to be retained within the reservoir, the channel downstream was found to have degraded. The downstream channel often became wider, as lateral migration eroded the banks.

Channel changes recorded on the Zambezi have been found to reflect this widening trend. Guy (1981) reported widespread erosion of the riverbank bordering Mana Pools National Park and Nugent (1983) described the same process between Nyamuomba and Chirundu. Nugent attributed this widening trend to the very low gradient of the river (about 1:4 000) and the fact that its course between Kariba and Mupata Gorges is divided into at least four alluvial tracts by resistant rock outcrops in the bank and presumably the bed. Unable to deepen its bed significantly, the extra erosive potential of the river was being used in widening.

In order to estimate degradation since the construction of Kariba dam it is necessary to determine the current rating curve and compare it with that produced in 1958. It is not possible to produce a full rating curve without spilling water from floodgates, in order to measure discharge at a range of stages. During a single day small changes in the discharge through Kariba's turbines, resulting from fluctuating electricity generation, produce a small range of water levels at Nyamuomba. A rating curve can be constructed over this

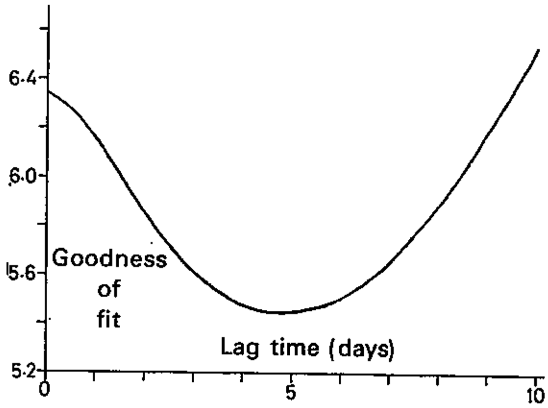


Figure 7: The root mean square of the apparent lower catchment discharge (1948 to 1958, May to September only) is plotted at different lag times ie.with the data offset by different numbers of days. The best fit between the hydrographs can be found as the smallest variation between these (dry season) segments of the curve and is 4.8. days.

range of streamflow by gauging. This was done by Jameson High School, Kadoma, while on a Zimbabwe Hunters' Association educational camp on August 21st, 1985. Stage was measured at ten minute intervals between dawn and dusk (Figure 8).

Streamflow data on this day has been estimated by CAPCO as a function of power generation, recorded at 30 minute intervals. The streamflow data has been converted to water levels using the 1958 rating curve (Figure 6) and the best fit found for the two graphs (Figure 8). The difference between the stage calculated for this flow in 1958 and the stage measured in 1985 is a tentative estimate of the amount by which the channel has incised into its bed.

Unfortunately there is no direct relationship between the 1958 and 1985 stage/discharge relations. For the range of discharge calculated by CAPCO, the rating curves are not parallel (Figure 6). Figure 9 illustrates the relationship between discharge and the apparent channel degradation. It can be seen that at higher discharges the channel appears to be more degraded than at low discharges. This effect should not be attributed to changes in grade, it results from the fact that the rating curve is affected by factors other than the level of sediment in the bed.

One factor which must have reduced water levels at Nyamuomba is channel widening downstream. The wider channel is also shallower and has the effect of reducing stage at the end of the gorge. The rating curve may also have been affected by a change in water velocity. The anticipated direction of change is a reduction in water velocity, due to a lower gradient and greater friction with the wider bed. Reduced water velocity would increase stage, thus at least partially offsetting the reduction of stage caused by widening.

At present, it is not possible to isolate these various elements of channel change and assess how much each of them have affected the stage/discharge relationship. It can only be said that the water surface at this range of streamflow has been lowered by about 1.60 to 1.75 in 27 years.

Grade changes prior to damming at Kariba

Changes in grade before 1958 cannot be inferred directly from changes in the stage/discharge relationship as there is no record of what this might have been. The effect of grade changes, by putting the rating curve in error, is to record a greater or lesser discharge than would otherwise be expected. During the dry season, when there is little or no lower catchment runoff, the upper catchment flood should be passed through to Nyamuomba with little change. By analysing the ways in which the apparent lower catchment hydrograph deviates from this expectation, changes in the rating curve and hence grade changes in the channel can be determined implicitly.

This technique assumes that grade has remained stable at the Victoria Falls recording stations. There is no evidence for this assumption. The Institute of Hydrology (1981) reported an overall increase in discharge since the late 1940's and this could have precipitated a change in grade above the Falls.

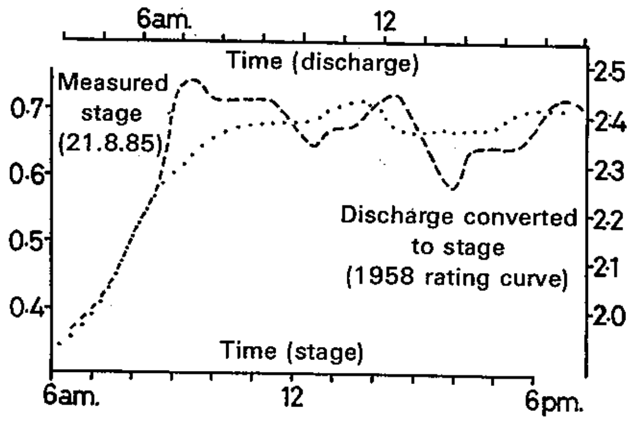


Figure 8: The best fit between stage at Nyamuomba (dotted line) and discharge through Kariba, converted to stage using the 1958 rating curve (dashed line) plotted from data collected on 21.8.85. The best fit was found by superimposing the graphs and moving them relative to each other in order to minimise the area between them. The correspondence between stage and discharge has been used to construct the 1985 rating curve (figure 6) and assess the apparent degradation (Figure 9). Note: The time lag taken for water to pass through the gorge from Kariba to Nyamuomba can be seen from the displacement of the X-axes to be about 2.28 hours at this range of discharge.

Although the geomorphological situation of the Victoria Falls recording stations, just above a major waterfall, should minimise changes in bed level, grade changes at Nyamuomba inferred using this technique could in fact represent changes in the opposite sense at Victoria Falls.

Grade is the product of a balance between the supply of water and sediment (Lane, 1955). A nett increase in water discharge could degrade the channel while an increase in the discharge of sediment results in aggradation. This balance is well illustrated by the Zambezi situation, in which the upper catchment supplies most of the water and the lower catchment supplies most of the sediment.

During "normal" years, when the upper catchment flood peaked after *Gumbura* was over, an anomalous effect was recorded at Nyamuomba. The apparent lower catchment discharge (figure 5) often fell significantly below zero. In such a case, either the rating curve relationship had been altered or water had been absorbed by the banks. The rapid recovery of the curve suggests the latter cause. As the waters of *Murorwe* rose over the terraces recorded by Bond and Clarke (1954) which now lie under Lake Kariba, they were readily absorbed by the alluvium of the river bank, which by this time would have been drying up. The positive pulse of water which often appears on the apparent lower catchment hydrograph during the falling stages of *Murorwe* around May, June or July probably reflects the release of this stored water. During 1949, when the upper catchment flood was very poor, the apparent lower catchment hydrograph does not display this pattern, since *Murorwe* did not rise sufficiently to flood the terraces. During 1953 and 1958, the pattern seems to have been obscured by a late *Gumbura*.

The annual storage of water by gravel terraces could account for a slight depression on the apparent hydrograph. Figure 5 shows several years in which the apparent hydrograph falls to less than minus 500 cumec. It seems improbable that alluvial terraces could absorb discharges of this magnitude and therefore likely that grade changes have also occured to exert a the grade changes have also occurred to exert a systematic error on the flow data.

peak in the apparent hydrograph, the curve levels off for a period of several months, until the start of the next rainy season. It is at this time that the difference between discharge at the two stations should be at a minimum and it is this point in the hydrograph that supplies the most information on grade changes.

During the first four years of record, poor lower catchment runoff led to degradation at Nyamuomba. This resulted in the artificial lowering of the hydrograph, which reached a low point in 1951, when it plots below zero for more than half the year. Heavy lower catchment floods during 1952 and 1953 seem to have aggraded

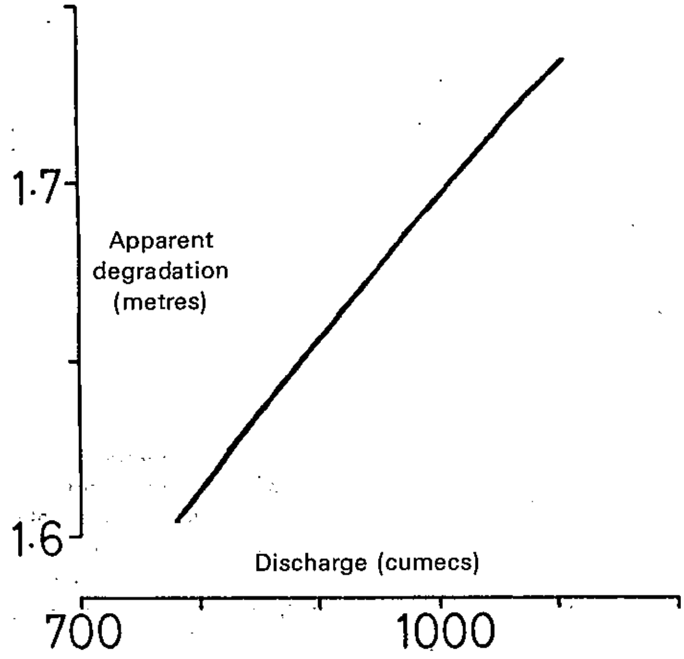


Figure 9: Variation in the apparent degradation at Nyamuomba over the range of discharge recorded on 21.8.85.

the bed somewhat although much of this sediment was removed again after the poor *Gumbura* of 1954. The 1955 data are anomalous, as the channel apparently continued to degrade after a strong *Gumbura* and a comparatively weak *Murorwe*.

The period from 1956 to the final closure of Kariba Dam towards the end of 1958, records aggradation of the bed of the channel. This would appear to be a predictable consequence of dam construction, reflecting the deposition downstream of the sediment load introduced into the river by building activities at the dam site. Such a conclusion ignores the massive upper catchment discharge during the two years prior to dam closure. The record streamflow at Victoria Falls during March 1957 was exceeded by a new record in 1958. These raging torrents must have swept an enormous volume of bedload through Kariba Gorge, dwarfing the meagre sediment input from the dam site. If the high discharges recorded during the dry season sections of the apparent lower catchment hydrograph do represent channel aggradation, then it is probably related to these two flood events. One possible explanation is that the 1957 and 1958 floods scoured stones from the bed of Kariba Gorge which had lain immobile since the last such flood event. These stones may then have been dropped as a result of the reduction in water velocity at the end of the gorge, resulting in local aggradation at Nyamuomba.

Conclusions

The hydrographs from Victoria Falls and Nyamuomba record major differences in the upper and lower catchment flow regimes. The upper catchment flood is seen as an annual rise in discharge, usually to a single peak. The lower catchment is characterised by a series of brief floods during the summer, separated by periods of comparatively low flow. Floods emanating from both catchments must be coincident to produce a major flood event downstream.

Anomalies in the apparent lower catchment hydrograph reveal fine detail of the movement of water between Victoria Falls and Nyamuomba. After the end of the lower catchment flood, upper catchment waters continued to rise and store water in the banks. Although some of this water was undoubtedly lost in transpiration of riparian vegetation, the remainder was released during the following winter.

The apparent lower catchment hydrograph at the end of each dry season has been interpreted to reveal changes in grade. "Grade" in Mackin's (1948) sense refers to changes in the level of the bed over a period of years and is the sum of random seasonal variations. A true measure of grade should therefore be taken over several decades. The brief record considered here can only be taken as an indication of the probable behaviour of the river over the longer term. The period 1948 to 1954 exhibits a fluctuation between degradation and aggradation of the bed, which is explicable in terms of the proportion of the flow discharged from each catchment. There are no systematic trends covering this period and it is concluded that the Zambezi river, prior to the beginning of the construction of Kariba Dam, was at grade. This interpretation appears to be at variance with the increase in upper catchment discharge reported by Institute of Hydrology (1981), as increased upper catchment flow would be expected to increase the ratio between water and sediment discharge and thus promote degradation. The views are not incompatible however as an increase in the upper catchment discharge may have been matched by a similar increase in the lower catchment to maintain grade. Alternatively, the channel prior to dam construction may already have cut through its alluvium to flow directly over the underlying bedrock, at least at the critical stretches identified by Nugent (1983). Scour of the the underlying Karroo sediments would be a slow process and could not possibly be recognised over the brief flood record considered here.

The river bed in the Nyamuomba area has degraded since Kariba Dam was built. Changes in the channel width and flow characteristics prevent the magnitude of degradation from being assessed exactly, although it appears to have been in the order of 1 to 2 metres.

Acknowledgements

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