THE REGULATION OF THE ZAMBEZI IN MOZAMBIQUE:

A STUDY OF THE ORIGINS AND IMPACT OF THE CABORA BASA PROJECT

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CHAPTER 5
THE INFLUENCE OF SEDIMENT TRANSPORT ON THE OPERATION OF THE CABORÁ
BASSA PROJECT AND THE DEVELOPMENT OF THE ZAMBEZI BASIN

The complex nature of erosion, deposition and sediment transport processes and the lack of adequate information and data make it impossible to give these subjects as rigorous treatment as that given to questions related to hydrology. Although the implications of sediment movement for the development of water resources may be diverse and far-reaching, engineers have, in the past, tended to regard them as a relatively low priority in the design of major projects. This may be explained by the fact that the effects are usually long-term and always difficult to quantify. For the geomorphologist, however, both the processes and the time-scales are familiar; indeed, human activities frequently cause an acceleration of the natural processes of sediment erosion and deposition. For this reason, there has been increasing interest and involvement in investigating the influence of human activities on such processes; see, for example, Coates (1972), Gregory and Walling (1973), Cooke and Doornkamp (1974) and Leopold, Wolman and Miller (1964). In certain cases geomorphologists are now being consulted directly by engineers in the design of new projects; see, for example, Doornkamp et al. (1982). Nevertheless, despite the increased understanding of natural erosion and deposition processes which has been achieved, there remain considerable difficulties in relating such knowledge to the evaluation of parameters which could be applied in the design of specific projects.

Similar difficulties have been experienced in applying the results of theoretical and empirical studies of sediment transport phenomena in river channels to project design. Considerable progress has been made, in recent years, in the formulation of algebraic relationships from both theoretical and empirical studies, to describe the transport of sediment particles in channels; White, Milli and Crabbe (1975) review much of this work. Such work has been applied, with some success, to the understanding of changes in channel form following human interventions in the river system. These investigations, however, require considerable numerical computation and their results

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will, clearly, depend both on the approximations and assumptions on which the analysis is based and on the quantity and quality of available data. Methods of analysis based on 'regime' concepts have been successfully applied in the investigation of the properties of natural channels\textsuperscript{305} and in the design of artificial channels\textsuperscript{306}, but these are applicable only to the study of stable conditions not in describing transient conditions.

Various developments have occurred in recent years in the techniques of sediment sampling in rivers including the use of pump sampling\textsuperscript{307}, which enables large volume samples to be obtained at an accurately determined depth in the flow, and the use of turbidity meters\textsuperscript{308}. The latter are being used increasingly because of their ability to provide continuous monitoring of sediment concentrations and, of importance in most underdeveloped regions, because they are relatively inexpensive and can be operated automatically. An important series of studies, using turbidity meters, by Walling (1977), has shown the possible inaccuracy of previous sediment load calculations which were based on the use of a single sediment rating curve for a given sampling station. The assumption, made in producing such a curve, that a unique relationship exists between fluid discharge and sediment discharge is shown by Walling's work to be invalid.

Many studies relating to sediment movement in tropical regions have been undertaken although few long-term systematic records are available either of sediment loads in tropical rivers or of sediment deposition rates in tropical reservoirs. One important area of study has been the rate of erosion of soil under different types of vegetation or methods of cultivation and the effectiveness of different soil conservation methods; see, for example, Hudson (1971) and Morgan (1981). Work of this nature, however, is not readily applicable to the estimation of sediment loads in streams. Complete catchments of tropical rivers have been studied, for example, in Malaysia, by Douglas (1968), in Tanzania, by Rapp, Berry, Temple et al. (1972) and in Kenya, by Dunne and Ongweny (1976) and Moorhead and Sims (1982). A common finding of several studies relating to rivers where reservoirs are in operation has been that siltation rates have, in practice, been far higher than those predicted during the
design of the projects. Detailed studies of reservoir sedimentation have largely been confined to reservoirs of relatively small capacity. The pre-impoundment study of the Mangla Dam in Pakistan, reported by Szechowycz and Qureshi (1973) provides a notable exception.

The references cited above are selected only as examples which illustrate some of the major areas of study related to sediment transport. More detailed introductions to the subject may be found elsewhere. Such work is largely confined to investigations of specific technical questions. There are, however, important social and economic considerations related to sediment transport. A useful introduction to soil conservation measures which considers such questions, in the context of river basin management in the tropics, is provided by Douglas (1980).

In the lower Zambezi basin, prior to the building of the Kariba and Cabora Bassa dams, the principal published accounts of the effects of sediment transport were concerned with problems of navigation along the lower Zambezi and, in particular, through the delta. The influence of sediment movement on agricultural production was not given detailed consideration in Mozambique either as regards its erosion from upland areas or its deposition on the alluvial plains. In Zimbabwe and Zambia, by contrast, there has been a long history of involvement in studies of soil erosion and soil conservation. The effect of soil erosion in the Zambezi basin, within Mozambique, will be of considerable importance in any future plans to develop upland agriculture, particularly in tributary catchments. Rates of erosion will also influence the rate of siltation of any reservoirs created on these tributaries. In Lake Cabora Bassa, because of the size of its catchment area, it is unlikely that changes in land-use practices will have a significant effect in the foreseeable future. However, because of the lack of information it has not been possible, in this thesis, to consider in detail these and other aspects of soil erosion and conservation.

With the construction of the Kariba and Cabora Bassa dams important changes occurred in the pattern of sediment transport in the Zambezi. It is the consideration of the effects of these changes and the possible effects of sediment accumulation on the operation of the
two projects which forms the main substance of the present chapter. Three topics of particular relevance have been identified: the accumulation of sediment in reservoirs; the scouring and deposition of sediment in the channel downstream of Cabora Bassa and its impact on plans for navigation; and the deposition of sediment on the alluvial plain.

Sediment accumulation in reservoirs

Engineers did not, in general, consider it necessary to undertake detailed studies of the possible effects of reservoir sedimentation before the construction of any of the dams now operating in the Zambezi basin. The reason for this appears to be that, for the continent of Africa as a whole, sediment yields are widely believed to be amongst the lowest in the world. Holeman (1968), for example, suggests that 'average' sediment yields in Africa are about 27 tonnes/km²* compared with 35 t/km² for Europe, 45 t/km² for Australia, 65 t/km² for South America, 95 t/km² for North America and 600 t/km² for Asia. On the basis of such estimates, the designers of reservoir projects appear to have assumed that within the 'economic life' of a proposed project, usually taken as thirty to fifty years, accumulation of sediment would have a negligible effect on the project's performance and the value of its outputs. This was considered to be particularly true for lakes Kariba and Cabora Bassa with their large storage capacities.

In view of the lack of information and data for undertaking a rigorous study of the problem of siltation in reservoirs of the Zambezi basin, it has been necessary to approach from various angles in an attempt to identify the principal characteristics of sediment transport processes in the basin. This is necessary to ascertain which reservoirs are likely to be the most vulnerable to heavy siltation rates.

* This value should be viewed with considerable caution. Holeman had only five sources of data for the whole of Africa - the Zaire, Niger and Nile rivers together with two relatively small rivers in Algeria and Tunisia. None of these rivers has characteristics which are similar to the Zambezi. Furthermore, in a continent as large and diverse as Africa it is meaningless to talk of 'average' sediment yields. Holeman, himself, noted that 'evidence of excessive erosion in South Africa exists'. (p740)
Important differences between the siltation rates of the different reservoirs found in the basin are noted including significant differences between Lake Kariba and Lake Cabora Bassa.

a) The siltation rate of Lake Kariba: Before the construction of the Kariba Dam the subject of reservoir siltation was barely considered, apart from the following 'order of magnitude' approximations given in an official report published in May, 1951, and which are quoted in full:

The anticipated low rate of siltation, based on samples taken in 1948, 1949 and 1950 indicate a useful life for the dam of at least 1 000 years\textsuperscript{313}. (...) 

With the top water level at 1644 [ft] RL, the draw down level is 1610 RL at which the residual storage is about 50 million acre-ft [62 x 10\textsuperscript{9} m\textsuperscript{3}]

With an average inflow of 32.4 million acre-ft [40 x 10\textsuperscript{9} m\textsuperscript{3}] it would take 100 years to silt up the residual storage and 160 years completely to fill the reservoir if the average silt contents were 1 to 150 by volume and the whole of the silt were deposited.

There are few data of silt contents available. Observations taken by the [Inter-Territorial Hydroelectric Power] Commission in March 1948, showed 1 in 3 200 by weight (say, 1 in 1 600 by volume) during the flood, falling to one tenth of this by June. The general indications appear to be that the Zambezi in the gorge does not carry a high silt content and that no anxiety need be felt as to the reservoir silting up. It would be desirable, however, to make a continuous and systematic series of silt observations\textsuperscript{314}.

The longer passage requires some explanation. The reservoir levels given in the first paragraph are based on the initial designs for the dam, which were later rejected, and on a different reference level from that currently in use. The 'residual' (or 'dead') storage, quoted is about one-half the volume which has been used in subsequent reports, 116 x 10\textsuperscript{9} m\textsuperscript{3}\textsuperscript{315}.

In the second paragraph, the average inflow given is equivalent to 40 x 10\textsuperscript{9} m\textsuperscript{3}/yr. However, on the basis of data presented by RPT (1980) the value now adopted by the CAPC is over 30\% greater. Furthermore, the calculation based on a hypothetical mean sediment concentration of
1 to 150 by volume has been repeated and the results do not agree with those given in the quotation; correcting this apparent arithmetic error and substituting the updated values for reservoir storage and average inflow, the periods '100 years' and '160 years' in paragraph two should be amended to '320 years' and '440 years' respectively.

In the interpretation of the term 'by volume' with reference to sediment concentrations in the passage, it must be assumed that the volume referred to is the volume of sediment and water in the deposits formed in the reservoir rather than the volume of the sediment particles alone. This conclusion is drawn from the fact that the correspondence between values '1 to 3200 by weight' and '1 to 1600 by volume' in the third paragraph, suggests a value of dry density of only 500 kg/m³. Such a value would be impossible for individual sediment particles. Even for reservoir deposits it is extremely low; according to the work of Lane and Koelzer316 such values are only found in unconsolidated deposits of clay-sized particles. In view of the large particle sizes carried by the Zambezi317 and the long time-scale involved in the siltation of Lake Kariba, which allows considerable consolidation to occur, the dry specific weight of these deposits should be at least a factor of two greater. Incorporating this additional modification into the 1951 calculation results in an overall increase in the estimated value of the siltation life of Lake Kariba by at least a factor of five, to over 5000 years.

Before attaching undue significance to the above calculation it must be noted that it is based on samples taken at only one location and over the relatively short period, 1948-50. Moreover, no details have been published of the method or frequency of sampling. The reference to a sample taken during the flood of March 1948 is, however, significant. According to the data used in Chapter 3 the discharge in that month gave the sixth highest monthly total for March on record. Furthermore, the shape of the hydrograph shows a steeply rising flood discharge during the month indicating that the tributary basins between the Victoria Falls and Kariba Gorge contributed a considerable proportion of the peak flow. Since these tributaries are expected to provide the bulk of the sediment input upstream of Kariba Gorge, see below,
it is likely that calculations based on samples taken during the March 1948 flood would, if anything, yield an over-estimate of the average rate of sediment discharge at Kariba Gorge. It should be noted that any conclusion is dependent on the assumptions that sampling was undertaken at the peak of the flood and that the samples obtained were representative of the sediment concentrations of all depths in the flow.

An alternative method of estimating the sediment input rate to Lake Kariba is to estimate separately the sediment yield from each part of its catchment. For the purposes of this calculation it has been assumed, with reasonable justification, that the Barotse Plain and Chobe Swamps act as sediment deposition zones for all sediment discharged from the catchment upstream of the Victoria Falls. Thus, a reasonable estimate of the sediment input to Lake Kariba can be obtained solely from the yield of tributary basins downstream of the Victoria Falls.

On the basis of work considered in detail below, the sediment yield from tributaries draining Zimbabwe appears to lie between 40 and 400 t/km²/yr. The catchment area of such tributaries, upstream of Kariba Gorge, is approximately $1.4 \times 10^3$ km² and that of tributaries in Zambia, assumed to have similar values of sediment yield for the purpose of this calculation, $3.0 \times 10^3$ km². Assuming, as in the previous calculation, that the average dry density of sediment deposits in Lake Kariba is at least 1 000 kg/m³, the mean annual loss of storage from Lake Kariba would be between $10 \times 10^6$ and $100 \times 10^6$ m³/yr. Thus, its 'dead' storage would be filled in a period of between 1 000 and 10 000 years provided that the present rates of erosion and sediment transportation continue. This estimate again suggests that the value placed on the siltation life of Lake Kariba in the 1951 report was probably conservative. The conclusion, that 'no anxiety need be felt as to the reservoir silting up', appears, therefore, to be reasonable.

Nevertheless, the 1951 report made the recommendation, 'to make a continuous and systematic series of silt observations'. For this purpose five sections across tributary inlets to the lake were accurately
surveyed prior to inundation, as well as several sections across the inlet of the Zambezi at Devil's Gorge. Periodic echosounding runs along the same survey lines could provide information about rates of sediment deposition in the parts of the lake where sediment is believed to be accumulating most rapidly. Such information would be valuable not only in calculating the rate of storage depletion in the reservoir, and the study of delta formation at the inlets, but also in monitoring the rate of sediment yield from particular catchments to show whether the rate of soil erosion is changing over a long time period. To date, however, no report on such work has been published.

b) Studies of sediment loads in rivers in Zimbabwe: P R B Ward and R Chikwanha sought to establish, over a period of five years, a programme of sediment sampling at selected river gauge sites in Zimbabwe using simple techniques. Summaries of the characteristics of the principal sites selected for sediment sampling and of the results obtained are presented in Tables 28 and 29. Two of the rivers studied, the Gwaai and Umsweswe lie in Kariba's catchment and the third, the Hunyani, lies in Cabora Bassa's catchment, see Figure 39 below.

Before considering the significance of the results obtained by Ward and Chikwanha, their choice of sampling technique will be examined. One important feature of the sampling programme was that full recognition was given to the fact that accurate assessments of sediment loads can only be made if samples are obtained sufficiently frequently to cover any rapid changes in discharge which may occur. They decided, therefore, that, where possible, four or five samples each day should be taken. This sampling programme compares very favourably with that used in many other studies, undertaken without automatic equipment, for which details have been published. Its main weakness was that no samples were taken during the hours of darkness. As a result, calculations of sediment discharge could only be made on the basis of the relatively long time interval of twenty-four hours using mean daily sediment concentrations estimated from the four or five samples available. Ward and Chikwanha do not discuss, in any of their reports, the possible error which might result from these sampling and calculation procedures.

The decision to undertake relatively frequent sampling had
Table 29: Characteristics of principal sediment sampling sites used by Ward and Chikwanha

<table>
<thead>
<tr>
<th>River</th>
<th>Catchment area to site (km²)</th>
<th>Dominant geological formation</th>
<th>Land use (% catchment European agriculture)</th>
<th>Mean annual rainfall (mm)</th>
<th>Mean annual runoff (mm)</th>
<th>Mean slope of catchment</th>
<th>Principal Reservoirs (capacity, where known, m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gwaii</td>
<td>14 500</td>
<td>Kalahari sand, sandstone</td>
<td>62</td>
<td>520</td>
<td>22</td>
<td>3.1 x 10⁻³</td>
<td>{Khami Railway, Umgusa, Umgululu, Khami River (3.8 x 10⁶)}</td>
</tr>
<tr>
<td>Umsweswe</td>
<td>1 990</td>
<td>granite, sandstone</td>
<td>80</td>
<td>760</td>
<td>52</td>
<td>4.5 x 10⁻³</td>
<td>Pasi</td>
</tr>
<tr>
<td>Hunyani</td>
<td>1 510</td>
<td>granite</td>
<td>58</td>
<td>890</td>
<td>125</td>
<td>4.2 x 10⁻³</td>
<td>Prince Edward</td>
</tr>
</tbody>
</table>

Principal Source: Chikwanha and Ward (1979)
Table 29: Results of sediment sampling work undertaken by Ward and Chikwanha

<table>
<thead>
<tr>
<th>River</th>
<th>Season</th>
<th>Water runoff ratio*</th>
<th>Suspended sediment yield (t/km²)</th>
<th>Estimated yield at runoff ratio of one</th>
<th>Mean annual concentration of suspended sediment (ppm by weight)</th>
<th>Overall mean concentration = total suspended sediment + total runoff (ppm by wt.)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Particles &lt;64µ All particles</td>
<td>Particles &lt;64µ All particles</td>
</tr>
<tr>
<td>Gwaai</td>
<td>1975-76</td>
<td>0.23</td>
<td>13.5</td>
<td>42</td>
<td>1000</td>
<td>1600</td>
</tr>
<tr>
<td></td>
<td>1976-77</td>
<td>0.91</td>
<td>38.9</td>
<td></td>
<td>1200 1900</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1977-78</td>
<td>3.41</td>
<td>115.3</td>
<td></td>
<td>940 1500</td>
<td></td>
</tr>
<tr>
<td>Umweswe</td>
<td>1975-76</td>
<td>0.60</td>
<td>21.0</td>
<td></td>
<td>550 680</td>
<td>390 490</td>
</tr>
<tr>
<td></td>
<td>1976-77</td>
<td>1.13</td>
<td>34.0</td>
<td></td>
<td>530 660</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1977-78</td>
<td>3.94</td>
<td>80.4</td>
<td></td>
<td>320 390</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1978-79</td>
<td>0.11</td>
<td>0.55</td>
<td></td>
<td>100 100</td>
<td></td>
</tr>
<tr>
<td>Hunyani</td>
<td>1976-77</td>
<td>1.76</td>
<td>24.8</td>
<td>**</td>
<td>100 110</td>
<td>70 80</td>
</tr>
<tr>
<td></td>
<td>1977-78</td>
<td>2.48</td>
<td>21.1</td>
<td></td>
<td>60 70</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1978-79</td>
<td>0.55</td>
<td>1.65</td>
<td></td>
<td>25 25</td>
<td></td>
</tr>
</tbody>
</table>

* Ratio of actual runoff to mean annual runoff.

** Results ambiguous

Source: Derived from Chikwanha (1980)
important implications for other aspects of the work:

(i) It was necessary to have a technician located permanently at each of the sampling sites to undertake the bulk of the sampling work. To meet the requirements of the sampling programme with the personnel and equipment available the sampling procedure itself had to be relatively simple. In fact, the majority of samples were taken using a hand-held bottle sampler. Thus, no attempt was made to investigate variations in sediment concentrations at different depths across the profile of the river section, and no direct attempt was made to measure the bed-load transport. However, an allowance was made for bed-load by applying the general algebraic function proposed by Einstein\textsuperscript{322}. Calculations using this function suggested that the bed-load discharge in the Gwaai is equal to approximately 10\% of the suspended sediment discharge. For the other two rivers it is considerably smaller.

(ii) A simple method had to be devised whereby the concentration of suspended sediment in a large number of samples could be determined relatively quickly. Rather than adopting a direct method of measurement, such as filtration or evaporation of the samples, Ward and Chikwanha chose to measure sediment concentrations indirectly using a simple commercial turbidity meter. It was found that the meter produced reliable results only for samples containing sediment of a single particle size in concentrations no greater than 3,000 ppm by weight; on the infrequent occasions when higher concentrations occurred preliminary dilution of the samples was found to be necessary. In order to allow for different particle sizes it was decided to sieve out all particles greater than 64\(\mu\). For the remaining particles it was assumed that their size distribution for a given river remained constant over the full range of discharges in a given season. Thus, provided that the turbidity meter was calibrated directly, by evaporation of selected samples from the river in question, subsequent samples could be analysed using the meter alone*. It was also assumed that the ratio of the mass of particles less than 64\(\mu\) to the mass of particles greater than 64\(\mu\) was a function of river discharge, for a given river in a given season, provided that the proportion of the larger particles was less than 50\%. Having

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* As an alternative, Ward and Chikwanha also attempted to calibrate the instrument using a standard calibration curve and theoretical correction factor based on knowledge of the particle size distribution.
established the form of this relationship, by analysis of a number of bulk samples, an allowance was made in the calculations to account for the larger particles. The assumptions about the characteristics of the particle size distributions on which these two aspects of the analysis were based were not adequately substantiated by Ward and Chikwanha and provided another possible source of error in their work.

(iii) Because of lack of adequate facilities and qualified personnel in the vicinity of the sampling sites the analysis of samples, described above, was undertaken at a single laboratory, in Harare, to which samples had to be transported. During transportation a number of samples were lost. Furthermore, a considerable period elapsed between sampling and analysis, during which the sediment settled to the bottom of the sample containers. Sufficient time also elapsed for a prolific bloom of algae to develop. It was, therefore, necessary to treat the samples with a sterilizing agent before transit and a dispersing agent on arrival at the laboratory.

One advantage of the procedures adopted by Ward and Chikwanha was that they did not depend on the use of a sediment rating curve. However, on the occasions when the required number of samples was not obtained, or where samples were lost in transit, a sediment rating curve, using river discharge records, was used to provide the missing data. It is significant, in view of the work of Walling (1977), referred to above, that Ward and Chikwanha found that a single curve adequately represented the relation between river discharge and sediment concentration for a given river in a given season. The only exception to this was during the first major floods of each season when sediment concentrations were considerably higher than those at equivalent discharges later in the season. In algebraic form their work showed that, apart from during these early floods, it was possible to use a relationship of the form:

$$C = aQ^b$$

where: C is the mean daily sediment concentration (ppm by wt); Q is the water discharge (m$^3$/day). The values of a and b showed considerable variation between different rivers in the same season, and between the same river in different seasons.
Regarding the yield of suspended sediment, the work of Ward and Chikwanha gave results which varied from 0.55 t/km²/yr, for the Umweswe in a very dry season, to 115 t/km²/yr, for the Gwaai in a very wet season. The conclusion was drawn that mean annual yields were of the order of 40 t/km². Comparison of the results in Table 29 indicates that the differences between the three basins studied were very small in terms of the annual sediment yield. It is possible that this similarity is coincidental in view of the substantial differences in catchment characteristics noted in Table 28. For example, the large catchment area and high proportion of European agriculture in the Gwaai catchment might be expected to produce lower sediment yields whereas higher yields arising from the more arid conditions and sandstone formation found there might serve to counteract these effects.

In terms of mean annual sediment concentrations, however, the results of Ward and Chikwanha show very great differences between the three rivers studied, ranging from approximately 100 ppm by weight in the Hunyani to 1600 ppm by weight in the Gwaai. These values are, in fact, dependent on the high concentrations recorded during the few peak floods which carry the bulk of the sediment each season and rarely affecting more than twenty days a year. Throughout the remainder of the year the suspended sediment concentrations are considerably smaller than these mean values. For this reason a substantial improvement might have been made to the accuracy of these results had the frequency of sampling (including night-time sampling) been increased during periods of high discharge. Ward and Chikwanha have offered no explanation for the large differences in the sediment concentrations found in the three rivers. A possible explanation might be in the inverse relationship which appears to exist between sediment concentration and mean annual runoff.

In attempting to obtain general values of sediment yield, for predicting siltation rates in Lake Kariba, based on the work of Ward and Chikwanha two important features about the three catchments under study should be noted. Firstly, all the catchments lie on the plateau rather than on the escarpment slopes of the Gwembe trough. Their mean slopes are, therefore, relatively mild. Secondly, for the Gwaai and
Umsweswe catchments it was noted that:

neither ... are undergoing advanced erosion due to overpopulation problems\(^{23}\).

In this respect the Hunyani catchment, which, in any case, drains into Lake Cabora Bassa not Lake Kariba, may be different since it has up to 40% of its area under intensive peasant cultivation. Nevertheless, other features of the catchment, in particular, the presence of the Prince Edward Dam 10 km upstream of the sampling site\(*\), may counter any tendency to produce high sediment loads. Both features would suggest that the sediment yield of the catchments sampled might be lower than that of the majority of the undammed tributaries which flow into Lake Kariba. A reasonable estimate of the mean annual sediment loads of such tributaries, based on this work, would, therefore, be at least 40 t/km\(^2\).

An important motive for the choice of sampling sites on the Umsweswe and Hunyani rivers was the desire to study the siltation rates of downstream reservoirs; on the Umsweswe, the John Mack Lake and, on the Hunyani, Lake McIlwaine. It was estimated that the John Mack Lake traps between 42% and 100% of the incoming sediment, depending on the spill discharge, whereas Lake McIlwaine traps virtually all its sediment input. On this basis, using the results of their studies, Ward and Chikwanha calculated siltation rates which suggest that the John Mack Lake will have lost half of its present storage capacity in 50 - 300 years and Lake McIlwaine will have lost half its present storage capacity in 800 - 5 000 years at present rates of siltation. The Darwendale reservoir further down the Hunyani would appear to have an even longer life in view of its larger storage capacity and the protection afforded to it by Lake McIlwaine.

c) Estimation of soil erosion rates: In order to provide further evidence of the possible rates of sediment yield from the catchments of reservoirs in the Zambezi basin, reference may be made to published studies of soil erosion rates. Some of the earliest and most celebrated work is

\* Small reservoirs also exist upstream of the other two sampling sites but these would affect the sediment input from only a small proportion of their catchments.
that of Fournier who, by analysis of data from a large number of tropical rivers (mainly in South-East Asia) derived algebraic relationships from which sediment yields could be calculated from the physical characteristics of a catchment. The relationships were used to map values of soil erosion hazard over the whole of Africa. According to this map much of the catchment of Lake Kariba lies in zones where erosion hazards of 200 - 1000 t/km²/yr are predicted. Between Lake Kariba and Lake Cabora Bassa parts of the catchment have predicted erosion rates rising as high at 2000 t/km²/yr. Repeating this work in greater detail, Doornkamp and Tyson (1973) applied Fournier's relationships to predict soil erosion hazard throughout the region which includes Lesotho, Swaziland and the RSA. They found that, for this region, predicted erosion rates ranged from 50 to 3000 t/km²/yr although the areas where rates of over 600 t/km²/yr were predicted were relatively small.

The application of Fournier's work in this way has been called into question by Douglas (1967) who maintained that the areas from which Fournier drew his data were:

much affected by changes in vegetation and soil stability induced by human activity. (p926)

From his own studies of rivers in Australia, Douglas concluded that where the effects of human activity are less marked erosion rates might be a whole order of magnitude smaller. His work suggests that estimates of sediment yield based solely on the physical characteristics of a catchment are likely to be unreliable.

The high rates of erosion predicted by Doornkamp and Tyson are, however, partly supported by evidence from Schwartz and Pullen (1966) based on direct measurements of sediment loads in rivers and siltation rates of reservoirs. Although their account provides insufficient detail to access the accuracy of their sources of data, it appears that the study was based on a large number of records spanning periods of up to twenty-five years. From these records average yields ranging from less than 20 to over 1200 t/km²/yr were estimated. A remarkable feature of their results was the high values of mean suspended sediment
concentration reported, from 780 to 35,000 ppm by weight. Schwartz and Pullen presented their results in the form of a graph relating sediment yield to catchment area for regions ranging from very low to very high erosion hazard, see Figure 38. These results indicate that as catchment area increases there is a slight reduction in the sediment yield in a region of 'average' erosion (presumably caused by deposition of some of the sediment within the catchment) and the difference between the upper and lower limits of erosion narrows (presumably because a larger catchment is likely to include a wider range of erosion conditions, the regions of highest erosion being counterbalanced by regions of least erosion). The work of Schwartz and Pullen does not include regions within the Zambezi basin so care must be exercised in applying their results to the present study. Nevertheless, it is interesting to note that for a catchment area of 170 x 10^3 km (the area of tributary catchments providing the main sediment input into Lake Kariba) values of sediment yield in the range 45 - 900 t/km²/yr are predicted. This range is close to that suggested in the present thesis on the basis of other published work.

The observation made above concerning the narrowing of the range of expected values of sediment yield as catchment area increases, see Figure 38, is graphically illustrated by the work of Campbell (1977) based on a study of the Red Deer River in Alberta, USA. He found that in this basin, which has an area of 43,000 km² and mean annual rainfall of 450 mm, 90% of the total sediment load originated from about 2% of the catchment area. The sediment yield of this small 'badlands' region, estimated at over 8,000 t/km²/yr, bore little relation to the mean sediment yield of the whole catchment, estimated at only 35 t/km²/yr. His conclusions carry a warning for those attempting to estimate sediment yields over large catchments in the manner of the present work:

> to refer to regional erosion rates or sediment yields in the light of these findings is an exercise in simplistic speculation. (p183)

As noted above, Zimbabwe has, for many years, had an active research programme into the implications of soil erosion for arable
Figure 38: Sediment yield of rivers in the RSA based on Schwartz and Pullen (1966).
agriculture. Some of the more recent studies have been undertaken by Elwell and Stocking. Of particular interest is their investigation of erosion hazard throughout Zimbabwe, see Stocking and Elwell (1973). Besides studying physical parameters, such as those used by Fournier, erosivity of rainfall, vegetation cover, slope and erodibility of soils, they also included a parameter related to the intensity and type of human occupation. Selected values of each parameter were assigned factor ratings on an arbitrary scale, with the final measure of erosion hazard being provided by summing the factor ratings of each of the five parameter values for the area under study. Results were then reproduced in the form of a map, see Figure 39. This work has a number of weaknesses: it assumes that the five factors interact in a simple incremental fashion; there is a subjective element in the evaluation of the human occupation factor; and, most importantly, no attempt was made by Stocking and Elwell to relate the final 'factor scores' to absolute values of sediment yield since the scores relate only to potential erosion hazard. Actual sediment yields will be affected by other factors such as cultivation practices. Nevertheless, the work fulfilled its purpose of identifying areas where soil erosion hazard is likely to be high and where further studies and possible conservation work may be needed.* It is also of interest to compare results of Stocking and Elwell with those of Ward and Chikwanha. For this purpose, the catchments studied by Ward and Chikwanha have been superimposed on the results of Stocking and Elwell's study in Figure 39. It can readily be seen, from this diagram, that the three catchments studied by Ward and Chikwanha were in areas of below average erosion hazard and that much of the southern escarpment draining into Lake Kariba shows above average erosion potential. On the basis of this comparison it would be reasonable to assume that the sediment yields measured by Ward and Chikwanha, of about 40 t/km²/yr, are below the 'average' sediment yield of the catchment areas which provide the main sediment input into Lake Kariba.

Further evidence of the soil erosion characteristics of the region is provided by a separate study undertaken by Stocking (1978) in one

* A similar study of the upland catchments of the Zambezi basin in Mozambique would be of value in planning the agricultural development of the region.
Figure 39: Potential erosion hazard in Zimbabwe based on Stocking and Elwell (1973).

Catchments studied by Ward and Chikwanha:

G = Gwaai

U = Umweswe

H = Hunyani
of the catchments sampled during Ward and Chikwanha's study, the Umsweswe. Stocking intended to make a detailed study of an area where extensive gully erosion had occurred in the sandstone region of the catchment. Somewhat surprisingly he found that the gullies had a relatively small influence over the rate of sediment production from this region; his results indicated that, at the time of the study, sheet erosion contributed approximately 150 t/km²/yr and that gully erosion added only about 40 t/km²/yr to this figure. In addition he compared the sediment yield from the sandstone region with that from the remaining, granite, region of the catchment. His results were similar to those of Campbell cited above; the granite region had erosion rates of only 25 t/km²/yr and, as a result, the sandstone region exerted a dominant influence over the total sediment yield, by producing over 50% of the sediment from 11% of the catchment area. Such findings make it extremely difficult to provide reasonable estimates of sediment yields from large and diverse catchments. On the other hand, they suggest that considerable reductions in yields might be achieved in future by means of conservation measures concentrated in relatively small areas. Additional evidence cited by Stocking indicates that, on individual plots, rates of erosion as high as 10 000 t/km²/yr have been measured in Zimbabwe although such studies have generally given values in the range 10 t/km²/yr to 1 500 t/km²/yr.

In the light of the various studies, it would be unwise to attempt to predict a precise value for the 'average' sediment yield of tributaries downstream of the Victoria Falls draining into Lake Kariba. Nevertheless, to provide the basis for an order-of-magnitude calculation it would probably be correct to suggest that, under present conditions, the value lies between 40 and 400 t/km²/yr. This is the range of values adopted in the calculation given earlier in this chapter.

d) The siltation rate of Lake Cabora Bassa: Interviews and correspondence, undertaken in the course of the present study with engineers and other officials associated with Hidrotécnica Portuguesa (the principal design consultants for the Cabora Bassa Project), LTA (one of the firms which formed the ZAMCO consortium), HCB (the operating company for the project),
as well as various government departments in Mozambique concerned with the present operation of the dam, indicated a broad consensus of opinion that siltation presents no threat in Lake Cabora Bassa, and that rates of siltation are probably of the same order as those in Lake Kariba. Unfortunately, none of those who expressed such opinions were able to point to recorded evidence to support their belief.

The MFPZ did not undertake a detailed programme of sediment monitoring, in respect of the possible siltation rate of Lake Cabora Bassa, despite a commitment in the Relatório Preliminar, 3, that:

>a study of sediment transport will be established, the importance of which may be fundamental. (p6, writer's translation)

The omission is surprising in view of the fact that, at a later date, the GPZ (1971a) listed 'excessive siltation' amongst the possible adverse consequences of the building of the Cabora Bassa Dam. In the Plano Geral, by contrast, the trapping of sediment within the reservoir was included as one of the expected benefits of the project because it was believed that this would facilitate the establishment of a stable navigation channel downstream (see below). It may have been partly for this reason, and because decisions concerning the economic viability of the project were based on a project life of only sixty years326, that, in the event, no detailed assessment of siltation rates was made.

If the assessment of siltation rates was neglected by the MFPZ, solely on the basis of a comparison with Lake Kariba, confidence in the belief that Lake Cabora Bassa would not be affected by siltation would have been, to some extent, misplaced. Lake Kariba has a 'dead' storage capacity of $116 \times 10^9$ m$^3$ whereas Lake Cabora Bassa has only $12.5 \times 10^9$ m$^3$ (assuming a minimum operating level of 295 m O.D.), see Appendix 1. The unregulated catchment of Lake Cabora Bassa is slightly smaller than that of Lake Kariba but since the major part of Kariba's catchment can be disregarded as a potential source of suspended sediment it is likely that the annual sediment input into Lake Cabora Bassa is at least as great as that into Lake Kariba. Thus, the 'dead' storage in Lake Cabora Bassa would probably be filled in less than one tenth
of the time taken to fill that in Lake Kariba. This comparison has been made solely to illustrate the significant differences which exist between the two reservoirs. A more detailed examination of the possible siltation rate of Lake Cabora Bassa is necessary.

It is convenient, for the purposes of the present study, to consider the inflow to Lake Cabora Bassa as originating from five sources: the outflow of Lake Kariba, the Kafue basin, the catchments of tributaries in Zimbabwe downstream of Kariba, the Luangwa basin and the catchments of several minor tributaries in Zambia and Mozambique. These may be treated separately:

(i) Lake Kariba: It may safely be assumed that the discharges from Kariba are free of sediment since the trap efficiency of a reservoir of this size must be virtually 100%.

(ii) The Kafue basin: No studies of sediment transport in the Kafue basin have been published. However, there are large areas of floodplain in the catchment, as well as the two dams of the Kafue Project, so it is highly unlikely that discharges from the basin will contain significant quantities of suspended sediment.

(iii) The catchments of tributaries in Zimbabwe downstream of Kariba:
The total catchment area of these tributaries is of the order of 42 000 km$^2$. One of the larger tributaries, the Hunyani, was studied, in its upper reaches, by Ward and Chikwanha, see Figure 39. Their results, together with those of the other studies considered above, including the map of erosion hazard produced by Stocking and Elwell, suggest that the sediment yields of these catchments are at least as high as, and probably higher than, those of the tributaries draining into Lake Kariba from Zimbabwe. On the other hand, the Hunyani is controlled by a series of dams; the furthest downstream being the Darwendale Dam which has a catchment area of approximately 3 800 km$^2$. For reasons discussed earlier in the chapter, the sediment discharge from this dam is negligible. Using a range of values of sediment yield slightly higher than that used for the Kariba tributaries, and assuming the effective catchment area is approximately 38 000 km$^2$, the sediment input to Lake Cabora Bassa from these tributaries is estimated to lie in the range 2 x 10$^6$ to 20 x 10$^6$ t/km$^2$/yr.
(iv) The Luangwa basin: This basin which covers 148,000 km², provides by far the most important source of sediment for Lake Cabora Bassa. Although, until recently, there have been no attempts made to undertake a systematic study of sediment loads in the Luangwa, there can be little doubt that sediment yields from its catchment are amongst the highest in the Zambezi basin. A number of factors contribute to these high sediment yields.

Firstly, the natural rates of erosion are high because of the physical characteristics of the Luangwa valley. Webster contrasted the plateau areas of Zambia, where erosion occurs slowly and the products stay, more less, in situ, with the valleys in the south and east of the country including the Luangwa, which are actively eroding. The erosion occurs most rapidly on the steep valley sides. Its effects on the valley bottom can be seen in the frequent changes which occur in the course of the meandering river channel due to the heavy sediment load it carries.

Secondly, erosion rates have been accelerated by human activity in the present century. An important factor was the colonial policy of restricting the African population to certain 'reserve lands' which brought about population densities above those which are ecologically 'safe' for the traditional shifting agricultural practices which continued to be followed. The authorities recognized the hazard created and, during the 1940s, attempted to control erosion by population resettlement and soil conservation measures. The attempts were not successful; for example, in the early 1950s, it was reported, that 'reserve lands' near Chipata were suffering very serious erosion. A similar picture was presented by the Regional Conservation Officer following a survey in 1958-59 of soil erosion in the north and east of the Luangwa basin. He identified three causes of the observed high rates of erosion: natural processes, cattle damage and the practice of shifting agriculture (the traditional 'Chitimene' system) in areas where population densities were high. A more recent survey, conducted under the auspices of the FAO, arrived at similar conclusions in respect of excessive erosion for the entire basin. To the list of possible causes this report added inadequate conservation measures where sloping ground is cultivated, inadequate maintenance of roads and overgrazing.
by wildlife. Conservation work continues to be undertaken but, as yet, has had little noticeable effect on overall rates of erosion.\textsuperscript{332}

The FAO report, Albrecht (1973), referred to above states that:

a thorough file and literature search and requests for information on systematically recorded field data in the Luangwa watershed have been unsuccessful. (p32)

The only published work in which an attempt has been made to quantify sediment yields from this region is the general map of erosion hazard in Africa by Fournier referred to earlier. The possible shortcomings of Fournier's work have been noted above but it is, nevertheless, significant that his algebraic relationships suggest values of sediment yield for the Luangwa basin which are higher than those in any other part of the Zambezi basin - above 2 000 t/km\textsuperscript{2}/yr for much of the catchment.

A number of recent attempts to study sediment concentrations in the Luangwa are described in Appendix 8. The National Council for Scientific Research in Zambia\textsuperscript{333} undertook a preliminary programme of sampling, with a depth-integrating sampler, which indicated that concentrations of suspended sediment may lie in the range 200 - 3 000 ppm by weight. However, no samples were recorded in the months of February and March when the discharges of the river usually reach their peak. Furthermore, samples taken in the dry season (August 1980) show that, even in periods of low discharge, concentrations approaching 1 000 ppm by weight can occur. It is probable, therefore, that peak concentrations in excess of 3 000 ppm are not uncommon in the Luangwa. Since peak values have a dominating influence over the value of the 'average' concentration*, this value may also be higher than any of the concentrations recorded in the preliminary survey results. It is understood that the National Council for Scientific Research intends to continue its surveys and a more accurate assessment may, therefore, be possible in due course.

* See the discussion of the results of Ward and Chikwanha above.
Superficial samples were taken, in 1973-74, by Hall and Valent and a single superficial sample was taken by the writer in April, 1980. The results, which are also shown in Appendix 8, are inconclusive particularly because there is no evidence that samples were taken during flood peaks. Nevertheless, they appear to indicate that concentrations in the wet season rarely fall below 1 000 ppm by weight.

From the figures assembled above, the 'average' suspended sediment concentrations in the Luangwa appears to lie in the range 900 - 9 000 ppm by weight. For a mean annual discharge of approximately $17 \times 10^9$ m$^3$ such values suggest sediment yields in the range 100 - 1 000 t/km$^2$/yr and rates of sediment deposition in Lake Cabora Bassa in the range 15 - 150 $\times 10^6$ t/yr.

(v) Minor tributaries in Zambia and Mozambique. Draining into the Zambezi between the Kafue and Luangwa basins, in Zambia, lie a number of small tributaries whose catchment areas total about 10 000 km$^2$. In Mozambique, tributaries with catchment areas totalling approximately 25 000 km$^2$ also drain directly into Lake Cabora Bassa. Although no records of sediment yields for these catchments are available, the following indirect evidence suggests that sediment yields slightly lower than those of the Luangwa basin may occur. Firstly, Fournier's study showed these regions to have similar yields to those of the Luangwa. Secondly, in the Plano Geral it was assumed that the rate of siltation of proposed reservoirs on the Mozambican tributaries, both upstream and downstream of Cabora Bassa, was of the order of 200 m$^3$/km$^2$/yr which is equivalent to over 200 t/km$^2$/yr (dry weight). Thirdly, samples obtained by the writer, from similar tributaries downstream of Cabora Bassa, suggested heavy concentrations of suspended sediment but probably not as heavy as those of the Luangwa, see Appendix 8. Assuming, therefore, that the 'average' yield of minor tributaries is in the approximate range 80 - 800 t/km$^2$/yr, the sediment input from them to Lake Cabora Bassa would be from 3 to 30 $\times 10^6$ t/yr.

Thus, in the basis of the very approximate calculations of sediment

* No explanation was offered as to how this value of siltation rate was selected.
yield from the three areas which contribute significant amounts of sediment to Lake Cabora Bassa, the mean annual input of sediment to this reservoir appears at present to lie in the range $20 - 200 \times 10^6$ t/yr. Using a value for dry density of deposited sediment of $1\,000$ kg/m$^3$, previously used for Lake Kariba, the rate of loss of storage capacity in Lake Cabora Bassa would be $20 - 200 \times 10^6$ m$^3$/yr. Provided no significant significant change in the rate of siltation takes place its 'dead' storage (minimum operating level, 295 m O.D.) would, therefore, be filled in a period of between 60 and 600 years if, as was suggested following the simulations of Chapter 3, drawdown to the minimum operating level of 295 m O.D. would not, in practice be worthwhile and a minimum level of 305 m O.D. or higher were adopted this would more than double the period it would require for the 'dead' storage to become completely filled. At the same rate of siltation the entire storage capacity of the reservoir would be filled in $300 - 3\,000$ years.

It should be noted that these rates of siltation would not be greatly affected by the construction of a dam, as proposed, at Mpata Gorge. A significant reduction would only occur in the unlikely event of a dam being built in the lower Luangwa valley or if widespread soil conservation measures throughout the Luangwa valley were to be effected.

e) The location of sediment deposits in Lake Cabora Bassa: Following a general study of reservoir siltation, in which rates of storage loss were generally found to be low compared with the economic life of the projects studied, Buttling and Shaw (1973) contended that:

> the more valid question is not 'what is the % rate of loss?', but 'where in the reservoir is that loss occurring?' (p575)

The latter question was found to be important in predictions about sediment accumulation in the Hendrik Verwoerd Dam, RSA, where Olivier (1969) reported that dead storage would begin to fill 'only after many years'. Likewise in a study of reservoir siltation in Bulgaria Zanev and Dobrev (1973) found that:

Almost half of [the deposited] material will occupy a part of the dam's usable storage capacity ... decreasing
the dam's effectiveness prior to the expiring of the dam's designed operational period.

The rates of siltation of Lake Cabora Bassa estimated above, although far higher than those of Lake Kariba, do not of themselves provide immediate cause for alarm. Nevertheless, some consideration must be given to the possible location of the deposits since it appears unlikely that the 'dead' storage will be totally filled before the 'live' storage is affected as has been assumed in the foregoing analysis. In the absence of direct information about the location of the sediment deposits this discussion must rely on an examination of the characteristics of the reservoir.

The bed of Lake Cabora Bassa shows a convex longitudinal profile which steepens markedly towards the dam, see Figure 40. Thus, although depths of over 130 m may be found in the reservoir close to the dam, for the upper half of the lake the maximum depth is less than 50 m. This means that the 'dead' storage capacity is located well away from the head of the reservoir. For example, when the reservoir is at its normal maximum operating level it stretches a distance of approximately 260 km from the dam to Zumbo whereas at its minimum operating level it stretches only about two-thirds of that distance. Since the bulk of the incoming sediment enters at the head of the reservoir, it must be conveyed 70 - 100 km if it is to reach the 'dead' storage zone. Although sediment settling at the head of the reservoir may, when the water level is low, be eroded and redeposited closer to the dam, the shape of the reservoir will to some extent inhibit such movement. As the outline shown in Figure 41 indicates, there are a series of constrictions along the reservoir which divide it into separate basins. Incoming sediment will settle mainly in the Mucangadze Basin where it will form a more or less uniform layer. When the reservoir level is low these deposits will be exposed but it will be only the deposits in the deepest parts of the basin, along the original river course, which will be extensively eroded and carried further into the reservoir. A considerable amount of sediment will, therefore, remain in the upper part of the reservoir's 'live' storage zone. Such accumulation will, in course of time, change the project's operating characteristics. In particular, the
Principal source: Jackson (1975a).

Figure 40: Longitudinal profile of Lake Cabora Bassa.
Principal source: Jackson (1975a).

Figure 41: Outline of Lake Cabora Bassa (at normal maximum level).
flood storage capacity of the reservoir will be reduced. Assuming that sediment enters at an 'average' rate of $20 - 200 \times 10^6$ t/yr, storage capacity will be lost at a rate of $20 - 200 \times 10^6$ m$^3$/yr; in other words, in fifty years $1 - 10 \times 10^9$ m$^3$ of storage will have been lost. If, by way of illustration, it is postulated that $5 \times 10^8$ m$^3$ of sediment were deposited in the 'live' storage, then at the end of the fifty-year period it would be necessary to provide extra drawdown to compensate for the lost flood storage capacity. The extra drawdown would, in practice, need to provide slightly more than $5 \times 10^8$ m$^3$ of additional storage because, with increased drawdown, the discharge capacity of the gates decreases. Thus, in the example selected, the minimum level of the flood rule curve would have to be, perhaps, 3 m lower to provide the same flood protection. Such a change in the operating characteristics would occur within the project's economic life and would have an appreciable influence on the potential for power production, see Simulations 1, 2, 3, 7, 9, 13 and 14 in Chapter 3.

In addition to the lost storage capacity which sediment accumulation in the Mucangadze Basin would cause, there is also a possibility that backwater effects would cause aggradation of the channel upstream thereby increasing the flood hazard at Zumbo in Mozambique and Feira in Zambia. Leopold, Wolman and Miller (1964, p260) reported the results of studies of small reservoirs, in the USA, which suggested that such aggradation effects are likely to be small and limited to within 5 km of the head of the reservoir. However, there appears to be no firm evidence to suggest that their conclusions could be applied in other situations.

Whilst there is, as yet, no direct evidence of progressive aggradation of the river channel at Zumbo, the effects of sediment deposition and scouring appear to have had a considerable influence over the relationship between discharge and gauge level at the Zumbo river gauge since the closure of the Cabora Bassa Dam as demonstrated below. Comparison between the levels of the Zumbo gauge and the reservoir level, see Figure 23, suggests that, provided the reservoir level is below 322 m, the water levels at Zumbo are determined solely
by the discharge of the river and are not influenced by backwater effects from the reservoir. Further analysis and comment will, therefore, be restricted to periods in which the reservoir level was below 322 m O.D. For each period a graph was plotted of daily mean river gauge level against the three-day rolling mean* of reservoir inflow, as calculated by HCB from changes in reservoir level. The results are plotted on Figure 42, together with the long-term discharge rating curve for the gauge prior to the closure of the dam. It should be noted that the preparation of these curves using the three-day mean value calculated from the HCB data required two approximations to be made. Firstly, that the inflow to the reservoir from tributaries downstream of Zumbo was small and, secondly, that the inflow at Zumbo was not changing rapidly; neither is likely to have had a significant effect on the results.

From Figure 42 it appears that the level of the channel at Zumbo fluctuated by as much as one metre during successive periods of scour and deposition from 1977 to 1980.

From the above considerations it is clear that further information is necessary before an accurate forecast of the effects of siltation in Lake Cabora Bassa could be made. Although it appears at present, that it will be a matter of decades before significant problems will arise from sediment accumulation, it would be extremely worthwhile to undertake an early survey of the reservoir and river upstream along selected, well-defined profiles in order to verify the tentative predictions made and to provide a base-line for future surveys. A certain amount of information about sediment deposits might also be obtained from the study of sequential satellite images. Regular monitoring of suspended sediment concentrations in the rivers flowing into Lake Cabora Bassa would provide valuable information but, because of the lack of skilled technicians and the poor communications in the region, it would be difficult for Mozambique to undertake the necessary work unaided.

* It was found that daily inflows, as calculated by HCB, tended to oscillate in a manner which resulted in a poor correlation with changes in the gauge levels at Zumbo. The three-day rolling mean provides a better correlation.
Figure 42: The effect of sediment scour and deposition on the rating curve at Zumbo.

River gauge level m.

8.0

Discharge (m$^3$ x 10$^3$/s)

Jun 1977 - May 1977
Nov 1977 - Feb 1978
Jan 1979 - May 1979
Dec 1979 - Jan 1980
Long-term mean prior to the Cabora Bassa Dam.
Development of a navigable channel downstream of Cabora Bassa

The importance of navigation in the MFPZ's plans for the Zambezi valley has been noted in Chapter 2. That chapter also contained an assessment of the attitudes of the present authorities towards navigation along the Zambezi and considered some of the problems which would have to be overcome if such a project were to be implemented. These include fluctuating levels of Lake Cabora Bassa, additional works necessary to carry vessels or cargoes past dams and provision of suitable deepwater port facilities which could be linked, economically, with the proposed river transportation system. The present section is concerned with the further difficulty to be faced in creating a navigation system along the lower Zambezi; the formation of a stable, navigable river channel.

The principal difficulty in creating such a channel is that for much of the river's course of over 500 km, from the Cabora Bassa Dam to the delta, the river divides into multiple channels which have inadequate depths for navigation by normal commercial vessels. The bed of the channel is formed from particles of sand which are readily moved by the river, especially under flood conditions, to produce constant changes in the river's cross-section. Short sections of the river where the channel has been confined with rocky gorges are more stable, most notably at Lupata and upstream of Tete.

Apart from the gorge sections, the lower Zambezi can be regarded as having an alluvial channel. The characteristics of such channels have been studied by geomorphologists and engineers who generally place them in one of two broad categories, meandering channels and braided channels. The former have been studied in greater detail because they occur more commonly, are more readily used for navigation and their characteristics are more susceptible to mathematical analysis. The lower Zambezi shows many of the characteristics of the braided channel.

Although a number of common features of braided channels have been identified, it is not always easy to distinguish between those which could be regarded as causes of braiding and those which are the result. Several features of braiding have been noted in the literature.
(i) A heavy sediment input: It is generally held that one of the principal causes of braiding is that the sediment load of the river as it enters a particular reach is higher than the channel's carrying capacity. In other words, braiding may be an indication that aggradation of the channel is occurring. Heterogeneous particle sizes also appear to facilitate the process of braid formation since larger particles are deposited and act as nuclei for the formation of bars.

(ii) High values of channel slope: Since a single large channel is a more efficient means of carrying a given discharge than a number of smaller channels a braided river must be steeper than a meandering river of equivalent size. Observations on natural channels suggest that the ratio of the slopes of equivalent braided and meandering rivers lies between 1.4 and 2.3. Flume experiments have shown that steep gradients may, in certain cases, be regarded as a cause of braiding; braided channels have been formed when the slope of the flume has been increased while other parameters have been held constant.

(iii) Seasonal discharges: In certain cases the braided pattern is only seen at low discharges. During flood discharges the water level rises above the bars which divide the flow thereby forming a continuous water surface between two relatively stable banks. Major changes in the braided pattern of the channel are found when the flood recedes.

(iv) Banks and bed material easily eroded: Large-scale transport of bed material is required to achieve the changes noted above. In certain cases considerable bank erosion also occurs leading to dramatic lateral movements of the channel such as those observed in the lower Yellow River, China.

(v) A high width to depth ratio: In natural rivers the ratio of the sum of the widths of the separate branches of a braided channel to their maximum depth has been found to be a factor of 1.6 - 2.0 greater than that of an equivalent individual channel.

A number of the features noted above are found in the lower Zambezi. The flows were markedly seasonal before the construction of the two mainstream dams with daily mean values, at Mutarara, varying from 250 m³/s to 25 x 10³ m³/s. In this section the channel is relatively steep having gradients of 160 - 370 x 10⁻⁶.

* In the middle section of the Mississippi, which in its natural state carried a similar range of discharges, the channel was predominantly meandering and had gradients approximately half as large as those found in the lower Zambezi.
The MFPZ/GPZ recorded considerable evidence of channel modification occurring in the lower Zambezi, with aerial photographs being taken at intervals between 1953 and 1972. One example of the changes, from 1953 to 1960, observed in a short stretch of the river upstream of Tete, where the braided patterns are not fully developed, was recorded by MFPZ in surveys*. Lateral movements of the river's thalweg were also noted in a study by the GPZ (1974):

The constant mobility of the bed of the Zambezi is readily apparent from a study of a short period of ten years between 1962 and 1972. River sections were found in which the deepest channels were located more than 1 km apart in the two surveys. (p17, writer's translation)

Nevertheless, such movements are small compared with those in the Yellow River referred to above. Furthermore, unlike the Yellow River, the Zambezi does not appear to carry unusually heavy sediment loads to account for the braided channel.

Various attempts have been made to obtain algebraic functions by which the different types of alluvial channel may be distinguished. Leopold and Wolman (1957) suggested that a channel would be braided, rather than meandering, if:

\[ S > 12.5 Q_b^{-0.44} \times 10^{-3} \]

Where \( S \) is the channel slope and \( Q_b \) is the bankfull discharge (m³/s). Using gradients given above and a \( Q_b \) of 7 000 m³/s this function identifies the Zambezi as braided. Lane replaced this single threshold function with a dual function such that for braided rivers:

\[ S > 4.1 Q_{ma}^{-0.25} \times 10^{-3} \]

and for meandering rivers:

\[ S < 0.7 Q_{ma}^{-0.25} \times 10^{-3} \]

* In archives of the SPA Tete.
Where $Q_{ma}$ is the mean annual discharge (m$^3$/s). It is interesting to note that, according to this categorization, the Zambezi is not identified clearly as braided but as intermediate between the two thresholds. Finally Chien (1961) developed a two threshold criterion, based on his study of rivers in China, in which he employed eleven stream parameters. Although the available data does not permit an exact evaluation of these formulae in respect of the Zambezi, the channel of the lower Zambezi again appears to fall in the intermediate category. From the foregoing it appears that the lower Zambezi shows many of the features common to braided rivers elsewhere but lacks certain others, in particular, the very high sediment loads found, for example, in the Yellow River. Rather than treating the Zambezi as fully braided, it is probably best regarded, therefore, as having intermediate characteristics showing a braided pattern within a stable and relatively straight course. If this interpretation is correct it holds important implications for the hydraulic engineer: a relatively minor change in one of the stream-flow parameters might be sufficient to change the channel from braided to meandering, and bring considerable benefit to navigation. Two aspects of this suggestion are considered more fully below: the effect of the Cabora Bassa Dam on the natural channel form and the possibility of further modifying the channel by means of engineering intervention.

a) **Channel changes in the lower Zambezi following closure of the Cabora Bassa Dam:** The construction of a dam upstream of a stretch of alluvial river channel will generally cause degradation of the channel since the downstream transport of bed material continues, but the supply of fresh sediment from upstream, which had previously replaced the eroded material, has been stopped or appreciably reduced by the presence of the dam. Neither the extent nor the time-scale of these effects are readily predicted, however, since the changes occurring under natural conditions have rarely been adequately studied before construction of the dam. The erosive power of the river will almost certainly be modified by the regulation of discharges from the dam and sediment will continue to enter the channel from tributary sources. For example, Buma and Day (1977), in a study of the effects on selected channel sections downstream of a dam in Ontario, found that after five years
few of the channel sections showed progressive degradation changes although in the majority an enlargement of the cross-sectional area had taken place through bank erosion. The researchers found it difficult to isolate the effects of the dam from those associated with the 'natural' shifting of the river channel or with other man-induced changes such as those caused by bridges. Other studies, in North America, in which degradation of alluvial channels occurred following the construction of dams are, however, well documented.

No direct evidence of channel degradation has so far been reported in the Zambezi following the construction of the Kariba Dam although Begg (1973) observed accelerated river bank erosion a short distance downstream. There has also been some speculation about possible erosion of the delta and this will be examined in Chapter 6.

In the Plano Geral, as in its earlier publications, the MFPZ predicted that the trapping of sediment in the Cabora Bassa Dam would be wholly beneficial to the purposes of navigation downstream. In subsequent reports, however, the complexity of the processes and the importance of other factors were acknowledged. A report by the GPZ (1974) stated:

it is important to bear in mind ... the profound changes which Cabora-Bassa will introduce into the sediment discharge regime of the river channel of the Zambezi ... The considerable reduction or virtual elimination of solid discharges from the impounded bed, retained in future in Lake Cabora-Bassa, will cause an increase, to a greater or lesser extent, in the erosive power of the current. This will be apparent downstream of Mepanda-Uncua and, above all, downstream of Lupata Gorge. It is important to take advantage of this erosive power through its contribution towards accelerating the formation and stabilization of the navigation channel although we may not know, in advance, to what extent and in what way this contribution will be shown. (p3-4, writer's translation)

The lower Zambezi shows evidence of having considerable erosive power, as seen in the constant changes in the position of sand bars, noted above, and in dramatic changes in the cross-section of the channel at specific locations. For example, in 1979, two profiles of the river section taken three months apart, under the bridge at Tete, show the
effects when the river had experienced a flood discharge of moderate intensity, with flows of slightly over 10,000 m³/s lasting no more than three days. As a result of this flood, however, the bed level changed, by as much as three metres at some points, and the deepest channel changed from the middle to the left-hand span of the bridge. The change does not appear to have been part of a process of aggradation or degradation and the overall cross-section of the channel did not change appreciably.

Aggradation and degradation, if they were occurring would also be evident from a study of the discharge rating curves for the river gauges at Tete - the only location on the river where, in recent years, regular metering of flows has taken place. Although these curves have fluctuated appreciably over the twenty years since flow measurements were first undertaken at this location there is no clear indication of progressive aggradation or degradation of the channel.

A number of theoretical models of river degradation have been developed. The application of one such model to the Zambezi by Savenije is described in Appendix 8. The results of his analysis suggest that degradation at Tete is progressing at a very slow rate; Savenije calculated that it would be 88 years before half the anticipated degradation at this location would have taken place following the closure of the Cabora Bassa Dam. On this basis it is unlikely that degradation will yet be apparent. For the model used by Savenije it was assumed that the final extent of the degradation will be constant at all points downstream, but the time taken to reach this value will be a function of the distance from the dam. Other models, such as that of Komura and Simons (1967), are based on the assumption that the extent of the degradation decreases from its greatest value, at the foot of the dam, to zero at some finite distance downstream. In addition, few models are capable of taking adequate account of complex boundary conditions and the influence of such factors as tributary inputs, the occurrence of rocky gorges and the possibility of bed armouring. In the light of these factors, Vanoni (1975), concludes that:
it is not possible ... to predict accurately ... the amount of aggradation or degradation that will occur in a stream when a dam is installed. (p18)

Although it does not attempt to quantify the changes which are likely to occur, the study by Schumm (1969) provides a useful basis for a qualitative description of channel characteristics and the changes which may result from dam construction. Schumm analysed data from thirty-six stable alluvial channels in the semi-arid to sub-humid regions of the Great Plains, of the USA, and the Riverine Plain of New South Wales, Australia*. He found good correlations between selected stream parameters and two primary variables, one of which being related to discharge and the other to sediment size. For the Zambezi, Schumm's relations yield the following approximate values for his selected channel parameters:

- sinuosity (ratio of channel length to valley length), 1.0;
- mean channel width, 1 000 m;
- mean channel depth, 6 m;
- width to depth ratio, 200;
- meander wavelength**, 30 km (which is equivalent to a total absence of meanders), and;
- mean channel slope, 280 × 10⁻⁶.

These values are, in fact, remarkably close to those indicated by the available measurements on the natural channel of the Zambezi in the braided sections. The values of channel slope, in particular, agree closely with those of the GPZ (1974) quoted above.

Schumm considered the possible results if, through changes in climate or through human activities, the characteristics of the river systems were to change. But he had reservations about applying his relationships to give quantitative predictions in such situations because the data on which they were based were not fully representative of all river types. Nevertheless, he examined some such changes in a qualitative manner. He suggested, for example, that a major decrease

* The rivers studies were all small relative to the Zambezi with the largest river having a mean annual discharge of one-twentieth of that of the Zambezi.

** Meander wavelength is an ill-defined parameter. Meanders rarely adopt a uniform wave pattern.
in bedload, such as that resulting from the construction of the Cabora Bassa Dam, would tend to increase the river's sinuosity and depth and decrease its width, meander wavelength and slope. On the other hand, a decrease in mean annual flood or mean annual discharges, might also be anticipated in the case of Cabora Bassa, particularly if water is extracted for irrigation. This would, Schumm suggests, decrease the channel's width, depth and meander length but increase its slope. The effects would, therefore, counteract each other to some extent. The final form of the channel would be expected to have decreased width and meander wavelength and increased sinuosity. However, there could be either an increase or a decrease in channel slope and depth depending on the relative importance of the changes in discharges and sediment loads. The channel is, therefore, likely to change, in due course, from braided to meandering but whether or not the depth of the channel will increase, with consequent benefit to navigation, cannot be predicted.

Schumm cited an example of a river in the USA, the North Platte, whose channel had been changed from braided (mean width, 1 000 m) to meandering (mean width, 50 m) between 1895 and 1967 as a result of a substantial decrease in flood peaks and mean annual discharges over that period. He suggested that, in a similar way:

many of the wide, sandy, 'unstable' rivers of the Western United States could be transformed to stable channels by reducing flood peaks and bedload transport. (p269)

However, Schumm warned that in rivers with uncontrolled tributaries providing large sediment inputs, control of the discharges in the main stream may simply lead to congestion of the channel and aggradation at the tributary mouths. For this reason he recommended that:

a basin-wide evaluation of tributary sediment loads and discharge is required before the effects of main stream regulation can be determined. (p269)

Engineers of the MFPZ were, apparently, aware of this potential problem in respect of the lower Zambezi and, from the limited sediment sampling work undertaken, appear to have been particularly concerned
about the input of sediment from the Luenha. The Luenha 7 Dam, details of which are presented in the *Plano Geral*\(^3\text{47}\), was proposed largely to trap the sediment from this tributary.

In view of the complexity of the processes involved, it would be wise to monitor the changes now occurring in the channel of the Zambezi if, in the future, the stabilization of the channel for navigation is to be considered. The report by the GPZ (1974) recommended that such monitoring be undertaken and, in addition, proposed that certain pilot structures be constructed in the channel to assess how the channel responded to their influence. These proposals were not implemented. A survey of selected cross-sections would still be an extremely worthwhile undertaking, as it would provide baseline data from which future studies could assess the changes which might have occurred since the dam was built. This would be of value not only for the purposes of navigation but also to assess physical and environmental consequences, such as the damage to bridges and dikes or the lowering of groundwater levels which would result from a significant degradation of the channel\(^3\text{48}\).

**Additional measures required to create a navigable channel**

The plans of the MFPZ/GPZ, cited earlier, suggested that it would be possible to increase the volume of traffic on the lower Zambezi from virtually zero to over \(1.5 \times 10^9\) t.km/yr within a period of a few years. No report of the expansion of navigation to such levels over a comparable period has been found for any other river in the world. In most cases large-scale channel stabilization works have only been attempted where navigation is already established and where some experience of the effects of pilot works has been gained. Nevertheless, examples, drawn largely from the USA, may serve to indicate some of the principal problems involved in implementing such a project in the Zambezi.

The Lower Colorado\(^3\text{49}\) and Missouri\(^3\text{50}\) rivers were both, in their natural state, braided rivers with highly mobile channels. In the early days of navigation, vessels frequently became grounded in sand banks.
The advent of shallow draught paddle steamers in the mid-nineteenth century brought a rapid growth in river transport along the two rivers, but this began to decline from the late 1870s due to competition from the railways. On the Lower Colorado, navigation ceased and has never been re-established although levees were constructed in the 1960s for flood protection purposes. On the Missouri, Federal Government support made it possible for the Corps of Engineers to undertake dredging and channel stabilization works providing, in effect, a subsidy for navigation. The initial aim was to create a minimum channel depth of 1 m but, following the decision to create a 2 m channel in the Mississippi, it was decided, in 1912, to enlarge the Missouri's channel to that depth. Terral (1947) believed that, with the small volume of commercial traffic using the river, the expense of creating and maintaining such a channel could not be justified. Unfortunately, in 1930, a decision to increase the Mississippi's channel to a 3 m minimum depth was taken thus rendering the Missouri's partially completed channel virtually obsolete. After long debate the Missouri's channel was also deepened but the work was only completed in the 1960s.

In terms of their physical characteristics, comparison of such rivers with the lower Zambezi may be misleading. The Missouri carries smaller discharges than the Zambezi and, as with another braided river of similar size, the Arkansas, its gradient is at least 40% less than that of the Zambezi whilst its sediment load is at least a factor of ten greater. Another section of braided river with similar sediment loads to those of the Missouri, the Middle Rio Grande (Rio Bravo del Norte), has gradients three times as steep as those of the Zambezi but its discharges are considerably less. In this case river stabilization has been undertaken for the purposes of flood protection, and to reduce evaporation losses, but commercial navigation has never been considered feasible.

One of the few braided rivers in North America where river stabilization for navigation has been an undoubted success is the Columbia where permeable groins have been effective in creating a minimum channel

* Data about these and other rivers in the USA is derived from ASCE (1965) Table 1.
depth of 11 m $^{352}$. Although the discharges of this river are comparable with those of the Zambezi both its gradient and sediment load are considerably less.

In the example cited the stabilization of the channels was achieved by the construction of groins, levees and bank protection works. In other cases, most notably the Upper Mississippi $^{353}$, the channel has been formed by constructing a series of dams provided with locks to allow the passage of shipping.

Of the examples given in the report by the Task Committee of the ASCE (1965) the only navigable river in the USA with gradients equal to or greater than those of the lower Zambezi is the Willamette which has a gradient about 40% greater. The navigable channel in this river, which is maintained by continuous dredging, is no more than 2 m in depth.

The stabilization of river channels may, as indicated by the various examples given above, be approached in a number of ways. At one extreme the natural condition of the river may be totally changed. This is the approach which has been used in the Upper Mississippi and also in the Lower Mississippi $^{354}$. In the latter case, artificial channels have been formed to shorten the meandering river course but these can only be maintained by 'comprehensive' stabilization works which involve continuous bank reinforcement and heightening over almost its entire length. At the other extreme some rivers are kept navigable by relatively small amounts of dredging on a regular basis. Colyer, Thorn and Ball (1981) recommend wider application of this 'minimum interference' approach on the basis of studies undertaken on the Paraguay and Paraná rivers in South America. The method is particularly useful where it is possible to arrange for the main bulk of navigation traffic to take place during the wet season, and thereby use the increased depths which high discharges bring.

Between these two extremes lie a number of approaches which depend on adapting, to a greater or lesser extent, the natural channel formation processes. Schumm and Beathard (1976) have drawn attention to various
'geomorphic thresholds', such as the threshold between meandering and braided rivers referred to above. They suggest that if a braided channel has characteristics which place it close to the thresholds, between braided and meandering, it is more likely to be susceptible to stabilization through the use of groins and cut-offs. Although this appears to be the case with the lower Zambezi, the examples cited above indicate that such stabilization work is less likely to be successful in channels with steep gradients.

Another important consequence of steep channel gradients is that vessels travelling upstream have to overcome considerable hydraulic resistance. This aspect of the development of navigation channels has been studied by Langbein (1962) who derived expressions which enabled him to calculate the specific tractive force \( \left( \frac{P}{V \cdot W} \right) \), where \( P \) is the vessel's engine power, \( V \) is the design speed and \( W \) its displacement weight) which is required for a vessel to travel upstream under different flow conditions. In the examples which he studied, Langbein found rivers which required values of specific tractive force in the range 0.2 to over 120 N/kg*. Whereas he found that economic freight vessels generally had values of specific tractive force less than 2.5 N/kg. In this way he derived a simple criterion by which to predict whether a particular river would be navigable upstream. The application of Langbein's analysis to the available data for the Zambezi suggests that it is likely that the river would be navigable upstream as far as Tete but that, in places, the specific tractive force required would be close to the 2.5 N/kg limit. The vessels required would, therefore, have to be amongst the most powerful in commercial operation.

According to the proposals set out by the MFPZ, the transport of cargo on the Zambezi would be predominantly in a downstream direction. In such circumstances the specific tractive force becomes a less critical factor and development of an economically feasible river transport system would be less difficult.

Hydrographic surveys of the Zambezi were undertaken by the MFPZ and GPZ to determine minimum navigation depths at various discharges.

* Expressed in metric units by this writer.
For example, if a flow of 3 000 m$^3$/s* could be maintained it was found that the minimum depths of the natural channel would frequently be less than 3.0 m and in places would fall as low as 1.5 m. Against this, the minimum size of vessel envisaged, in GPZ (1974), for the massive bulk exports referred to earlier, was at least 2 000 t and possibly 4 000 t. Such vessels have draughts of between 3.0 m and 3.7 m and require minimum depths of 3.5 - 4.2 m. The report, GPZ (1974), gave only limited details of how such a channel could be created. In the Esquema Geral this question was considered more fully and it was calculated that a minimum channel width of 500 - 600 m would be required. The form of the proposed stable channel was based on curves of mean radius six times the channel width connected by short straight sections. This was to be achieved by the construction of groins, cut-offs and bank protection works. The capital cost of such work, according to estimates contained in GPZ (1974), would have been approximately US $ 35 million for a channel depth of 4.2 m. This would have included about 90 km of permeable groins, together with considerable expenditure on dredging and buoyage. The capital cost of the fleet of vessels was found to be almost twice the cost of the navigational works. Clearly, a large volume of freight would be necessary to justify such costs together with the costs of port facilities, channel maintenance and fuel. In consequence existing plans have been based on the assumption that a rapid growth in traffic can be generated.

At this stage it is possible to draw only tentative conclusions for the lower Zambezi from the foregoing. Nevertheless, the following considerations will determine the success of future large-scale works:

(i) the trapping of sediment in the Cabora Bassa Dam may be beneficial for navigation downstream, but the effects might be counteracted by changes in the natural pattern of river discharges produced by the dam;

(ii) the characteristics of the river suggest that if the changes produced by the dam do not, by themselves, enable the braided channels to be changed into a single channel additional engineering structures might achieve this objective;

* This is rather higher than the value suggested from the results of the simulations in Chapter 3.
(iii) on the other hand, the channel is relatively steep in comparison with those of existing navigable rivers and study of several examples, from the USA, suggests that this might create difficulties as regards both the stabilization of the channel and the extra drag which vessels travelling upstream must overcome;

(iv) also, to stabilize a channel of 400 - 500 km in length and provide adequate navigation markers would require considerable capital investment before any revenue could be generated;

(v) the project would, therefore, only be feasible if a rapid increase in bulk exports could be assured once the work was completed; and

(vi) in this context, the observations made earlier, about the difficulty of carrying cargo past the Cabora Bassa Dam and of linking the river system to a suitable deep-water port, must be borne in mind.

In purely technical terms, the collection of further information about minimum river flows and the response of the river channel to the presence of the Cabora Bassa Dam would be a necessary preliminary to any major investment. Investigations using pilot structures would also provide valuable information about the ease with which the form of the channel could be modified and maintained. In the short-term, however, it would be preferable to establish limited navigation based on smaller vessels, using shallow channels which could be maintained by dredging. This would allow time for the information necessary for a more ambitious project to be collected and would also allow time for the expertise in navigation, and in channel and boat maintenance, necessary for the efficient operation of such a river transport system to be acquired.

Sediment deposition in floodplain regions

The discussion of channel changes in the lower Zambezi was concerned with effects caused by the movement of particles mostly of sand size. At moderate or low discharges any particles smaller than this are not deposited in the river bed but carried out to sea. During high discharges, however, sediment-laden water will inundate floodplain areas and, in many cases, will remain there until the water is lost.
by evaporation or seepage. The entire sediment load is, thus, deposited on the surface of the soil. These sediment deposits mostly comprise the smaller particle sizes since the sand particles will have been already deposited, either in the river bed or on the floodplain close to the river banks where 'natural levees' are formed. Under natural conditions some tropical rivers inundate their floodplains almost every year whilst others, including the Zambezi, do so less frequently.

The value of such inundations for floodplain agriculture depends on various factors. In many parts of the world, particularly in Asia, the development of rice paddy irrigation has enabled farmers to retain the flood waters for cultivation long after the discharges of the river have receded. The sediment deposited from the water is generally considered to be beneficial although this is not always the case. In the Yellow River, and other rivers of northern China, the most heavily sediment-laden water is diverted onto the fields to produce a 'warp' of fertile sediment often as much as 0.1 m thick. In the process, the sediment load in the river is reduced bringing benefits for the reservoirs and river control works downstream. A long tradition of floodplain irrigation has also been established on the banks of the Nile in Egypt but in this case there appears to be some disagreement about whether or not the sediment which, until the construction of the Aswan High Dam was deposited by the irrigation water, was, beneficial. Keim (1969) suggested that it did little to improve the land's fertility and that irrigation by the clear water discharged from Lake Nasser would be equally effective for cultivation. Shibl (1971), on the other hand, maintained that the sediment both improved the soil structure and provided important nutrients.

Few systematic studies of these factors have been published. One of the most detailed available is that of Sramaki and Takayama (1960) on the effects of a major flood on the Kano River in Japan in 1958. They studied both soil structure and nutrient input, and concluded that, in the upper basin, the deposits left by this flood especially where they contained gravel and stone sized particles, were probably detrimental to agriculture, whereas in the lower basin there was a possibility that fertility was improved by the sediment. However,
massive sediment movements and flooding in both parts of the basin caused considerable disruption and were, therefore, detrimental to agricultural output in the short-term.

The type of agriculture being practised in a given region is an important factor in determining the possible effects of floodplain inundation and sediment deposition. Where agriculture is highly mechanized, or depends on extensive systems of irrigation and on drainage canals, large deposits of fresh sediment may be highly disruptive. It is for this reason that in the USA sediment deposition in floodplains is generally regarded as a hazard rather than a benefit.

In the Zambezi basin there is insufficient information available to make a confident assessment of the importance which these processes had for the maintenance of floodplain agriculture or to predict the effect which construction of the Cabora Bassa Dam will have in the long-term. Basic information about the extent of subsistence agriculture in the floodplain areas of the lower Zambezi valley was not recorded in the past; and neither the MFPZ nor Loxton Hunting considered the matter worthy of detailed study.

A general picture of the extent of floodplain occupation in the 1960s can be obtained from an aerial photographic study of hut densities undertaken by RPT (1979). In the area believed to have been inundated by the 1978 flood, RPT's study located 95 grid squares (1.8 km by 1.8 km) in which over fifty huts were counted and over 450 squares in which between ten and fifty huts were counted. For a more moderate flood, of 7 000 m³/s, the number of squares in which these hut densities were recorded fell to approximately 30 and 100 respectively. Although, in comparison with population densities in the Nile valley for example, the number of inhabitants in the seasonally inundated areas of the lower Zambezi appears to be relatively small, it is certainly higher than in large areas of central Mozambique. The fact that huts were built in places where they were susceptible to fairly regular flooding indicates that their occupants considered the risks of flooding to be sufficiently counteracted by the benefits of floodplain agriculture.
(and possibly fisheries). A more detailed study of existing agriculture in the region prior to the construction of the Kariba Dam would not, however, by itself provide any direct evidence about the extent to which agriculture benefited from sediment deposition. Any benefit would supplement the benefits from natural irrigation by river water and from the replenishment of groundwater which also occurred during flooding.

Various characteristics of the sediment previously carried by the Zambezi might have influenced agricultural production. As noted above, the deposits on the floodplain would have been composed of the smaller sediment sizes with certainly no appreciable amounts of gravel. While this might prevent the problems which were observed by Sramaki and Takayama in Japan, it is possible that the particle size distribution of the soils would cause other problems. For example, certain soils with homogeneous fine particles are more susceptible to waterlogging or to baking and cracking. As regards its chemical composition, the sediment appears to originate from relatively freshly eroded rock and is, therefore, more likely to enrich the soil than if it had been heavily weathered. On the other hand, the results presented in Appendix 8 suggest that it contains excessive amounts of iron oxide. This iron tends to act as a 'scavenger' of various non-metallic elements, especially phosphorus. Thus, where iron oxide concentrations are high the amount of phosphorus in the soil available for plants is low. Moreover phosphorus, added to the soil as fertilizer in moderate amounts, may, in certain cases, be rendered ineffectual by the presence of large amounts of iron.

From the available information it is impossible to assess further whether the net effect of the construction of the dams at Kariba and Cabora Bassa will be beneficial or detrimental. Undoubtedly the rate of deposition will decrease both because of the trapping of sediment in the reservoirs and because the large floods which caused floodplain inundation will occur less frequently. On balance, the evidence suggests that the loss of this sediment will not be seriously detrimental to agriculture. At the dyke-encircled plantations of the Sena Sugar Estates, which have not experienced sediment deposition for over fifty years,
these effects might be assessed more accurately. The general investigation of such effects in the floodplain would be complicated by the fact that the dams have changed the supply of surface water and have, possibly, also altered groundwater levels. Identification of effects caused solely by the reduction in sediment deposition would, therefore, be very difficult.
CHAPTER 6
SOCIAL AND ENVIRONMENTAL CHANGES ASSOCIATED WITH THE CABORA BASSA PROJECT

Goodland (1977) made the following observation about the impact of hydroelectric projects in underdeveloped regions:

Development projects seek to improve the quality of life. But improvement in the quality of life of a segment of population in a given area often is related to a concomitant deterioration of the quality of life elsewhere ... Most disadvantages are environmental in nature and occur near the project, whereas the advantages frequently accrue largely to distant communities, and are usually economic rather than environmental. (p10)

Since the completion of the Kariba Project there has been growing concern, particularly amongst scientists, that the social and environmental consequences of this and other large dam projects in various underdeveloped countries were not considered in sufficient detail either by the planners or by politicians who authorized the projects. In addition the effects of the tropical climate, to which many of these projects are exposed, introduced environmental factors which had not, previously, been experienced. Bennett (1974) examining the origins of this situation has described the position as:

The basic planning issue is the suitability in tropical regions of large reservoirs designed for a temperate ecology. For none of these tropical reservoirs were the ecological aspects of creating large bodies of relatively still water in high-temperature climates intensively investigated. In fairness to the planners and engineers, the assessment of ecological and social impacts in such unprecedented circumstances, and in an atmosphere of powerful nationalistic advocacy, was realistically impractical and often beyond the capacity of the agencies. Each of the major dams has a history of complex political and financial negotiation which often prevented adequate or properly timed feasibility surveys. (p48)

Nevertheless, Bennett maintained that although some excuse for the neglect of social and environmental issues could be made with respect to the initial large dam projects, such as Kariba, such neglect was less
defensible for subsequent projects:

There is, of course, a more general issue here. Inherent in the nature of large-scale resource development and utilization schemes is the fact that a certain amount of trial-and-error experience is hard to avoid ... Nevertheless, as technology and a capability for adequate evaluation of consequences improve, the trial-and-error argument, and the whole policy of 'instant development' under political imperatives, becomes harder to defend. Despite the extent to which experience with error in the cases of the Kariba and Volta dams demonstrated need for prefunding feasibility surveys in depth, the Koffu Dam in the Ivory Coast was constructed with no ecological studies and a social impact survey was made after construction. (p48, emphasis in original)

In many industrialized countries, including the USA, statutory regulations have been introduced to control certain activities which might be ecologically harmful. As a result, engineers and planners are now required, in many cases, to provide environmental impact assessments of any proposed dam construction project. Although a growing number of tropical countries, including Brazil, are beginning to demand that such assessments be made in the planning of reservoir projects, the majority of projects are so far advanced by the time that these reports are prepared that their recommendations have little influence. In addition, it is difficult to describe the complexities of social and environmental interactions in the precise manner demanded for their effects to be included in technical and economic calculations. Nevertheless, as mentioned in Chapter 1, ecologists are making an increasing contribution to the study of water resources planning in underdeveloped countries. General principles have been set out in such works as Dasmann, Milton and Freeman (1973), Lagler (1969) and SCOPE (1972) whilst details of numerous case studies are provided in such works as Ackermann, White and Worthington (1973), Farvar and Milton (1972), Lowe-McConnell (1966), Obeng (1969), Panday (1977) and Stanley and Alpers (1975). Reference will be made to a number of these case studies.

In the introduction to this thesis it was stated that insufficient information is available to undertake a realistic post-audit of the Cabora Bassa Project. In the three previous chapters technical and economic factors related to the operation of the project and its effects
have been examined. Wherever these effects have influenced social or environmental factors in the lower Zambezi valley these, too, have been considered. The present chapter includes a more detailed study of the social and environmental consequences of the building of the Cabora Bassa Dam. Since the available data and information are so limited, much of the study relies on what must be tentative comparisons with the effects observed at similar projects, in particular the Kariba and Kafue Basin Projects. As a preliminary to the discussion of the Cabora Bassa Project the published accounts of studies of the social and environmental aspects of these two projects are considered.

The Kariba Project

The history of the Kariba Project, given in Chapter 2, showed the influence which political decisions concerning the formation of the Federation of Rhodesia and Nysaland had over the implementation of the project. Public debate about the proposed project was confined, almost exclusively, to technical issues until a relatively late stage in the planning process. Scudder (1965) noted that, as a result:

Though feasibility studies extended over a number of years these were narrowly conceived involving only the usual engineers, geologists and economists. Virtually no research was included on the potential for the future lake basin, its hinterland, or its inhabitants. (p7)

Nevertheless, being the first of the large man-made lakes in the tropics, the possible impact of Lake Kariba generated considerable academic and public interest as the construction of the dam proceeded. In addition, the Federal Government, together with the governments of the territories bordering the future lake, began to show an interest in certain aspects of the project's impact including, in particular, the fisheries potential of its waters. In December, 1955, the Kariba Lake Fisheries Committee was formed by these governments, although it was not until November, 1957, that, with the formation of the Kariba Lake Co-ordinating Committee, it was given executive authority and a budget of US $ 8.4 million. A large part of this sum was spent on bush clearance from large areas which were to be inundated. It was believed that this would be beneficial to future fisheries and navigation on the reservoir.
Over a period of several years, beginning before the dam was closed, an independent study of the Tonga society in the Zambezi valley, and of the effects of resettlement on the 57,000 people displaced by Lake Kariba, was undertaken by Scudder and Colson. Despite worldwide interest in the rescue of stranded animals, no comparable study was initiated, prior to impoundment, into wider environmental effects of the dam, including the ecology of the shoreline areas, to which wildlife would be displaced by the rising water, and the effects of regulated discharges on the river and valley downstream.

Following the closure of the dam, in late 1958, several largely unexpected effects attracted scientific investigation. These included the high level of seismic activity induced by the weight of water in the reservoir, the rapid erosion of the stilling basin by discharges from the dam, and the rapid increase in aquatic vegetation in the early years of impoundment. Nevertheless, it was in the fields of fisheries development and aquatic biology that the most detailed and sustained programmes of research were undertaken. Unfortunately, the work was seriously disrupted following the break-up of the Federation in December, 1963, and the growing political tension of the years after UDI. According to Joeris (1973):

*a basis for co-ordination of any type of lake-wide research or development had disappeared. Kariba had, for all practical purposes, become two separate lakes with little or no exchange of ideas or interests other than those concerning the Central Africa Power Corporation. (p143)*

Research on the Zambian side of the lake suffered particularly badly and, by 1974, had virtually ceased.

The Kafue basin

The lack of detailed social and environmental impact studies during the planning phase of the Kariba Project may be contrasted with the relatively large amount of work undertaken in the Kafue basin. There are several reasons for this difference. Firstly, following the decision to build the Kariba Dam, in preference to the Kafue Project, there was a period of inactivity in the Kafue basin which allowed detailed investigations to
be undertaken. Secondly, Zambia's independence in 1964 brought several offers of technical and economic assistance from United Nations and international aid agencies. Thirdly, the agricultural potential of the basin has long been recognized and, as a result, few officials were prepared to see the basin's water resources developed solely for the benefit of hydroelectric power generation.

The first major study after independence, a seven volume report, FAO (1968), adopted a comprehensive and integrated approach to the planning of the basin's water resources. At about the same time, the University of Zambia sought to support the authorities in their planning activities in the basin by creating the Kafue Basin Research Committee:

to develop a balanced programme of interdisciplinary research with the aim also of contributing to the planned development of the Kafue Basin and, especially, of the Kafue Flats; and to demonstrate both the concepts and mechanics of a truly-comprehensive approach to regional planning.

Over the years, however, the research undertaken appeared to have little influence on the major planning decisions which were taken. Williams and Howell (1977) suggest that the reason for this failure lies in the fact that:

the provision of information, in itself, does not ... guarantee its use, and the contribution of KBRC in its purely research and advisory capacities may be very limited. Thus, there is need for a much broader range of Kafue research directed towards creating clear policy options and recommendations for future development. (p95)

As a step in this direction a National Seminar on the Kafue Basin was held in 1978; this brought together academic researchers, administrators, politicians and technical staff of the company operating the hydroelectric facilities. The proceedings of this seminar have been published, Howard and Williams (1982), and provide considerable insight into the different perceptions of the individual participants and the organizations which they represented.

It is clear that special care is needed in the co-ordination of
planning activities for the future of the Kafue basin. In the upper basin the most important demands on the available water resources arise from the existing urban and mining developments and the possibility of large-scale agricultural developments. In the lower basin conflicts in water management and use are already apparent in the Kafue Flats region which has been described as:

a seasonally flooded riverine plain, approximately 255 km long, up to 56 km in width, and covering approximately 7,000 km².

Through the Flats, the river gradient is very low giving a fall of only 10 m in 450 km of channel length (a slope of $22 \times 10^{-6}$). Traditionally this was an important fishing area, attracting fishermen from throughout Zambia and beyond, as productivity was high in the nutrient-rich water of the seasonally flooded plain. The inundations also produced a rich terrestrial environment supporting a rich variety of wildlife and, in the dry season, large herds of cattle. National Parks and Game Management Areas were set up over a large part of the region to protect the wildlife and to provide income from tourism.

The hydroelectric project, details of which are given in Chapter 2 and Appendix 1, has had a considerable influence over the ecology of the Flats. The dam at Kafue Gorge, although relatively low, can cause flood water to remain on the Flats for longer than it would under natural conditions. Until the building of the Itezhitezhi Dam, upstream of the Flats, this was the only way in which the storage capacity of the project could be increased to provide adequate discharges for power generation during the dry season. With the Itezhitezhi Dam now in operation the Kafue Flats are threatened with the opposite danger, that the natural floods will no longer occur. Both extremes would be extremely damaging to the ecological balance of the region and the livelihoods of the local people. Investigations by the Dutch consultants DHV have shown that, under the present conditions, annual flood freshets could be achieved by careful regulation of the Itezhitezhi Dam without affecting power output. However, the hydroelectric scheme has a guaranteed water right to 93% of the dry season flow whereas domestic industrial and agricultural users have combined rights to only 7%. Thus, if agricultural production
based on irrigation, were to be greatly expanded it would not only be competing for water with power generation but would also restrict the ability of those operating the Kafue Project to provide flood freshets.

Despite the investigations into the possible comprehensive development of the basin's water resources, referred to above, it may be seen that social and environmental issues have a relatively low priority as against power generation. The neglect of these aspects, in the face of published research work, arises, in part, from the hydrological and ecological characteristics of the region which are complex and extremely difficult to analyse in quantitative terms and, in part, because planning in the region is undertaken on a single project basis under the control of separate government agencies with no single agency having the responsibility for overall co-ordination of the development of the basin.

Other proposed projects upstream of Cabora Bassa

Upstream of Cabora Bassa, four new major hydroelectric schemes have been proposed in recent years. So far, detailed studies of the possible social and environmental effects have been completed for only one project, the Mpata Gorge Dam. Consideration of the effects of the other three is limited, at present, to an examination of their general characteristics. Information about these proposed projects is presented in Figure 6 above.

The Katombora Dam, upstream of the Victoria Falls, has been proposed as a reservoir storage project to regulate the river discharges and, thereby, increase the firm power potential at the falls. This project does not yet appear to have been studied in sufficient detail, and it is unlikely to be implemented in the near future. The reservoir which would be created by this dam would have a high surface area to capacity ratio, and its social and environmental impact is, therefore, likely to be high.

Between the Victoria Falls and Lake Kariba two possible projects are being examined at the Batoka and Devil's Gorges. The reservoirs,
being relatively narrow and deep, would be less disruptive than either the Katombora or Mpata Gorge Projects and would provide fairly limited capacity for river regulation.

At present, the Mpata Gorge Project appears to be favoured by officials of the CAPC. Environmental objections have, however, been voiced against it because the reservoir would cover part of the Mana Pools National Park, one of the best remaining habitats for black rhinoceros in the world. The area has already suffered substantial ecological changes since the closure of the Kariba Dam. Furthermore, people previously displaced by Lake Kariba to this area would have to be resettled a second time. In 1979, the Natural Resources Board of Zimbabwe set up the Mupata Gorge Scheme Ecological Committee, on which CAPC was represented, to study the environmental effects of the proposed dam. Having submitted its final report, the committee was dissolved, in 1981, although a new committee was then formed to look more generally at the environmental implications of all major development projects in Zimbabwe.

The Cabora Bassa Project: pre-impoundment studies and general characteristics

Pre-impoundment studies related to the Cabora Bassa Project, and to other plans for the development of the Zambezi valley, were undertaken by a special section of the MFPZ called the Brigada de Estudos Economico-Sociais, BEES (Brigade for Socio-Economic Studies). The influence of the BEES was, at first, relatively strong within the MFPZ as indicated by the fact that it contributed eight of the twenty-three reports in the Esquema Geral. However, even at that time, the economic aspects of its work appear to have been given priority over social aspects and few environmental questions were examined. The initial reports from the BEES provide a clear statement of the main social and economic objectives of the MFPZ with reference to the local population: it was intended that they would become totally dependent on, and integrated within, the monetary economy controlled by the European settlers. To achieve this, it was suggested that 'modern techniques of community development' be adopted since 'forced evolution' was considered to be
less effective. Such 'community development' work was to be concentrated in certain 'problem areas'. Elsewhere the transformation would occur through the local population becoming involved in the various agricultural and industrial projects proposed. The importance of the agricultural projects is indicated by the fact that the leader of the BEES, Henrique Manzanares Abecasis, was an agronomist rather than a social scientist. In essence, 'community development' work appears to have been defined as agricultural extension work, community education and the provision of schools, health posts and water supplies. A major objective was to encourage the men to engage in wage-employment which, it was suggested, might be achieved by introducing the wives to various consumer goods so that they would persuade their husbands to earn money to buy them. Only limited reference was made in these early reports to the problem of resettling people displaced, by Lake Cabora Bassa and the smaller projects, and the possible health implications of irrigation schemes.

As work progressed on the preparation of the Plano Geral the work of the BEES was increasingly transferred to other sections of the MFPZ and confined to specific projects. In the event, of the forty-one reports which comprised its annexes, only five were concerned solely with socio-economic questions. Nevertheless, two of these are of considerable interest. The first, Plano Geral, 35, presented the results of some broader surveys. These included a study of the prevalence of certain diseases in the children of the local population and a study of the traditional economy of the Bárué region, which, because of the lack of funds, was never completed. The second, Plano Geral, 37, was concerned with three areas, Angônia, Mutarara and Sena, which were selected for 'community development'. The report gives the results of surveys conducted at meetings with local chiefs and representatives of the people of the different areas. The participants of these meetings were invited to state what were the greatest needs of the people they represented. Remarkably, some responses went beyond requests for amenities, such as health centres and schools, to open criticism of the colonial regime for its practices of forced cotton cultivation and low wages. The BEES personnel, who believed that these meetings would form the basis for a new spirit of 'co-operation' between the local population and the
Portuguese authorities, argued that certain of the needs expressed should be met as rapidly as possible to maintain the momentum for change. In consequence the cost of providing health facilities, schools, wells, grain mills, bridges and cattle grids in these areas was calculated. The capital cost, estimated at 11 000 contos (US $ 390 000), and the annual expenditure, estimated at 7 700 contos (US $ 270 000), were to be included in the 1965-67 budget of the MFPZ.

These plans of the BEES do not appear to have found general support since, from 1960 onwards, its budget was progressively reduced and many of its staff were transferred to other departments\(^3\). This may have been the result of a change to more forceful policies, by the Portuguese authorities, in an attempt to combat the growing influence of Frelimo. Very little further work of a sociological nature appears to have been undertaken in the lower Zambezi: studies of agricultural potential by Loxton Hunting were, as mentioned in Chapter 2, notable for their neglect of the indigenous population.

Various 'scientific' studies were undertaken, under the direction of the GPZ, as construction of the Cabora Bassa Dam grew imminent. These included archaeological surveys, studies of terrestrial and aquatic biology and an anthropological study of the Tawara people. The studies were severely restricted by the presence and activities of Frelimo supporters in the region. In addition, a conference was convened, in June, 1972, to discuss all aspects of proposals to rescue wildlife stranded by the rising water of the reservoir and to create natural reserves along parts of its shore\(^3\). These proposals were not implemented. Consultants were however, employed to study two important aspects of the future reservoir; its fisheries potential and the possibility of weed infestation.

Although the work referred to provides some useful information about social and environmental issues it was, in general, inadequate in detail, was too selective, covered too short a period and was too poorly co-ordinated to provide the basis for a rigorous pre-impoundment investigation of social and environmental conditions. Furthermore, despite attempts by HCB to assume responsibility for such studies\(^3\), there has been very little survey work undertaken since the dam was completed. It is, therefore, unlikely that an accurate assessment...
of the changes induced by the building of the Cabora Bassa Dam can be made at this time. The only attempt made to provide a comprehensive assessment of the impact of the Cabora Bassa Project was that of Hall and Davies (1974). Although their paper is of limited practical value, as the information on which it is based is very general and speculative, they reach two important conclusions: firstly, that the maximum benefit from the project can be derived only if the economy of the valley as a whole is considered rather than just the economics of energy production; and, secondly, that integrated planning of the resources of the valley would require a much greater knowledge of the ecological systems it contains. They recommended, therefore, that a scientific research station be created.

Since very little new information is currently available the form of the present study can be little different from that of Hall and Davies. Nevertheless, much greater use may be made of complementary material from published studies of other projects. A number of important parameters of such projects are tabulated, see Table 30. One important parameter is the ratio between power output and reservoir surface area which, as suggested by Goodland (1977), provides an indication of the environmental impact of a project. Other parameters in the table include the ratio of reservoir capacity* to mean annual inflow, which provides an indication of the type of aquatic environment in the reservoir and the degree of regulation it provides over the natural discharges; the extent of the maximum reservoir drawdown, which has important implications for inhabitants of the shoreline; and the number of people displaced by the reservoir.

From a study of the examples in Table 30 two extreme reservoir types may be identified. The first type, as exemplified by the Kariba, Akosombo and, to a lesser extent, Aswan High Dam Projects, has relatively stable conditions in the reservoir which leads to the development of a lacustrine environment. The characteristics of such projects include high values for the ratio of reservoir capacity to mean annual inflow

* It might be preferable to use 'live' storage capacities rather than total reservoir capacities but these data are not always readily available from the literature.
<table>
<thead>
<tr>
<th>Dam</th>
<th>River</th>
<th>Country</th>
<th>Approx. mean latitude</th>
<th>Projected ultimate capacity (MW)</th>
<th>Reservoir area (km²)</th>
<th>Reservoir capacity (m³ x 10^9)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cabora Bassa</td>
<td>Zambezi</td>
<td>Mozambique</td>
<td>16° S</td>
<td>3 800</td>
<td>2 700</td>
<td>72.5</td>
</tr>
<tr>
<td>Kariba</td>
<td>Zambezi</td>
<td>Zimbabwe/Zambia</td>
<td>17° S</td>
<td>1 500 - 1 800</td>
<td>5 200</td>
<td>185</td>
</tr>
<tr>
<td>Kafue Gorge</td>
<td>Kafue</td>
<td>Zambia</td>
<td>16° S</td>
<td>1 350</td>
<td></td>
<td>800*</td>
</tr>
<tr>
<td>Itezhitezhi</td>
<td>Kafue</td>
<td>Zambia</td>
<td>16° S</td>
<td>80</td>
<td>370</td>
<td>5.7</td>
</tr>
<tr>
<td>Darwendale</td>
<td>Hunyani</td>
<td>Zimbabwe</td>
<td>18° S</td>
<td>0**</td>
<td></td>
<td>81</td>
</tr>
<tr>
<td>Akosombo</td>
<td>Volta</td>
<td>Ghana</td>
<td>7° N</td>
<td>900</td>
<td>8 300</td>
<td>148</td>
</tr>
<tr>
<td>Kainji</td>
<td>Niger</td>
<td>Nigeria</td>
<td>10° N</td>
<td>1 250</td>
<td>1 300</td>
<td>15</td>
</tr>
<tr>
<td>Aswan High</td>
<td>Nile</td>
<td>Egypt/Sudan</td>
<td>23° N</td>
<td>2 100</td>
<td>5 470</td>
<td>157</td>
</tr>
<tr>
<td>Itaipu</td>
<td>Paraná</td>
<td>Brazil</td>
<td>26° S</td>
<td>10 500</td>
<td>1 460</td>
<td>29</td>
</tr>
<tr>
<td>Tucurui</td>
<td>Tocantins</td>
<td>Brazil</td>
<td>4° S</td>
<td>6 500</td>
<td>2 160</td>
<td>43</td>
</tr>
</tbody>
</table>

* Including partial inundation of the Kafue Flats.
** This is a water supply reservoir rather than a hydroelectric scheme.
### Table 30 continued

<table>
<thead>
<tr>
<th>Dam</th>
<th>Approx. mean annual flow ($\text{m}^3 \times 10^9$)</th>
<th>Power output + area (MW/km²)</th>
<th>Reservoir capacity + mean annual inflow</th>
<th>Drawdown, max. in normal operation*</th>
<th>Displaced population</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cabora Bassa</td>
<td>84</td>
<td>1.4</td>
<td>0.86</td>
<td>34 (7)</td>
<td>25 000</td>
</tr>
<tr>
<td>Kariba</td>
<td>52</td>
<td>0.3</td>
<td>3.5</td>
<td>9 (4)</td>
<td>57 000</td>
</tr>
<tr>
<td>Kafue Gorge</td>
<td>10</td>
<td>1.2</td>
<td>0.6</td>
<td>{</td>
<td>very few</td>
</tr>
<tr>
<td>Itezhitezhi</td>
<td></td>
<td></td>
<td></td>
<td>27</td>
<td>very few</td>
</tr>
<tr>
<td>Darwendale</td>
<td>0.36</td>
<td>-</td>
<td>1.4</td>
<td>10**</td>
<td>unknown</td>
</tr>
<tr>
<td>Akosombo</td>
<td>36</td>
<td>0.11</td>
<td>4.1</td>
<td>8 (3)</td>
<td>70 000</td>
</tr>
<tr>
<td>Kainji</td>
<td>80</td>
<td>0.96</td>
<td>0.2</td>
<td>16 (10)</td>
<td>44 000</td>
</tr>
<tr>
<td>Aswan High</td>
<td>84</td>
<td>0.37</td>
<td>1.9</td>
<td>34</td>
<td>110 000</td>
</tr>
<tr>
<td>Itaipu</td>
<td>270</td>
<td>7.2</td>
<td>0.11</td>
<td>23</td>
<td>unknown</td>
</tr>
<tr>
<td>Tucurui</td>
<td>290</td>
<td>3.0</td>
<td>0.15</td>
<td>16</td>
<td>20 000</td>
</tr>
</tbody>
</table>

* Typical drawdown in a single year shown in brackets where known.

** Estimated from live storage.

**Principal sources:** Goodland (1977), Beadle (1974), Stanley and Alpers (1975), Balek (1977), Williams and Howard (1977), ZESCO (1977) and Olivier, *Great Dams* ...
and small values of drawdown. Because these projects generally have large reservoirs the values of the ratio between power output and reservoir area also tend to be low. The second type, of which the Itaipu Project is the prime example amongst those considered, experience a rapid exchange of water in the reservoir leading to the development of a riverine environment. Characteristics of this type of project include low values for the ratio of capacity to inflow and high values of drawdown. As such projects provide for only short-term retention the ratio of power output to reservoir area is generally high. In comparison with the second type, the first permits the evolution of a more stable aquatic environment, including the growth of rooted aquatic vegetation, and the establishment of agricultural and fishing communities along the reservoir's shores. On the other hand to form such reservoirs large areas of rich alluvial soil may have been inundated and a large number of people displaced. Furthermore, such reservoirs have a relatively low fisheries potential per unit volume and have a greater impact on both the upstream and downstream environments than do the second type of project.

The foregoing characterization helps to identify some important differences between the Kariba and Cabora Bassa Projects. The former provides a good example of the lacustrine reservoir whilst the latter shows similarities with the riverine type, although the reservoir will be far more lacustrine than that at Itaipu. Other features which distinguish the projects in Table 30 such as differences in latitude, climate and topography are liable to limit any attempts to derive general conclusions about the examples studied, but in the Kariba and Cabora Bassa cases such differences are relatively small and, therefore, the parameters of Table 30 are of considerable importance in studying the different social and environmental impacts of the two projects.

The considerations in the remainder of this chapter refer, largely, to the effects of the Cabora Bassa Dam and the ways in which these might be modified by the actions of the Mozambican authorities. This discussion, therefore, has little bearing on the question of whether or not the North Bank Station should be built, as the only significant changes which would occur if this project were to be implemented would
be slight increases in the reservoir fluctuations and in the minimum discharges downstream. These changes would be small in comparison with the changes which occurred when the dam itself was constructed.

Resettlement

a) Demographic changes prior to the Cabora Bassa Project: The results of the 1950 census in Mozambique indicated that the population of the Zambezi basin in Mozambique was approximately 1.1 million, see Table 31. By 1960, this figure had increased only slightly, to 1.2 million, although figures for the same year published by the MFPZ put the total at 1.5 million\(^{385}\), based on a larger basin area which included the districts of Mocuba, Milange and Gorongosa.

Table 31: Population statistics for the Zambezi basin in Mozambique

<table>
<thead>
<tr>
<th>Province/Districts</th>
<th>Area(km(^2))</th>
<th>1950 Census Population</th>
<th>Population per km(^2)</th>
<th>1960 Census Population</th>
<th>Population per km(^2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tete: Tete, Angônia, Macanga, Mágue, Marávia, Moatize, Mutarara, Zumbo</td>
<td>97 000</td>
<td>436 000</td>
<td>4.5</td>
<td>474 000</td>
<td>4.9</td>
</tr>
<tr>
<td>Zambézia (part): Quelimane, Chinde, Mopeia, Morrumbala, Namacurra</td>
<td>30 000</td>
<td>468 000</td>
<td>15.6</td>
<td>488 000</td>
<td>16.3</td>
</tr>
<tr>
<td>Manica/Sofala (part): Bárue, Chemba, Cheringoma, Marromeu, Sena</td>
<td>58 000</td>
<td>238 000</td>
<td>4.1</td>
<td>279 000</td>
<td>4.8</td>
</tr>
<tr>
<td>TOTAL</td>
<td>185 000</td>
<td>1142 000</td>
<td>6.2</td>
<td>1241 000</td>
<td>6.7</td>
</tr>
</tbody>
</table>

Source: The census data are presented in Plano Geral, 35.1, p3-5.

Census data such as these must be viewed with caution, since access to some of the remote areas of the basin was difficult and many of the basin's inhabitants made temporary emigrations in search of employment. By 1970, the presence of Frelimo guerrillas in the region made access
still more difficult and is the likely reason why the census result for Tete gave almost exactly the same figure as that published in 1960\textsuperscript{386}. After independence a preliminary survey was undertaken, in 1978, on the basis of vaccination records. This showed the population of Tete Province to be 786,000\textsuperscript{387}. By the time of the 1980 census this figure had increased to 831,000, a mean population density of 8.6 per km\textsuperscript{2} for this province\textsuperscript{388}. Comparable figures for the parts of the other provinces within the Zambezi basin could not be derived from the available sources. It is impossible to determine whether the very erratic growth rate in population in Tete Province, from 1950 to 1980, was a result of errors in the census or whether it is indicative of other factors, such as population emigration in response to the Portuguese \textit{aldeamento} programme described below.

The statistics of mean population densities in each province given above, serve to indicate how sparse the population is over much of the basin. However, they give no indication of regional differences due to heavy concentrations of population around the principial urban areas, along the banks of the main rivers and along the coast. When such factors are taken into account, it appears that large areas of the basin, including much of Tete Province had population densities, in 1960, of the order of 2 per km\textsuperscript{2}. Some indication of these effects is given in Figure 43, which shows mean population densities of individual districts. Even within districts, however, there were significant variations. For example, it was reported, in GPZ (1971a), that the mean population density in areas to be flooded by Lake Cabora Bassa was 11.7 per km\textsuperscript{2} as compared with 1.5 per km\textsuperscript{2} in the parts of the same districts which would not be flooded. Similar population concentrations occurred along the banks of the river down-stream of Cabora Bassa and, in particular, around the Ilha de Inhangoma. Thus, the construction of the dam and the subsequent regulation of the river would have affected a high proportion of the population in any district bordering the river.

Although the construction of the Cabora Bassa Dam had a considerable effect on the lives of these people, the Portuguese authorities had the intention to effect changes which would be felt even more widely. One
Figure 43: Mean population densities in individual districts in the lower Zambezi basin in 1960.

Source: *Plano Geral, texto* (Figure 22)
of their principal intentions was to introduce a large number of European settlers into the region. The 1960 census recorded very few Europeans in the lower Zambezi basin; only 1.2% of the population was reported to be non-African. Even if the, now discredited, figure of one million white settlers is rejected the scale of the settlement envisaged was still vast. In the Esquema Geral, for example, it was suggested that 25 000 white settlers, at least five times the existing population, would be established in the region in the first six years. This estimate is not unreasonable when compared with the rate of white immigration to Mozambique, reported to be about 10 000 per year in 1960. However, by the end of the 1960s, Portugal was beginning to suffer the effects of its massive emigration policies to Africa and Europe with labour shortages arising in certain sectors of its home economy.

In comparison to the provision made for the African population which was resettled, the terms offered to European settlers were very generous. Jundanian (1974) reported that, in the north of Mozambique, settler families were given from 100 to 250 ha by the authorities together with, perhaps, 25 cattle. In addition, free transport was provided from Europe. On this basis the total cost of installing each family was estimated to be equivalent to between US $ 8 000 and US $ 20 000 in the early 1970s. From a study of such figures Ferreira (1974) concluded that:

emigration to the colonies is an expensive undertaking that cannot be justified from the economic point of view and in its present form has one aim: to create the conditions for the long-term maintenance of the colonies. (p22)

The implementation of the Portuguese white settler policies for the Zambezi basin would have displaced numerous Africans from their traditional homes in addition to those who would have been displaced by the reservoirs which were to be created. No estimate of the total number of people involved was made by the MFPZ, although it was estimated in the Esquema Geral that 20 000 would be displaced by Lake Cabora Bassa alone. The report which contained this estimate called for adequate preparations to be made for resettlement. On the basis of costs derived from the Kariba Project, where the cost of resettlement had been about US $ 200 per
person on the north shore and US $ 160 on the south, the MFPZ suggested that relocation at Cabo da Basse would cost US $ 175 per person, making a total cost of about US $ 3.5 million. These preliminary remarks, published in 1961, were not followed by more detailed investigations and preparations until about eight years later when construction of the dam was beginning.

b) The effects of relocation: experience from other projects: The displacement of the Gwembe Tonga by Lake Kariba provided material for the first detailed studies of the effects of relocation caused by a large man-made lake in Africa. Other studies followed and have been reviewed by Scudder (1973 a & b and 1975), Brokensha and Scudder (1968) and Bennett (1974). Chambers (1969) considered reservoir relocation in the wider context of other types of settlement scheme in Africa. Together they provide extensive bibliographic material.

A number of important characteristics of relocation programmes may be identified from a study of the examples considered in these works. In the majority of cases, the population would have experienced the effects of economic, political and social changes even without the reservoir project. The creation of the reservoir resulted, however, not only in the need for the population to leave their former homes but also for them to accommodate many other changes which occurred within a short space of time. Although, in some instances, attempts have been made to involve the people in decisions concerning their future, lack of time and resources has more often led to a programme of relocation imposed by the authorities without serious consultation. Furthermore, such programmes have rarely been allocated sufficient funds and personnel to undertake the work, they have lacked adequate preliminary planning, the operation has been poorly co-ordinated and follow-up surveys have been neglected. In the majority of cases the area to which the people were moved is agriculturally less productive and unsuited to the methods of cultivation previously followed. For this reason potentially effective relocation has had to be accompanied by agricultural innovation.

The studies undertaken by Scudder have highlighted, in particular, the many factors which may lead to high levels of physiological and
psychological stress amongst the displaced population. These include
the exposure to health hazards associated with unfamiliar diseases,
particularly water-borne diseases; failure of the authorities to take
account of the cultural habits of the people; the provision of
inappropriate housing; inadequate public services, including domestic
water supplies; problems of integration with the 'host' population and
of increased population densities in the areas of relocation; inadequate
communication from the authorities on such matters as reservoir fluctuations
particularly where there is no demarkation of high water levels; and
inadequate food supplies during the period until agricultural output can
be re-established. In such situations, Scudder (1973b) reports, high
morbidity and mortality rates have been indicated. In the short-term
the population generally becomes dependent on government agencies whilst
in the long-term their subsistence economy may be undermined. The disruption
may, in part, be compensated by new opportunities which arise, for example,
through fishing in the reservoir. Nevertheless, to benefit to the full from
such opportunities the population would require government assistance
and this has rarely been provided. Furthermore, competition has sometimes
arisen from other people migrating to the area. In the long-term, however,
many resettled populations have shown a considerable ability to adapt and
to re-adapt when initial projects have failed.

At Kariba, the process of resettlement was strongly influenced by
political factors. The Southern Rhodesian authorities refused monetary
compensation for lost lands and property and gave the relocated people
no choice in the location of resettlement villages whereas the Northern
Rhodesian authorities sought to provide a greater degree of freedom by
allowing the people to participate in the selection of sites for their
villages and by providing them with some monetary compensation. In both
cases, however, the local population viewed with suspicion the motives
of the colonial authorities who were undertaking the project. Similar
suspicion may also arise in an independent country if the resettled
population comprises a politically weak ethnic minority.

As mentioned above, the Northern Rhodesian authorities attempted
to achieve the co-operation of the resettled population and to provide
them with some freedom of choice. In a number of subsequent projects
this degree of freedom has been greatly increased. Although diversity
of opportunity is considered, by some, to be of advantage to the resettled population the success of such schemes depends on an adequate dissemination of information to enable the population to make reasonable decisions.

Many of the problems of reservoir resettlement which have been indicated above will give rise to additional economic costs which both the individual and the community must bear. Such costs are in addition to the direct costs of the resettlement programme and may be spread over many years. In the opinion of the writers of the SCOPE (1972) report, the cost to governments of resettlement:

would rarely be less than 25% of the combined cost of power generation and transmission and dam construction.

(p25)

c) Resettlement from Lake Cabora Bassa and the Portuguese aldeamento programme: Despite the recognition, by the MFPZ, as early as 1961, that resettlement should be carefully planned it was not until 1968, when the final negotiations over the dam construction contract were taking place, that the question was again discussed in detail. A report, MFPZ (1968), outlined an ambitious programme including provision for land clearance, water supply, transport for relocation, schools, social centres and agricultural, sanitary and health improvement work. The total cost was estimated at some 200 000 contos (US $ 9 million). Unlike the Kariba Project, where the cost of resettlement was included in the calculations on which the production costs of the electrical energy were based, at Cabora Bassa resettlement was to be paid for separately by the Government. Nevertheless, it was proposed that the finance should be provided, initially, by means of a loan from the dam construction consortium to the Government. Provision for this loan was, therefore, included in the conditions set out in the pre-tender documents. The total value of the loan, 505 500 contos (US $ 21 million), also included money for other 'rural development' work in the Zambezi valley.

The resettlement programme was regarded by the Portuguese authorities, according to their official publications, as more than a side-effect of the hydroelectric project. It was regarded as an opportunity to:
promote the living standards of the native population so that they may quickly progress from a subsistence economy to a market economy\(^\text{397}\). 

As such, it was only the first part of a much broader programme of rural development envisaged for the whole of the region. Official publications\(^\text{396}\) claimed that relocation sites would be selected after discussions with the people themselves and take into consideration their cultural habits and ethnic allegiances; that relocation would take place at an appropriate time in the agricultural year; that 8,000 people would be moved from the reservoir site each year for a period of three years; that each family would receive two hectares of cleared land, three hectares of uncleared land, compensation for land lost, transport to the new site, free materials for house construction, free food and the loan of seeds for crops; and that they would be exempt from taxes for one year.

The majority of the people displaced by Lake Cabora Bassa had previously been living close to the Zambezi, or one of its tributaries, where a varied subsistence existence was achieved through cultivation of crops, hunting, fishing and the rearing of livestock\(^\text{399}\). Although 'slash and burn' cultivation was widely practised, perennial gardens were also used along the banks of the river in areas exposed as flood waters receded.

Very little has been published on the actual resettlement operation. It is difficult, therefore, to make assessments of the impact on the people or to make comparisons with other projects. The armed conflict in the region between Frelimo and the Portuguese armed forces, was a major reason for this lack of information. The conflict also had a considerable influence over the actual resettlement programme and Henderson (1972) reported that the authorities regarded it as a 'hypersensitive operation' (p331). Access to the area by observers, even those with official sanction, was virtually impossible, as is testified by de Oliveira (1976) who was compelled to rely on 'informants', in his anthropological study of the Tauara people, in 1972, because, 'participant observation was reduced to a minimum' (p113).
As a result of the armed conflict the Portuguese authorities decided to speed up their 'rural development' programme and move as much as possible of the population of the region into aldeamentos*, along with those displaced by the reservoir. For this reason it is not always possible to identify information relating solely to the reservoir resettlement programme. However, from the information available the important features of the programme, viewed solely as a reservoir resettlement operation, include the following: that there was inadequate preparation either of the people or of the relocation sites; that people accustomed to live in dispersed dwellings were transferred to relatively densely populated villages often at a considerable distance from their previous homes; that cultural traditions were largely ignored; that people of different ethnic groups were settled in the same village; that they had to become accustomed to the use of wells having previously had access to plentiful supplies of river water; that the land provided was dry and sandy in contrast to the rich alluvial soils from which many were displaced; and that to cultivate such soils successfully would normally have required irrigation and the use of artificial fertilizer to which they had no access and with which they were not familiar.

It would be misleading to regard this operation as part of the reservoir project as the military objectives, according to Henderson (1972), were paramount:

the selection of resettlement areas and the village organization for the resettled Africans suggests a military advisor's decision rather than that of an agricultural expert or social worker. (p334)

On the other hand the decision to build the Cabora Bassa Dam provided a focus for, and impetus to, resistance against the Portuguese authorities and, to this extent at least, there was a close connection between the project and the widespread resettlement of the rural population into aldeamentos.

* Because of their military significance, aldeamentos are generally referred to, in English translation, as 'fortified' or 'strategic' villages.
The aldeamentos were very different from the resettlement villages envisaged in the MFPZ (1968) report. Jundanian (1974) reported that the preparation of an aldeamento in Tete Province took about a month, during which time about one hectare of land per family was cleared for cultivation. No consultation with the local population over the siting of the village took place, and there was generally no provision for the pasturing of cattle in such dense communities. He observed that:

of the scores of aldeamentos currently planned for the district, many do not possess any feature except a water supply. Again, high-ranking military sources have disclosed that very few services are being installed now; the concern is simply to group the Tete populations together as quickly as possible. Electrical generators, clinics, schools, stores and community centres must wait. (p527)

Viewed solely in terms of stated Portuguese objectives, the aldeamento programme was, Jundanian concluded, a failure. In fact, from a military standpoint the programme appeared, to him, to have been counterproductive since:

there appears to be a correlation between intensification of the aldeamento program in a district and the spread of insurgency southward. (p540)

The difficulty of obtaining an objective assessment of these events is emphasized by the fact that Middlemas reached entirely the opposite conclusion, maintaining that the social aspects of the aldeamento programme brought agricultural, educational and medical benefits which were fully appreciated by the population.

It is also difficult to judge the extent of the population relocation which occurred; the dam resettlement programme certainly did not go according to initial plans. Instead of moving 8 000 people in each of the years 1971, 1972 and 1973, a total of only 2 500 were reported to have been moved by the end of 1971 and under 5 000 by the end of 1972. The contract to clear 11 000 ha of agricultural land in preparation for the resettlement also ran considerably behind schedule, with the result that the family allocation was cut from 2 ha to 1 ha.
Although the GPZ was principally concerned with resettlement from the reservoir, it also had responsibility for 'rural development' in a number of other localities in the lower Zambezi basin. This work was accelerated as part of the _aldeamento_ operation. Eleven villages were formed around Estima, near Songo, and nine around Changara. These two locations received 4,500 and 5,000 new inhabitants, respectively, in 1971 and similar influxes in 1972, bringing their combined populations to around 16,000. Meanwhile the Governor of Tete Province took over the _aldeamento_ programme in the GPZ's other main area of operation, Mutarara, and, in 1972 alone, resettled 10,000 people in thirteen villages. The locations of these villages are shown in Figure 44. It may be seen that reservoir resettlement villages were all located on the north shore, presumably for strategic reasons, although it was intended that some of those displaced from the reservoir would be relocated in the villages around Estima. Up to the end of 1972, the total cost of resettlement and 'rural development' work undertaken by GPZ staff was 120,000 contos (US $5 million), less than a quarter of the sum set aside for the work through the loan originally sought from the construction consortium.

Details of resettlement work undertaken in 1973 and 1974 are not well documented but it is clear that the methods adopted during that period would have been far more forceful and hurried than those previously used. In those two years the remaining 20,000 people from the reservoir basin were either relocated or fled. In addition, enormous numbers of other people in the region were moved to _aldeamentos_; Jundanian claimed that 200,000 people, 42% of the population of Tete province, were in _aldeamentos_ by the end of 1973. Middlemas reported a total of 235,000 by the end of 1974, although his statistics included parts of the Zambezi basin outwith Tete Province. Population relocation on such a scale is unprecedented in the history of dam construction projects, and by the time of independence the major proportion of the rural population in the Zambezi basin had either been recently relocated, in inadequately prepared villages, or had fled to 'liberated' areas to avoid the authorities. The independent Frelimo Government was faced, therefore, with the task of formulating policies in the Zambezi basin which would enable the rural population, which over a period of at least five years had experienced considerable disruption, to re-establish
Figure 44: Locations of resettlement villages and aldeamentos in areas where the GPZ was operating.

Source: GPZ (1973a)
agricultural production and to improve their social conditions.

d) The creation of *aldeias comunais*: Reference was made in Chapter 2 to the unequal distribution of land between African peasants and European settlers at the time of independence. Many peasants had been forced into areas of very low productivity, having been dispossessed of their land, or had fled to such areas in order to avoid the imposition of taxes or the enforced production of cotton. In response to this situation Frelimo established *aldeias comunais* (communal villages), in 'liberated' areas of northern Mozambique, to enable independent groups, free of Portuguese control, to become self-sufficient in food production and to provide surplus food to support the guerrillas.

During the First National Agricultural Seminar in Maputo, three weeks before Independence Day, the President designate, Samora Machel, spoke of the need to organize the rural population into 'communal associations' in order to provide adequate food and clothing. On 25 October of the same year, the President defined the role of *aldeias comunais* as follows:

The *Aldeia Comunal* constitutes the back-bone for the development of productive forces in the countryside. It is in the *Aldeia Comunal* that we bring together the collective endeavour for production of the rural masses, where the collective life of the organized People liberates its immense creative initiative.

Politically, and this constitutes the essential characteristics of the *Aldeia Comunal*, it is the instrument by which the Power of the workers is materialized at the level of the administrative institutions, the structures for defense, production, commerce, education, culture, health, in sum, in all sections of life. *Aldeias Comunais* form this political instrument because they unite and organise us and thus enable us to exercise effectively the Power that has been won. We must be aware that dispersed and disorganised we cannot exercise power.

The emphases on political mobilization and on productive output imply a very different philosophy from that of independent self-reliance, which was the basis of the original *ujamaa* movement in Tanzania. Frelimo maintains that *aldeias comunais* can be formed not only through the formation of rural co-operative associations but also through the creation of state farms, by the nationalization of the larger farms and plantations.
of the European settlers. In addition, Frelimo policy states that the aldeias comunais programme, like the rest of the economy must be centrally planned:

The building of Socialism demands that the economy be centrally planned and directed by the State. Planned management is one of its basic characteristics.413

The emphasis by Frelimo on aldeias comunais was widely recognized before independence and many observers foresaw that experience gained in the 'liberated' areas would be applied more widely following independence. A number of writers, whose work was published between the 1974 Lisbon coup and Mozambique's independence, speculated on the form an aldeias comunais programme in the Zambezi basin would take. Middlemas,414 believing that the aldeamentos had been provided with the benefits of good water supplies, improved agricultural land, schools and other social services, predicted that it would require only the removal of features associated with the aldeamentos' military objectives and a modification of their organization, in accord with Frelimo's policies, to transform them into aldeias comunais. In physical terms, he saw little difference between the two types of village. A similar view was held by Jackson415 who prepared two reports on fisheries potential in Lake Cabora Bassa which were published before and after the coup respectively. He used the recommendations of his first report with few modifications to provide the basis for his second report. The 'protected fishing villages' in the former became 'communal villages' in the latter.

The origins of the present aldeias comunais are diverse. Even the records of the National Commission for Communal Villages in Maputo contained few details, in early 1980, of the origins of many aldeias comunais in the Zambezi basin. Nevertheless, of the fifty villages in Tete Province, listed in these records, no more than four could be identified as having developed directly from the resettlement villages and aldeamentos indicated in Figure 44. A large number of the aldeias comunais are associated with state enterprise; in particular, there are at least sixteen associated with the agro-industrial complex in Angônia. Of the sixty aldeias comunais in parts of the Zambezi basin outwith Tete
Province at least thirty-three appear to have had their origins in the aftermath of the 1978 floods, nine others were listed as having been formed by 'political mobilization' and only three were identified as having developed from aldeamentos. Many of the aldeias comunais listed in the records were, however, relatively small. Population statistics ranged from 200 to 5,000 per village.

Middlemas' expected transformation of aldeamentos into aldeias comunais clearly did not occur in the majority of cases. A major reason for this failure is that the aldeamentos were not, in general, located near satisfactory agricultural land and were not endowed with the services and resources which Middlemas records. In addition, since the aldeamentos were apparently formed with considerable coercion, the present authorities might wish to avoid using these sites in order to emphasize the differences between their own methods of rural development and those of the Portuguese colonialists.

The floods of 1978 provided an opportunity for the Government to form aldeias comunais from amongst people who had lost their homes. With very little preparation, a large number of new villages were established. The problems of establishing such villages, many of which were in remote locations, put considerable strain on the limited resources available to the authorities. Similar situations in other parts of Mozambique led Friedmann (1980) to refer to 'the present crisis of the villagization movement' (p. 105). There are various reasons for this 'crisis'. Agricultural production fell markedly after independence and has since been affected by several major floods and droughts. This has led to conflicts at government level over the most effective use of the scarce resources available and their allocation between aldeias comunais and mechanized state farms. Within the aldeias comunais movement centralized planning, and the national policy of providing exactly the same resources to each area of the country, have resulted in very little regional or local integration between villages. At village level, few aldeias have, as yet, developed the socialist organization intended, although co-operative ventures with specific objectives are now widely found. Inadequate planning has resulted, in many cases, in the location of villages a long distance from the most suitable agricultural land and from sources of drinking water; in a survey of forty villages in Manica Province it
was found that only seven had water supplies within one kilometre of the village.\(^{416}\)

From such considerations it appears that the formation of *aldeias comunais* is still in its infancy and in many areas has, as yet, done little to improve the lives of the rural population. On the basis of the official records available at the beginning of 1980, it is probable that no more than 10% of the population in the Zambezi basin were counted as members of *aldeias comunais*. Many of these villages, appear to have few amenities. Against this background, a report from the FAO\(^{417}\) recommended, for the country as a whole, that there should be a moratorium on the creation of new *aldeias comunais* to allow for the consolidation of existing villages. Friedman (1980) went further and suggested that, given the present resources of finance and personnel, the authorities cannot develop the present *aldeias* programme sufficiently rapidly to effect a significant transformation of the social conditions in the rural areas and prevent massive migration to the towns. He recommended, therefore, that resources should be concentrated in district centres which would act as resource centres and catalysts for the development of surrounding areas within a radius of, say, 60 km. Such a programme would, he suggested, require a remodelling of the government agency responsible for *aldeias comunais* including giving it wider powers to co-ordinate rural development work and undertake the currently neglected areas of physical planning and project assessment. The need for greater co-ordination in physical planning was also highlighted in the First National Seminar on Physical Planning in Maputo in October 1980.\(^{418}\)

**Health**

Study of the MFPZ's plans suggests that, had they been implemented, they would have had a considerable effect on the health of the people of the Zambezi basin. On the one hand, the plans included proposals to improve sanitation and medical care for the local population. On the other hand, the prevalence of water-related diseases would, almost certainly, have increased. Some increase may have occurred already with the construction of the Cabora Bassa Dam, although there is, as yet, no empirical evidence available to verify this suggestion. Possible effects of the project must, therefore, be considered in relation to
The health of the population living in the lower Zambezi basin in the early 1960s, and the extent of medical provision available in the region, is indicated in results of investigations undertaken at that time by the BEES. For example, in 1960, Tete Province appears to have had the poorest medical provision of any region in Mozambique, three doctors for 450,000 people in an area of 100,000 km², compared with one doctor for 33,000 people in an area of 4,500 km² over Mozambique as a whole.

The results of detailed health surveys conducted over a large part of the Zambezi valley in 1961-62 were published in the *Plano Geral*, 35.1. Infection by filarial worms was found to be relatively uncommon, except in the region of Fingoé where over 30% of the population was found to be infected. Intestinal parasites were rather more common infecting between 10% and 40% of the population. *Falciparum* malaria (*Plasmodium falciparum*) was found widely amongst both adults and children, with 35% to 60% of the population infected in all areas except in the cooler highland district of Angónia where the level was 8%. Wide variations were found in the incidence of *Schistosomiasis* (bilharzia). *S. haematobium*, which resides in the veins of the bladder, was found to be the most prevalent form of the disease, with sample results suggesting that all the children around Tambara were infected although in the remoter highland regions infection levels as low as 10% were found. In general, *S. mansoni*, which lives in the veins of the intestines, was only found in about 10% of the people examined, although levels as high as 50% were recorded in one district. In many areas malnutrition was recognized and this, together with gastroenteritis, was blamed for the high rates of infant mortality which were reported. Finally, blindness resulting from infection of corneal lesions was found to be relatively common.

The only other available information on the prevalence of disease in the lower Zambezi is contained in a report on the region of the lower Shire, by Sir William Halcrow and Partners, in which it was found that the entire population of many river-side villages was infected with both malaria and *schistosomiasis*. The report also noted
the occurrence of human sleeping sickness, \textit{trypanosomiasis}, and, river blindness, \textit{onchocerciasis}, although neither was common.

The officials of the MFPZ indicated their awareness of the health implications of the projects under consideration and made proposals to minimize the risks, particularly in areas in which European settlement was planned. \textit{Schistosomiasis} was regarded as 'the principal health problem of the Zambezi basin'\textsuperscript{421} and the need for further investigations was recognized in the \textit{Plano Geral}:

\begin{quote}
A more complete knowledge ... could certainly provide indications that would influence the planned projects and could even cause methods of hydraulic engineering to be adopted which would be less favourable to the existence of particular species [of the disease vectors]\textsuperscript{422}.
\end{quote}

The report also contained a recommendation that a pilot study be undertaken to test the effectiveness of various means of eradication. In fact, \textit{schistosomiasis} is not generally transmitted in the water of the main Zambezi which appears to be too fast flowing for the vectors to become established. Nevertheless, the lagoons which form along either bank of the river in the alluvial plain are heavily infested as too are certain tributaries, including the Condedzi and Revúboë. The MFPZ officials were, however, chiefly concerned that high levels of infestation would become established in the reservoirs and canals of the proposed irrigation projects.

During the period of construction of the Cabora Bassa Dam health officials of the GPZ were largely concerned with making provision for the construction workers at Songo and, to a lesser extent, with the health aspects of the \textit{aldeamento} programme. It is the latter which is examined here.

In the plans for 'community development', as set out in the \textit{Esquema Geral}\textsuperscript{423}, it was suggested that health posts, staffed by itinerant nurses, should be established for every 200 adults and that permanent maternity posts should be created for every 10 000 adults. Not surprisingly, such ambitious plans were not adopted in the rush to realise the \textit{aldeamento} programme in the early 1970s, although about six health posts
and two maternity posts had been set up in the Estima and Changara regions by the end of 1971. These enabled approximately one-half of the population resettled in these areas to receive medical examinations and immunizations during 1971. Middlemas, without quoting his source, claims that, as a result, the rate of infant mortality amongst the aldeamento population fell sharply. By contrast, he suggests that immediately after relocation, the mortality rates of older people rose. However, it is unlikely that sufficient information was available to reach firm conclusions on such questions. Scudder, from his studies of other reservoir projects, believes that the stresses of resettlement invariably lead to increased mortality rates and that the elderly are worst affected. But, he has been unable to identify a single project for which there are sufficient reliable data to test these hypotheses adequately.

In the case of the Cabora Bassa Project, the level of resettlement stress would almost certainly have been increased by the haste and force which were employed in the aldeamento programme and by the inadequate facilities provided within the majority of villages established. Hall and Davies (1974) described conditions of inadequate sanitation, lack of hygiene and poor drinking water in new aldeamentos. They identified the safeguarding of drinking water supplies as a particular problem since many of the wells and boreholes were sited in low-lying areas where stagnant pools soon formed and contaminated the supply.

Although the health hazards arising from the aldeamento programme are considerable they could be reduced significantly by adopting appropriate remedial measures in areas where the aldeamentos are still inhabited. However, if the prevalence of water-related diseases has been increased by the impounding of Lake Cabora Bassa, the long-term consequences may be far more damaging.

Schistosomiasis is widely spread and endemic amongst the populations of many tropical regions where it causes considerable suffering, and debilitation, to individuals as well as heavy economic costs to their communities. Its prevalence is highest in people living beside slow-flowing water where the aquatic snails, which act as intermediate hosts...
for the fluke cercariae, find a suitable habitat amongst the aquatic vegetation. However, levels of infection are affected by a large number of ecological factors and it is, therefore, difficult to predict the impact of a particular water resources project. Furthermore, in many studies, including that of Hira (1969) concerning the impact of the Kariba Project, absence of any previous work makes it virtually impossible to monitor changes as they occur. In other cases research has given conflicting conclusions. The published studies of the prevalence of the disease amongst people living along the Nile in Egypt illustrate this; Dawood\textsuperscript{428} found that the disease was spreading with the expansion of perennial irrigation, whilst Miller (1978) found that its incidence had decreased over a period of many years. The issue is of considerable importance to the Aswan High Dam Project according to van der Schalie\textsuperscript{429} who suggested that the costs of increased incidence of schistosomiasis would outweigh the benefits of the project. Farid (1975) anticipated that the disease would not be confined to the irrigation canals but would extend to the shores of Lake Nasser once the pattern of reservoir fluctuations became established. He observed, however, that, initially, water snails had been prevented from becoming established in the reservoir because of the lack of aquatic vegetation resulting from the large fluctuations in its level. One of the projects for which large increases in the level of schistosomiasis infection have undoubtedly been recorded is that of the Volta River above the Akosombo Dam\textsuperscript{430}. Studies showed that a correlation exists between the establishment of aquatic vegetation and the spread of the disease\textsuperscript{431}. On the other hand, no dramatic increases in the incidence of the disease have been found at the Kainji\textsuperscript{432} and Kamburu\textsuperscript{433} Projects, where large reservoir fluctuations occur, or at the Brokopong Project\textsuperscript{434} where the water is acidic.

On the basis of such work it appears that, at present, the conditions in Lake Cabora Bassa, with its large fluctuations in water level, do not favour the establishment of the snail hosts which transmit schistosomiasis. Nevertheless, if semi-permanent pools are left by the receding water, such as those occurring in the Zambezi's floodplain, habitats favourable to aquatic snails may be formed. Although the Cabora Bassa Project may not, as yet, have increased the hazard from this disease future developments may serve to increase the levels of infection in the region. In
particular, the 'constant level' operation of Lake Cabora Bassa which, according to SWECO (1982) could be achieved by increasing the discharge capacity of the dam, would be likely to increase the prevalence of the disease along the reservoir's shores. Likewise, implementation of any of the irrigation projects which have been proposed would lead, almost certainly, to the increased prevalence of schistosomiasis.

Another important water-related disease in tropical and subtropical regions is malaria. The TVA has had spectacular success in erradicating the malarial mosquitoes by operating its reservoirs in such a way as to disrupt the mosquitoes' breeding cycle. Bradley (1977) has shown that the conditions in the Tennessee Valley are very different from those in Africa. Firstly, the principal host in Africa is the mosquito Anopheles gambiae which, because it has different breeding habits from those of the mosquitoes found in the Tennessee Valley, would not be affected by this control technique. Secondly, over much of Africa A. gambiae is already well established. The creation of a reservoir would, therefore, have only a minor effect on the incidence of malaria since the disease is already endemic. This has been found to be true for both the Kainji and Volta River Projects and may be expected to be true for the Cabora Bassa Project where the survey in the early 1960s, referred to above, found that malaria was endemic in most of the Zambezi valley. On the other hand, the results of initial post-impoundment studies indicate that a significant increase in the number of mosquitoes has occurred. This will cause increased discomfort to the population of the region, will increase the difficulty of eradicating the disease and may cause other mosquito related diseases, such as encephalitis, to increase.

Trypanosomiasis is not generally regarded as a water-related disease because the life-cycle of its host, the tse-tse fly, does not require open water. Nevertheless, the adult flies thrive in areas of shade where the humidity is high and are, therefore, attracted to the banks of rivers and lakes. Furthermore, the impounding of a new reservoir, and relocation of the population, can displace the flies from their previous habitats and disperse them to new areas in which they were previously unknown. This occurred with the impounding of Lake Kariba where cattle fatalities added additional burdens to the resettled population. The presence of the reservoir was also found to make the job of tse-tse fly eradication
more difficult because the flies were carried to new areas by the wide-spread movement of fish traders. A further hazard is that DDT, used in the eradication programme, appears to be accumulating in the fish of the lake and is thought to be the principal cause of a recent decline in the population of fish eagles.

In the vicinity of Lake Cabora Bassa, both human and bovine trypanosomiasis were found before the construction of the dam although, according to Hall and Davies (1974), they were confined to the north-west of Tete Province. Hall and Davies expressed the belief that the impoundment of the lake would cause the disease to spread and that vessels crossing the lake might even carry tse-tse fly to its southern shores.

The effect of dam construction on the prevalence of onchocerciasis is determined by the characteristics of the project. The blackfly which transmit this disease breed in fast flowing, well oxygenated water. In the majority of cases the prevalence decreases as a result of the flooding of previous breeding sites by the new reservoir. Breeding sites downstream of the dam are also affected both by the high levels of inorganic sediment in the river, which arises during the construction of the dam, and by intermittent discharges, which may result from the operation of the spillways. On the other hand, spillways themselves may become ideal breeding grounds. In certain cases, insecticides have been sprayed over the water to protect the construction workers and dam operators. Downstream of Lake Kainji, for example, the spraying of insecticides was continued after the completion of the dam. This was found to be effective in eliminating blackfly but only over a relatively short distance (15 km). The constant discharges from the Akosombo Dam enabled blackfly to continue to breed downstream in the Volta River.

The MFPZ does not appear to have considered onchocerciasis to have posed a significant hazard in the lower Zambezi valley. However, the report by Halcrow (1954) suggested that the disease was found on the Shire River and it would be surprising if blackfly did not breed in the region of Cabora Bassa Gorge before the dam was built. If this supposition is correct, the dam will have eliminated a large proportion of the suitable stretches of rapids but, downstream of the dam, other rapids still exist.
where the blackfly could continue to breed.

The tentative conclusion from the sparse available information can only be that the potential hazard, to the population in the lower Zambezi, from the diseases considered above, does not appear to have been significantly increased following the construction of the Cabora Bassa Dam. But, from experience elsewhere, it is reasonable to infer that the prevalence of both malaria and schistosomiasis is more likely to have increased than decreased. There are, however, considerable health problems associated with the various proposals to develop irrigated agriculture in the region. In particular, such projects are very likely to produce an increase in the level of schistosomiasis infection in the population. Nevertheless, further information is required before firm conclusions can be drawn about the health implications of the Cabora Bassa Dam, the grouping of the population into villages, aldeamentos or aldeias comunais, and the plan to undertake large-scale irrigation projects in the region.

Fisheries in Lake Cabora Bassa

The construction of a dam affects fisheries in various ways. In temperate climates the principal effect is to interrupt the passage of migrating fish. In tropical rivers there are, generally, fewer important migratory species although possible damage to the breeding of eels as a result of dams on the Zambezi and Tana rivers has been noted. Against this, many man-made lakes offer a higher fisheries potential than does the natural river. For example, important fisheries rapidly developed around Lake Kariba. Even so, in comparison with the size of the reservoir, returns have been small*. Many studies of the development of fisheries in tropical reservoirs have been published the most detailed of which have been those relating to the Kariba and Volta River Projects. Studies have been made not only of the ecological factors which affect fish production but also of the social and economic factors associated with fisheries' development. These factors are considered separately below.

* In Zambia, when output of fish from Lake Kariba was at its peak, catches from the reservoir amounted to only 12% of the national fish production. See Harding (1966) p16.
On the basis of published studies\textsuperscript{443} it is possible to identify the more important factors which affect the ecology of a new reservoir. These include climate, topography, fluctuations in water level, nutrient input from tributaries, types of soil and vegetation which have been inundated, and the species of organism present in the river system before the dam was built. One other important factor, referred to above in presenting Table 30, is the ratio of reservoir capacity to mean annual inflow. For natural lakes this ratio is very high; for example, about 100 for Lake Victoria and 1,500 for Lake Tanganyika\textsuperscript{444}. The data in Table 30 indicate how much smaller the values of this ratio are for reservoirs; the highest value in the table is 4.1 for Volta Lake. In other cases the values are considerably smaller. Thus, even the most stable reservoir environments experience a far higher rate of exchange of water than the majority of natural lakes of comparable size.

In the two cases which have been best documented, the Kariba and Volta Lakes, their ecological evolution has followed relatively similar routes. In the initial stages of filling, both lakes contained large quantities of decaying vegetation and, as a result, large amounts of nutrients were released. At the same time, in the case of Lake Kariba, appreciable amounts of hydrogen sulphide were released as the decaying vegetation removed the available oxygen from the water. For part of the year the hydrogen sulphide was trapped in the deeper parts of the reservoir by a pronounced thermal stratification, but, with the seasonal cooling of the surface waters, the stratification broke down, by the middle of July, to allow mixing of the reservoir water and release of the hydrogen sulphide\textsuperscript{445}. This alternate stratification and mixing was not observed in Lake Volta in its initial period of filling\textsuperscript{446}. However, both reservoirs experienced a rapid increase in fish productivity as a result of the sudden release of nutrients and the removal of population pressure on the natural fish species. As conditions in the reservoirs began to stabilize the level of free nutrients declined and a gradual decline in fish productivity occurred. It is anticipated that fisheries output will reach an equilibrium level well above the output from the natural river but below the peak levels which occurred in the newly-formed reservoir, although Balon (1978) forsees a slow rise in fish productivity as the area of the catchment under cultivation and the level of sewage
discharge increase.

In the long-term, it is the equilibrium level of fish productivity which is important from both an ecological and economic point of view. The productivity in Lake Kariba is relatively low because the major tributaries carry few nutrients into the reservoir. In Lake Kainji, the low productivity is thought to arise not only from the low level of nutrient input but also from its low capacity/inflow ratio and the large drawdown which prevents littoral hydrophytes from becoming established. On the other hand, investigations on the shores of Lake Kariba suggest that terrestrial vegetation, and the droppings of browsing animals, on the drawdown zone could be important sources of nutrients for the reservoir.

Under favourable conditions commercial and peasant fisheries may develop side by side. This provides both protein and income, to lakeshore communities, and fish for market at other population centres. Since many of these communities are formed from people resettled from the reservoir area, Scudder (1973a) and Jackson (1975b) regard the principal benefit of fisheries as allowing such people to gain their independence from government assistance more rapidly. Scudder believes that peasant fisheries will develop without, or in spite of, government intervention. Nevertheless, a positive effort to improve the fisheries potential is generally made by the authorities and this may take various forms.

One controversial area of possible intervention is in the clearing of vegetation from the land to be inundated. Such clearance has been advocated in order to facilitate the movement of boats and enable trawling techniques to be used. At Kariba an area of approximately 950 km² was cleared and burned (18% of its surface area) whilst at Kainji 500 km² was cleared (40% of its surface area). By contrast virtually no bush clearing was undertaken for the Volta Project. Jackson advocated complete bush clearance as a long-term investment in fisheries even though at Kariba the fishing techniques used initially meant that no benefit was derived from the £3 million (US $ 8 million) invested in bush clearance. Others have suggested that bush clearance
should not be undertaken because the decaying trees contribute to maintaining high levels of biological productivity in the lake and that fishing in uncleared areas is more productive than in cleared areas

Another controversial question is whether or not new fish species should be introduced to a reservoir. The policy has been advocated in the belief that the natural river species would be incapable of inhabiting the deeper, open reaches of the reservoir, that selected introduced species would be more productive or that biological control of aquatic weeds and disease vectors could thereby be achieved. Pre-impoundment studies of fish species in the Zambezi indicated that Lake Kariba would contain certain species which could become important for fisheries, but it was feared that their numbers might not increase sufficiently rapidly. It was decided, therefore, to stock the reservoir, between 1959 and 1962, with two species of fish one of which was new to the river system. The programme appears to have been ineffective. A new approach was adopted in 1967 and 1968 when Tanganyika sardine (Limnothrissa miodon) and a number of other species were introduced to colonize the deep water of the reservoir. The species were slow to establish themselves but by 1975 Kenmuir (1975) suggests that large catches were being made.

Rather less has been written about the introduction of new species for the biological control of pests. However, ecologists have generally advocated extreme caution lest the new species introduce fresh imbalances which would be harmful to native species or to the environment as a whole.

As regards government measures to stimulate fisheries, the development on the opposite shores of Lake Kariba followed very different paths. In Zambia, the authorities sought to give preference to the displaced Tonga peoples, by closing the reservoir to all other fishermen, and by providing training centres. Resettlement compensation payments

* Ironically although the Zambian Government was responsible for the introduction of these species there were, at the time, no facilities for catching them from the Zambian shore. Meanwhile, commercial enterprises operating from Rhodesia were able to profit from the operation.
were, in many cases, used to buy fishing equipment\textsuperscript{458}. By 1963, over 2,000 fishermen were operating from the Zambian shore but, as biological productivity declined in the reservoir, the number of fishermen fell to about 500 by 1967. Many of the initial fishermen, by that time, had made sufficient profit to establish themselves in alternative occupations, but those who had recently invested in new equipment suffered considerable losses as output fell\textsuperscript{459}. The level at which output stabilized after 1967 is believed to be well below the potential output but, at present, fish production is constrained by the limitations of the transport and marketing systems\textsuperscript{460}.

The Rhodesian authorities initially imposed a total ban on the sale of fish from Lake Kariba in the mistaken belief that fish stocks would suffer. In 1962, following the lifting of this restriction, two European-controlled enterprises were given licences and began supplying frozen fish to white consumers\textsuperscript{461}. African peasant fishermen were gradually allowed to market their catches and, from 1964 on, the two fisheries enterprises found it more profitable to buy from the African fishermen than to undertake their own fishing. In 1965, a third, independent, organization was permitted to buy fish\textsuperscript{462}. Its operation was on a smaller scale than that of the other two enterprises whilst its production of brined, smoked and dried fish was designed for African consumption. With a labour force of twelve it achieved an output of 450 t in ten months in comparison with a total output of 1275 t in the same period from the two established enterprises. These, however, employed a work force of two hundred, at that time, and had investments over fifteen times greater. Since the new organization was threatening their supplies the larger operators combined to force it out of business. The number of individual fishermen, working from the southern shore of the reservoir, reached a peak of 1100 in 1966 but fell to below 500 by 1970\textsuperscript{463}. Few of these could be regarded as permanent fishermen as the majority lived in scattered camps from whence they returned to other regions once they had earned sufficient income.

In contrast with the different forms of government intervention and control on the two shores of Lake Kariba, the authorities in Ghana did very little to promote commercial fisheries in the Volta Lake.
Nevertheless, within five years an estimated 20,000 fishermen were operating on the reservoir which proved to be considerably more productive than Lake Kariba. The subsequent decline in productivity reduced this number but the number of fishermen appears to have stabilized at about 12,000. At its peak productivity fish catches from the Volta Lake exceeded 60,000 t/yr and a sustained output of 38,000 t/yr has subsequently been achieved.

The bulk of the published information about fisheries in Lake Cabora Bassa is based on pre-impoundment studies undertaken during 1973 and 1974 by scientists and consultants employed by the GPZ. A description of this work by Morais (1974, part 1) lists the principal objectives as follows: to investigate the effects of the dam on fish migration; to investigate whether indigenous species might colonize the reservoir or whether new species should be introduced; to estimate the probable fish productivity; and to examine ways in which that productivity might be exploited. Morais suggested that existing species of fish would colonize all but the deepest parts of the reservoir and that the reservoir's productivity per unit surface area would be higher than that of Lake Kariba. The latter suggestion was based on the results of chemical analysis of river samples which indicated that the inflow was well oxygenated, slightly alkaline, had favourable levels of electrolytes and was rich in phosphates. The Kafue and Hunyani were identified as tributaries which were particularly rich in nutrients although Hall, Valente and Davies (1977) warned that the Hunyani, together with the Messenguezi, might become increasingly polluted with industrial effluent.

In 1974, P B N Jackson was approached by the GPZ to advise on fisheries development in Lake Cabora Bassa. Following a brief visit to the location he wrote a report, Jackson (1974a), which recommended the establishment of about ten villages each with 100 fishermen using gill nets and either canoes or powered boats. Two aspects of this report are of particular interest: Jackson appears to have been led to believe that the drawdown would be relatively small, no more than six metres; and he recommended that bush clearing would make no economic sense. In this he was adopting a view which was the complete opposite of that which he had previously held but he may, in part, have been
influenced by the fact that even if he had recommended extensive bush clearing it could not have been carried out at that late stage.

There is considerable duplication between the principal published studies of fisheries potential in Lake Cabora Bassa. It was predicted that an explosion of biological productivity in the initial phase would occur, as in Lake Kariba, and that this might result in a dense cover of floating vegetation. On the other hand, it was anticipated that, unlike Lake Kariba, rooted vegetation might also establish itself in certain parts of the lake, a prediction which depended on a relatively small fluctuation of level being established. The consensus of these papers appeared to support the view of Jackson and Davies (1976), that Lake Cabora Bassa will become 'an enormous asset' to Mozambique 'as a potential earner of foreign currency through export of fish products', (p133). Nevertheless, Hall and Davies (1974) foresaw a number of potential difficulties. On the gently shelving south shore, they believed that mats of floating vegetation, tangled round submerged trees, would impede fishermen. Other problems would arise on the steeper north shore where floating vegetation and debris would accumulate because of the direction of the prevailing wind. Finally, Hall and Davies considered that the marketing of the fish could present difficulties since European consumers in Mozambique were already adequately supplied from sea fisheries. As a result they concluded that much of the output would be dried or smoked for local consumption.

The question of whether or not to introduce Lake Tanganyika sardine to Lake Cabora Bassa was discussed in the papers cited above. Kenmuir (1975) saw the possibility that they might survive the passage downstream, from Kariba, and become established unaided. Others, ruling out self-colonization, believed that artificial introduction would be desirable, with Hall and Davies (1974) suggesting that it could be delayed until stable aquatic conditions had become established and Jackson and Davies (1976) recommending early introduction.

Following closure of the dam, investigation of the reservoir environment was undertaken for a period of about six months. During this time high levels of biological activity were observed and no
stratification of the water took place. Fishing communities also became established but the level of official supervision in their formation is unrecorded. In mid-1977, T Williams observed almost 150 fishermen, from two villages, operating near Chicoa and sending brined, dried and smoked fish to be sold to markets in Songo, Angónia and Chimoio. The average catches reported were comparable with, or better than, the 10 kg/man/day predicted by Jackson (1975a); the price also appears to have been better than that predicted by Jackson.

In assessing the fisheries potential of Lake Cabora Bassa, it is difficult to obtain an objective evaluation either of the difficulties to be overcome or the possible benefit to the economy of Mozambique. Reports written by fisheries consultants appear to place undue emphasis on those aspects, such as species introduction, which would require further supervision and outside expertise. In addition, reports of a more general nature tend to overstress the fisheries potential of the reservoir without close examination of the facts. In reality the benefits in strictly economic terms would, according to estimates made by Jackson (1975a), be relatively small. He suggested that fewer than 1 500 fishermen could be supported and that their gross annual revenue would be approximately equivalent to US $1 million. A further US $0.8 million could, he suggested, be earned if a successful sardine fishery became established, but even this would bring revenue from fish sales to only 3% of that from energy sales from the project.

Hydrobiologists are, understandably, concerned that fisheries research is being neglected at present. According to Jackson (1975a):

All the artificial lakes in Africa have a fish station working continually: Cabora Bassa ought not to become the exception. (p49)

Clearly, the development of fisheries should be monitored by the authorities in order to identify particular problems associated with

* Compare this with Volta Lake where fisheries account for revenue equivalent to 30% of that from energy production (Hart (1980) p89) or Nam Pong Lake in the Mekong Basin where the figure is 60% (SCOPE (1972) p59).
equipment, training, fishing techniques, communications, marketing or environmental changes. The resources which should be allocated to detailed investigations will, nevertheless, depend on the importance assigned to the activity and whether it is viewed as a source of export revenue, as a source of protein for the local population or as a source of employment. However, the establishment of a hydrobiological research station is unlikely to be considered to be the Government's highest priority at present.

Aquatic Weeds

The possible hazards associated with extensive growths of aquatic plants on reservoirs have been extensively documented. They include health hazards, the obstruction of navigation, damage to fisheries and the risk of damage to power installations. The two plants regarded as the most difficult to control are *Eichhornia crassipes* (water hyacinth) and *Salvinia auriculata* (water fern). Both are free-floating plants, capable of propagating extremely rapidly, from small fragments of parent plant, and of forming dense mats of vegetation. Both species appear to be well suited to the unstable and nutrient-rich conditions of new tropical impoundments. Along with the hazards mentioned above, these plants are thought to provide few benefits although *Eichhornia* has been harvested from shallow ponds and channels to provide animal fodder or to provide a raw material for biogas production. In addition, some benefits to fisheries may accrue as a result of the shelter which these plants provide to young fish and their trapping of nutrients in the reservoir which would otherwise have been lost downstream.

In a number of cases cited in the literature large expenditures on weed control have brought only limited success. The principal methods of control may be classified as mechanical, chemical or biological. Mechanical control is expensive, whether performed manually or by machine, and is generally only effective on confined areas. Chemical control is the most widely used at present but there is a danger that the herbicides may be harmful to other organisms including man. The introduction of herbiverous fish and certain types of insect appears to offer the most effective long-term method of
control. There is, however, a danger either that the new species will be eliminated, by predators already present in the environment, or that they will become so prolific that they introduce new hazards. Certain reservoirs appear to have been kept free of serious infestations of these plants as a result of the dam operating procedures adopted. For example, Odingo(1979) attributed the lack of aquatic weeds on Lake Kamburu, on the Tana River in Kenya, to the large annual drawdown which the reservoir experiences.

The growth of Salvinia in Lake Kariba was rapid and unexpected\textsuperscript{471}. By 1962, it was covering an estimated 1,000 km\textsuperscript{2}, some 20% of the surface area of the reservoir. Thereafter, the covering decreased and, in 1973, it was reported to have fallen as low as 150 km\textsuperscript{2}\textsuperscript{472}. The first control measures were not introduced until the early 1970s when the grasshopper Paulinia acuminata was released\textsuperscript{473}. The power installations have been relatively unaffected by the plants since the prevailing wind direction carries them away from the dam. Similarly, areas of open water, from which trees were cleared, have remained free of infestation since wave action prevents mats from forming. However, estuaries and sheltered inlets have become clogged with the plants and they have caused difficulties to fishermen. Despite its presence in other parts of the Zambezi basin the other common species of weed, Eichhornia, has never been seen on Lake Kariba.

The pre-impoundment studies of Lake Cabora Bassa suggested that weed infestation would probably be far worse than that experienced in Lake Kariba\textsuperscript{474}. Four potential weeds were known to be present in the reservoir's catchment, Salvinia molesta, Eichhornia crassipes, Pistia stratiotes* (water lettuce) and Azolla nilotica. It was recognized that the storminess of the reservoir might restrict the spread of mats of vegetation. Most hydrobiologists believed, however, that there would be only minor annual fluctuations in water level or, where they foresaw

* In the Volta Lake, which suffered no major weed infestation, P. Stratiotes was the most abundant aquatic plant in inlets and sheltered areas. Although the proportion of the reservoir affected was relatively small it provided an ideal habitat for aquatic snails and was, therefore, an important factor in the spread of schistosomiasis, see Beadle (1974) p291.
larger fluctuations, failed to recognize their significance in the control of weeds.

Following the closure of the Cabora Bassa Dam the anticipated rapid spread of aquatic weeds did not occur. *Eichhornia* was present in the gorge behind the dam and *Pistia* spread into narrow backwaters, at the western end of the reservoir, but the affected areas were never large and drawdown between June and August, 1975, resulted in a significant reduction of this area. As the reservoir level became stabilized in August, 1975, an invasion of *Eichhornia* was again feared but, instead, some existing stands began to wilt and die in a manner which suggested a deficiency of chemical nutrients in the water.

A report by a UN consultant, in 1977, continued to forecast increasing infestation of the lake on the basis of very approximate estimates of infested area which suggested that the area affected, albeit relatively small, had doubled between 1975 and 1977*. Again, no mention was made of dramatic reductions in infestation which had occurred, at least once, during this period when the reservoir was drawn down. The report's recommendation, that an elaborate control programme be sponsored by the FAO and the Mozambican Government, appears to have been far from justified. In the event no effort was made to implement the report.

Prior to independence, the GPZ had commissioned Loxton Hunting to study and establish a control programme for weed infestation. Two booms were constructed across the gorges behind the dam, one close to the turbine intakes and one about 11 km upstream. In addition, equipment and personnel were assembled to undertake manual, chemical and biological control. However, despite forceful representations from the consultants in 1975, the Mozambican authorities refused to continue with the programme or to sanction an extensive chemical control operation which, they feared, might have serious environmental consequences. This appears to have led to a dispute, between HCB and the Government, as to where the responsibility

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*The 1977 figure was 500 ha (5 km²) which is still only 0.5% of the surface area of the reservoir. Almost half this total was in the gorges by the dam but, even there, the infested area was only 5% of the total.*
for weed control lay, a dispute which was aggravated by poor maintenance of the booms\textsuperscript{482}. In response, the Government established a special research unit, within the National Agricultural Research Institute, to monitor the situation, instigate whatever control measures might be considered necessary and undertake research, particularly into biological control agents\textsuperscript{483}. The visit by the UN consultant, referred to above, was arranged by this unit in recognition of their own lack of expertise. They were wisely cautious in accepting his conclusions under the present pattern of reservoir operation*. 

Environmental implications of extensive drawdown

Although large annual fluctuations in reservoir level appear to have been beneficial in the control of aquatic weeds, other important environmental consequences may still occur. With regard to the reservoir itself, such fluctuations impede the establishment of rooted vegetation along the shore-line which, in turn, may affect the fisheries. For example, it was shown, at Lake Kariba, that this effect became significant with an annual drawdown cycle of amplitude greater than 3.5 m, that is, with monthly changes in water level greater than 0.6 m\textsuperscript{484}. The present pattern of fluctuations at Lake Cabora Bassa exceeds this limit.

The possible health implications of excessive reservoir drawdown, discussed above, arise mainly from the proliferation of disease vectors, including insects and aquatic snails. These effects are most severe where the reservoir shores are gently shelving and allow temporary pools to occur as the water level falls.

Finally, there are important implications for agricultural cultivation in the drawdown zone. These arise not only from health factors but also from the unpredictable fluctuation in reservoir level. Such fluctuations may cause inundation of a crop before it reaches maturity, and changes in the properties of the soil. An investigation carried out in the drawdown zone of the Volta Lake\textsuperscript{485} suggested that such changes may include leaching of soluble minerals, decrease in free

* Should 'constant level' operation, as proposed by SWECO (1982), be adopted the problems of weed infestation might increase dramatically.
oxygen levels, associated with the replacement of aerobic organisms by anaerobic organisms, and, in the long-term, changes in the structure of the clay particles. Whilst some of these changes are reversible once the reservoir level falls and the soil begins to dry out, long periods of inundation may cause permanent changes to occur.

**Environmental effects downstream of Cabora Bassa.**

Davies (1979) undertook a review of the literature on regulated streams in Africa which shows that, apart from the Nile, very little systematic work has been undertaken on the downstream effects of dams. The Zambezi was one of three rivers which featured prominently in his paper yet elsewhere it was claimed that there had been 'little if any biological work on the effects of the dam' before construction and that a 'lack of deep quantitative data on the below dam area' was evident. Morais (1974) supported the latter view claiming that the river and floodplain below Cabora Bassa formed the least studied part of the whole basin. Certainly no studies of the effect of the Kariba Dam on this region were made, and it was not until 1973 that 'pre-impoundment' studies for Cabora Bassa were begun. By this time the effects of the construction work would have caused considerable changes to occur in the quality of the river water. No further studies have been undertaken since the dam was completed.

Davies (1975 a and b) was greatly concerned about the short-term effects of the closure of the Cabora Bassa Dam. On 5 December, 1974, when the temporary diversion tunnels were sealed, river discharges at the gorge fell to zero. At this stage, in a normal year, they would have been increasing at the start of the wet season. The closure caused the river at Tete to fall to its lowest level since records began. This affected water extraction, including the town's water supply, and, presumably, navigation downstream. Davies was particularly concerned about the effects on fish stocks which resulted from the loss of their breeding grounds and from the overfishing which occurred in the reduced flows of the river. However, his appeals to the authorities to prevent such a drastic interruption of flows from taking place came far too late. The design of the dam and temporary works prevented any discharges from being made until the reservoir level reached the sill level of the
discharge gates. In the event, this took about a month, although the time could have been reduced if prior agreement had been made with the CAPC to increase the discharges from Kariba during this period.*

The long-term effects of a dam on the downstream environment can be considered in terms both of the quality and quantity of the regulated discharges. The possible changes in water quality include those caused by the trapping of sediment in the reservoir, considered in Chapter 5, and those caused by chemical changes affecting water in the reservoir. Begg (1973) speculated that because the spillway intakes at the Kariba Dam would draw water from the lower part of the reservoir, where hydrogen sulphide concentrations were high, large discharges might produce significant effects on the ecology of the river downstream. Such effects were expected to be most severe in the early years of the reservoir's operation. No study of the river ecology was made at the time but Hall, Valente and Davies (1977) found well-oxygenated water at a point 200 km downstream of the dam in an investigation conducted in 1973 and 1974. The most important change, which they attributed to the influence of Lake Kariba, apart from a decrease in turbidity, was a decrease in the level of conductivity in the dry season when, under natural conditions, a peak value would have occurred as a result of the leaching of electrolytes. The influence of the reservoir, in this respect, was detected at least 800 km downstream in the period before the Cabora Bassa Dam was completed.

Other possible downstream changes in river ecology include those caused by increases in the concentration of certain metallic ions, as occurred in the river downstream of Volta Lake, and the effects of organic pollution. The latter has been recorded in the Zambezi basin below Lake McIlwaine, which received effluent from the city of Harare, but the pollution could only be detected for approximately 30 km downstream.

Ecologists have predicted that none of the detrimental effects mentioned above will be found in the river downstream of Cabora Bassa. Indeed, Davies, Hall and Jackson (1975) predicted that a slight nutrient enrichment of the river would occur which, together with flow regulation.

* Despite high reservoir levels at Kariba, its discharge gates were not opened from before the beginning of December, 1974, until late January, 1975.
would probably be beneficial to fish in the river.

In the lower Zambezi valley, floodplain regions have, in the past, been a more important source of fish than the river itself, despite the fact that the floodplain is much smaller than might be expected from a river of this size. As in other rivers in Africa, the seasonal inundation of the Zambezi floodplain created large areas of warm shallow water which were rich in nutrients and provided ideal breeding grounds for fish. The full extent of fisheries production from this region has not been studied in detail and remains the subject of some dispute. An impassioned editorial in African Wildlife claimed that:

places like Lake Danga [supported] thousands of Africans on its fish.

On the other hand, Morais (1974) suggested not only that the fisheries potential of the lower Zambezi floodplain was relatively poor*, but also that it had been declining over the hundred years prior to the construction of the Cabora Bassa Dam. He identified a number of semi-permanent lakes as well as the channels around the Ilha de Inhangoma as areas of higher potential output. The latter had been partially disrupted by a dam built across the Ziu-Ziu although this eventually collapsed in 1974.

Apart from any changes which might have been caused in the sediment and nutrient characteristics of the river, the principal influence of the Kariba and Cabora Bassa Dams on the environment and, in particular, on floodplain fisheries was expected to be their regulation of flood discharges. This aspect forms the main substance of the only technical report prepared to date on the ecological effects of the Cabora Bassa Dam, SWECO (1981). On the Pongola River in the Transvaal, a study of the effects of an irrigation dam showed the importance of annual flood peaks for fish breeding. Their importance was found to lie not only in the replenishment of water in the pools of the floodplain but also in triggering the fish breeding cycle. Unseasonal flood peaks were found to result in very poor breeding rates. Similar effects were recorded by Kenmuir (1976) following a study of fish in the Mana Pools,

* The productivity of the lower Shire Valley was, he suggested, considerably higher.
downstream of the Kariba Dam.

Not only fisheries but also other parts of the environment may be affected by changes in the pattern of flood releases. In the case of the Cabora Bassa Dam the possible effects of flood regulation, which have been considered, include changes in groundwater levels and in the natural vegetation of the floodplain, coastal erosion of the delta region and salt water intrusion. Such changes might affect both agricultural activities in the region and the survival of wildlife. There does not appear to be evidence of extensive flooding occurring annually in this region, but the difficulty of analysing flood frequencies from the available data are considerable, as is demonstrated in Appendix 9. Nevertheless, the results of Appendix 9 appear to suggest that a major inundation of the floodplain occurred about once every five years and that, although the Kariba and Cabora Bassa Dams cannot eliminate such floods, their frequency has been reduced since the closure of the dams. Whether the change is great enough to have had, by now, a detectable influence on such factors as groundwater is not known and there would be great difficulty in distinguishing effects produced by the dam from those resulting from other environmental and climatic changes. Nevertheless, Attwell (1970) believes that vegetation changes in the Mana Pools region can be directly attributed to the regulation of discharges by the Kariba Dam. No direct evidence exists that similar changes have occurred in the lower Zambezi valley since the Kariba Dam was closed, although a number of ecologists have expressed the belief that such changes are occurring. Particular concern has been expressed about the possible effects on the large area of savanna grassland in the coastal region, around Marromeu, and the delta which supports one of the largest populations of wild buffalo in Africa. Deterioration of these grasslands might jeopardize the economic potential of the region. At present the principal economic benefit derives from the programme of buffalo culling organized by the authorities but proposals for economic improvement based on the integrated development of the region's natural resources have been put forward.

Although a reduction in flood peaks has inevitably followed the construction of mainstream dams on the Zambezi, flood releases will still be made from time to time with their magnitude and seasonal distribution
being determined by the operating procedures which are adopted for a particular project. At Kariba, following the initial filling phase, there were relatively few occasions on which it became necessary to make unseasonal discharges. As a result the downstream flood peaks showed a pattern which was similar to that of the natural river, see Figure 45. In the four years following the closure of the Cabora Bassa Dam, this pattern was seriously disrupted, as Figure 45 shows. The erratic and unseasonal discharges which have occurred may, in the course of time, become more regular as the operating procedures become more firmly established. But, until this is achieved, the dam poses a threat not only to the ecology of the region downstream but also to its human population; sudden, unseasonal discharges present a hazard to anyone using the river whether for washing, fishing or transport. It is for this reason that the report by the ICE (1978) on floods and reservoir safety stresses:

the need to limit the rate of rise of flood levels downstream ... to no more than the natural rates prior to dam construction.

(p19)

Such considerations do not appear to feature in present operating procedures at Cabora Bassa. Following the report on downstream ecological effects, referred to above, SWECO undertook the first hydrological study of the project in which special consideration was given to the possibility of providing flood freshets to reproduce the natural pattern of flood peaks, (SWECO, 1982).

The effects of river regulation on the complex processes of delta formation deserve special consideration. In comparison with such rivers as the Nile and Niger, the Zambezi does not have a well formed delta and appears to experience a much slower rate of sediment deposition. On the other hand, it was suggested, in a report in the Esquema Geral, that the bars across the mouth of each branch of the Zambezi's delta have been formed from sand of fluvial origin. The MFPZ suggested, therefore, that a decrease in sediment load following the closure of the Cabora Bassa Dam would lead to the erosion of these bars and, thereby, to improving the access to the river by marine vessels. Whether more serious consequences could also occur, such as those predicted in the Nile delta.
Figure 45: Monthly maximum and minimum levels of the Tete river gauge (E-320), 1970-79.
following closure of the Aswan High Dam\textsuperscript{496}, is unknown. Tinley (1971) foresaw this possibility and expressed particular concern about the possible effect of coastal erosion on the important shrimp fisheries of the region.

Regulation of river discharges may also affect the position of the intrusion interface between salt water and fresh water in the delta region. On the Volta River, an initial downstream movement of the interface occurred as a result of the increase in minimum river flows produced by the regulation of the Akosombo Dam\textsuperscript{497}. On the Limpopo, by contrast, progressive intrusion is feared as the extractions of irrigation water are increased\textsuperscript{498}. Should salt water intrude up to points at which irrigation water is extracted, the irrigation projects would be placed in jeopardy. On the Zambezi the salt water interface has probably moved downstream since the closure of the Kariba and Cabora Bassa Dams, but this may be reversed if large-scale irrigation projects are implemented.

The problem of floods in the lower Zambezi valley

Wisner (1979), in a study of floods in Mozambique, estimated that since independence as many as 100 people per year had lost their lives in floods and that material damage in excess of US $ 40 million per year had been caused\textsuperscript{*}. One reason, identified by Wisner, for this high level of vulnerability, is the large proportion of the land area (44\%) covered by flat coastal plains susceptible to saturation from rainfall and to inundation by rivers.

The Zambezi valley, downstream of Mutarara, is a region of particular flood hazard. Precise evaluation of the effects of past floods is difficult from available sources although their severity can be judged from contemporary newspaper reports\textsuperscript{499}. In 1952 and 1958, for example, large floods made tens of thousands of people homeless. In addition they caused extensive material damage, including the erosion of part of the embankment of the Trans-Zambézia Railway and the partial inundation of the Sena Sugar Estates. The area affected by the 1958

\textsuperscript{*} Wisner compared this with the national annual budget which, he suggested, 'rarely exceeds US $ 350 million'.

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flood was studied by aerial reconnaissance and is shown in Figure 46. In fact, the map exaggerates the extent of the flooding because it fails to show local areas of higher ground which were not inundated and on which the majority of homes were located.

Following the flood of 1978, an attempt was made to provide a precise evaluation of the losses which it had caused. According to the published estimates, at least forty-five people died, 200,000 were made homeless and material damage equivalent to US $60 million occurred. In addition, the cost of salvage and aid operations was put at US $40 million. Although the difficulties involved in making such estimates undoubtedly affect their accuracy, it is clear that the scale of the losses suffered in 1978 was considerable.

The MFPZ appears to have overestimated the benefits which the Kariba and Cabora Bassa Dams will bring. As the summary of its work, in Chapter 3, suggests, the early reports indicated that the projects would provide total control over the discharges. Later reports recognized, however, that some flooding might still occur. Subsequent work, also referred to in Chapter 3, in particular that by Rendel, Palmer and Tritton, has served to demonstrate the limited extent of the flood control benefits provided by the Cabora Bassa Dam under its present operating procedures. However, some improvement in those procedures is believed to be possible without affecting energy production. On the other hand, since the risk of floodplain inundation cannot be entirely eliminated by operation of the dam, further responses to the hazard should be examined. Unfortunately, objective assessments of the merits of various proposals are difficult to make in studies of flood relief benefits. This is clearly demonstrated by the TVA system of reservoirs which is widely believed to have brought substantial flood relief benefits to the Tennessee valley but which Hibdon (1958) found to be hard to justify, in economic terms, as a means of flood control.

a) Flood forecasting and warning services

Flood forecasting and warning services provide the simplest and least expensive of the possible responses to the hazard of flooding. The
Figure 46: The approximate extent of the 1958 flood in the lower Zambezi valley according to aerial reconnaissance.

Source: Sketch map prepared by the MFPZ, SPA files, Tete
first recorded evidence of an attempt to provide flood warning in the lower Zambezi is found in a communication, from the Hydrological Service of the Directorate of Public Works and Communications in Lourenço Marques, to the Governor of Tete, in 1959. The attempt was unsuccessful partly as a result of a misunderstanding over the original communication and partly because, with Lake Kariba impounding, there was no threat of floods through the following two years. Nevertheless, Vieira (1961) prepared a report in which he examined the hydrological aspects of a flood warning system for the river, based on river gauge levels at Zumbo.

Meanwhile, the MFPZ had established an independent flood warning system by obtaining an agreement with the engineers at Kariba to provide notification of flood releases. In addition to those sent to the MFPZ, warnings were to be sent from Kariba directly to the Office of the Governor General of Mozambique and to the Sena Sugar Estates as well as being broadcast by radio. During 1962 and 1963, the issue became the focus for increasing bitterness between the Hydrological Service and the MFPZ. The Hydrological Service considered that it was being by-passed by the MFPZ in respect of the collection and dissemination of flood warning information for the Zambezi. The extent of the ensuing confusion and the duplication of messages which occurred may be seen in Figure 47, where the messages sent out in response to warning of a single flood release from the Kariba Dam, in January 1963, are presented. This inter-departmental conflict was eventually resolved in favour of the MFPZ. Thereafter, the relaying of information concerning long-term forecasts of floods, as well as detailed warnings of gate openings at Kariba, was carried out on a routine basis. Nevertheless, the warning system was not completely satisfactory as was indicated by a letter from the MFPZ to the CAPC, in August 1966, complaining of damage to a test rig in Cabora Bassa Gorge caused by an unexpected discharge from the Kariba Dam.

During the construction of the Cabora Bassa Dam, the discharges from Kariba were carefully controlled in order to assist the construction schedule but, thereafter, communications with the CAPC deteriorated as is exemplified by the slow response by HCB to warnings of flood releases from Kariba in early 1978, referred to above. Even more serious was the
Figure 47: Communications relating to warnings of impending flood discharges from the Kariba Dam in January 1963.

Date

Governor General of Mozambique

Governor General of Mozambique

Governor General of Mozambique

Junta Provincial de Povoamento*

Hydrological Service

Governor in Tete

Governor in Quelimane

Governor in Beira

Governor General of Mozambique

Governor in Tete

Governor in Quelimane

Governor in Beira

Hydrological Service

DISCHARGES

COMMENCED

* the regional office of the ministry to which the MFPZ was responsible.

Direct communications generally by telegram

Letters containing copies of communications received

Origin of messages

Ultimate destination of messages

Source: compiled from communications in the file 'Cheias do Zambeze', DNA, Maputo.
inadequate warning, from HCB to the population of the Zambezi valley, about flood releases from the Cabora Bassa Dam. In 1979/80, for example, the officials of the SPA in Tete were responsible for notifying the Governors of Tete, Zambézia and Sofala Provinces as well as various other agencies, including Rádio Moçambique. In general, the SPA officials received warnings from HCB only on the day the discharge gates were opened.

The reports by Rendel, Palmer and Tritton, considered earlier, were produced, principally, as a feasibility study for a flood warning system. The system proposed was relatively sophisticated and was designed to provide predictions of river levels downstream of Mutarara, on the basis of mainstream and tributary river levels. These would be transmitted by radio to a central control centre located at Tete. It was envisaged that the system would be sufficiently accurate to gain widespread credibility and, at the same time, provide sufficient warning for evacuation of the areas at risk. Although the amounts of capital and the number of personnel which would be required were relatively high, in relation to Mozambique's resources, RPT (1979) argued that the investment would be justified by the benefits which would be achieved at the time of floods such as that of 1978. This assessment appears to be over optimistic, in present circumstances, since there are no rapid means of communicating warnings to the population in the more remote parts of the region at risk. For many of them it would be impossible to move to substantially higher ground in the time available and loss of crops, livestock and other property could not be prevented.

b) Flood-proofing measures

An alternative response to flood hazard, adopted in certain parts of the USA, is to construct property in such a way as to minimize the damage which flooding could cause. In terms of individual structures, this approach would have only limited application in the lower Zambezi where there are few industrial buildings and the majority of dwellings are constructed from non-permanent materials; an improvement in the design of some specialized buildings, including grain stores, might be possible. On a regional basis, more substantial efforts, such as the construction
of levees along the entire river channel or of dykes encircling villages and other important areas, might be considered. The first dykes constructed in the lower Zambezi were those to protect the plantations of the Sena Sugar Estates. Over the years, these have been heightened and extended and, as a result, provided almost complete protection during the 1978 floods*. More extensive systems of dykes and levees have been proposed including the schemes, put forward by Halcrow and Partners (1954), to build a dyke across the Ilha de Inhangoma in order to protect the lower Shire valley. The most ambitious scheme was, however, that given in the Esquema Geral⁵⁰⁷, comprising two 2 m high levees, 5 – 7 km apart, paralleling the river from Lupata Gorge to its mouth. In the Plano Geral⁵⁰⁸ this proposal was extensively modified; levees were only contemplated in the stretch between Mutarara and Marromeu, and then only in places where they could be justified by the protection they would provide to agricultural production.

In view of the high capital costs involved, it is unlikely that extensive dyke and levee construction will be undertaken in the Zambezi valley in the foreseeable future. Moreover, although considerable success has been claimed for structural methods of flood protection in the USA, particularly along the Mississippi⁵⁰⁹, they generally result in an increase in river levels for a given discharge, and thereby increase the risk of inundation unless levees are heightened regularly⁵¹⁰.

**c) Non-structural floodplain and catchment management**

Under favourable circumstances non-structural methods have proved effective in the control of floods. In catchment regions such methods include the introduction of land-use regulations with a view to preserving a cover of suitable types of vegetation in order to control surface flows. In the floodplain itself land-use regulations may also be introduced to prevent developments which would restrict the passage of a flood or which would suffer damage if a flood were to occur. In the Zambezi basin, catchment management schemes are likely to be ineffectual in reducing flood peaks because, given the available resources,

* The principal dyke system was within 0.5 m of being overtopped and minor breaches of secondary dykes occurred.
only a small proportion of the catchment could be adequately treated. Moreover, as Leopold and Maddock (1954) have argued, there is insufficient evidence that such measures could be effective in reducing flood peaks in any situation in which the catchment is large or the intensity of storms high. This is not to deny that, in appropriate situations, proper catchment management is beneficial for the control of soil erosion and the improvement of agricultural potential.

A form of floodplain management was introduced in the lower Zambezi when, as described above, people displaced by the 1978 flood were resettled in villages situated in areas of lower risk. A more comprehensive approach, to floodplain management, is precluded at present by the technical and administrative difficulties which would have to be overcome. On the technical side, the task of mapping the areas at risk from floods of different intensities, delineating their boundaries on the ground and establishing refuge zones on high ground would be considerable. On the administrative side, the implementation of comprehensive floodplain regulations would place an impossible burden on available resources. The problem may be overcome, to a limited extent, by introducing simplified regulations, such as those applied in certain parts of the USA \(^5\), but there is a danger that such regulations would adversely affect most of the present cultivation of the floodplain of the Zambezi. This would lead to an immediate and significant reduction in output, and could not be contemplated in the short-term.

It is clear that there is no easy solution to the problem of flood hazard in the lower Zambezi. Some relief could be achieved by adopting modified operating procedures for the Cabora Bassa Dam and by introducing some of the other measures outlined above. In view of the region's topographical characteristics and the lack of the technical and financial resources necessary to achieve substantial improvements by any of these methods, it is likely that the development of the floodplain region will proceed in a more-or-less \textit{ad hoc} fashion for a considerable period. The principal danger in this approach is that new developments such as roads, bridges and flood protection dykes, for new irrigation projects, might introduce restrictions which would aggravate the flooding problem. Such works might also prevent flood freeways from being established in the most
appropriate places at a later date. It is unlikely that such difficulties will be avoided unless a detailed study of the hydraulic behaviour of the floodplain is undertaken in adequate detail at a sufficiently early stage.

The development of agriculture and forestry in the Zambezi valley

The potential for increasing agricultural and forestry production in the Zambezi valley and the social, political, economic and environmental implications of various options deserve detailed and careful investigation, in view of the importance of agriculture for the people and the economy of Mozambique. However, decisions concerning agricultural and forestry development are unlikely to be greatly affected by, or affect greatly, the operation of the Cabora Bassa Project for the foreseeable future, except in respect of the cultivation of seasonally inundated areas in the floodplain and the possible cultivation of the drawdown zone of the reservoir itself. The regulation of the river by the dam has increased its minimum dry season flow but, even in its unregulated state, the river carried sufficient water to irrigate areas in the floodplain region had this been required. Thus, the selection of appropriate agricultural and forestry projects, for the future development of the region, will depend on factors other than those relating directly to the hydrology of the river. Amongst such factors the following are likely to feature prominently:

a) Much of the information on the physical potential of the region remains inadequate as the basis of large-scale investment. There are few examples of commercial enterprises in the valley where sustained output has been achieved successfully, apart from at the Sena Sugar Estates. Loxton Hunting was unable to locate large irrigation projects operating successfully in regions of similar physical and climatic conditions in any other part of the world. The establishment of pilot projects would, therefore, be essential if the risk of failure is to be minimized in a large project.

b) The human resources of the region, in particular the skills required to construct and maintain agricultural projects of different types are limited and a full assessment of them has yet to be made. Such a study was omitted from all studies undertaken by the Portuguese authorities.

c) The available economic resources will influence greatly the type of agricultural project which can be undertaken as will the rate and
manner in which the region's economy begins to develop. Deficiencies in the existing transport and communications systems present important, and continuing constraints on certain types of agricultural projects.

d) The risks of salination or waterlogging of soils, and of other environmental hazards associated with some types of agricultural and forestry projects, must be carefully considered, particularly in the floodplain and delta regions of the lower Zambezi where the risk of upsetting the ecological balance appears to be greatest. Risks of this type have been fully recognized by Frelimo in its policy of using the country's natural resources:

in such a way as to ensure that the ecological equilibrium is maintained.

Types of agriculture or forestry developed in other regions of the world, particularly in temperate climates, are unlikely to be directly suitable for Mozambique's present requirements. A broad range of alternatives will have to be examined and tested if the most effective use is to be made of available resources whilst minimizing disruption of the environment. Such alternatives must be such as to develop, extend and modify existing agricultural systems, including the cultivation of the floodplain irrigated naturally by the flood discharges of the river, and to exploit the potential of species of the natural flora and fauna found in the region.
Although this thesis has drawn together material from many disciplines, it is essentially an engineering study; that is, its primary purpose has been to investigate those factors which might influence the selection, design and operation of projects which regulate the flow of water in large river basins in underdeveloped countries. That the majority of engineers have not, during the present century, considered studies as broad as this to be the domain of the engineer reflects both the narrowness of the role which many engineers have been happy to assume and the constraints placed upon them by those responsible for project funding. On the other hand, social and political scientists, economists and ecologists often fail to grasp the technical and physical constraints of a given project with the result that their expectations of the project are not fulfilled. It is for this reason that particular emphasis has been placed in this thesis on the assessment of technical and physical constraints and their implications in terms of possible planning objectives.

Consideration of the development of the Zambezi basin in Mozambique, and in particular the case of the Cabora Bassa Project, clearly illustrates many of the difficulties which arise in the planning and operation of large-scale river regulation projects in underdeveloped regions. The conclusions reached apply, therefore, not only to the Zambezi basin but also to other areas of the world where similar river regulation work has been or may be undertaken.

In the first part of this chapter conclusions reached in the previous chapters are summarized. Many of these conclusions are specific to the lower Zambezi. It is believed that such conclusions will enable a clearer understanding to be gained of the factors which govern water resources development in the region. Such knowledge will be of benefit in the future planning and management of those resources. Conclusions of a more general nature are then presented. Many of these are applicable not only in the Zambezi basin but also in other regions. Finally, predictions are made about the likely course of water resources
development in the Zambezi basin.

* * *

In the introduction, an outline of the background to the Cabora Bassa Project is traced. In addition the principal questions to which the thesis is addressed are summarized. Attention is drawn to factors which have played an important part in determining how the Cabora Bassa Project functions. These include geographical, economic and administrative features. Of particular importance has been the fact that the economic and administrative resources of Mozambique, at the time of independence, were poorly developed for operating a project of this scale. In comparison with similar projects elsewhere, the Cabora Bassa Project's most distinctive feature is its historical and political setting. The harsh colonial conditions under which the project was conceived had been replaced, before it entered commercial service, by the 'socialist' ideals of the Frelimo government. This change brought important repercussions as a result of the heavy involvement of the RSA in the project both as a major creditor and as the market for the bulk of its energy production. This involvement, which cannot readily be avoided, is a source of embarrassment to the Mozambican authorities who wish to dissociate themselves from the internal policies of the RSA and to free themselves from its economic and political domination of the region. The policies of Frelimo, as stated clearly by its leaders, are aimed at eradicating poverty and creating the conditions for economic and political self-determination in a united Mozambique. It is in the light of these policies that the effects of the Cabora Bassa Project have been studied.

The need for a broad interdisciplinary approach to the study of water resources development is highlighted in the literature review which forms Chapter 1. This need has been recognized, in various parts of the world, in the application of the concept of integrated river basin development and in the formation of a number of 'river basin authorities'. Apart from the TVA, however, few such authorities have had the necessary resources and administrative powers to undertake their assigned task. Moreover, in river basins which cover more than
one country particular problems have arisen because projects designed to provide the best overall use of resources would not have resulted in an equitable distribution of costs and benefits between the basin states. These factors influenced the Cabora Bassa Project which is located both in a large international river basin and in an impoverished region. The design and execution of the project was also strongly influenced by the objectives of the Portuguese authorities. The MFPZ, which was established in the late 1950s to undertake regional planning in the lower Zambezi valley, was ostensibly modelled on the TVA but its major achievement, the Cabora Bassa Project, became a single purpose undertaking, heavily dependent on foreign capital, technology, expertise and markets, destined to supply cheap electrical energy to the RSA. The MFPZ's failure to achieve integrated river basin development arose because its area of operation comprised only the lower part of the Zambezi basin (11% of the total area); its plans were formulated to benefit the colonial economy and intended European settlers rather than the African population; and, it had no executive authority to implement its plans.

Chapter 2 provides a detailed history of the lower Zambezi valley over the last four centuries and traces the origins of the Cabora Bassa Project. From the time of the first settlers, through the long period of indirect administration by prazos and land companies, to the final forty-year period of direct administration, the Portuguese authorities viewed the Zambezi basin as a source of wealth and a suitable area for European settlement. Yet, it was an area in which they were unwilling to make substantial investments. As a result, minerals, ivory, slaves, migrant labourers and agricultural production each at different times yielded short-term profits. But the over-all effect of the colonial period was to undermine the established rural economy without providing the basis for an alternative economic system which could be sustained. The establishment of the MFPZ in the late 1950s was intended as a means of asserting Portuguese authority in the region, to provide new sources of raw material for the Portuguese economy and to provide the basis for attracting European settlers. It showed similar features to initiatives in other Portuguese colonies at that time: the overall objective was to concentrate resources in narrow zones or
'axes' where European settlement would take place. As a result elaborate planning was undertaken with little reference to existing conditions. Indeed, the extravagance of the planos gerais which were produced for the lower Zambezi and other parts of Mozambique contrasts sharply with the impoverished conditions still found in those regions.

The Cabora Bassa Project was initiated, in part, as a response by Portuguese engineers to the building of the Kariba Dam upstream. An invitation from the British authorities to discuss the proposed Kariba Project and the possible formation of a Zambezi River Authority raised concern, amongst a number of influential engineers, in Lisbon that little was known about the hydrology of the Zambezi. As a result, a number of studies were undertaken which subsequently provided the foundation for the work of the MFPZ. Despite the Portuguese Government's rejection of the idea of an international Zambezi River Authority, it was happy to co-operate with Britain over the building of the Kariba Dam, albeit from a false understanding of its hydrological implications. Close contact was established between the MFPZ and the CAPC which brought various benefits to Mozambique including the provision of flood warnings. Since Mozambique's independence, co-operation over the regulation of the lower Zambezi has been poor within Mozambique, where disputes have arisen between HCB and various government agencies. Co-operation between agencies in different basin states has also been poor.

The hydrological characteristics of the Cabora Bassa Project are examined in Chapter 3. Study of the most suitable form of the flood rule curve, needed to prevent overtopping and possible collapse of the dam, indicates that in the past inadequate attention was paid to the sensitivity of this curve to changes in input data and to operating procedures. There is some doubt as to the exact form of the flood rule curve currently in use but it does not appear to have been calculated according to the dam safety procedures applied, for example, in the UK with regard to the magnitude of the design flood or the influence of possible damage to discharge gates and the shutdown of turbines. Such factors should be studied in more detail. Also,
firm agreements over the amount of flood storage to be provided at
upstream projects should be sought since such agreements would be
beneficial to the Cabora Bassa Project.

As regards power output, the project's flexibility of operation
has been greatly reduced, under present conditions, by the requirement
to supply a limited amount of peak power on demand as part of the
contract with the RSA. Problems may arise during periods of spillage
from the dam since this results in an appreciable rise in the tailrace
level which reduces the hydraulic head. December and January are the
most critical months because, during these months, the hydraulic head
is also reduced by the drawdown levels required by the flood rule curve.
In order to reduce the amount of spillage occurring in these months an
agreement about acceptable levels of discharge from the Kariba Project
would be required. Even so, should one of the five generating sets be
out of commission during the flood season there is a strong possibility
that power supply commitments to the RSA could not be met. The study
of the ultimate capacity of the project, also included in Chapter 3,
indicates that the firm power output might only be increased by some
25%, to approximately 2 000 MW, by the building of the North Bank Power
Station. However, this conclusion is heavily dependent on the accuracy
of data records for the 1930s and on the form of the flood rule curve.
If, as SWECO has proposed, earlier discharge data can be ignored* and
the reservoir be held at a permanent level of 326 m, following the
construction of additional spillway capacity, further increases in
generating capacity could be achieved. Against this, the construction
of a new spillway would bring considerable changes in downstream flood
releases and in the ecology of the reservoir.

Flood control is also considered in Chapter 3. The extent of
the project's flood control capability has been consistently over-
estimated. Nevertheless, the devastating floods of 1978 could have
been reduced substantially by operating the Kariba Dam, and to a
lesser extent the Cabora Bassa Dam, with closer regard to established
flood rule curve procedures and by improving the lines of communication

* Neglect of this data, despite its shortcomings, cannot be justified
on the basis of the evidence at present available, see Appendix 6.
between the operators of the two projects. In future, moderate discharges from Cabora Bassa could be reduced without jeopardizing power output by adopting a policy of 'threshold' releases. A simple system of flood warning, based on projections of inflow to the reservoir, could help to mitigate the effects of more serious floods in the absence of a more elaborate flood warning system.

There are several other important hydrological implications in the operation of the Cabora Bassa Project. Upstream of the dam, agriculture, fisheries and navigation are all affected by the magnitude and seasonal pattern of reservoir fluctuations. It would be possible, to the benefit of these activities, for HCB to adopt a more regular pattern of drawdown, than that used hitherto, without loss of energy production. Downstream of the dam the regulation of river discharges has a considerable effect on aquatic and terrestrial ecology, including factors affecting agriculture and fisheries. In this case remedial action, through the provision of flood freshets, could not be taken without some prejudice to power production. By contrast, there appears to be little conflict between power production and either navigation or small-scale irrigation. However, these activities would be harmed by the sudden loss of river flow which would occur if generating sets were shut-down without allowing compensatory spillage.

In the first part of Chapter 4 various proposals for mineral extraction and industrialization in the lower Zambezi basin are examined. The authors of the Plano Geral envisaged the creation of a large steel complex utilizing local coal and iron ore deposits together with hydroelectric energy. They did so even though the existing low level of mining and industrial development, the limited geological information available, the poor transportation systems in the region and the presence in the iron ore of titanium and vanadium impurities, all suggested that such a project was over-ambitious. Furthermore, once the agreement over energy sales from the Cabora Bassa Project to the RSA had been signed the Portuguese authorities realised that the project would have insufficient spare generating capacity to supply heavy industrial consumption in the Zambezi valley. A partial relaxation of the terms of the contract with the RSA appeared
to have been reached, before independence, on the understanding that the North Bank Project would be rapidly implemented. Other mineral based projects which were considered by the MFPZ included an aluminium smelter and a copper refinery. Such projects are unlikely to bring substantial benefits to an independent Mozambique not only because of doubts over the extent of the reputed mineral resources but, also, because comparisons made with similar projects in other countries suggest that they would be unlikely to make a significant contribution towards stimulating balanced industrial growth. In addition such comparisons would show that, unless they are undertaken with considerable caution, their social, political, economic and environmental effects were likely to outweigh their benefits.

In the second part of Chapter 4 the supply of electrical energy from the Cabora Bassa Project is studied by reference to selected case studies of the growth of electricity supply systems in under-developed regions. The clear conclusion is that no alternative markets exist at present for the output from Cabora Bassa. For this reason, and because of constraints which arise from the characteristics of the existing d.c. supply line to the RSA and the financial and contractual arrangements which govern the operation of the project, it is unlikely that Mozambique will choose to break the supply agreement with the RSA. On the other hand, a clear case can be made in support of the Mozambican authorities seeking a renegotiation of that agreement both to allow greater flexibility in the hydraulic operation of the project and to provide increased revenue. In practice, however, the nature of the relationships between the parties involved creates difficulties in any attempt at renegotiation particularly over financial matters. Mozambique only derives indirect benefit from the sale of energy to the RSA through a gradual transfer of HCB's shares to Mozambique in lieu of taxes. It might hope for a more rapid transfer of such shares if revenue from energy sales could be increased but such an outcome would, presumably, not be welcomed by the staff and other shareholders of HCB, including the RSA itself. Meanwhile, Mozambique appears to have little formal control over the activities of HCB. The situation is complicated by the fact that the electrical energy for Maputo is supplied via the RSA and that Mozambique has been unable to guarantee continuous power.
supplies from Cabora Bassa to the RSA because of periodic sabotage of the transmission by guerrillas, reportedly backed by the RSA. The Mozambican authorities have been actively considering the building of the North Bank Power Station in order to provide sufficient energy to meet their projected needs in central and northern Mozambique. However, the financing of such a project would have required external markets to be found for a large part of the output. Zimbabwe was seen a possible major consumer. With the apparent failure of this initiative doubts must be raised over the economic viability of the new 220 kV transmission line which is being built into northern Mozambique from Cabora Bassa. The wisdom of implementing this project was already questionable in view of the inherent problems of operating a transmission line of its intended length (over 1 000 km) and in view of the great vulnerability of such a system to faults. Without the North Bank Station very little firm power can be supplied to this system from Cabora Bassa unless renegotiation of the supply contract with the RSA takes place.

Chapter 5, together with Appendix 8, provides a summary of the available data on soil erosion and reservoir sedimentation in the Zambezi basin. The inadequacies of these data are readily apparent. Nevertheless, they serve as a basis for order-of-magnitude calculations of sedimentation rates in the Kariba and Cabora Bassa Lakes. Such calculations reveal important differences between the sedimentation characteristics of the two lakes; the 'dead' storage in Lake Cabora Bassa filling in about one tenth of the time which it will take for that in Lake Kariba to fill. Even so, assuming that a minimum drawdown level of 305 m O.D. will be adopted for Lake Cabora Bassa, the sediment input is unlikely to exceed the capacity of its 'dead' storage in less than 300 years, at present rates of deposition. However, since a significant proportion of that sediment is likely to be deposited in the 'live' storage of the reservoir the effects of such deposition will become apparent much sooner by affecting both flood control and power production within the project's economic life. The principal source of sediment for Lake Cabora Bassa is the Luangwa basin. The proposed dam at Mpata Gorge would, therefore, have little effect on these conclusions. The trend of increasing soil erosion rates in the Luangwa
basin over the present century can only be reversed by a sustained programme of soil conservation and land-use control. In a catchment of this size the effects of such a programme on the sediment input to Lake Cabora Bassa might only become apparent over a very long period.

The trapping of sediment in Lake Cabora Bassa will also influence the channel and floodplain downstream. The engineers of the MFPZ believed that the increased erosive power of the river downstream of the dam would assist in the creation of a navigable channel. The natural channel of the lower Zambezi, through most of the floodplain, is wide, shallow, sandy, braided and relatively steep. However, consideration of the morphology of this channel suggests that with suitable modification and stabilization work a single, narrower, meandering channel could be formed. Empirical relationships, as formulated by Schumm, suggest that this stabilization process would be assisted both by the trapping of sediment and the regulation of discharges which have resulted from the operation of the Cabora Bassa Dam. However, according to Schumm's analysis, the effect on the two parameters most critical for navigation, channel depth and slope, might be either beneficial or detrimental. Moreover, the effect of large sediment inputs from tributaries such as the Luenha cannot accurately be predicted and might also be detrimental. As regards navigation the slope of the channel presents particular difficulties because of the large tractive force which would be required to transport cargoes upstream. In addition, the investments required to stabilize the channel would be very high in comparison with the volume of traffic which can be guaranteed in the initial phases. Even with the assurance of bulk cargoes from, say, mineral exploitation uncertainty over the response of the channel to particular stabilization measures together with the difficulties of transhipment, past the Cabora Bassa Dam and from the delta to a suitable deepwater port, raise serious questions about the viability of such a waterway.

The effect of the dam on the deposition of sediment in floodplain areas is also studied. The precise effects of extensive inundation of the floodplain, which occurred periodically in the lower Zambezi valley, are unknown but such areas were certainly used for traditional
The concentration of agriculture in the floodplain may, however, have owed more to the benefits of natural irrigation than to increased fertility of the soil since analysis of the sediment carried by the Zambezi suggests that it carried large amounts of iron oxide which would, to some extent, counteract the benefits of the other nutrients present. The effect of the dam has been to reduce both the sediment load in the lower Zambezi and the frequency of over-bank discharges.

The social and environmental effects of the Cabora Bassa Dam are considered in Chapter 6. Studies of social aspects of the development of the lower Zambezi were undertaken by the MFPZ but these were selective, concerned mainly with transforming the local economy to benefit colonial plans for the region and, after the first few years, given very low priority. Environmental effects were not considered in detail apart from an initial survey of the river in the early 1970s by a team of hydrobiologists. By this stage the river had been affected by the Kariba Dam for fifteen years and the Cabora Bassa Dam was already under construction. The only attempt to make a comprehensive assessment of the Cabora Bassa Project was contained in a short paper by Hall and Davies (1974). The paper presents two important conclusions: that the maximum benefit from the project can be derived only if the economy of the valley as a whole is considered; and that integrated planning of the resources of the valley requires a much greater knowledge of the ecological systems it contains. No major studies of the social or environmental effects of the Cabora Bassa Dam have been undertaken in the valley since the dam's completion.

The resettlement of the 25 000 people displaced by Lake Cabora Bassa was strongly influenced by the growing support for Frelimo in the region. Access by Portuguese personnel to many areas became hazardous and reservoir resettlement became integrated into a much larger programme to resettle the scattered rural population into fortified villages for strategic reasons. By 1974, at least 200 000 people had been moved in this way. The effects of this programme have not been recorded in detail but it is clear that, at least in
the latter stages, resettlement was undertaken with undue haste, excessive force and inadequate preparation leaving considerable disruption in the region at independence. The present government is committed to a policy of promoting communal villages, *aldeias comunais*, in rural areas but has made little use of the bulk of the villages created during the Portuguese resettlement programme, presumably because their poor location and lack of amenities made them unsuitable for long-term habitation. However, the *aldeias comunais* programme does not have adequate resources and does not appear to be achieving the transformation of the rural areas which was intended.

The Portuguese resettlement programme caused various health problems; resulting from poor sanitation, high population densities and relocation stresses. As far as is known the Cabora Bassa Dam itself has not had an appreciable impact on health. This is partly because there has not been, as yet, any widespread introduction of irrigated agriculture and partly because many water-related diseases, particularly malaria, were already endemic in the region. Nevertheless, the formation of stagnant pools in the drawdown zone of the reservoir and in the floodplain poses a potential health hazard.

A number of reports have been written, based largely on pre-impoundment information, in which the characteristics of the reservoir with regard to potential fisheries development and weed infestation are considered. Although fishing provides employment and a useful source of protein for the population around the lake, it is unlikely to become a major factor in the Mozambican economy. Part of the reason for this lies in the difficulties of fishing in Lake Cabora Bassa as a result of its gently sloping shores, large fluctuations of level, submerged vegetation and exposure to strong winds. Another factor is the lack of an adequate transportation system to carry fish to distant markets. Infestation of the new reservoir by floating aquatic weeds was considered, by a number of authorities, to constitute a major threat to its future utilization. Despite some weed accumulation in the gorge behind the dam, this threat does not appear to have materialized mainly, it is suggested, because the large annual fluctuations of reservoir level which occur leave much of the vegetation stranded.
The floodplain and delta of the lower Zambezi form the region in which the impact of the Cabora Bassa Dam may, in the long-term, be the most far-reaching. Yet it is also the region in which it is most difficult to assess those effects because of the lack of pre-impoundment information and because of the complexity of the biological and geomorphological processes operating. Gradual changes in the vegetation of the region, the level of the water table and the development of the delta are anticipated as a result of the regulation of the river. In consequence, traditional agriculture, fishing in inland lagoons, coastal shrimp fisheries and the distribution of wildlife, in particular buffalo, could all be affected. Further changes would follow if large-scale irrigation projects were to be undertaken in the floodplain. Unless well managed, such projects could, themselves, generate problems due to soil salination and waterlogging. Under such circumstances it would be unwise for Mozambique to commit large investments to such projects without first examining the possible environmental effects in more detail and undertaking suitable pilot studies. The possible benefits of providing flood freshets from Cabora Bassa should also be assessed. In the long-term a carefully prepared floodplain management strategy is required if a stable system, making effective use of the region's resources, is to be developed. Until resources are available to undertake the necessary planning and research, care must be taken to avoid implementing projects which would place significant constraints on the alternatives which might be considered in preparing the final management strategy.

* * *

Two features inhibit the drawing of simple conclusions from the material of this thesis: first, the complex inter-relationships which exist between the various factors which influence the development of water resources in the lower Zambezi; and second, the serious deficiencies, which have been noted, in the available sources of data and information. These features are present, to some degree, in all river regulation projects in underdeveloped regions but they are particularly significant in the present case. Nevertheless, various general conclusions may be drawn.
A number of observations may be made about the effects of the Cabora Bassa Project and the way in which these have been perceived in Mozambique. There is little merit in dwelling at length on the question of whether the Cabora Bassa Project as planned has been a success — whether it has fulfilled the various expectations of those who planned it — since those expectations became largely irrelevant after independence. Nevertheless, it should be noted that the Portuguese authorities did not achieve their political objective of enhancing their control over the region by building the dam. Neither were their original economic and technical expectations from the project met; namely the creation of a new zonal integrated economy based on agriculture, mineral extraction and industrialization. This aim was almost as far from realization in 1974 as it had been twenty years earlier, when the initial planning had begun. In part this failure may be attributed to underestimation by the Portuguese authorities of the physical constraints governing the regulation of the lower Zambezi. But an even more significant factor was that their plans would have required far larger investments than the Portuguese exchequer was able or willing to provide. The need to provide a source of funds, therefore, became the dominant factor in the final formulation of their plans. As a result multiple purpose objectives were sacrificed to the single objective of supplying bulk power to the RSA. It was soon apparent that, as a direct consequence, very little energy from the Cabora Bassa Project could be supplied to consumers in the Zambezi basin, or in other parts of Mozambique, unless the North Bank Power Station were built.

The leaders of Frelimo who, prior to independence, had been totally opposed to the dam accepted Portugal's demands that, in order to protect foreign investments in the project, the agreement to sell power to the RSA should be retained and that the project should be operated by a Portuguese company, HCB. Nevertheless, in order to direct attention away from the project's dependence on the RSA and in the belief that Cabora Bassa could be transformed to provide tangible benefits for the people of Mozambique, the independent Government sought ways of deriving additional outputs from the project. Attention has, therefore, been focussed on possible multiple purpose benefits
suggested in the original Portuguese plans; energy supply within Mozambique, flood control, navigation, irrigation and fisheries. To date the authorities have been largely disappointed in such expectations. As has been noted earlier, the present power supply contract with the RSA only a limited amount of electrical energy is available to Mozambique from the existing generating capacity at Cabora Bassa. The limitations of the project as regards flood control were vividly demonstrated in the flood of 1978. Navigation, either in the river or in Lake Cabora Bassa, would require large investments and even then its success would not be assured. The development of irrigated agriculture, although feasible, would depend on a large number of factors of which river regulation is relatively minor. Only the establishment of reservoir fisheries appears to be capable of providing tangible benefits to Mozambique from the project in the short term, yet even this has developed at a slower rate than had been anticipated and is unlikely to assume a major importance in the national economy. In order to increase the benefits to Mozambique from Cabora Bassa the authorities have considered implementing the Portuguese plan to build the North Bank Power Station. The output from such a station would, however, be higher than the foreseeable demand in the region and, therefore, new markets would be required either by export to neighbouring countries or by the creation of energy intensive industries in the region. Unfortunately, both of these would increase the dependency of the economy on outside factors. Moreover, no suitable markets have yet been found.

In respect of the expectations of the inhabitants of the Zambezi valley from the Cabora Bassa Project, and its effects upon them, very little information is available. It is also difficult to isolate the effects of the project from the disruption caused by other aspects of the Portuguese colonial administration. Nevertheless, to date, the overall effect of the project on the people living in the valley has, almost certainly, been detrimental. The fertile banks of the Zambezi upstream of the dam have been flooded by the new reservoir whilst downstream fertile land has been threatened by the regulation of the natural river discharges. Agriculture on the shores of the new reservoir is hazardous because of the large and unpredictable fluctuations
in the water level. Finally, the use of fresh-water lakes and lagoons in the alluvial plain for fisheries and for water supply has been detrimentally affected by the regulation of the river.

Whilst it is important to recognize the disappointing performance, to date, of the Cabora Bassa Project, from the viewpoint of both the government and the inhabitants of Mozambique, it is of more practical value to determine, from the material of this study, the constraints which govern the future actions of the Mozambican authorities in their operation of the project.

As with many similar projects in other underdeveloped regions, the effect of a large-scale hydroelectric scheme is to give a long-term lease over a particular national asset to outside interests. In the operation of the project the constraints imposed by those who seek to guarantee these interests and investments are paramount. Such constraints take various forms:

(i) Direct control over the project may become established. In the present case such control is provided by the operating company, HCB, whose terms of reference place the interests of investors and of the RSA above those of Mozambique.

(ii) Foreign governments may exert political influence to protect their national interests. With the Cabora Bassa Project the RSA is in a position to ensure its continued power supply against any threat of interruption by Mozambique because of the pressure it can apply through other areas of the Mozambican economy, and because of its control over the supply of electrical energy to southern Mozambique. The supply to the RSA is also safeguarded by the fact that European countries, which have investments in the project, would apply economic and political pressure if, as a result of Mozambique cutting the supply to the RSA, insufficient foreign currency could be earned from energy sales to repay their loans.

(iii) The scale and sophistication of a particular project impose their own inherent constraints. By itself, Mozambique would be able to utilize only a small fraction of the electrical output from the Cabora Bassa Project and lacks the skills and resources necessary for its efficient operation.
The lack of technical and administrative skills in Mozambique imposes other constraints on future developments in the Zambezi basin. Firstly, it is not possible for the authorities to prepare new detailed development plans in a short period. Existing plans, in this case the plans prepared by the MFPZ, will be utilized wherever possible despite the fact that their technical basis may be of questionable quality and their political objectives very different from those of an independent Mozambique. The indirect influence of the Portuguese administration is, therefore, likely to remain for a considerable period. Secondly, Mozambique will be in receipt of substantial technical and financial assistance from foreign governments and international agencies for the foreseeable future. Such governments and agencies will also exert some influence over the type of development project which is undertaken.

Thus, both in the specific case of the Cabora Bassa Project and in the general development of the Zambezi valley, Mozambique's freedom of action in determining future policies is limited. The constraints outlined above together with physical constraints determined by the region's climate, hydrology, ecology, geology and topography present the authorities with difficult choices in the allocation of the scarce financial and technical resources available to them. The extent of these difficulties, and their influence over even the most fundamental political issues, is illustrated by the apparent changes which have taken place in the Government's attitude towards aldeias comunais. Originally it was maintained, in various official statements, that aldeias comunais would receive priority as the chosen instrument whereby the rural areas would be transformed. However, over much of Mozambique, far greater resources have been provided to large projects and state farms than to aldeias comunais. This bias has arisen because of the desire to produce certain commodities for export and for consumption in Mozambique, by the urban population in particular. In the Zambezi basin such a bias has also arisen because the size of the river and the physical characteristics of the region dictate that attempts to regulate and utilize the available resources will generally require large investments. Moreover, if the North Bank Power Station Project is implemented, and unless substantial export markets can be
established, further investments will be required to create local markets to absorb the surplus energy available.

Consideration of the technical aspects of water resources development in the lower Zambezi occupies a large part of this thesis. The conclusions from the hydrological studies, described in Chapter 3 and summarized above, indicate that with its present installed capacity, which is below the ultimate potential of the site, the Cabora Bassa Project could achieve its single purpose power production objective with relative ease, especially if the peak power requirement were to be relaxed. In such a case the principal operating constraint would arise from the need to adopt an appropriate flood rule curve to protect the installation against extreme floods. On the other hand, if power production is to be optimized, either with or without additional generating units, study of the basin's hydrology and of the regulation provided by projects upstream becomes increasingly important. Likewise, the effects of sediment accumulation in the reservoir become apparent more rapidly if optimization of power production is attempted. Technical considerations also become increasingly important if multiple purpose outputs from the project are envisaged. In each case the process of optimization, whether for single purpose or multiple purpose operation, provides additional outputs. But such optimization also increases the risk of additional costs being incurred whenever the project fails to achieve these outputs. This is readily seen in the case of flood control but applies to other outputs as well. Such costs can only be assessed in probabilistic terms because of the stochastic variations in river discharge from which they originate. Furthermore, the level of risk can rarely be stated with a high level of confidence. This is because of the problems created by using short and inaccurate records and by allowing for possible trends in climate or changes in catchment characteristics. Available methods of economic analysis provide only a partial picture of the implications of such risks and are unlikely to offer an adequate basis for full evaluation of alternative operating policies. Nevertheless, as has been shown in Chapter 3, careful application of suitable numerical models can provide a clearer picture of the operation of the system and the implications of a
particular operating policy under given hydrological and sediment transport conditions.

By contrast, environmental effects, including possible health implications, of a particular form of river regulation cannot be readily quantified and cannot, therefore, be studied in this way. As a result such effects tend to be ignored in the formulation of operating policies. This attitude is clearly seen in the studies undertaken by the MFPZ/GPZ for the Cabora Bassa Project. Power generation, flood control, navigation and irrigation were all, at various times, studied in quantitative terms by reference to the results of various numerical models. Yet environmental effects were barely mentioned even in qualitative terms. The recent study, by the consultants SWECO, which considers the possibility of providing flood freshets downstream of the Cabora Bassa Dam, marks the first recorded attempt to include environmental constraints in the formulation of operating policies for the project.

The lower Zambezi valley remains, today, an impoverished area whose development is strongly influenced by the Zambezi river. The ideas of integrated river basin development have been advocated as a solution to the problems of such a region. A number of reasons why such ideas are unlikely to be applicable in the lower Zambezi in the foreseeable future have been highlighted in this thesis. On the basis of such observations general conclusions about the application of an integrated river basin policy in similar situations elsewhere may also be drawn:

(i) The integrated development of the resources of the Zambezi valley would require huge investments. As indicated above, this was the principal factor which prevented Portugal from implementing the original plans of the MFPZ. The inter-dependence of industry, mineral exploitation and agriculture in these plans and their dependence on the creation of an energy supply system and, more importantly, a transportation system prevented a process of gradual implementation from being adopted. Despite the completion of the Cabora Bassa Dam, which the MFPZ saw as the linchpin of its plans, the mining enterprises, heavy industry and irrigation projects
proposed for the region could still not be developed without a substantial new source of electrical energy and, because domestic consumption is so low, without an economical means of bulk transportation to a major sea port. In general terms it may be seen, therefore, that, unless there is an adequate basis for economic development in existing domestic and export markets and in the supply and communications systems in a region, the investment required to establish a programme of integrated river basin development is likely to be high and to show poor financial rates of return for many years.

(ii) Leading on from this, another factor which inhibits the authorities from undertaking a programme of integrated river basin development in a region, such as the lower Zambezi valley, is the long time-scale which would be involved. Such programmes demand a long-term perspective not only because of the slow initial rates of return on investments, referred to above, but also because to do otherwise might result in adverse environmental effects or in a failure to make the most effective use of non-renewable natural resources. As a newly independent country, Mozambique is faced with very great economic, political and social problems, following the rapid ending of Portuguese rule, and is not in a position to adopt the necessary long-term perspective. If a river basin development programme is to be undertaken, therefore, long-term loans must be provided by foreign governments or international agencies on whom will fall the additional responsibility of assessing the long-term social, economic and environmental implications of such processes as reservoir sedimentation, floodplain utilization, the introduction of irrigated agriculture and the consumption of non-renewable resources.

(iii) Mozambique is unable to engage seriously in integrated river basin development in the Zambezi valley not only because of financial constraints but also because of its lack of technical and administrative resources, a factor to which reference has already been made. This is a problem which is particularly acute in the case of an integrated development programme in a large river basin. At present the Mozambican authorities have chosen to employ their slender resources of trained personnel primarily in centralized agencies located in Maputo. In the short-term there may be no sensible alternative to such a policy. Nevertheless, this form of administrative structure tends to prevent the successful integration of development work in a particular region.
The work of the various agencies responsible for different aspects of the development of the lower Zambezi basin has not been adequately co-ordinated since independence, with the result that effects caused by the interaction between various projects have not been fully assessed or rationalized. This has been shown most clearly in the operation of the Cabora Bassa Project. No single agency is responsible for evaluating the implications of its operating procedures. As a result, Mozambique's ability to exert a beneficial influence on the policies of the operating company, HCB, has been reduced. In the long-term, the most effective solution would be for Mozambique to establish a Government Secretariat responsible for co-ordinating the development of the Zambezi, similar to that which has been created for the Limpopo and Incomati valleys. Such a body would require both technical personnel, to investigate the physical implications of proposed projects and devise a coherent physical plan for the development of the valley, and administrative personnel, to co-ordinate the activities of the other agencies operating in the region. In due course, with an increase of experienced personnel, this Secretariat could, if desired, be expanded into a river basin authority with responsibility for the planning and implementation of all development work in the valley.

(iv) A particular consequence of Mozambique's shortage of trained personnel is that it could not, from its own resources, maintain a large programme of data collection and interpretation such as would be required to support integrated river basin development work in the Zambezi valley. The MFPZ established an extensive system of data collection as well as doing surveys of the region's topography, geology and agricultural potential. Although this work is useful, it does not provide an adequate basis for future planning. The data and information published in the reports of the MFPZ were frequently presented without due regard to their accuracy. Such information and data would, therefore, have to be totally reassessed if it were to be of value in future planning. The network of hydrological stations which the MFPZ established operated for a period of only a few years before stations began to fall into disuse. Other stations which remained in operation have records which are discontinuous. In order to provide a basis for future planning Mozambique must maintain an adequate data collection network.
able to operate within the limits of the resources currently available. This may, for a time, entail reducing the number of recording stations with a view to ensuring that higher quality records are obtained at the remaining stations. The interpretation of existing data records and the planning of data collection networks which make the most effective use of available resources are activities which are of considerable importance for the future development of many underdeveloped regions but which few countries undertake unaided.

(v) International factors may often place a constraint on integrated river basin development. In the case of the lower Zambezi reference has already been made to the constraints arising from foreign control over the financing of the Cabora Bassa Project. In addition, in many international river basins, conflict over navigation rights or water rights frequently occurs between riparian states. At present, the regulation of the Zambezi in Zimbabwe and Zambia is not likely to create substantial difficulties for Mozambique, in the development of the lower Zambezi valley, provided that upstream dams are operated in a safe and consistent manner and that good communications are maintained between their operators and the operators of the Cabora Bassa Dam. Nevertheless, specific areas in which agreements between the respective governments might be sought have been identified in this thesis. It is only through such agreements that the most effective use of the available resources can be made.

* * *

As the foregoing discussion suggests the degrees of freedom available to Mozambique in the development of the lower Zambezi basin and the operation of the Cabora Bassa Project are severely restricted. In the final part of this chapter suggestions are made, on the basis of the conclusions reached in this thesis, as to the most likely course of events in the region in, say, the next ten years.

As regards the Cabora Bassa Project, the uneasy situation created by its heavy dependence on the RSA will probably continue since there are no alternative markets for the bulk supplies of energy which the RSA purchases and, for the RSA, the continuation of the agreement is
clearly to its economic and political advantage. Nevertheless, periodic interruptions of the supply initiated either directly or indirectly by the RSA will probably continue as a means of emphasizing Mozambique's dependence on that country for the operation of the project. Under such circumstances it is extremely unlikely that the RSA will agree to any increase in the rates paid for the energy it buys unless pressure from other governments, convinced of the justice of Mozambique's case, causes the RSA to revise its position. The likelihood of Mozambique persuading the RSA to renegotiate other aspects of the power supply contract, to allow greater flexibility in the hydrological operation of the project and access to larger amounts of energy for consumption in Mozambique, is rather higher, especially if suitable compensation agreements can be reached. In this respect the recent improvement in relations between Portugal and Mozambique should ensure the co-operation of HCB in any approach made to the RSA as well as ensuring that benefits to Mozambique are optimized whatever the outcome of such an initiative. These conclusions are based on the assumption that no dramatic political changes will take place, in the short-term, in the RSA or Mozambique. In the extremely unlikely event of an independent majority government being formed in the RSA in the near future a complete reappraisal of the Cabora Bassa Project and the possible contribution of the proposed North Bank Station would be possible.

Co-operation between the independent countries of southern Africa through the agency of the SADCC is unlikely to have a major effect on the development of the lower Zambezi in the near future. Its creation may facilitate the exchange of information and the resolution of any conflicts which may arise, between basin states, concerning the regulation of the Zambezi. SADCC initiatives may also result in improved transportation systems in and around the lower Zambezi valley. However, the river itself is unlikely to be developed as an international transportation system. Moreover, there seems little prospect, at present, of substantial co-operation between SADCC members in the planning of their electricity supply systems, still less of the integration of those systems. Without such integration Mozambique could not free itself from its dependence on the RSA as the main
consumer of Cabo Bessa's output nor undertake a new project of the size of the proposed North Bank Power Station.

Mozambique must, therefore, face the problems of developing the resources of the lower Zambezi basin largely without reference to the activities of its neighbouring states. In particular, new sources of electrical energy must be established within Mozambique to meet growing demand in central and northern parts of the country. In areas not connected to the newly built northern transmission line, local thermal generating units or small-scale hydroelectric stations are likely to be the appropriate technical and economic way to provide electrical power. The creation of dispersed units of modest size will also offer many opportunities for the training of Mozambican technical personnel. For meeting larger industrial demands in centres linked to the transmission system the construction of a coal-fired power station, using locally mined coal, at Moatize appears to be the logical first step. Large hydroelectric sources might then be tapped at a later date as industrial demand rises.

The stimulation of agricultural production and the regeneration of rural communities in the Zambezi basin will remain the major concern of the Mozambican authorities for the foreseeable future. The creation of large capital-intensive projects with international assistance will be actively considered because of the speed with which they can, reputedly, generate large amounts of export revenue. On the other hand, the problems of ensuring the efficient management of such schemes and of reducing their adverse effects are enormous. The risks and long-term dangers involved in the promotion of less sophisticated technologies are far less. It is unlikely that Mozambique will be able to undertake integrated river basin development in the lower Zambezi valley as a whole. However, the development of smaller catchments, including the parts of the Revúboê basin in which the important agricultural area of Angônia lies, could be undertaken on an integrated basis. For the lower Zambezi as a whole, one of the agencies already involved in the development of the region could, as an interim measure, be given responsibility for co-ordinating all other activities. Whether this agency is primarily concerned with energy, water, agriculture or aldeias
comunais will depend on what are seen to be the government's economic and political priorities at the time.
Appendix 1

The Cabora Bassa Project: Technical details

SECTION THROUGH DAM AND SLUICE GATES

Figure 48: The Cabora Bassa Dam
Figure 49: General view of the Lake Cabora Bassa Dam from upstream showing power station intakes on the right bank protected by a weed control boom.
(Source: Olivier, Great Dams)

Figure 50: The Cabora Bassa Project layout plan

KEY:
1 DAM
2 FUTURE NORTH BANK POWERHOUSE
3 SOUTH BANK POWERHOUSE
4 INTAKES TO POWERHOUSE
5 SURGE CHAMBER
6 TAILRACES
7 DIVERSION TUNNELS DURING CONSTRUCTION
Figure 51:

CABORA BASSA
HYDRAULIC CENTRAL CIRCUIT

(Source: Olivier, Great Dams)

KEY:
1. INTAKE GATES AND PENSTOCKS
2. TRANSFORMER HALL
3. POWERHOUSE
4. SURGE CHAMBER
5. TAILRACES

(m)
375
350
325
300
275
250
225
200
175
150
434
205
200
175
150
Table 32: Comparison of the technical details of the Cabora Bassa, Kariba and Kafue projects.

(Sources: Technical references cited in notes 75, 76, 77 and 112 of the text).

<table>
<thead>
<tr>
<th></th>
<th>Cabora Bassa</th>
<th>Kariba</th>
<th>Kafue Gorge Dam</th>
<th>Kafue Itezhitezhi Dam</th>
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</thead>
<tbody>
<tr>
<td>Dam details</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Type</td>
<td>cupola arch</td>
<td>cupola arch</td>
<td>gravity</td>
<td>gravity</td>
</tr>
<tr>
<td>Material</td>
<td>concrete arch</td>
<td>concrete arch</td>
<td>earth-rockfill</td>
<td>earth-rockfill</td>
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<tr>
<td>Maximum height (m)</td>
<td>163</td>
<td>131</td>
<td>50</td>
<td>65</td>
</tr>
<tr>
<td>Crest length (m)</td>
<td>303</td>
<td>633</td>
<td>375</td>
<td>1800</td>
</tr>
<tr>
<td>Volume of dam (m³ x 10⁳)</td>
<td>550</td>
<td>975</td>
<td>1200</td>
<td>8500</td>
</tr>
<tr>
<td>Rock excavation underground (m³ x 10³)</td>
<td>1100</td>
<td>580 + 320*</td>
<td>--</td>
<td>0</td>
</tr>
<tr>
<td>Dam crest altitude (m O.D.)</td>
<td>331.0</td>
<td>489.5</td>
<td>981.5</td>
<td>1035.5</td>
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<tr>
<td>Spillway capacity (m³/s)</td>
<td>13950 (at 329 m)</td>
<td>9500 (at 489 m)</td>
<td>4250</td>
<td>4200</td>
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<tr>
<td>Reservoir details</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Storage capacity: live</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(m³ x 10⁵)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>dead</td>
<td>12.5 (&lt; 295 m)</td>
<td>116</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>flood</td>
<td>8 (326-329 m)</td>
<td>25</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>total</td>
<td>72.5</td>
<td>185</td>
<td>0.84</td>
<td>5.7</td>
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<tr>
<td>Surface area, normal operation (km²)</td>
<td>2700</td>
<td>5200</td>
<td>800**</td>
<td>370</td>
</tr>
<tr>
<td>Maximum length (km)</td>
<td>270</td>
<td>280</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>Maximum projected drawdown (m)</td>
<td>34</td>
<td>9</td>
<td>9</td>
<td>27</td>
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- value not known; * includes the North Bank Power Station; ** includes partial inundation of the Kafue Flats.
### Hydrology

<table>
<thead>
<tr>
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<th>Kariba</th>
<th>Kafue Gorge Dam</th>
<th>Itznhaiti Dam</th>
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<tbody>
<tr>
<td>Catchment area (km² x 10³)</td>
<td>1000</td>
<td>650</td>
<td>150</td>
<td>105</td>
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<tr>
<td>Approx. mean annual inflow (m³ x 10³)</td>
<td>84*</td>
<td>52</td>
<td>10</td>
<td>10</td>
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<tr>
<td>Approx. min. regulated flow (m³/s)</td>
<td>2100</td>
<td>1500</td>
<td>180</td>
<td>--</td>
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<tr>
<td>Maximum unregulated flow (m³/s)</td>
<td>30000</td>
<td>16000 (in 1958)</td>
<td>2400</td>
<td>2700</td>
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<tr>
<td>Minimum unregulated flow (m³/s)</td>
<td>200</td>
<td>200 (in 1949)</td>
<td>10</td>
<td>3</td>
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### Power Generation

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<th>Kariba North</th>
<th>Kafue Gorge</th>
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<tbody>
<tr>
<td>Turbine type</td>
<td>Vertical Francis</td>
<td>Vertical Francis</td>
<td>Vertical Francis</td>
<td>Vertical Francis</td>
</tr>
<tr>
<td>Number of sets</td>
<td>5</td>
<td>6</td>
<td>4</td>
<td>4 + 2</td>
</tr>
<tr>
<td>Rated output per set (MW)</td>
<td>415</td>
<td>111**</td>
<td>150</td>
<td>150</td>
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<tr>
<td>Maximum turbine discharge (m³/s)</td>
<td>452</td>
<td>140</td>
<td>200</td>
<td>42</td>
</tr>
<tr>
<td>Maximum gross head (m)</td>
<td>128</td>
<td>110</td>
<td>108</td>
<td>397</td>
</tr>
<tr>
<td>Generator output at 50 Hz (kV)</td>
<td>18</td>
<td>18</td>
<td>18</td>
<td>17.5</td>
</tr>
<tr>
<td>Power factor</td>
<td>0.85</td>
<td>0.9</td>
<td>0.9</td>
<td>--</td>
</tr>
<tr>
<td>Principal transmission voltage (kV)</td>
<td>+533 (d.c.)</td>
<td>330 (a.c.)</td>
<td>330 (a.c.)</td>
<td></td>
</tr>
<tr>
<td>Projected energy potential (TWh/yr)</td>
<td>18.5 (99% prob)</td>
<td>18.5 (99% prob)</td>
<td>20.5 (95% prob)</td>
<td>20.5 (95% prob)</td>
</tr>
<tr>
<td>Projected ultimate capacity</td>
<td>3800</td>
<td>1500 - 1800</td>
<td>1430</td>
<td></td>
</tr>
</tbody>
</table>

* - value not known; * allowing for evaporation at Kariba; ** originally rated at 100 MW
Appendix 2

Details of the meeting between technical representatives from Portugal and the three British territories in Central Africa held at headquarters of the Central African Council in Salisbury (Harare), 30 - 31 May 1950 (Source: Conferência do Zambeze, documents 1.27, 1.30, 1.31, 1.32 and 1.33).

Portuguese delegates:
Virato de Novonha de Castro Cabrita (chief delegate - Civil Engineer);
Augusto Guimarães Esteves (Electrotechnical Engineer);
Emílio Eugênio de Oliveira Mertens (Geographer).

British delegates:
A B Cowen (Chairman of Electricity Commission of S. Rhodesia and of the Inter-Territorial Hydro-Electric Power Commission);
P H Haviland (Director of Irrigation, S. Rhodesia);
T W Longridge (Director of Water Development, N. Rhodesia);
J H Fletcher (Water Engineer, N. Rhodesia);
T A Creaney (Irrigation Engineer, Nyasaland);
C L Robertson (Chairman of the Natural Resources Board of the Inter-Territorial Hydro-Electric Power Commission).

Agenda:
1. Welcome, R F Halsted, Minister of Trade and Industrial Development;
2. Statement, A B Cowen;
3. Technical discussions:
   (a) River discharges and the quantity of water impounded;
   (b) Discharges from the proposed dam at Kariba and its effects on river flows (Central African Council, Mem. No. 7/50);
4. Agreed Conclusions.

The conclusions were prepared in both English and Portuguese but with one important omission in the Portuguese text. All items except number 3, were proposed by the Portuguese delegation.

**English Text of the Agreed Conclusions**

1. The delegates from Portugal and the delegates from Southern Rhodesia, Northern Rhodesia and Nyasaland agree that in order to enable all those territories in Africa riparian to the Zambezi River to exercise their rights in regard to that river without detriment to others, and to discharge their duties as regards the maintenance and safeguarding of the river, a strong recommendation should be made to their respective Governments that those Governments collaborate in providing each other with the fullest possible hydrographic information relating to the Zambezi River.
[and its major tributaries. The assembled delegates look forward to the time when some internal organization can be created to collect, keep up to date, and distribute to all Governments concerned information regarding the Zambezi River*.]

Over and above the hydrographic information referred to above, it is highly desirable that all Governments should have the earliest possible information about any plans or projects of irrigation or power or navigation in order that by mutual consultation the river may be used to the best advantage of all the riparian territories. The assembled delegates agreed that, pending the establishment of such an organization, all riparian Governments should transmit such information to the Central African Council for collation and distribution to the other Governments concerned. To this end all delegates would recommend to their Governments the installation of a sufficient number of gauging stations in the various reaches of the river and its major tributaries, and a sufficient number of rainfall measurement stations within the catchment area, to enable a full compendium of hydrographic information to be collected about the whole river system.

2. The delegates from Lisbon representing the Portuguese Government expressed the opinion that, if during the period of constructing the proposed dam at Kariba Gorge an annual average of 10000 cusecs [283 m³/s] could be passed downstream, there should be no serious adverse affect to the present irrigation systems in the territory of Mozambique. As regards the minimum quantity of water required for navigation on the lower Zambezi it was agreed by delegates from Lisbon that, in the absence of accurate information about this matter, they would be satisfied if during the period of dam construction the Central African Governments were prepared to pass sufficient water in excess of the 10000 cusecs from the dam to enable the river to be navigable during months of low flow. Provided that in no circumstances would the quantity of water passed from the proposed dam during its construction be more than the inflow to it.

3. The delegates from Lisbon took note that the Southern Rhodesian Government might wish to extract from the Zambezi River a quantity of water not exceeding 50 cusecs [1.4 m³/s] in connection with the development of the Wankie Colliery and agreed that so small a diversion could have no appreciable effect on the needs of Mozambique.

* This section was omitted in the copy of the Portuguese text seen by the writer. It is possible that this may have been a typographical error since the previous sentence and the section omitted both conclude with the words 'Zambezi River'.

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4. The delegation from Portugal agreed that not more than $1\frac{1}{2}$ million acre feet* of water per annum $[1.5 \times 10^9 \text{ m}^3/\text{yr}]$ should be diverted from the Zambezi River in Angola during the next 25 years, during which period investigations should be carried out to determine the exact requirements of Angola for irrigation, power and other purposes. As soon as this information was available further consultations should take place between representatives of the Governments concerned to consider the matter and ensure that the needs of Angola are met. Should no mutual agreement on the matter have been reached at the end of the 25 year period, the question would fall to be decided by agreement between the Governments of Portugal and the United Kingdom.

5. The assembled delegates agreed that there might well be considerable mutual advantage in so carrying out the hydroelectric projects planned by their respective Governments as to permit of their eventual interconnection and the spreading of load factors.

* A footnote on the Portuguese text possibly inserted by a member of the Portuguese delegation or a Portuguese engineer studying the text at a later date indicated a complete misunderstanding of the units used. Having decided that the text did not refer to the maximum allowable irrigated area, the footnote's author concluded that there had been a typographical error and that 'million acre feet' should have read 'million cubic feet'. This would have reduced their interpretation of Angola's allocation from $1.5 \times 10^9 \text{ m}^3/\text{yr}$ to only $35 \times 10^3 \text{ m}^3/\text{yr}$. 
Appendix 3

Text of dispatch from Prof. Dr. Raul Ventura, Ministro do Ultramar*,
10 March 1956 (Source: Plano Geral, Texto, p 1-2, writers translation).

1. In conversations held recently between myself, the Undersecretary of State and Prof. Manzanares Abecasis, the idea arose of conducting an immediate study of the Cabora-Bassa rapids, on the Zambezi, for hydroelectric and possibly hydroagricultural development.

An initial survey of the topic has shown that the project would be technically viable and of enormous importance for the development of the province, which, it should be noted, the Brigade** was taking as one of the principal objectives of its study.

2. I now know that the Government of the Federation of Rhodesia and Nyasaland made an official declaration to the Portuguese Government concerning its Kariba Gorge Project, guaranteeing that it will not cause prejudice to the river regime, but rather the opposite.

I requested the Ministro dos Negócios Estrangeiros*** that in reply he should say that the technical information provided up until now by the Federation concerning that project does not permit the effects on the river regime to be evaluated with the necessary rigour; that the Portuguese Government has now decided to undertake studies for a similar project on its own section; that these studies could be affected if we were not to have constant and complete knowledge of the development of the Kariba project.

3. I am thus recommending to the Governo Geral**** and to the Brigada do Revué that they should place the keenest interest in the rapid preliminary study of the Cabora-Bassa project and that they should gather the necessary information in order to determine the effect on it of the Kariba Gorge Project.

* Literally 'Overseas Minister' which may be rendered 'Minister of Overseas Territories'. The Ultramar referred to the Portuguese possessions or provinces overseas.

** The initial survey was made by the brigade at that time undertaking hydrological studies in the basin of the Revué: Brigada de Estudos Hidráulicos do Revué.

*** The Minister of Foreign Affairs.

**** The Governor General (of Mozambique).
An abridged transcript of 'Relatório da visita efectuada a Moçambique ..'

(Report of a visit made to Mozambique and Southern Rhodesia between 27th May and 17th June 1956) by Prof. Alberto Abecasis Manzanares*

To achieve a better appreciation of the role of Kariba, as well as the possible international repercussions for energy production on the Zambezi in Mozambican territory, it is useful to set out the position of the Federation of Northern and Southern Rhodesia and Nyasaland regarding energy and transport even if only in broad terms.

Southern Rhodesia, with a white population of 250 000, produced, and consumed, in 1955 about 2800 x 10^6 kWh. The projects at Kariba and Kafue - where an installed capacity of 550 MW is planned - should have their entire output absorbed by around 1970, that is, within 14 years, even considering an annual rate of growth of consumption clearly below that at present and despite the installation of 5 thermoelectric power stations of 100 000 kW each which will be necessary to meet the growth in energy demand before Kariba begins its production.

It is important to stress that there appear to be no other notable possibilities of storage in the whole territory of the Federation since the only possible sources of significant amounts of energy, the Victoria Falls and the river Shire, can only be operated, in practice, as run-of-the-river schemes. This would result in Kariba's output forming, in dry periods, the basis of the supply, accentuating even more the dry season reversal of the hydrological regime in the basin it dominates. (...)

From the point of view of transport the Federation currently depends, in large part, on routes to the sea through the ports of Lourenço Marques [Maputo] - via the Limpopo Railway - and Beira - via the Beira Railway, - although in the future the route through the port of Nacala may be included once the level of Lake Nyasa has been stabilized and the railway built.

Clearly the present economic development will cause the Federation either to obtain other routes to the sea, even ones that are less economic (for example, through Walvis Bay on the west coast) or to obtain a large increase in the carrying capacity of the present lines, whether by duplication or electrification, unless some more economical solution can be shown to be practicable.

* Writer's translation, in full, of the version which appears in Plano Geral, Texto, p 2-9.
The conditions that have been noted enable us to understand better the considerations which will influence the development of the Zambezi in National Territory.

Having examined some factors related to the Zambezi and its influence on the economy of the Federation let us look at the characteristics of the basin of this river in the territory of Mozambique. (…)

From the point of view of human settlement and agriculture we can consider, in the territory in question, two clearly differentiated zones; one, corresponding to the high areas of Macanga, Marávia and Angónia, situated above 500 m, with general conditions and climate which permit adaption of the white man without difficulty in types of occupation similar to those recommended for the upper Revué basin, and the other, on the plain downstream of Inhacoro, or better still downstream of Mutarara, at levels below 100 m, consisting of poorly drained lands periodically inundated by floods, in which intensive white occupation is not thought to be favourable but in which development of the type of industry which is based on large agricultural companies with considerable use of native labour is thought to be possible.

Clearly to achieve an efficient occupation of the high regions it is necessary to evaluate the potential for irrigation and, especially, energy, since it is thought that a large part of it will have to rely on pumping. On the other hand occupation of the low areas will require effective flood protection, drainage and irrigation of the whole region under consideration.

Even more fundamental, whether for the aspect which we have just considered or for the efficient development of industry in general and mining industry in particular, is the existence of an economical means of communication to permit easy movement of products.

In the opinion of the signatory, the effective economic occupation of the Zambezi basin requires that the export of the products obtained should take place after the maximum possible amount of industrial processing. Again, it seems advisable, for the benefit of the economic return, to attempt to process in situ the fortuitous mineral riches of the region to the highest degree possible. None of these objectives could be attained, however, without abundant and cheap energy and easy and economical means of communication.

We confirm, therefore, that the bases for the economic occupation of the region considered lie in the production of energy abundantly and at a low price, in flood protection and drainage of the low zone and in the possibility of navigation along the Zambezi.
Let us see how far it is possible to achieve those objectives.

As has already been stated the Zambezi enters Mozambique near the confluence with the Luangwa, at an elevation of 323 m, and runs with a very gradual inclination for 212 km through a broad valley until the vicinity of Chicoa where the elevation of the bed is around 250 m. No exact information exists of the longitudinal profile between this place and Taulo, that is, the area in which the Cabora-Bassa rapids occur. In this stretch, over a distance of about 90 km, following the line of the river, the Zambezi drops to an elevation of 157 m. A survey undertaken by aeroplane, however, enabled at least the apparent conclusion to be drawn that the fall is concentrated in a 10 to 15 km stretch situated about 15 to 20 km downstream of Chicoa. (...

The construction of a dam - which, from the observations made, would be extraordinarily economic - at the upstream end of the rapids, in a locality chosen from the many which seem apparently to be suitable, would enable a reservoir to be created with characteristics similar to those of Kariba with the height of dam probably not exceeding 100 m. (...

That is to say, the basin of the Zambezi river, which at the Cabora-Bassa rapids has an area of the order of 900 000 km², could be totally controlled interannually with a minimum guaranteed flow of the order of 2300 m³ s⁻¹ available at the approximate elevation of 320 m. Taking into consideration the total available head to sea level, the theoretical energy potential would be about 50000 x 10⁶ kWh, that is, about 6 times that which could be obtained from Kariba. It is clear, however, that not all the available head could be utilized especially downstream of the confluence of the Shire, or rather, downstream of the bridge of Mutarara. It is still essential to make suitable study of the series of projects that would be necessary for this in order to ascertain which of them would be uneconomic.

In the opinion of the signatory the utilization of such a large energy potential could, in principal, be achieved in a large project situated on the Cabora-Bassa rapids using directly the dam already referred to with a head of about 140 m, and, downstream in a number of successive run-of-the-river projects or projects with a small storage, up to the point of entry of the Zambezi into the alluvial plain. In any event that first project could produce around 22000 x 10⁶ kWh, that is to say, 3 to 4 times the energy potential at Kariba*, at a price which we predict would be considerably lower. Clearly, this quantity of energy could be obtained in phases, by successive increases of the intake and power station works. (...

* An original footnote draws attention to the fact that this is also about 15 times the energy production in metropolitan Portugal in 1955.
We thus confirm that the natural conditions of the River Zambezi in Mozambique are - and will become still more so with the construction of Kariba - among the best in the world for obtaining enormous quantities of energy at a very low price.

Bearing in mind that with the creation of Kariba and Cabora-Bassa lakes about 75% - 900 000 km² - of the Zambezi hydrographic basin will be totally controlled leaving 300 000 km² uncontrolled of which approximately a half - 148 600 km² - corresponds to the Shire basin which will also be partially controlled by Lake Nyasa, the conclusion is reached that the floods of the lower basin are readily controllable although clearly it would be necessary to take account of the possibility of exceptional discharges from the gates of Kariba and Cabora. In fact, knowing that the maximum flood foreseen at Kariba is of the order of 15000 m³ s⁻¹ and that that which has been considered possible at Mutarara is about 43000 m³ s⁻¹, bearing in mind also the ratio of the respective basins, it is thought possible that a reduction of at least 50% in the value of the maximum flood foreseen can be guaranteed.

On the other hand, bearing in mind that almost all the solid material carried by the Zambezi will be retained in the reservoirs referred to above, the conclusion has been reached that it will, in the future, be possible, with the river's erosive power which will obviously be increased, to conserve the channels of the Zambezi and to enable works for the canalization, flood protection, and stabilization of the river to be planned with greater security.

It is clear that the conditions listed above concerning the reduction of floods and sediment transport, plus the fact of a much higher incidence of augmented flows and the possibility of relying on guaranteed minimum flows of the order of 2500 m³ s⁻¹ and in addition the need to build run-of-the-river projects or projects with a small amount storage in order to make use of the available head between the mouth of the Luia and the alluvial zone, will produce conditions necessary for the establishment of navigation of some importance along the river at least to the vicinity of the Cabora station and possibly to Kariba Gorge by way of the stabilized river in the alluvial zone, the canalized river from there upstream to Cabora, the reservoir from Chicoa and the river either stabilized or canalized between Zumbo and Kariba Gorge. (...)

Now that the scope of the problem has been indicated, and the manner in which it presents itself, we should not conclude without trying to make suggestions as to the direction which could be followed if one were to attempt to undertake studies.

The information and data at present available are not very plentiful; however some reliable data are already available. For others, especially the hydrological data, the exchange
of technical data which has been agreed with Rhodesia will be very useful.

From a topographic point of view it is only possible to count on maps of 1:250,000 scale for this region and on accurate levelling currently taking place parallel to the Zambezi from the sea to the border at Zumbo.

From a hydrological point of view the most useful data at the plano geral stage will probably be those which the Rhodesian authorities have provided on daily flows over a long period of years for the Zambezi at Kariba. This data is especially useful when compared against the poor data which can be derived from the existing hydrometric stations in National Territory.

With this in mind the direction to follow could be:

a) to establish, as from now, a rational programme of rainfall and hydrometric observations in the Zambezi, its principal tributaries and their respective basins;

b) to seek to obtain topographic information necessary for the plano geral, in particular, longitudinal profiles of the Zambezi and its principal tributaries based on the accurate levelling currently being undertaken, aerial photoplanimetry of the stretches of river which appear advantageous for the siting of dams and of the zones of the corresponding reservoirs, measurement of the lowest and average levels of the bed of the Zambezi in stretches which are of interest for navigation, stabilization and flood protection and surveying of the zones of interest for the first phase of the drainage and irrigation works;

c) study of the development zones to define their characteristics for agriculture;

d) preparation of a Plano Geral, based on the available information, which would include initial outline plans of the works under consideration, the most complete hydrological study possible and an economic assessment of the various works both from the point of view of costs and from the point of view of returns.

It is thought that the completion of such a plano geral would require about 4 years, to enable it to be done conscientiously, and that therefore the corresponding allocation of funds ought to be included in the next development plan together with funds for the drawing up of construction plans for the works on which it would subsequently have been decided to concentrate.

It is still thought that the initial execution of such works could only take place during the 3rd development plan, that is from 1964, unless it were subsequently decided to accelerate some of them. (....)

To conclude, the signatory believes that the report of the
extraordinary possibilities for economic development which the Zambezi region of Mozambique presents was, for him, a cause of surprise and wonder. It is clear that the utilization of those possibilities, accompanied by a well defined policy of industrial development and mineral prospecting and mining could completely transform the economic prospects for the Province of Mozambique and, in consequence, for metropolitan Portugal. Rarely, I am not saying uniquely to avoid falling into the sin of, perhaps, exaggerating, have conditions occurred which are so favourable for the economic development of a region.
Cabora Bassa Phase 2: Invitation to tender*

The national electricity company "Electricidade de Moçambique" is, by this means, announcing its intention of implementing the second phase of the Cabora Bassa hydroelectric scheme.

The fulfilment of the project is an integral part in the implementation of the development plan for the decade 1980-1990, which, amongst other things, seeks the increased industrialization of the country through investment in projects with high energy consumptions such as industries for the production of aluminium, steel, cement, fertilizers, paper and textiles.

As part of the development plan and with the aim of increasing the benefits from the potential hydroelectric energy of the country, an increase in the export of electrical energy to neighbouring countries is foreseen.

This project will consist of at least the following principal components:

1. an underground power station situated on the north bank of the River Zambezi including electrical and mechanical equipment with capacity to produce about 1750 MW;

2. the strengthening of the present electricity transmission systems to neighbouring countries;

3. an electricity transmission system for the southern region of the country consisting of 500 km of overhead line at 110 kV, 1000 km of overhead line at 220 kV and 7 substations;

4. an electricity transmission system for the central region of the country consisting of 500 km of overhead line at 220 kV and 3 substations;

5. an electricity transmission system for the northern region of the country consisting of 1300 km of overhead line at 110 kV, 350 km of overhead line at 220 kV and 12 substations;

6. the urban development of Songo consisting of residential, administrative, commercial and other requirements for the establishment of an operations and training centre for Electricidade de Moçambique.

7. a training programme for Mozambican technicians in the various specializations required for the efficient construction, operation and maintenance of the system and the supply of the necessary teaching staff for this;

8. supply of the technical staff needed for the operation and maintenance of the new power station until these activities can be undertaken by Mozambican technicians.

The whole project, outlined above, will be awarded as a single contract.

To this purpose interested companies should form a consortium under the leadership of a principal company.

The consortium to which the contract will be awarded should obtain in advance the foreign currency, and possibly part of the local currency, necessary to finance the execution of the project.

The preparations of the plans, supervision of construction and superintendence of the project will be entrusted to an independent firm of consultants.

Interested companies are invited to register themselves with Electricidade de Moçambique.

Interested companies should, with their registration, provide preliminary information on the consortium and an outline of the proposed conditions of finance before 31st October 1980.

Electricidade de Moçambique

Maputo, 12th July 1980.
Appendix 6

Hydrological data from the Zambezi basin: the significance of apparent fluctuations, trends and discrepancies for the operation of water resources projects.

The work described in this appendix originated as an investigation into the reason for an apparent change in the recorded mean annual discharge of the Zambezi upstream of Kariba, in the 1950s, and an examination of certain discrepancies between this data series and the data on which the design of the Cabora Bassa Project was based. Unfortunately, over most of Africa, hydrological records are sparse, of relatively short duration and of variable quality. This makes it difficult to assess the significance of a particular phenomenon using the hydrological techniques normally applied in Europe or North America; that is the analysis of a long data series or cross-correlations between the records of stations in the same locality. Although the first river gauge was established in the Zambezi basin at the beginning of this century, the systematic collection of gauge data only began in the 1920s and the number of gauges has remained relatively small. Such records as are available are not sufficiently long to provide a basis for examining the significance of apparent changes in climatic conditions in the region. It has, therefore, been the practice, in the past, to design water resources projects in the basin on the assumption that the mean river discharge calculated from the available data may be regarded as a stable long-term mean discharge over the life of the project. This assumption depends on three separate assumptions: that the river discharges were accurately measured in the record; that there are no long-term changes occurring in the prevailing climatic or hydrological conditions; and that the natural fluctuations which occur are either entirely random or occur in a cyclical pattern which is of short duration relative to the length of the record. These assumptions were not examined in any of the reports prepared by the MFPZ. The first formal attempt to consider the significance of such assumptions for the operation of the Cabora Bassa Project appears in a recent report by SWECO (1982).

For the operation of the three major hydroelectric projects in the
Zambezi basin the most important hydrological parameters are the minimum regulated discharge, which determines their maximum firm power outputs, and the design flood inflow, which determines the form of the flood rule curves to be adopted. Since the storage capacity of these three projects is relatively large, the most critical minimum discharge is likely to occur as a result of a succession of years in which the total inflow has been low. This parameter is related, therefore, to the pattern of total annual discharge values and is examined, in this appendix, by means of cumulative annual discharge data. The calculation of the design flood inflow, by contrast, requires a study of flood discharges of a given duration. In the case of the Cabora Bassa Project, discharges of between one and three months duration have been studied.

Climatic fluctuations and trends

On a geological time-scale the African continent has experienced considerable changes in climate. Although there is no evidence of widespread glaciation in Africa in the last four million years there appear to have been significant changes in the amount of precipitation. For example, evidence provided by a study of the fluctuations of lake levels since the end of the Pleistocene (18 000 years ago) suggests that short-term fluctuations have been superimposed on trends of higher or lower precipitation rates which have lasted 2 500 to 5 000 years\textsuperscript{514}. The results of that study indicate that the most recent 5 000 year period has been one of the most arid. On a rather longer time-scale Butzer (1978) has noted that the climate in Africa over the last 100 000 years has, apparently, been at its most unstable for over four million years but he conceded that this may be illusory:

The wave-length of late Pleistocene and Holocene variation ranges from less than a century to several millennia; whether the different time scales, compared with the Plio-Pleistocene record, are due to finer resolution or to greater climatic instability during the last 100 000 years or so, is uncertain. (p208)

Climatic changes over the last 3 000 years or so have been studied using both geomorphic and historical evidence. Nicholson (1979) undertook such a study for Sahel region on the basis of which she concluded
that the present century may have been the driest for about a thousand years in that part of Africa. A similar study of climatic change in the Zambezi basin would be more difficult to undertake because of the absence of long-term historical records and of many of the geomorphological features used in the Sahel investigation. Nevertheless, Clarence-Smith (1977) has provided a useful introduction to such work based on evidence of floods, droughts and other natural disasters amongst the Lozi people of the Barotse Plain for the period 1847 to 1907. Unfortunately, these records do not allow either a precise evaluation of the severity of particular events or a comparison with subsequent hydrological records.

Although the documentary evidence for climatic fluctuations on short and long time scales is considerable only a partial understanding of the processes which control these changes has so far been achieved. One approach which has been adopted has been to analyse meteorological records for evidence of cyclical fluctuations of different amplitudes and wave-lengths. Evidence of similar periodicity in other natural phenomena, in particular the intensity of sun spot activity, has then been sought. An alternative approach has been to compare local weather patterns with changes in the circulation of the atmosphere on a global scale. Veryard (1963) summarizing the results of such work, suggested that an increase in global circulation had been accompanied by a general warming of most parts of the globe from 1850 to 1940. In both approaches the ultimate aim has been to develop a model to help predict future climatic variations but success in this direction has been fairly limited.

Hydrologists have sought to accommodate the effects of climatic variations in their calculations ever since Hurst (1951) drew attention to the fact that hydrological records do not exhibit truly random fluctuations because of a 'persistence effect' arising from alternate wetter and drier periods. Leopold, Wolman and Miller (1964) showed that, for American rivers, the statistical variation which occurred in a 100-year record were equivalent to the variations one would expect to find in random series of only twenty-five years. Yet, in the design of water resources projects such effects are still largely ignored. Even in the
detailed work on which the UK Flood Studies Report was based, no account appears to have been taken of the fact that the majority of records used in its preparation cover the middle years of the present century when weather patterns in Europe were generally less extreme than previously\textsuperscript{318}.

Evidence provided by Hofmeyr and Schulze (1963) suggests that, in the first part of the present century, the Cape region of South Africa experienced a gradual warming trend and a progressive decrease in rainfall. This trend, they believe, was associated with a contraction of the intertropical convergence zone. It is likely, therefore, that the Zambezi basin was also affected by this trend, an assumption which appears to be supported by evidence from the limited river flow data available. Future trends of increasing or decreasing rainfall would have an appreciable effect on the operation of the Cabora Bassa Dam and other projects on the Zambezi.

Errors in data records

The interpretation of data records is greatly complicated by the possibility that errors exist over part of the period. Bruce and Clark (1966) emphasized the difficulties:

while it is desirable to have a long record for hydrologic analysis, it should be kept in mind that the longer the period over which the data have been collected at a particular site, the greater will be the possibility that physical changes to the drainage basin, environmental changes in the vicinity of the gauge, or changes in methods of observation, have occurred. (p159-60)

Little discussion of data quality was included in the project reports for the Cabora Bassa and Kariba Dams. In fact, a false sense of precision was created by the widespread use of mean annual discharge values which were quoted to three or more significant figures. Although errors can sometimes be eliminated by comparing simultaneous records from nearby gauging stations, the small number of records available limits the use of such comparisons along the main Zambezi. Nevertheless, two data series will be considered in this appendix in some detail.
The original records on which the comparison is based are taken from the two longest river gauge records on the Zambezi, at Livingstone (the Victoria Falls) and at Mutarara (Dona Ana). Because the two locations are 1,500 km apart the records cannot be compared directly. However, hydrological studies for the Kariba Project enabled the Livingstone record to be transformed into inflow data for Lake Kariba. Further work by RPT (1979 and 1980) transformed the same data into inflow data for Lake Cabora Bassa. Similarly the Mutarara record was used by the MFPZ and by the DNA (1980a) as the basis for a largely independent series of Cabora Bassa inflows. The details of this work are examined below. Since the discharges of the river have been considerably modified by construction of the major hydroelectric projects, hydrologists attempted to eliminate the effects of such regulation in the preparation of these series. The resulting records will hereafter be referred to as the 'natural discharge' series of Cabora Bassa inflows. Cumulative annual discharge data for the two records are shown below in Figure 52. Curve A shows the data series calculated from the Livingstone data, and other hydrological records from upstream, and Curve B shows the series calculated mainly from downstream data.

The two curves in Figure 52 show close agreement up to 1942/3. This is remarkable in view of the large number of sources of error which exist in the two principal records and in view of the lack of information about tributary flows in this period. Sources of error in the principal records include the absence of any accurate discharge rating measurements before 1942/3, the fact that river levels were recorded relatively infrequently, usually once a day, and the mobile nature of the river channel at the gauging stations. Changes in the river channel produce an unstable discharge rating curve which prevents accurate discharges from being calculated from river gauge records.

In 1943, a new river gauge was installed on the Zambezi 60 km downstream of the Kariba Gorge, at Chirundu Bridge. Being closer to Cabora Bassa its records would presumably have improved the accuracy of the data in Curve A after this date. Furthermore, since the gauge is at a bridge, direct discharge measurements could have been undertaken with relative ease. The accuracy of the discharge rating relationship
Figure 52: Cumulative discharge curves of Cabora Bassa 'natural' inflow series from two data sources.
should, therefore, also have improved. From 1949 onwards a gauge, installed in Kariba Gorge, provided further data which could be used to improve the accuracy of the Curve A series.

As regards the Curve B data, the first attempt to produce an accurate discharge rating for the gauge at Mutarara was not made until 1958. Even then, the rating was done indirectly by measuring discharges at Lupata Gorge, 150 km upstream. Although Lupata Gorge provides a relatively stable cross-section it was found that it was necessary to adopt different parameters for the relationship between gauge levels at Lupata and Mutarara in each of the seasons from 1958/9 to 1961/2. Such results appear to confirm the suggestion, as made above, that the Mutarara section is extremely unstable. However, the hydrologists who undertook the study believed that the changes observed in the period 1958/9 to 1961/2 were entirely due to the changes in river regime resulting from the impounding of Lake Kariba. On this basis they made the entirely unsubstantiated assumption that rating curves obtained during the season 1958/9 represented a stable pre-dam condition and could, therefore, be applied to the analysis of earlier river gauge records.

As may be seen in Figure 52, relatively close agreement between the two series of annual discharge data is maintained for the period 1942/3 to 1946/7. Thereafter, the annual discharges of the Curve A data are, until 1952/3, approximately $8 \times 10^9$ m$^3$/yr greater than those of Curve B. A possible cause of this discrepancy is discussed below with reference to the tributary discharges from the Luangwa. From 1952/3 to 1962/3 the curves lie parallel on Figure 52, indicating that in this period annual discharge data from the two sources were again comparable.

The closure of the Kariba Dam, towards the end of 1958, brought significant changes in the river discharges downstream which complicate the present hydrological analysis. In order to provide a continuous, homogeneous, record of inflows to Lake Cabora Bassa it is necessary to adjust recorded discharge data after 1958 so as to allow for changes in storage and evaporation losses in Lake Kariba. An estimate of the
'natural discharge' is thereby made. From the end of 1974, data based on river gauges downstream of Cabora Bassa must, likewise, be adjusted for the storage and evaporation effects of that project.

Figure 52 shows that from 1962/3 to 1977/8 there is a progressive divergence between Curves A and B. This indicates that the discharges of the Curve A series were approximately \(8 \times 10^9\) m\(^3\)/yr greater than those of Curve B. The possible source, or sources, of this discrepancy are examined below. The study illustrates the difficulties inherent in the interpretation of hydrological records of this nature.

The data for the Curve A series after 1958 are calculated by the following summation:

\[
\text{Cabora Bassa 'natural discharge'} = \text{Inflow to Lake Kariba} + \text{discharges from tributaries downstream of Kariba.}
\]

For Curve B the data, for the period 1958 to 1974, were calculated as follows:

\[
\text{Cabora Bassa 'natural discharge'} = \text{Cabora Bassa recorded discharge} + (\text{Kariba inflow} - \text{Kariba outflow}).
\]

It may be seen that, for both data series, knowledge of the inflow data for Lake Kariba is necessary. By ensuring that the same values for this data are used in the preparation of both curves it is possible to eliminate this component as the source of the discrepancy referred to above*. The discrepancy must, therefore, arise from errors in one or more of the other components from which the data for the two curves are derived. Separate consideration is given to these below.

Tributary discharge data are required in the preparation of

* The original references, RPT (1980) and DNA (1980a) do, in fact, use different values for the Kariba inflow, see below. In preparing Curve B, in Figure 52, the writer modified the DNA data to incorporate the same Kariba input data as in Curve A.
Curve A. For estimating these discharges RPT developed a procedure which involved various approximations. Such approximations, however, are unlikely to have been the sole cause of the discrepancy between the two curves in Figure 52 after 1963 since to produce a discrepancy of the magnitude observed would have required errors of the order of 20% in the tributary component. Moreover, no change was made in the calculation procedure yet the values calculated before 1963 appear to have resulted in close agreement between the two data series.

For the data of Curve B two possible sources of error exist. The first, the Lake Kariba outflow data, is unlikely to be significant because accurate determination of the discharge characteristics of the spillways and turbines at the Kariba Dam would be relatively straightforward. The second, the recorded discharges at Cabora Bassa, is the more likely source of error because of the difficulty of making accurate discharge measurements in the channel of the lower Zambezi. In 1954, three new river gauges were installed in the lower Zambezi, at Boroma, Tete and Matundo, and it would appear that these would have been used to improve the accuracy of the Curve B data after this date. However, their gauge records were rated using a single set of discharge measurements determined from a boat at Tete. The three records were, therefore, interdependent. Comparison of these records with the Mutarara/Lupata data for the years 1954/5 to 1962/3 suggests that the data were reasonably accurate. But in 1963, the year in which the discrepancy referred to above appears, the Mutarara/Lupata data series was discontinued and a new rating curve was introduced for the three gauges close to Tete. This curve continued in use until 1978. There is, therefore, no independent means of determining the accuracy of the Cabora Bassa 'recorded discharge' data from 1962/3 until the closure of the Cabora Bassa Dam in 1974. Further river gauges were installed in this period, most notably at Cabora Bassa Gorge*, but their records were rated by means of the same discharge measurements at Tete. Thus, for example, a 10% error in the

* Although it is based on the same discharge data, L. Kranendonk (pers. comm., 1979) found that the Cabora Bassa record did not correlate closely with the records for Boroma, Tete and Matundo. He rejected it, therefore, in the preparation of the report DNA (1980a). Nevertheless, SWECO (1982) appears to have made considerable use of these data.
calibration of the current meter used to measure discharges at Tete, in the period 1962/3 to 1974, would be sufficient to produce the discrepancy between Curves A and B in Figure 52. On the other hand, such an error would not account for the continuing divergence of the two curves after 1974, when it became possible to calculate the Cabora Bassa 'recorded discharges' by means of water budget calculations for Lake Cabora Bassa.

It is unlikely that discrepancies between the data of Curves A and B could ever be entirely accounted for without a more detailed study of the hydrology of the Zambezi including an examination of channel storage and evaporation effects. Before the closure of the Kariba Dam, widespread inundation of floodplain areas downstream of Kariba was common. If the pattern of these inundations has been changed by the regulation of the dam the channel storage and evaporation losses will also have changed. Nevertheless, it is unlikely that such changes would be sufficiently large to account for the $8 \times 10^9$ m$^3$/yr discrepancy between Curves A and B.

Man-induced changes in the hydrology of the catchment

In addition to the effects of climatic fluctuations, and of data errors, a third factor also complicates the interpretation of hydrological records, the effect of human activity on hydrological processes. Human influence ranges from possible global changes in climate, which have been suggested as a consequence of an increasing accumulation of carbon dioxide in the upper atmosphere, to regional and local changes associated with the impounding of reservoirs or the modification of land-use patterns and vegetation.

For the Zambezi, the most obvious changes which have been made, to the hydrological characteristics of the basin, are those associated with the large storage reservoirs of the Kariba and Cabora Bassa Projects. In addition to modifying the hydrograph of downstream river discharges these projects are also believed to cause a reduction in the mean annual discharge as a result of high evaporation losses from the reservoir surfaces. However, this effect has proved difficult to quantify and requires further examination.

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There have been significant changes in the importance assigned to evaporation losses in the various hydrological studies undertaken for the Kariba and Cabora Bassa Projects. For the Cabora Bassa Project, after having been neglected in the earliest work, evaporation was considered first as a constant monthly debit and finally as a variable amount calculated by means of monthly coefficients, see Chapter 3. For the Kariba Project estimates of the magnitude of evaporation losses have varied from $4.2 \times 10^9$ m³/yr to $9.1 \times 10^9$ m³/yr. The latter figure represents 18% of the mean annual inflow to Lake Kariba. The two figures are the result of different approaches to the calculation of evaporation losses. In the first, the figure quoted was estimated by subtracting mean annual rainfall from gross evaporation rates to give 'net evaporation' from the reservoir. In the second, it is the value of gross evaporation which has been used. In fact neither of these values adequately represents the changes which have occurred in the area inundated by the reservoir. Use of gross evaporation implies that the only factor changed by the presence of the reservoir is evaporation from its surface, thus ignoring the hydrological processes of rainfall, runoff and evapotranspiration which previously occurred within the area. With this approach, additional adjustments must be made to the reservoir inflow data for ungauged tributaries to allow for such factors if balanced water budget equations are to be produced for the reservoir. Use of 'net evaporation' provides only a marginal improvement on this approach since evapotranspiration losses from the area prior to impoundment are again ignored. Moreover, in both cases it is implicitly assumed that evaporation rates from the lake surface are accurately known and that the pattern of rainfall over the reservoir and catchment has not been affected by the impoundment.

In both of the projects under consideration there is a marked deficiency of rainfall and evaporation data for the reservoir areas before, and after, inundation. The CAPC undertook a study of evaporation as part of its hydrological work for Lake Kariba but had records from only two evaporation pans close to the shore together with a very short record from a pan located on an island. The study was further complicated by the fact that evaporation rates from the reservoir surface have been affected by the varying proportions of the area covered by floating aquatic vegetation at different times. Although there are more
rainfall gauges than evaporation pans, in the vicinity of the reservoir, the rainfall data are also deficient, particularly as regards rainfall on the reservoir surface.

The effects of large impoundments on local and regional climate have rarely been studied in detail. One of the chief areas of uncertainty is whether evaporation from a large reservoir leads to increased rainfall nearby. If this were to occur, and if the majority of such extra precipitation were to fall on the catchment of the reservoir it would provide a further factor which would require consideration in assessing the effect of the project on river discharges. The increased inflows to the reservoir would compensate for part of the evaporation losses from the reservoir surface with the result that the net reduction in mean annual discharge below the dam would be reduced. The difficulty of studying such effects is illustrated by Kumi (1973) who identified changes both in the quantity and distribution of rainfall and runoff over the Volta basin following construction of the Akosombo Dam. He was cautious, however, in concluding that such changes were brought about by the influence of the reservoir created. As regards the Kariba Project, Hutchison (1975) studied rainfall data for stations in Zambia within 30 km of Lake Kariba and detected a 10% increase in precipitation which he attributed to the influence of the lake. Further study over a longer period is necessary before this suggestion can be fully justified.

The other major effect of human activity is the effect on runoff characteristics of changes in land use and vegetation. The difficulty of quantifying this effect is illustrated below by reference to three catchments upstream of Cabora Bassa: the upper Zambezi basin, upstream of Livingstone; the Kafue basin; and the Luangwa basin.

The natural hydrological behaviour of the upper Zambezi and Kafue basins is strongly influenced by the existence of large floodplain areas, most notably the Barotse Plain and the Kafue Flats. As a result of the high evaporation losses from these regions the runoff coefficients* of the catchments are low. Furthermore, a small change in these runoff

* The runoff coefficient is the ratio between the runoff and the rainfall for a given catchment.
coefficients indicates a large change in river discharges downstream. One factor which influences the runoff coefficient is the rainfall; when the rainfall is low a greater proportion is lost by evaporation and the value of the runoff coefficient falls. In addition, there are a number of factors which introduce delay and feedback components into the response of the catchment to a given pattern of rainfall. For example, during a series of dry years the channels in the floodplains will become choked with sediment and vegetation. These impede the flow of water and thereby cause increased evaporation losses in subsequent seasons. At the other extreme, new channels may be formed during high discharges which substantially alter the drainage patterns of a floodplain. A possible example of such a change was noted in 1957 when an exceptionally large flood in the upper Zambezi appeared to by-pass the Chobe Swamps, which lie 100 - 200 km upstream of Livingstone. Previously, when the Zambezi was in flood, appreciable quantities of water had inundated this area reversing the direction of the normal low season drainage. Such factors as these make it extremely difficult to identify, or quantify, man-induced changes in hydrological records for these catchments.

Human activity may influence the response of runoff to rainfall in various ways. In the Barotse region of the upper Zambezi basin two changes appear to have had significant effects. The first is a change in settlement patterns which, according to Prins (1980), has had a serious effect on vegetation around the edges of the floodplain:

there has been a steady abandonment of the transhumant life and, especially during and after the 1950s, increasingly intensive permanent settlement in the narrow but stable region of the floodplain margin; large areas of forest cover were lost as some people, notably Mbunda immigrants from Angola, carved out cassava gardens in the scrub, using 'slash and burn' techniques. (p708)

Continuing deterioration of the catchment is anticipated as natural population pressures increase and are augmented by the present influx of refugees. The other important influence, also described by Prins, is the construction, at various times, of canals through the Barotse Plain. An extensive system of canals was built under King Lewanika
in the 1890s after he had seen the canal built by a Swiss missionary-aide, Auguste Goy, near Sefula. The canals, besides providing improved navigation through the floodplain, drained large areas of rich peaty soil which were then cultivated. With the increasing strength of colonial powers and, in 1916, the death of King Lewanika, the canals were neglected and rapidly became choked with vegetation. In the 1950s, the British colonial officers attempted to re-establish a canal system but the effects were short-lived. Since Zambia gained independence attempts to create agricultural development projects in the region, again incorporating canals, have not met with any sustained success. During periods in which the canals were in operation, the passage of river discharges through the Barotse Plain would have been improved, thereby reducing evaporation losses and changing the time constant in the response of downstream discharges to rainfall.

The effects of human activity also appear to have changed the hydrological behaviour of the Kafue basin. Throughout the twentieth century urban populations in Zambia have been increasing in the towns along the 'line of rail', many of which lie in the upper catchment areas of the Kafue basin. In the north of the basin lie the mines and towns of the Copperbelt Region. In general, urbanization increases the runoff from catchments as a result of the destruction of vegetation and the construction of roads and buildings. In the Copperbelt the removal of woodland has been particularly serious because of the demand for structural timber in the mines and also, during the late 1940s and early 1950s, because of its use as a fuel for the production of electrical energy from a 30 MW power station. Other man-induced changes which, it has been suggested, have affected the hydrology of the Kafue basin include the pumping of drainage water from mines into the rivers and the introduction of agricultural projects. However, the scale of the latter effect is, at present, relatively small, see Chapter 6.

The Luangwa basin does not contain large floodplain areas comparable with those of the two catchments considered above. On the other hand, large parts of the basin have suffered considerable deforestation and soil erosion during the present century, see Chapter 5. Such changes are likely to result in an increase in the runoff coefficient for
Comparison of selected river discharge data with rainfall records

a) Kariba inflow data: Two separate series of data have been published for the inflows to Lake Kariba. These are presented on Figure 53 as cumulative annual discharge values. Curve C, based on the data used in the design of both the Kariba and Cabora Bassa Projects, agrees with the data published in CAPC Annual Reports for the period 1958-80. Curve D shows a completely revised series of data which was produced by CAPC hydrologists in 1980. The other curve included in Figure 53, Curve E, shows the discharges at the Victoria Falls (Livingstone) as calculated from the original river gauge records. The following analysis is based on a comparison of these three data series and on an examination of the increases in mean annual discharge which appear to have occurred particularly in the 1950s.

In preparing data for the design of the Kariba Project, engineers of the Southern Rhodesian Irrigation Division calculated that 75% of Kariba's inflow passed over the Victoria Falls, 500 km upstream. Records from the river gauge of the Livingstone pump house, at the head of the falls, had been kept since 1905 but until 1925 the gauge was read only once every five days. Although, as Figure 53 indicates, discharge values based on these data have been published, the hydrologists engaged in the design of the Kariba Project regarded the pre-1925 data as unreliable. All subsequent studies have, therefore, used 1924/5 as the initial year for the discharge data series. From 1943, data from the gauge at Chirundu were used to provide inflow data for the Kariba Project. However, for the period 1924/5 to 1942/3 it was necessary to develop a simple catchment model in order to calculate the inflow data. The model used the Livingstone gauge record together with rainfall data from a small number of gauges in the catchments of tributaries between Livingstone and Kariba.

The origins of the revised series of data presented in Curve D are rather obscure. On the one hand, it has been reported that the revision took place as a result of the discovery by CAPC hydrologists, in 1978,
that an amended discharge rating curve, which had been introduced in 1958 for the gauge records at Livingstone, had not been applied retrospectively to data from the years prior to 1958. On the other hand, the study which had been in progress when this omission was detected was to develop a more sophisticated hydrological model for estimating the discharges of tributaries between Livingstone and Kariba. The model applied was, in fact, based on the work of Pitman (1973) and utilized rainfall data together with coefficients based on chosen catchment characteristics. As noted earlier, the evaporation losses from Lake Kariba were also being studied. That this work identified shortcomings in the original data series is not surprising, but what is surprising is that, according to Figure 53, the largest discrepancies between the two series occur for the period 1944/5 to 1957/8. The mean rate of divergence between the two curves is as follows: 1925/6 to 1943/4, $3.7 \times 10^8$ m³/yr; 1944/5 to 1957/8, $8.6 \times 10^8$ m³/yr; and 1958/9 to 1977/8, $0.3 \times 10^8$ m³/yr. During the first period the presence of large discrepancies might have been anticipated in view of the fact that the Livingstone records, which provide the primary data base in this period, were amended when the data were revised and also in view of the fact that an improved catchment model was developed for estimating tributary discharges. For the final period some discrepancies might also be anticipated as a result of revisions which might have been made to the evaporation component of the Lake Kariba water budget model used to calculate inflow data after 1958. However, for the middle period, 1944/5 to 1957/8, there appears to be no reason for a major revision of the data since the discharges would have been obtained directly from the Chirundu and Kariba gauge records. Yet it is precisely this period in which the greatest revision to the data appears to have been made. It was hoped that the study of rainfall records, described below, would not only throw light on hydrological changes occurring in the upper catchment but would also provide some indication of which of the two Kariba inflow series contains the more reliable data.

Fifteen rainfall stations located within Zambia in the upper Zambezi catchment* were selected for this study. Details of their locations

* Important parts of this catchment were not covered due to the lack of data from the relevant parts of Angola.
Figure 53: Cumulative discharge curves of Kariba inflow series (two data sources) and Victoria Falls gauge.
and of the records which are available are given in Table 33a. For each station a cumulative mass curve of annual precipitation was prepared to show fluctuations in the data. An alternative approach, adopted by Das (1975), using residual mass curves was rejected because it implies that in the long-term the mean annual rainfall, the principal parameter under study, is constant.

Study of the four longest rainfall records provided no firm evidence of climatic change over a period of sixty years. The records showed high rainfall totals in the 1950s, but the increase appeared to be more in the nature of a short-term secular fluctuation than of a long-term change. The curve for Mongu, Figure 54, is typical. In a number of the shorter records there appear to be two distinct periods, the first drier and the second wetter, with the change between them occurring in about 1950. With short records, however, it is impossible to distinguish whether such a change represents a long-term climatic trend or a short-term fluctuation. In the drier southern part of the catchment the increased variability in the annual rainfall totals introduces additional difficulties into the interpretation of the data.

The general pattern of rainfall fluctuations shown at the fifteen stations examined was for alternate wetter and drier periods of varying lengths. Although the correlation between the stations was not exact the general pattern observed was as follows:

- mid 1920s to mid 1930s, wetter;
- mid 1930s to late 1940s, drier;
- late 1940s to early 1960s, wetter; and
- early 1960s to early 1970s, drier.

The magnitudes of the fluctuations exhibited by the river discharge data of Figure 53 are very different from these, as demonstrated below, although the time periods are similar:

- 1925/6 to 1935/6, very dry;
- 1936/7 to 1948/9, dry;
- 1949/50 to 1962/3, very wet; and
- 1963/4 to 1977/8, wet.
<table>
<thead>
<tr>
<th>NAME</th>
<th>LOCATION</th>
<th>RECORDS CONSULTED</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mongu</td>
<td>15° 17' N 23° 08' E</td>
<td>1885/86 - 1978/79</td>
</tr>
<tr>
<td>Livingstone Rail</td>
<td>17° 52' N 25° 51' E</td>
<td>1904/05 - 1978/79</td>
</tr>
<tr>
<td>Seshake</td>
<td>17° 28' N 24° 18' E</td>
<td>1909/10 - 1977/78</td>
</tr>
<tr>
<td>Zambezi</td>
<td>13° 34' S 23° 06' E</td>
<td>1919/20 - 1978/79</td>
</tr>
<tr>
<td>Mwinilunga</td>
<td>11° 45' S 24° 26' E</td>
<td>1920/21 - 1969/70</td>
</tr>
<tr>
<td>Kaoma</td>
<td>14° 48' S 24° 48' E</td>
<td>1920/21 - 1969/70</td>
</tr>
<tr>
<td>Hillwood Farm</td>
<td>11° 15' S 24° 19' E</td>
<td>1925/26 - 1969/70</td>
</tr>
<tr>
<td>Sefula School</td>
<td>15° 23' S 23° 11' E</td>
<td>1925/26 - 1969/70</td>
</tr>
<tr>
<td>Kamapanda</td>
<td>12° 00' S 24° 07' E</td>
<td>1926/27 - 1969/70</td>
</tr>
<tr>
<td>Kalene Hill</td>
<td>11° 11' S 24° 11' E</td>
<td>1928/29 - 1969/70</td>
</tr>
<tr>
<td>Chavuma Mission</td>
<td>13° 05' S 22° 42' E</td>
<td>1930/31 - 1969/70</td>
</tr>
<tr>
<td>Senanga</td>
<td>16° 06' S 23° 16' E</td>
<td>1931/32 - 1969/70</td>
</tr>
<tr>
<td>Chitoloki</td>
<td>13° 50' S 23° 13' E</td>
<td>1935/36 - 1969/70</td>
</tr>
<tr>
<td>Lukulu Mission</td>
<td>14° 23' S 23° 15' E</td>
<td>1946/47 - 1969/70</td>
</tr>
</tbody>
</table>

Figures in brackets indicate long-term means calculated from available data making no allowance for missing data.

-- indicates precise data not available.
Figure 54: Cumulative rainfall curve for Mongu.
A more precise comparison has been made using the results of Tables 33 and 34. Rainfall and run-off for each of the four periods has been calculated as a percentage of the 45-year mean value* for the record in question.

Had the records contained data from the two periods 1936/7 to 1948/9 and 1949/50 to 1962/3 alone their interpretation would have appeared relatively simple. In the first of these periods, all but one of the rainfall stations showed totals below the long-term mean whilst in the second stations all but one had higher rainfall than the mean. The discharge data show much the same pattern, but it is significant that the deviations from the mean are greater in the discharge data than in the rainfall data. This behaviour would be expected from a catchment such as this which suffers high, and relatively constant, evaporation losses (that is, one with a low runoff coefficient). Reeve and Edmonds (1965) calculated that, for the period 1925 to 1958, the runoff coefficient had an average value of 9% but varied from 5% to 15% in individual years. A regime such as this would tend to produce changes in runoff which amplify any changes in rainfall since if a 1% increase in rainfall was largely lost as runoff the change in runoff might be as high as, say, 10%.

The data for the two remaining periods, prior to 1936 and after 1963, are more difficult to interpret. In these periods the pattern of rainfall appears to have been similar, with totals above the long-term mean in the north of the catchment and below this mean in the south. The only significant difference appears to have been that in the earlier period the north-west of the catchment received the heaviest rainfall whereas in the later period it was the north-east. Over the catchment as a whole the rainfall total was possibly slightly above average in both periods. This would not necessarily be expected to show in the river discharges at Livingstone since runoff from heavy rain falling on the north of the catchment would be reduced by evaporation losses in the floodplain areas. Nevertheless, there appears to be no obvious reason for the large

* The mean value for the period 1925/6 to 1969/70. Data after 1970 were not used in deriving this mean value because they were not generally available.
Table 33b: Analysis of the river discharge records shown in Figure 53

<table>
<thead>
<tr>
<th>Record</th>
<th>Mean annual discharge (m$^3 \times 10^6$)</th>
<th>Mean annual discharge in the given period as a percentage of the forty-five-year mean</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1925/6 to 1977/8</td>
<td>1925/6 to 1935/6 1936/7 to 1948/9 1962/3 to 1969/70 1963/4 to 1977/8</td>
</tr>
<tr>
<td></td>
<td>(53 yr) (45 yr)</td>
<td>1936/7 to 1949/50 (13 yr) (14 yr) (7 yr) (15 yr)</td>
</tr>
<tr>
<td>Kariba inflow</td>
<td>50.2</td>
<td>80 87 121 114 118</td>
</tr>
<tr>
<td>Curve C</td>
<td></td>
<td>(39.2) 39.4 75 80 126 123 (111)</td>
</tr>
<tr>
<td>Kariba inflow</td>
<td>54.6</td>
<td>78 89 124 106 109</td>
</tr>
<tr>
<td>Curve D</td>
<td></td>
<td>(39.2) 39.4 75 80 126 123 (111)</td>
</tr>
<tr>
<td>Livingstone*</td>
<td>50.2</td>
<td>80 87 121 114 118</td>
</tr>
<tr>
<td>Curve E</td>
<td></td>
<td>(39.2) 39.4 75 80 126 123 (111)</td>
</tr>
</tbody>
</table>

* The data record for the Livingstone discharges used in this table ends at 1975/6.

Figures in brackets are, therefore, based on incomplete data.
Table 34: Analysis of rainfall records for stations in the Zambezi basin above the Victoria Falls

<table>
<thead>
<tr>
<th>Rainfall Station</th>
<th>Mean annual rainfall (mm)</th>
<th>Mean annual rainfall in the given period as a percentage of the forty-five-year mean</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1925/6 to 1969/70 (45 yr)</td>
<td>1925/6 to 1935/6 (11 yr) 1936/7 to 1948/9 (13 yr) 1949/50 to 1962/3 (14 yr) 1963/4 to 1969/70 (7 yr) 1963/4 to 1977/8 (15 yr)</td>
</tr>
<tr>
<td>Mongu</td>
<td>978</td>
<td>99 98 107 92 97 97</td>
</tr>
<tr>
<td>Livingstone Rail</td>
<td>744</td>
<td>88 104 112 86 97 97</td>
</tr>
<tr>
<td>Sesheke</td>
<td>676</td>
<td>87 96 118 90 97 97</td>
</tr>
<tr>
<td>Zambezi</td>
<td>1080</td>
<td>105 91 105 98 98 101</td>
</tr>
<tr>
<td>Mwinilunga</td>
<td>1387</td>
<td>101 94 100 108 101 101</td>
</tr>
<tr>
<td>Kaoma</td>
<td>962</td>
<td>106 92 106 94 94 94</td>
</tr>
<tr>
<td>Hillwood Farm</td>
<td>1400</td>
<td>103 (93) 103 101 101 101</td>
</tr>
<tr>
<td>Sefula School</td>
<td>955</td>
<td>(90) (97) (110) 99 99 99</td>
</tr>
<tr>
<td>Kampaanda</td>
<td>(1356)</td>
<td>(101) 97 99 106 106 106</td>
</tr>
<tr>
<td>Kalene Hill</td>
<td>(1512)</td>
<td>(100) 93 104 104 104 104</td>
</tr>
<tr>
<td>Chavuma Mission</td>
<td>(1055)</td>
<td>(92) 90 107 113 113 113</td>
</tr>
<tr>
<td>Senanga</td>
<td>(823)</td>
<td>(97) 95 109 93 93 93</td>
</tr>
<tr>
<td>Chitoloki</td>
<td>(1082)</td>
<td>- 98 103 101 101 101</td>
</tr>
<tr>
<td>Liumba Hill</td>
<td>(963)</td>
<td>- 86 116 90 90 90</td>
</tr>
<tr>
<td>Lukulu Mission</td>
<td>(1054)</td>
<td>- (85) 100 105 105 105</td>
</tr>
</tbody>
</table>

For details of the records used in this table, see Table 33a. Figures in brackets indicate that mean values have been calculated from records which are not complete over the given period.
difference between the recorded discharges for these two periods shown in Table 33b; the very low discharges in the period 1925/6 to 1935/6 compared to the much higher discharges in the period 1963/4 to 1969/70 (or 1977/8). Possible causes of this difference are examined below:

(i) There may be errors in the discharge data. For the earliest period no direct rating curve for the Livingstone gauge data is available and for the latest period any error there might be in the estimated evaporation losses from Lake Kariba would affect the discharges calculated using a water budget model. Errors are unlikely to be the sole cause of the discrepancy, however, since to make the two periods comparable the Livingstone data in the first period would have to be increased by about 20%.

(ii) Changes may have occurred in the runoff characteristics of the catchment. This factor is also likely to have had some effect on the discharge data. Several significant changes which might have affected the hydrology of the catchment are described above.

To determine the relative importance of each of these factors, as against changes in rainfall, in producing the recorded changes in river discharges would require further investigation. A separate study has recently been undertaken by consultants appointed by the CAPC. Although few details of that work have been published its results appear to have been no more conclusive than those of the present study.

b) Tributaries to Cabora Bassa downstream of Kariba: Of the $40 \times 10^6$ m$^3$, 45% of the mean annual inflow to Cabora Bassa, which does not originate from Lake Kariba about 80% comes from two tributaries, the Kafue and the Luangwa. A study of the discharge data for these two rivers has been undertaken because of their importance in the calculation of Cabora Bassa's inflow data using the method of RPT. The only published comprehensive study of the hydrology of the Zambezi and its tributaries is that of Balem (1971), but the value of his work is reduced by its poor data base. In the following study the characteristics of the tributaries are examined separately.

The Luangwa basin: The Luangwa drainage an area of 148 000 km$^2$ in eastern Zambia, that is about 39% of the Cabora Bassa catchment downstream of Kariba. The principal river gauge, located by the 'Great East Road'
bridge, commands 95% of the river's catchment and was brought into operation in 1934. Attempts to provide a single rating curve for this station, by direct discharge measurements and by theoretical means, have enabled discharge data to be calculated from the gauge records. But the implied assumption that there is a stable channel in a river carrying a sediment load as high as that of the Luangwa is probably invalid.

Details from the principal published sources of discharge data derived from the Luangwa Bridge gauge records are given in Table 35. It may be seen that there are appreciable differences between these data series for which there is no apparent explanation. The series which, from comparison with other data, appears to be the most reliable is that of Mhango et al. (1977). These data are presented in Curve G, Figure 55. For the period 1953 to 1955, during which no data are available, it has been assumed that discharges were close to the long-term mean.

The RPT (1980) data were derived from the gauge records for the period 1956/7 to 1975/6 but for the periods prior to 1956 and after 1976 data were synthesized from the Kariba inflow data using correlations determined from the period for which the available gauge data were used. The resulting series is shown in Curve F, Figure 55. Comparison of Curves G and F indicates that the RPT data are, overall, about 10% higher than those of Mhango et al., and that shorter periods show much higher discrepancies. Rainfall data were, therefore, examined to determine whether certain of the discrepancies could be eliminated.

The study of rainfall data was undertaken in the same way as that for stations in the upper Zambezi basin described above. Details of the locations of the stations used and of the records consulted are given in Table 36. Graphical presentation of the data indicated that mean annual precipitation was relatively stable at all stations except Chipata, where for the thirty years to 1933 the mean was 993 mm whereas for the following forty-five years the mean was 1 049 mm. Since no other station showed this change it is probable that some local factor, such as, for example, a change in the location of the gauge, was responsible
Table 35: Details of available records of discharge data for the Luangwa at Luangwa Bridge
(Catchment area, 142 x 10³ km²)

<table>
<thead>
<tr>
<th>Source</th>
<th>Period of record</th>
<th>Mean annual discharge (m³ x 10³)</th>
<th>Total tributary discharge in the same period* (m³ x 10³)</th>
<th>Contribution of Luangwa to tributary discharges (%)</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mhango et al. (1977)</td>
<td>1935/6-1952/3 &amp; 1956/7-1973/4</td>
<td>15.5</td>
<td>35.5</td>
<td>44</td>
<td></td>
</tr>
<tr>
<td>Mhango (1977)</td>
<td>ditto</td>
<td>13.4</td>
<td>35.5</td>
<td>38</td>
<td>No obvious reason for discrepancy with previous data</td>
</tr>
<tr>
<td>MFPZ**</td>
<td>1957/8-1962/3</td>
<td>17.0</td>
<td>45.1</td>
<td>38</td>
<td></td>
</tr>
<tr>
<td>Balek (1971)</td>
<td>1961/2-1965/6</td>
<td>19.2</td>
<td>41.7</td>
<td>46</td>
<td>Data disordered</td>
</tr>
<tr>
<td>Table 3.2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Balek (1971)</td>
<td>Not available</td>
<td>13.7</td>
<td>--</td>
<td>41</td>
<td>Only mean value given</td>
</tr>
<tr>
<td>Table 3.3</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Starmans and Shalash (1971)</td>
<td>1945/6-1969/70</td>
<td>16.46</td>
<td>40.6</td>
<td>41</td>
<td>Actual data</td>
</tr>
<tr>
<td>RPT (1980)</td>
<td>1956/7-1975/6</td>
<td>17.3</td>
<td>35.0</td>
<td>49</td>
<td></td>
</tr>
<tr>
<td>RPT (1980)</td>
<td>1924/5-1977/8</td>
<td>17.5</td>
<td>36.1</td>
<td>48</td>
<td></td>
</tr>
</tbody>
</table>

Footnotes:  
* Estimated mean annual discharge based on the difference between data in Curve B, Figure 52, Cabora Bassa 'natural' inflow, and Curve D, Figure 53, Kariba inflow.  
** Plano Geral, 33.
Figure 55: Cumulative discharge curves for data from the Kafue and Luangwa rivers relative to 1925/26.
Table 36: Analysis of rainfall records for stations in the Luangwa basin

<table>
<thead>
<tr>
<th>Rainfall Station</th>
<th>Location Latitude Longitude Altitude (m)</th>
<th>Mean annual rainfall in the given period as a percentage of the forty-five-year mean</th>
<th>Mean annual rainfall(mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chipata</td>
<td>13° 38' 32° 39' 1 150</td>
<td>98 101 104 109 93</td>
<td>1 024</td>
</tr>
<tr>
<td>Feira</td>
<td>15° 37' 30° 24' 344</td>
<td>101 96 113 109 86</td>
<td>702</td>
</tr>
<tr>
<td>Isoka</td>
<td>10° 10' 32° 40' 1 350</td>
<td>110 95 99 105 104</td>
<td>1 107</td>
</tr>
<tr>
<td>Lundazi*</td>
<td>12° 18' 33° 12' 1 140</td>
<td>(101) 100 102 104 93</td>
<td>(884)</td>
</tr>
<tr>
<td>Mpika</td>
<td>11° 50' 31° 23' 1 470</td>
<td>99 103 108 104 87</td>
<td>1 111</td>
</tr>
<tr>
<td>Petauke</td>
<td>14° 15' 31° 17' 1 030</td>
<td>105 90 108 110 91</td>
<td>971</td>
</tr>
<tr>
<td>Serenje</td>
<td>13° 15' 30° 15' 1 440</td>
<td>98 96 99 116 97</td>
<td>1 140</td>
</tr>
</tbody>
</table>

* Records for Lundazi begin in 1926/7
for this change.

These rainfall data, together with the discharge data for Curves F and G, Figure 55, were analysed by subdivision of the records into five unequal periods, see Table 36 and 37. This analysis reveals that the largest discrepancy between the discharge data of Mhango et al. and that of RPT occurs for the period 1951/2 - 1956/7. Since the rainfall data show only a slight increase, which would not account for the high discharges of the RPT series for this period, and moreover, since the RPT data for this period are synthetic, it is proposed that an amendment should be made to the RPT series as shown in Table 37. The error in the RPT data appears to have arisen because the model used to synthesize the Luangwa data was based on Kariba inflow data. These data were increased, during the period in question, by heavy rainfall occurring locally over the upper Zambezi basin. Other parts of the synthetic record of RPT might also contain errors but, from the results of the present analysis the identification of specific errors is not possible. Nevertheless, closer scrutiny might be given to the period 1933-1935 when the RPT series indicates that discharges were close to the mean value but other evidence suggests that a drought as severe as that in the early 1970s occurred. Even with further amendments the RPT series is likely to show higher discharges overall than that of Mhango et al.

As noted earlier, the amendment proposed to the RPT data for the early 1950s would have the effect of removing one of the discrepancies identified between Curves A and B in Figure 52. In preparing the data for Curve A, RPT multiplied their Luangwa series by a factor of 1.6 to account for discharges from ungauged tributaries elsewhere. Thus, the proposed reduction of the Luangwa data by $5 \times 10^9$ m$^3$/yr for the period 1951/2 to 1956/7 would result in a reduction of $8 \times 10^9$ m$^3$/yr in the Curve A data during this period.

The Kafue basin: The Kafue drains an area of 154 000 km$^2$ in central Zambia, that is, about 41% of the Cabora Bassa catchment downstream of Kariba. The discharges are, however, lower than those of the Luangwa because the extensive swamp areas of the Kafue basin result in heavy evaporation...
Table 37: Analysis of discharge data series for the Luangwa

<table>
<thead>
<tr>
<th></th>
<th>1925/6 to 1938/9</th>
<th>1939/40 to 1950/1</th>
<th>1951/2 to 1956/7</th>
<th>1957/8 to 1962/3</th>
<th>1963/4 to 1969/70</th>
<th>1925/6 to 1969/70</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(14 yr)</td>
<td>(12 yr)</td>
<td>(6 yr)</td>
<td>(6 yr)</td>
<td>(7 yr)</td>
<td>(45 yr)</td>
</tr>
<tr>
<td>Mhango et al. (1977)</td>
<td>(15.3)</td>
<td>15.7</td>
<td>(16.3)</td>
<td>16.5</td>
<td>14.1</td>
<td>(15.6)</td>
</tr>
<tr>
<td>RPT (1980)</td>
<td>(17.3)</td>
<td>(15.7)</td>
<td>(22.3)</td>
<td>17.9</td>
<td>15.3</td>
<td>(17.3)</td>
</tr>
<tr>
<td>RPT (1980)-amended*</td>
<td>(17.3)</td>
<td>(15.7)</td>
<td>(17.3)</td>
<td>17.9</td>
<td>15.3</td>
<td>(16.7)</td>
</tr>
</tbody>
</table>

Mean annual discharge in the given period ($m^3 \times 10^9$)

<table>
<thead>
<tr>
<th></th>
<th>1925/6 to 1969/70</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mhango et al. (1977)</td>
<td>98</td>
</tr>
<tr>
<td>RPT (1980)</td>
<td>100</td>
</tr>
<tr>
<td>RPT (1980)-amended*</td>
<td>103</td>
</tr>
</tbody>
</table>

Mean annual discharge as percentage of the forty-five-year mean

<table>
<thead>
<tr>
<th></th>
<th>1925/6 to 1969/70</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mhango et al. (1977)</td>
<td>98</td>
</tr>
<tr>
<td>RPT (1980)</td>
<td>100</td>
</tr>
<tr>
<td>RPT (1980)-amended*</td>
<td>103</td>
</tr>
</tbody>
</table>

Brackets indicate the use of data which were not derived directly from recorded gauge levels.

* This series results from an amendment made by the writer to the RPT data, 1951/2 to 1956/7.
losses which give rise to very low values of the annual runoff coefficient, between 4.5% and 7.5%.

The first river gauge records for the Kafue were started in 1905 at Kasaka railway bridge. In 1946, the gauge was moved 10 km downstream to the road bridge where, in about 1951, direct discharge measurements were also begun. Using these measurements, together with a correlation equation between the gauge levels at the two sites, values of discharge were estimated for the entire period of the gauge records. It was found that separate rating curves were required for the rising and falling limbs of the annual hydrograph and that the scouring of the bed which occurred in high floods occasionally resulted in lower gauge levels in the following season. Such factors make it difficult to establish consistent data series particularly for the earliest years of the record.

The hydrology of the Kafue basin was examined in detail as part of the FAO (1968) study. Volume 3 of that report gives monthly discharge data at Kasaka from 1905/6 to 1963/4. This data series is identical to the one used by RPT (1980) for the years in which the two overlap. However, the RPT record begins in 1924/5 and ends in 1977/8. For the last seven years of their series RPT synthesized data by a method similar to the one which they used for the Luangwa data. The FAO and RPT data have been combined to give a continuous series, from 1905 to 1978, which is shown in Curve H, Figure 55. Details of these series together with details of other published data for the Kafue at Kasaka are presented in Table 38. The fact that no other source includes discharge data for the period prior to the first direct discharge measurement may indicate mistrust of these data for the reasons given above. As with the Luangwa data, many of the discrepancies between the published values given in Table 38 cannot readily be explained. The data of Balek (1971) in combination with those of Abou Zeid are shown in Curve I, Figure 55. Together they give a discontinuous record from 1956/7 to 1977/8 which corresponds reasonably well with the series of RPT, except that the latter series have values which are approximately 5% higher throughout.

Fluctuations in the discharge data were examined as in the
### Table 38: Details of discharge data series for the Kafue at Kasaka

(Catchment area, $149 \times 10^3$ km$^2$)

<table>
<thead>
<tr>
<th>Source</th>
<th>Period of record</th>
<th>Mean annual discharge ($m^3 \times 10^9$)</th>
<th>Tributary discharge in the same period* ($m^3 \times 10^9$)</th>
<th>Contribution of Kafue to tributary discharge (%)</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>F.A.O. (1968)</td>
<td>1905/6-1963/4</td>
<td>8.9</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>Balek (1971) Table 2.2</td>
<td>1956/7-1965/6</td>
<td>11.3</td>
<td>40.0</td>
<td>28</td>
<td>Hydrology influenced by increased evaporation at K. Flats and impoundment of Itezhitezhi</td>
</tr>
<tr>
<td>MFPZ**</td>
<td>1957/8-1962/3</td>
<td>13.5</td>
<td>45.0</td>
<td>30</td>
<td></td>
</tr>
<tr>
<td>Abou-Zeid†</td>
<td>1972/3-1977/8</td>
<td>12.7</td>
<td>38.5</td>
<td>33</td>
<td></td>
</tr>
<tr>
<td>Balek (1971) Table 2.3</td>
<td>Not available</td>
<td>12.9</td>
<td>--</td>
<td>--</td>
<td>Only mean values given</td>
</tr>
<tr>
<td>Starmans and Shalash (1971)</td>
<td>1954/5-1969/70</td>
<td>11.0</td>
<td>36.9</td>
<td>30</td>
<td>Recorded 'natural' flows</td>
</tr>
<tr>
<td>DHV (1979) ‡ ‡</td>
<td>1965/6-1968/9</td>
<td>9.0</td>
<td>22.6</td>
<td>40</td>
<td>Simulation with dam regulation</td>
</tr>
<tr>
<td>DHV (1979)</td>
<td>1965/6-1968/9</td>
<td>7.3</td>
<td>22.6</td>
<td>32</td>
<td></td>
</tr>
<tr>
<td>RPT (1980)</td>
<td>1924/5-1969/70</td>
<td>9.9</td>
<td>39.8</td>
<td>25</td>
<td>Recorded discharge data</td>
</tr>
<tr>
<td>RPT (1980)</td>
<td>1924/5-1977/8</td>
<td>10.2</td>
<td>39.3</td>
<td>26</td>
<td>Combination of recorded and synthetic data</td>
</tr>
</tbody>
</table>

Footnotes: * Estimated mean annual discharge based on the difference between data in Curve B, Figure 52, Cabora Bassa 'natural' inflow, and Curve D, Figure 53, Kariba inflow.

** Plano Geral, 33.

† S.M. Abou-Zeid, Chief Hydrologist, Zambia Electricity Supply Corporation, Lusaka (pers. comm.).

‡ ‡ Results obtained in the study outlined by Minderhoud (1978).
catchments considered above. The results of this analysis, given in Table 39, suggest that there has been a progressive increase in Kafue discharges from 1924 to the present. The impression is reinforced if data prior to 1924 are included; the FAO series shows a mean annual discharge of only \(6.9 \times 10^6\) m\(^3\) from 1905 to 1924. The FAO report highlighted an apparent discontinuity in the data in about 1935 but could offer no satisfactory explanation for it.

Data from ten rain gauge stations in the Kafue basin were analysed as in the two catchments considered above. Details of these stations and the results of the analysis are presented in Table 40. The table also includes an analysis of data for the mean rainfall over the whole of the Kafue basin as estimated by the FAO hydrologists. The results are more ambiguous than those of the studies of the two basins described above. In a number of cases individual records, notably those of Ndola, Kabwe and Kasempa, and in the combined data of the FAO report there appears to have been a gradual increase in rainfall over the period of records, although to a far lesser degree than the apparent increase in river discharges. Other stations show no such trend.

In general, the rainfall data show a similar pattern of changes to that of the discharge data. The first period appears to have been dry, the second and third periods intermediate and the final period wet. However, the changes in the discharge data have been much greater than those of the rainfall data. As with the upper Zambezi basin such behaviour might be expected from catchments with low values of runoff coefficient. In addition, human activities referred to earlier have probably caused a gradual increase in runoff. Further investigation of these factors has become more difficult since the building of the Kafue Gorge and Itehzitezhi Dams.

**Data used in the investigation of extreme floods**

The previous sections have concentrated on a comparison of annual totals of discharge and rainfall from various records. By contrast, in the calculation of flood rule curves for the Cabora Bassa and Kariba Projects discharge totals for individual months are significant.
Table 39: Analysis of discharge data for the Kafue

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Duration (years)</td>
<td>12</td>
<td>11</td>
<td>12</td>
<td>10</td>
<td>18</td>
<td>45</td>
</tr>
<tr>
<td>Mean annual discharge in given period (m$^3$ x 10$^9$)</td>
<td>7.3</td>
<td>10.5</td>
<td>10.3</td>
<td>11.8</td>
<td>(11.9)</td>
<td>9.9</td>
</tr>
<tr>
<td>Mean annual discharge as % of 45-year mean</td>
<td>74</td>
<td>106</td>
<td>104</td>
<td>119</td>
<td>120</td>
<td>--</td>
</tr>
</tbody>
</table>

Source: FAO (1968) and RPT (1980)

Brackets indicate that the analysis includes synthetic data generated by RPT for the years 1969/70 to 1977/8.
Table 40: Analysis of rainfall data from selected stations in the Kafue basin

<table>
<thead>
<tr>
<th>Name of Station</th>
<th>Location</th>
<th>Mean rainfall in given period as % of 45-yr mean</th>
<th>45-yr mean</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Latitude (S)</td>
<td>Longitude (E)</td>
<td>Altitude (m)</td>
</tr>
<tr>
<td>----------------</td>
<td>-------------</td>
<td>-------------</td>
<td>-------------</td>
</tr>
<tr>
<td>Bwana Mkubwa</td>
<td>13° 03'</td>
<td>28° 42'</td>
<td>1 321</td>
</tr>
<tr>
<td>Kabwe</td>
<td>14° 25'</td>
<td>28° 29'</td>
<td>-</td>
</tr>
<tr>
<td>Kafulufula</td>
<td>13° 16'</td>
<td>28° 20'</td>
<td>1 158</td>
</tr>
<tr>
<td>Kaempa</td>
<td>13° 28'</td>
<td>25° 50'</td>
<td>1 228</td>
</tr>
<tr>
<td>Mazabuka Rail</td>
<td>15° 52'</td>
<td>27° 45'</td>
<td>1 049</td>
</tr>
<tr>
<td>Mpongwwe</td>
<td>13° 31'</td>
<td>28° 10'</td>
<td>-</td>
</tr>
<tr>
<td>Mumbwa</td>
<td>14° 59'</td>
<td>27° 04'</td>
<td>1 067</td>
</tr>
<tr>
<td>Nchanga Mine</td>
<td>12° 41'</td>
<td>27° 52'</td>
<td>-</td>
</tr>
<tr>
<td>Ndola</td>
<td>13° 00'</td>
<td>28° 39'</td>
<td>1 269</td>
</tr>
<tr>
<td>Solwezi</td>
<td>12° 11'</td>
<td>26° 23'</td>
<td>1 320</td>
</tr>
</tbody>
</table>

Estimated mean for catchment

Brackets indicate means calculated from data which do not cover the entire period.

(1) Ndola water works.
(2) Record begins 1932/3.
(3) Record ends 1964/5.
(4) Data missing 1972/3.
(5) Record begins 1931/2.
(6) Record ends 1963/4.
Particular care has to be exercised in the interpretation of data to be used in flood frequency analysis for the following reasons: rating curves have rarely been calibrated with a sufficient number of discharge measurements at the upper end of the scale; where gauges are read infrequently, say once in twenty-four hours, flood peaks may not be accurately recorded; gauge boards are often dislodged or over-topped in extreme floods; channel discharge relationships change during a flood due to the large-scale transport of bed material; and high stream velocities make direct discharge measurements very difficult to undertake.

In an earlier part of this appendix, the origins and characteristics of two more-or-less independent series of 'natural' inflow data for Cabora Bassa were considered. From these sets of data, annual maximum one-month, two-month and three-month duration flood series have been prepared. Graphs of these flood data were given in Chapter 3 of the thesis, Figures 19 to 21. On the basis of these graphs the design flood inflows to Cabora Bassa were estimated.

The simplest way to assess the reliability of the available data is to make a direct comparison between the annual maximum series derived from the two sources. In Table 41 the magnitudes of various parameters describing these annual maximum series are compared. In Table 42 the series are examined for differences in the seasonal distribution of the flood events they contain. Table 41 reveals that, in quantitative terms, the differences between the data from the two sources are relatively small. In general the values of the RPT series appear to be slightly higher but are less scattered. If the analysis is restricted to the six highest members of each series the DNA values are higher. Such differences are unlikely to be significant for the purposes of the present work. Table 42 shows that the data from the two sources give flood series which have similar seasonal distributions apart from that of the six largest one-month duration flood peaks. The DNA data show March to be the month in which peak one-month floods occur most frequently, whereas the RPT data suggest that it is February. Thus, according to RPT, the highest members of the series show a different pattern of distribution from that of the series as a whole. Reeve and Edmonds (1965) proposed a physical mechanism which might account for such behaviour.
Table 41: Comparison of data from annual maximum flood series derived from two records of Cabora Bassa's monthly 'natural' inflows (see figures 19 to 21)

<table>
<thead>
<tr>
<th>Source</th>
<th>RPT (1980), 54-year series</th>
<th>DNA (1980a), 48-year series*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flood duration</td>
<td>1 month</td>
<td>2 month</td>
</tr>
<tr>
<td>Mean of series (m³/s)</td>
<td>7 410</td>
<td>6 860</td>
</tr>
<tr>
<td>Standard deviation (m³/s)</td>
<td>2 650</td>
<td>2 460</td>
</tr>
<tr>
<td>1:10 000-year flood (m³/s)</td>
<td>25 900</td>
<td>23 400</td>
</tr>
<tr>
<td>Standard error** in 1:10 000-year flood (m³/s)</td>
<td>2 800</td>
<td>2 600</td>
</tr>
<tr>
<td>Mean of six largest floods (m³/s)</td>
<td>12 600</td>
<td>11 600</td>
</tr>
</tbody>
</table>

* Amended to allow for revised Kariba inflow data after 1948.
** Cunnane (1975).
Table 42: Comparison of the distribution of extreme floods according to annual maximum series of Cabora Bassa's 'natural' inflows from two data sources

(number of occurrences in the given annual maximum series)

<table>
<thead>
<tr>
<th></th>
<th>RPT (1980)</th>
<th>DNA (1980a)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>One-month floods</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>All years</td>
<td>Jan</td>
<td>Feb</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>12</td>
</tr>
<tr>
<td>12 largest floods</td>
<td>0</td>
<td>4</td>
</tr>
<tr>
<td>6 largest floods</td>
<td>0</td>
<td>4</td>
</tr>
<tr>
<td><strong>Two-month floods</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>All years</td>
<td>Jan-Feb</td>
<td>Feb-Mar</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>25</td>
</tr>
<tr>
<td>12 Largest floods</td>
<td>0</td>
<td>7</td>
</tr>
<tr>
<td>6 largest floods</td>
<td>0</td>
<td>4</td>
</tr>
<tr>
<td><strong>Three-month floods</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>All years</td>
<td>Dec-Feb</td>
<td>Jan-Mar</td>
</tr>
<tr>
<td></td>
<td>0</td>
<td>10</td>
</tr>
<tr>
<td>12 largest floods</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>6 largest floods</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>
According to their hypothesis, very large floods pass more rapidly through areas of swamp, including the Barotse Plain. Floods from the upper catchment may, in this way, reach the Victoria Falls four or five weeks earlier than in a normal wet season. They are then more likely to coincide with floods from the smaller tributaries in Zimbabwe and augment the discharges still further. Although this hypothesis would explain the behaviour of the RPT data it does not provide an explanation of the difference between the RPT and DNA data sets. For this reason alternative flood distributions were included in the rule curve analysis in Chapter 3.

For a further analysis of these data it would be necessary to consider more carefully the time factors associated with flood propagation. In neither of the two sets of data were such factors considered. The timing of the flood peaks in the RPT series may tend to be earlier than those of the DNA series because the former are based on discharge records at Kariba whilst the latter are based on the records at Mutarara or Tete. In general, it is not expected that flood travel times will affect the monthly distribution of floods in the annual maximum series considered here. The differences of a few days in the timing of the flood peak will have little effect on the total monthly discharge and thus on the month in which the annual maximum discharge occurs. This appears to be borne out by the majority of the results in Table 42. However, where large floods occur close to the beginning or end of a month, one or other set of data may give an incorrect indication of which month contained the maximum discharge.

There are limitations to the extent to which data accuracy can be assessed by direct comparison between two sets of independent or semi-independent data. Furthermore, scrutiny of existing data is of little value in assessing 'sampling' errors - the errors arising from the use of data from a relatively short period to predict more extreme hydrological events. Various studies of this question will be examined below but it should be stressed that they are all based on the assumption of long-term hydrological and climatic stability. The effects of possible changes in the climate of the region or in the runoff characteristics of the catchment, as considered above, would also have to be taken into account.
Cunnane (1975) suggested that 'if a frequency distribution is estimated from N annual maxima, it is unsafe to extrapolate it beyond \( T = 2N \), [where \( T \) is the return period in years]. This would imply that for the data currently available for Cabora Bassa it would be 'unsafe' to extrapolate beyond a 100-year flood. Although this rather imprecise generalization appears to be too restrictive in situations where some estimate of the magnitude of extreme floods must be made, however short the data record, it does serve to emphasize the need for caution in the use of extreme flood values such as that of the 10 000-year flood when derived from short records. The conclusion is further supported by a statistical study undertaken by Benson (1952) on a theoretically produced record representing one thousand years of data.

The study of sampling error is of much greater value to an engineer if the results are presented in a quantitative or statistical form. Cunnane proposed that a 'standard error' value should be formulated as follows:

\[
\text{standard error} = C \sigma N^{-\frac{1}{2}}
\]

where \( N \) = the number of annual maxima in the series; 
\( \sigma \) = the standard deviation of the series; and 
\( C \) = a function of the return period, \( T \).

He proposed that for \( T > 5 \) the function should take the approximate form:

\[
C = 0.35 + 0.80 \ln(T - 0.5)
\]

The precise meaning of Cunnane's 'standard error' is not fully explained in the reference.

Attempts to evaluate sampling errors in statistical form include the calculation of 'confidence bands' for use in graphical analysis. Beard (1962) formulated tables of coefficients from which such bands could be calculated. The coefficients, which he proposed for use with fifty years of data to give 90% confidence bands, are shown in Table 43. These coefficients were used in locating the confidence bands in
Table 43: Coefficients for calculating 90% confidence bands for flood frequency curves produced from fifty years of data

<table>
<thead>
<tr>
<th>Return period (yr)</th>
<th>1 000</th>
<th>100</th>
<th>10</th>
<th>2</th>
<th>1.1</th>
<th>1.01</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upper band</td>
<td>+0.67</td>
<td>+0.54</td>
<td>+0.36</td>
<td>+0.24</td>
<td>+0.28</td>
<td>+0.39</td>
</tr>
<tr>
<td>Lower band</td>
<td>-0.49</td>
<td>-0.39</td>
<td>-0.28</td>
<td>-0.24</td>
<td>-0.36</td>
<td>-0.54</td>
</tr>
</tbody>
</table>

Figures 19 to 21. The appropriate coefficient is multiplied by the standard deviation of the series to give the amount by which the confidence band is offset from the curve for a given return period. At the upper and lower extremes of return period, the confidence bands diverge quite markedly from the curve. Benson's results, referred to above, have not been presented in the same form and comparison is, therefore, difficult. However, they suggest that the values of the coefficients given in Table 43 may be too low. Waldon and Prescott (1980) have undertaken further studies of flood frequency curves and their results also throw some doubt on the validity of Beard's coefficients. Their work showed that the width of confidence bands depends not only on the length of record and the return period but also on the shape of the flood frequency curve.

Attempts have been made to improve the accuracy of flood analysis by incorporating non sequential hydrological data or other types of information about historic floods which occurred before systematic data records were commenced. One such piece of work is described by Russell (1982). It seems unlikely that sufficient suitable information could be obtained to apply such procedures to the lower Zambezi.

Chapter 3 contained a brief discussion of the relative merits of graphical and numerical methods for the analysis of extreme flood events. The use of graphical methods in the present work was held to be justified because \( x = f(y) \) was assumed to be sufficiently close to linear. In other words, the curvature of the GEV function was believed to be 'mild'. To investigate whether this assumption is valid the curvatures of the annual maximum one-month, two-month and three-month series of Figures 19
to 21 were calculated using Jenkinson's 'method of sextiles' the coefficients of which are summarized in Table 8 of Chapter 3. The resulting values of the curvature parameter $k$ are shown in Table 44. From this it can be seen that the majority of series show a GEV type-2

distribution, although the DNA three-month duration series has a positive curvature suggesting that it would be a type-3 distribution. In all cases, given the accuracy of the available data and of the method of analysis, the approximation to a linear type-1 distribution is probably justified. The two data sources give comparable results for the one-month and three-month series but there is some discrepancy between the curvatures of the two-month series.

Jenkinson (1969) gave procedures by which the other parameters of the GEV function could be estimated. Although the results are less reliable than those from more rigorous methods of numerical analysis they do, nevertheless, illustrate certain important characteristics of this type of analysis, see Table 45. The results demonstrate clearly the importance of the curvature parameter: where the values of $k$ are close to zero, in the three-month series, there is close agreement between the estimated values of the 10 000-year flood from the numerical and graphical analyses; where $k$ is less close to zero, in the one-month series, the divergence between the results of the two methods of analysis is large; and where the values of $k$ are appreciably different for the

### Table 44: Investigation of the curvature of the annual maximum series from the two principal data sources

<table>
<thead>
<tr>
<th>Data source</th>
<th>RPT (1980)</th>
<th>DNA (1980a)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flood duration</td>
<td>1 month</td>
<td>2 months</td>
</tr>
<tr>
<td>$W_2 - W_1$</td>
<td>0.32</td>
<td>0.41</td>
</tr>
<tr>
<td>$W_6 - W_5$</td>
<td>-0.105</td>
<td>-0.020</td>
</tr>
<tr>
<td>Curvature, $k$</td>
<td>-0.105</td>
<td>-0.020</td>
</tr>
</tbody>
</table>
Table 45: Numerical analysis of the Cabora Bassa flood frequency data by the methods of Jenkinson (1969)

<table>
<thead>
<tr>
<th>Data source</th>
<th>RPT (1980)</th>
<th>DNA (1980a)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flood duration</td>
<td>1 month</td>
<td>2 months</td>
</tr>
<tr>
<td>GEV parameters:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$k$</td>
<td>-0.105</td>
<td>-0.020</td>
</tr>
<tr>
<td>$u$ (m³/s)</td>
<td>6 040</td>
<td>5 660</td>
</tr>
<tr>
<td>$a$ (m³/s)</td>
<td>1 960</td>
<td>2 000</td>
</tr>
<tr>
<td>Estimated 10 000-year flood (m³/s)</td>
<td>36 500</td>
<td>26 000</td>
</tr>
<tr>
<td>10 000-year flood from graphical analysis (m³/s)</td>
<td>25 900</td>
<td>23 400</td>
</tr>
</tbody>
</table>

two sources of data, in the two-month series, the effect is clearly seen in the values of the 10 000-year flood. Because of the possible inaccuracy in the values of $k$, as calculated by Jenkinson's method, and the sensitivity of the estimated values of extreme floods to this parameter the results of Table 45 should not be given undue weight. However, they serve to show that, at least for the one-month duration series, the assumption of a linear GEV type-1 distribution, on which the graphical analysis of Chapter 3 was based, may have resulted in an underestimation of the 10 000-year flood. More rigorous numerical analysis of these data may, therefore, be worthwhile.

Table 45 does not provide an adequate basis for assessing the accuracy of the data themselves but it appears, from the values of the 10 000-year floods, that the RPT data give more reasonable and consistent results using numerical methods, than do the DNA data. In addition, analysis of the DNA data suggests that the three-month duration series shows a type-3 distribution which is difficult to justify in physical terms.
The method adopted for the calculation of flood rule curves

The method used in the calculation of flood rule curves may be illustrated by reference to Table 46. The table records the values used in the sequential calculation of the flood rule curve under the initial conditions specified in Tables 10 and 11 of the text (Calculation 1). The following notes amplify the procedures involved in the calculation.

The diagrams referred to may be found in Chapter 3 of the text.

1. It is assumed that the critical duration of the design flood is three months and that it would be safe to allow the reservoir level to reach the chosen maximum (usually 329 m O.D.) at the end of the critical period. For a more rigorous treatment a longer period should be studied, particularly to assess the drawdown necessary in the months preceding the critical period.

2. The calculation proceeds in reverse order through the critical months so that storage requirements may be accumulated to provide the value of the initial reservoir level. Values in columns 4 to 11 are interdependent and are calculated by a process of iteration. In the calculation of gate and turbine discharges the month of February is assumed to have 28 days.

3. The figure in column 3 of Table 46 is obtained from the difference between values in columns 1 and 2.

4. The value in column 4 is obtained by taking the arithmetic mean of the reservoir levels at the beginning of the month in question and the beginning of the following month (column 11).

5. The discharge (column 5) is obtained from the relation represented in Figure 16 using the mean reservoir level (column 4). (It should be noted that where there is a large change in reservoir level during the month, use of the mean value to calculate the gate discharge provides only an approximate result. However, since these estimates provide conservative results they are considered to be adequate for the purposes of the present study).

6. The tailrace level (column 6) is obtained from Figure 15 on the basis of the combined discharges (columns 5 and 8).

7. The mean net head (column 7) is obtained from the difference between the mean reservoir level (column 4) and the tailrace level (column 6).
Table 46: Illustrative example of flood rule curve calculation

<table>
<thead>
<tr>
<th>Month</th>
<th>1. Unregulated inflow $(m^3 \times 10^9)$</th>
<th>2. Guaranteed flood storage upstream $(m^3 \times 10^9)$</th>
<th>3. Regulated inflow $(m^3 \times 10^9)$</th>
<th>4. Mean reservoir level (m O.D.)</th>
<th>5. Maximum discharge possible through gates $(m^3 \times 10^9)$</th>
<th>6. Tailrace level (m)</th>
<th>7. Mean net head (m)</th>
<th>8. Turbine discharge $(m^3 \times 10^9)$</th>
<th>9. Additional storage required during month $(m^3 \times 10^9)$</th>
<th>10. Total storage required at start of month $(m^3 \times 10^9)$</th>
<th>11. Reservoir level at start of month (m O.D.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>April</td>
<td>40</td>
<td>0</td>
<td>40</td>
<td>329.0</td>
<td>36.1*</td>
<td>225.3</td>
<td>100.7</td>
<td>4.5</td>
<td>0</td>
<td>0</td>
<td>329.0</td>
</tr>
<tr>
<td>March</td>
<td>67</td>
<td>13</td>
<td>54</td>
<td>326.5</td>
<td>36.0</td>
<td>225.0</td>
<td>98.5</td>
<td>4.7</td>
<td>13.3</td>
<td>13.3</td>
<td>324.0</td>
</tr>
<tr>
<td>February</td>
<td>53</td>
<td>22</td>
<td>31</td>
<td>325.0</td>
<td>31.9</td>
<td>224.7</td>
<td>97.3</td>
<td>4.3</td>
<td>-5.2</td>
<td>8.1</td>
<td>326.1</td>
</tr>
</tbody>
</table>

* It is, in fact, only necessary for the gates to discharge $35.5 \times 10^9$ m$^3$ during April.
A further 3 m is subtracted to allow for friction losses in the hydraulic circuit.

8. The turbine discharge (column 8) is derived from the information on turbine characteristics presented in Figure 17 using the value of mean net head (column 7).

9. The difference between the inflow (column 3) and the maximum possible discharge (columns 5 and 8) provides the value for the reservoir storage required (column 9). If the maximum discharge capacity of the gates and turbines exceeds the inflow the value in column 9 will be negative and the reservoir level at the start of the month will be higher than that at the end, see February. If, however, the maximum reservoir level is reached at the end of the month the level at the start cannot be higher and the value in column 9 is taken as zero. Under these circumstances the gates operate at below their maximum capacity, see April.

10. The total flood storage required (column 10), as obtained from the cumulative values in column 9, provides the appropriate value for the reservoir level at the start of the month (column 11) by reference to Figure 14.
Appendix 8

Review of studies and data relating to sediment transport in the lower Zambezi basin.

1. Suspended and bedload sediment transport in the Zambezi downstream of Cabora Bassa

a) Measurements undertaken for the MFPZ: Between 1963 and 1971, a number of attempts were made by staff of the MFPZ to measure the rate of transport of bedload and suspended sediment in the Zambezi. The bedload was measured at Tete, Marromeu and at two locations in the delta using a BTMA sampler*. The data were collected for the purpose of planning channel modifications for the benefit of navigation but the results, which are contained in files in the offices of the SPA in Tete, are of limited value for this purpose. Firstly, relatively few measurements were made and only a small proportion of these were made during periods of flood discharge. Secondly, to obtain accurate values of bedload transport using this type of apparatus requires a large number of short-duration samples to be taken at each sampling point; the MFPZ took three samples or less at each point. Thirdly, the MFPZ failed to record values of river velocity and, in some cases, omitted such vital information as the river gauge level.

Suspended sediment was studied at Marromeu over an eight year period using three different types of instantaneous sampler. The results from the different samplers do not appear to have been entirely compatible. Furthermore, no consistent method of sampling was adopted; the most common method was to take samples at three depths at each sampling point across the cross-section but occasionally a single sample was taken either at mid-depth or on the surface. Apart from such inconsistencies, the principal weakness of this sampling programme was that the peak floods were not sampled except in the first season of the work, 1963. Since peak discharges carry a disproportionately large part of the annual sediment load, the conclusions drawn by the MFPZ are, in effect,

* A type of pressure-difference bedload sampler developed in the Netherlands.
based on the data from this single season. Furthermore the method of analysis described in the *Plano Geral*, 63, was to assume that a stable and unique relationship exists between mean daily sediment discharges and river discharges. The possible errors involved in this simplification were not, however, considered. The relationship was used to estimate annual loads of \(51 \times 10^6\) t and \(125 \times 10^6\) t in the hydrological years 1961/2 and 1962/3, respectively \(^{539}\). The equivalent mean annual suspended sediment concentrations are 600 ppm and 900 ppm by weight.

Two further shortcomings of the suspended sediment programme undertaken by the MFPZ must also be examined. Firstly, the sampling was begun immediately following the impounding of Lake Kariba but no reference was made in the relevant reports of the *Plano Geral* to the possible effects of this project on sediment transport rates at Marromeu. The possible effects of the Cabora Bassa Dam were considered but only as regards its regulation of peak river flows downstream. The trapping of sediment was not considered. Nevertheless, the effect of flow regulation alone would, it was estimated, reduce annual sediment loads in individual years by up to 45% \(^{540}\). The second shortcoming of the MFPZ's study was that no systematic determination of sediment particle sizes was made. The only available data are from an analysis of eight samples obtained in 1963 and 1964. This indicated that 20 - 30% by weight of samples comprised particle sizes greater than 64\(\mu\) but that in flood peaks values of over 30% might occur. It is not known how representative these values are of other discharge conditions.

b) **Reassessment of the MFPZ data:** Savenije (1980) examined the MFPZ data in the light of various published sediment load formulae. He found that the best agreement between observed and calculated data was achieved using either the formula of Engelund and Hansen (1967) or that of Ackers and White (1973) for both of which 65 per cent of all data gave values of the ratio of observed to calculated discharges in the range 0.5 - 2.0\(*\). Because of its greater simplicity the Engelund and Hansen formula was adopted. Savenije assumed that sediment size and density characteristics remain constant, in which case the formula

\[ \text{This criterion is suggested in White, Milli and Crabbe (1975).} \]
may be expressed as:

$$S = k \cdot B \cdot \nu^2 \cdot (i \cdot \bar{h})^{\frac{1}{2}}$$

where:

- $S$ is the total sediment discharge (t/day).
- $k$ is a constant.
- $B$ is the width of flow (m).
- $\nu$ is the mean velocity across the section (m/s).
- $i$ is the water surface gradient.
- $\bar{h}$ is the mean depth of flow (m).

Savenije introduced a further simplification by assuming that the gradient remains constant to give:

$$S = 9.3 \cdot Q^2 \cdot (A \cdot B)^{-\frac{1}{2}}$$

where:

- $Q$ is the liquid discharge (m$^3$/day).
- $A$ is the cross-sectional area of the flow (m$^2$).

This formula reduces to a direct relationship between $S$ and $Q$ (such as that used by the MFPZ) if $A \cdot B$ can be expressed as a function of $Q$.

By assuming that the sediment load characteristics shown by the Marromeu data were similar to those which would occur at Tete, Savenije suggested the relationship between sediment load and river discharge at Tete to be:

$$S = 7.2 \cdot Q^2 \cdot (A \cdot B)^{-\frac{1}{2}} \ (m^3/day)$$

Applying this to data for the years 1977 to 1980 he showed that a direct relationship between $S$ and $Q$ would give results which would correspond adequately with the observed values. He applied this relationship to a nineteen year data series and, in this way, obtained values of annual sediment load which varied from $7 \times 10^6$ t to $95 \times 10^6$ t (equivalent to
a mean concentration of between 170 ppm and 560 ppm by weight). He
concluded that the mean annual suspended sediment discharge at Tete
is \(30 \times 10^6\) t (mean concentration of 350 ppm by weight). Although
Savenije's analysis of the data is more rigorous than that of the
MFPZ, the accuracy of his results is affected by the assumptions and
simplifications which it was necessary to make in applying the sediment
transport formulae. Nevertheless, his estimates of sediment transport
rates are the most reliable available at present.

c) Other information available about sediment loads in the Zambezi:
Results have recently become available, in a, so far, unpublished paper
by Hall and Valente Burholt\(^541\), from a study of suspended sediment in
the Zambezi undertaken between April 1973 and May 1975. The study was
part of a wider study of water quality in the Zambezi prior to the
closure of the Cabora Bassa Dam, see Hall, Valente and Davies (1977).
No details have been published about the method of sampling adopted but
it appears likely that a simple hand-held sampling bottle was used. The
sediment particles were removed from the sample by pressure filtration
through a membrane filter of 0.45 μm pore size. The membranes were then
removed to a laboratory where they were weighed to determine the sediment
concentration in the original sample. The particles were then subjected
to chemical analysis. The suspended sediment concentrations determined
from samples obtained during ten sampling trips are presented in Table
47a. These results are of particular interest because they give sediment
concentrations measured at a series of stations along the lower Zambezi
from just upstream of the Luangwa confluence to a point in the delta.
As would be expected the data show clear differences between sediment
concentrations in the wet and dry seasons. They also show relatively
large variations in concentration along the river during a particular
sampling trip. Such variations would probably be caused by the influence
of storms over individual tributary catchments. The principal difficulties
in interpreting and applying these results lie in shortcomings in the
sampling method used, which provided no measurement of particle size
distribution and would, in any case, have trapped only wash-load particles,
and in the infrequency of sampling. Since samples were taken on only one
occasion each month, the date of which is unrecorded, it is not possible
to relate the results to the pattern of river discharges. In the wet
Table 47: Results of sediment surveys undertaken by Hall and Valente Burholt.

### a) Concentrations of suspended solids in g/m³ (ppm by weight).

<table>
<thead>
<tr>
<th>Sampling Station</th>
<th>Sampling Trips</th>
<th>Averages and standard deviations</th>
<th>% of volatile matter</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>4/73 6/73 8/73 9/73 10/73 12/73 1/74 3/74 4/74 5/74</td>
<td>Dry season flood season flood season</td>
<td></td>
</tr>
<tr>
<td>Name</td>
<td>Av  SD</td>
<td>Av  SD</td>
<td>Av  SD</td>
</tr>
<tr>
<td>Rhodesia</td>
<td>64  30</td>
<td>344  220</td>
<td>67  15</td>
</tr>
<tr>
<td>Magoé</td>
<td>88  36</td>
<td>281  150</td>
<td>78  18</td>
</tr>
<tr>
<td>Zhicoa</td>
<td>89  30</td>
<td>490  318</td>
<td>53  22</td>
</tr>
<tr>
<td>Fumboe</td>
<td>79  19</td>
<td>463  283</td>
<td>51  21</td>
</tr>
<tr>
<td>Tete</td>
<td>70  9</td>
<td>588  289</td>
<td>47  20</td>
</tr>
<tr>
<td>Matabara</td>
<td>65  24</td>
<td>330  90</td>
<td>25  12</td>
</tr>
<tr>
<td>Mopesa</td>
<td>88  12</td>
<td>249  96</td>
<td>48  26</td>
</tr>
<tr>
<td>Chinde</td>
<td>40  21</td>
<td>216  146</td>
<td>51  26</td>
</tr>
<tr>
<td>Luangwa</td>
<td>54  10</td>
<td>1016 367</td>
<td>38  22</td>
</tr>
<tr>
<td>Shire</td>
<td>99  14</td>
<td>147  71</td>
<td>86  10</td>
</tr>
</tbody>
</table>

Trape Av(1-8) and SD 231 54 64 93 81 91 397 531 518 235

% vol.matter Av(1-8) and SD 27 27 68 67 70

### b) Mean concentrations in river samples of metals in particulate matter. Units: Na-Al g/m³ (ppm by weight); Cu-Zn mg/m³ (ppm x 10⁻³ by weight).

<table>
<thead>
<tr>
<th>METAL</th>
<th>All Zambesi Stations</th>
<th>Luangwa</th>
<th>Shire</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>DRY</td>
<td>FLOOD</td>
<td>DRY</td>
</tr>
<tr>
<td>Na</td>
<td>4.7</td>
<td>4.47</td>
<td>3.94</td>
</tr>
<tr>
<td>K</td>
<td>8.89</td>
<td>9.48</td>
<td>4.23</td>
</tr>
<tr>
<td>Ca</td>
<td>2.57</td>
<td>2.01</td>
<td>2.28</td>
</tr>
<tr>
<td>Mg</td>
<td>2.62</td>
<td>2.19</td>
<td>3.74</td>
</tr>
<tr>
<td>Fe</td>
<td>2.88</td>
<td>1.80</td>
<td>12.25</td>
</tr>
<tr>
<td>Mn</td>
<td>0.09</td>
<td>0.11</td>
<td>0.24</td>
</tr>
<tr>
<td>Al</td>
<td>19.82</td>
<td>18.04</td>
<td>23.00</td>
</tr>
<tr>
<td>Cu</td>
<td>12.7</td>
<td>7.2</td>
<td>29.0</td>
</tr>
<tr>
<td>Zn</td>
<td>147.0</td>
<td>92.3</td>
<td>160.5</td>
</tr>
</tbody>
</table>

499
season, in particular, short duration flood peaks originating in the tributaries carry heavy sediment concentrations which may not have been sampled during this study.

The writer obtained a number of sediment samples from the Zambezi during two visits to Tete in October 1979 and March 1980 but, because of the considerable difficulties encountered, the results are of limited value. Originally an intensive programme of sampling from the bridge at Tete had been planned using a 'water trap' sampling apparatus\(^5\). This apparatus proved to be too light-weight in strong currents with the result that it could not be lowered from the bridge to an exact position in the flow. A standard design US D-49 depth-integrating sampler was also available but the maximum depth to which this will operate, in flows of the velocity encountered, is of the order of 5 m\(^5\) whereas, in flood, the depth of flow under the Tete bridge exceeds 7 m. The samples analysed were, therefore, largely surface samples. The method used was to filter known volumes, of the order of 50 ml, through 40 mm diameter polycarbonate filters\(^5\). These were brought back to the UK for weighing and chemical analysis. An approximate particle size distribution was also obtained by first sieving out particles greater than 63 \(\mu\) and then using a form of pipette analysis\(^5\). The results are given in Table 48. Problems were encountered with the analysis of the first three samples shown in Table 48 since, in many cases, either the filter membrane ruptured or water leaked past it. Such results, therefore, had to be rejected.

The interpretation of the results in Table 48 presents a number of problems. Firstly, comparison between results of repeat analyses on a single sample indicates that errors in the filtration and weighing processes were probably no more than 10\% but that for low concentrations the errors may have been considerably higher. Secondly, there is no possibility of relating the measured results to the total sediment load in the river since it was largely wash load which was sampled. Thirdly, the results of Hall Valente and Burholt, Table 47a, show very high proportions of volatile matter in the sediment samples which they collected, particularly in the flood season. It was suggested that the volatile matter in the dry season would have been principally made up
Table 48: Analysis of superficial suspended sediment samples from the Zambezi

<table>
<thead>
<tr>
<th>Location</th>
<th>date</th>
<th>Sediment concentration (ppm by weight)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>63μ</td>
<td>31μ</td>
</tr>
<tr>
<td>Tete</td>
<td>6.10.79.</td>
<td>-</td>
</tr>
<tr>
<td>*</td>
<td>3.3.80.</td>
<td>40</td>
</tr>
<tr>
<td>*</td>
<td>5.3.80.</td>
<td>17</td>
</tr>
<tr>
<td></td>
<td>9.3.80.</td>
<td>1100</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>35μ</th>
<th>3.5μ</th>
</tr>
</thead>
<tbody>
<tr>
<td>Marromeu**</td>
<td>20.10.79.</td>
<td>80</td>
</tr>
</tbody>
</table>

- Lost sample or rejected results.
* These results may contain errors in excess of 10%
** The sample was obtained at approximately mid-depth and contains, therefore, a higher proportion of sand particles than would a superficial sample.
of living organisms whereas in the wet season the bulk would have been
dead organic matter. The living organisms are more easily decomposed
than the dead matter but, in either case, some loss of weight would be
anticipated in transporting filters for analysis. Thus the results of
Table 48 are likely to be too low. The results do, however, show an
important characteristic of the Zambezi and the influence of the Cabora
Bassa Dam. The dry season and wet season sediment concentrations at
Tete may be at similar low levels if the flow is originating mainly from
the dam. Nevertheless, flash floods from tributaries bring very heavy
sediment loads as demonstrated by the analysis of the sample taken on
9 March 1980. The sample was, in fact, taken a few hours after the
peak discharge occurred at Tete. Peak sediment concentrations may,
therefore, have been rather higher than the values in Table 48. Peak
concentrations in the tributaries themselves were estimated to have
been at least twice as high as those of the samples taken at Tete since
at Tete the sediment was diluted with clear discharges from Cabora
Bassa.

2. Suspended and bedload sediment transport in certain tributaries of
the Zambezi.

a) Measurements undertaken for the MFPZ: Apart from a programme of bedload
measurements using a BTMA sampler on the Luenha, from which the results
are of limited value, the MFPZ undertook no direct sediment surveys on
the tributaries of the Zambezi in Mozambique.

b) Surveys of the Shire and its tributaries: The Shire does not provide
a large input of sediment to the Zambezi because the floodplain and
swamps in the lower valley act as an effective sediment filter. Sediment
loads in the middle Shire were estimated for the report by Halcrow (1954)
where yields were reported to be relatively low, of the order of 50 t/
km²/yr, except in the catchment of the Ruo where yields five times higher
were reported. Low sediment concentrations were found in the Shire,
close to its confluence with the Zambezi, by Hall and Valente Burholt,
see Table 47a. A recent programme of sampling at Tedzani Falls on the
middle Shire has not, as yet, produced useful results but, again, the
concentrations appear to be low 546.
c) Other tributaries downstream of Cabora Bassa: As part of the sampling programme undertaken by the writer a number of sites on tributaries to the Zambezi within Mozambique were visited. Had access to these sites been easier it might have been possible to obtain useful results using both 'water trap' and US D-49 depth-integrating samplers. However, in the majority of cases it was only possible to visit sites on a single occasion. Dry season samples were taken in both the Revúbué and the Luenha but the concentrations of suspended sediment were so low that accurate analysis was impossible. The results from samples taken in March 1980, during the wet season, are shown in Table 49.

For the samples taken on 5 and 6 March 1980 the tributary discharges were moderate. Some difference between the loads of the three rivers sampled are apparent; the difference between the loads of the Mazoe and Luenha is thought to be significant. Heavy rainfall occurred on 8 March resulting in flood discharges from many tributaries. The samples taken on 10 and 11 March record, therefore, the elevated concentrations which occur in the recession of such flood peaks. Apart from general observations of this nature it is difficult to draw useful conclusions from these results for the reasons considered above with regard to samples taken from the Zambezi.

d) Sediment concentrations in the Luangwa: The Luangwa is thought to be the principal source of sediment to Lake Cabora Bassa. The National Council of Scientific Research in Lusaka has, since 1977, undertaken periodic sampling of this river at a number of sites. Unfortunately, it has not been possible to maintain a continuous sampling programme and it is, therefore, unknown whether flood peaks were sampled. It is understood that a depth-integrated sampler has been used for some of this work but full details of the sampling and analysis procedure could not be obtained. Selected results are shown in Tables 50a and 50b.

Table 50c shows the results of particle size analysis on a superficial sample obtained by the writer at Mfuwe Bridge in April 1980 at a time when the river was still receding from a major flood which occurred about ten days earlier.
Table 49: Analysis of suspended sediment samples from tributaries of the Zambezi in Mozambique

<table>
<thead>
<tr>
<th>River</th>
<th>Location</th>
<th>Date</th>
<th>Sampling method</th>
<th>Sediment concentration (ppm by weight)</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>&lt;63μ</td>
<td>&lt;31μ</td>
</tr>
<tr>
<td>Revúbuè</td>
<td>Chingose</td>
<td>5.3.80.</td>
<td>integrated</td>
<td>160</td>
<td>160</td>
</tr>
<tr>
<td></td>
<td>(N103 bridge)</td>
<td>10.3.80.</td>
<td>integrated</td>
<td>500</td>
<td>450</td>
</tr>
<tr>
<td>Luenha</td>
<td>Changara</td>
<td>6.3.80.</td>
<td>superficial</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td></td>
<td>(N102 bridge)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mazoe</td>
<td>N103 bridge</td>
<td>6.3.80.</td>
<td>integrated</td>
<td>180</td>
<td>-</td>
</tr>
<tr>
<td>Mavuzi</td>
<td>N221 bridge</td>
<td>11.3.80.</td>
<td>superficial</td>
<td>600</td>
<td>600</td>
</tr>
<tr>
<td>Cherize</td>
<td>N221 bridge</td>
<td>11.3.80.</td>
<td>superficial</td>
<td>200</td>
<td>140</td>
</tr>
<tr>
<td>Luia</td>
<td>Bene</td>
<td>11.3.80.</td>
<td>integrated</td>
<td>200</td>
<td>170</td>
</tr>
</tbody>
</table>

Errors of up to 10% may have been introduced during the processes of filtration and weighing. Further errors may have arisen due to the method of sampling and the loss of some volatile matter before weighing. The concentration of particles >63μ is particularly sensitive to the sampling method.
Table 50: Analysis of suspended sediment samples from the Luangwa

a) Dissolved and suspended load at Mfuwe Bridge (catchment area 55,000 km²)

<table>
<thead>
<tr>
<th>Date</th>
<th>Total solids (ppm by wt)</th>
<th>Suspended solids (ppm by wt)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nov 1977</td>
<td>430</td>
<td>300</td>
</tr>
<tr>
<td>16.1.78.</td>
<td>1,500</td>
<td>1,200</td>
</tr>
<tr>
<td>Apr 1978</td>
<td>4,100</td>
<td>2,700</td>
</tr>
<tr>
<td>May 1978</td>
<td>1,400</td>
<td>620</td>
</tr>
<tr>
<td>23.7.78.</td>
<td>200</td>
<td>170</td>
</tr>
<tr>
<td>28.6.78.</td>
<td>440</td>
<td>320</td>
</tr>
</tbody>
</table>

Source: Dr T C Sharma, NCSR, April 1980 (pers. com.)

b) Suspended load at various locations:

<table>
<thead>
<tr>
<th>Location</th>
<th>Date</th>
<th>Suspended solids (ppm by wt)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lufila</td>
<td></td>
<td>900</td>
</tr>
<tr>
<td>Chibindi Pontoon</td>
<td></td>
<td>200</td>
</tr>
<tr>
<td>Mfuwe Bridge</td>
<td>August 1980</td>
<td>340</td>
</tr>
<tr>
<td>Nyamaluna</td>
<td></td>
<td>900</td>
</tr>
<tr>
<td>Lusangazi</td>
<td>August 1980</td>
<td>930</td>
</tr>
<tr>
<td>Fundo</td>
<td></td>
<td>290</td>
</tr>
<tr>
<td>Great East Road</td>
<td></td>
<td>1,150</td>
</tr>
<tr>
<td>Bridge</td>
<td>Mfuwe Bridge</td>
<td>1,880</td>
</tr>
</tbody>
</table>

Source: Dr T C Sharma, February 1981 (pers. com.)

c) Analysis of superficial sample obtained by the writer at Mfuwe Bridge on 29 April 1980

<table>
<thead>
<tr>
<th>Particle size (ppm by wt)</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;63μ</td>
<td>650</td>
</tr>
<tr>
<td>&lt;31μ</td>
<td>620</td>
</tr>
<tr>
<td>&lt;16μ</td>
<td>570</td>
</tr>
<tr>
<td>&lt;8μ</td>
<td>430</td>
</tr>
<tr>
<td>&lt;4μ</td>
<td>310</td>
</tr>
<tr>
<td>&lt;2μ</td>
<td>230</td>
</tr>
<tr>
<td>Total</td>
<td>750</td>
</tr>
</tbody>
</table>
The suspended sediment concentrations indicated by these appear to be higher than those measured elsewhere in the lower Zambezi basin. This conclusion is also supported by results obtained by Hall and Valente Burholt, see Table 47a.

3. Particle size analysis of bed material samples

A detailed study of bed material in the Zambezi was undertaken by the MFPZ in August and September 1964. Samples were obtained from forty locations between Zumbo and the delta as well as at numerous locations around the outlets of the delta. The results, which are shown schematically in Figure 56, indicate that, although sorting of sediment occurs along the length of the lower Zambezi, the process is disturbed both by the presence of rocky gorges and the influence of certain tributaries. In a single sample the particles were found to lie within a relatively narrow range of sizes but where the channel is braided downstream of Lupata, samples taken in different branches on the same cross section showed significant differences in particle size distribution. This probably reflects the different hydraulic conditions found in primary and secondary channels. It should be noted that these samples were taken soon after the completion of the Kariba Dam and possibly represent the characteristics of the natural channel. Regulation of river discharges and sediment trapping by the Kariba and Cabora Bassa Dams may, in due course, alter these characteristics.

No survey of bed material, equivalent to that made by the MFPZ, has been undertaken recently. However, a small number of samples taken from exposed sand banks by the writer have been analysed, see Table 51. The results show similar median values to those reported by the MFPZ at Tete and Marromeu. Furthermore, the narrow range of particle sizes in each sample is clearly seen.

A knowledge of bed material characteristics is required for an assessment of the effects of the Cabora Bassa Dam on the channel downstream as well as for the design of certain channel regulation structures. In a paper referred to above, Savenije (1980) estimated the rate of degradation of the channel downstream of the Cabora Bassa
Figure 56: Mean particle sizes of bed material in the Zambezi downstream of Zumbo according to a survey by the MFPZ.

Source: Plano Geral, 63.
Table 51: Analysis of sand samples from exposed banks in the Zambezi

<table>
<thead>
<tr>
<th>Location</th>
<th>Sample number</th>
<th>Date</th>
<th>&lt;2000μ</th>
<th>&lt;900μ</th>
<th>&lt;400μ</th>
<th>&lt;250μ</th>
<th>&lt;200μ</th>
<th>&lt;150μ</th>
<th>&lt;63μ</th>
<th>Median grain size (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tete</td>
<td>A5</td>
<td>29.2.80.</td>
<td>96</td>
<td>69</td>
<td>21</td>
<td>11</td>
<td>7</td>
<td>4</td>
<td>&lt;1</td>
<td>0.68</td>
</tr>
<tr>
<td></td>
<td>A6</td>
<td>29.2.80.</td>
<td>91</td>
<td>70</td>
<td>18</td>
<td>7</td>
<td>4</td>
<td>2</td>
<td>&lt;1</td>
<td>0.74</td>
</tr>
<tr>
<td></td>
<td>A10</td>
<td>5.3.80.</td>
<td>98</td>
<td>86</td>
<td>24</td>
<td>4</td>
<td>1</td>
<td>&lt;1</td>
<td>.</td>
<td>0.60</td>
</tr>
<tr>
<td></td>
<td>A14</td>
<td>5.3.80.</td>
<td>96</td>
<td>77</td>
<td>23</td>
<td>3</td>
<td>&lt;1</td>
<td>.</td>
<td>.</td>
<td>0.65</td>
</tr>
<tr>
<td></td>
<td>A15</td>
<td>5.3.80.</td>
<td>99</td>
<td>86</td>
<td>15</td>
<td>3</td>
<td>&lt;1</td>
<td>.</td>
<td>.</td>
<td>0.60</td>
</tr>
<tr>
<td></td>
<td>A16</td>
<td>5.3.80.</td>
<td>99</td>
<td>95</td>
<td>18</td>
<td>3</td>
<td>1</td>
<td>&lt;1</td>
<td>.</td>
<td>0.48</td>
</tr>
<tr>
<td>Marromeu</td>
<td>D3</td>
<td>20.10.79.</td>
<td>&gt;99</td>
<td>99</td>
<td>33</td>
<td>9</td>
<td>4</td>
<td>&lt;1</td>
<td>.</td>
<td>0.27</td>
</tr>
</tbody>
</table>
Dam using an exponential equation in which he assumed that the final extent of the degradation would be equal at all points but that the rate of degradation would vary with the distance from the dam. For the purposes of comparison with other rivers he used the equation to estimate the time it would take for half of the expected degradation to occur at Tete. The value he obtained, 86 years, appears to indicate that the 'morphological time-scale' of the channel of the Zambezi was comparable with that of such tropical rivers as the Magdalena in Columbia, the Tana in Kenya and the Serang in Indonesia. Of the rivers for which he presented data, only the Mekong appeared to have a time-scale which was shorter - by about 60%. For general comparisons between rivers this form of analysis is useful. However, more sophisticated morphological models are available for studying more detailed aspects of channel changes.

4. Chemical analysis of river sediments

a) Mineral composition of bed material samples: The bed material samples obtained by the MFPZ were analysed for mineral composition. The results were recorded for individual samples, but for the sake of simplicity, they have been grouped according to sampling locations for the purposes of this appendix, see Table 52. This, in certain cases, is misleading because the use of mean values hides the wide variations which were found between the compositions of individual samples. Because of these wide variations it would be difficult to draw conclusions from the results. However, no clear evidence was found that particular tributaries act as major sources of given minerals.

b) Analysis of major elements in suspended sediment samples: Filtration of river samples using polycarbonate filter discs leaves a residue which may readily be analysed using an X-ray fluorescence spectrometer if such equipment is available. Selected filters from the surveys described above were analysed in this way in the Department of Geology, University of Edinburgh. The results, which are initially given as the mass of a given element on each filter, were converted to concentrations of the elements present in the sediment particles of the original sample by dividing this mass by the total mass of the sample before filtration,
Table 52: Summary of the results of mineral composition analysis on bed material samples

(mean values given as a percentage by weight)

<table>
<thead>
<tr>
<th>Location</th>
<th>Zambezi upstream of Luia</th>
<th>Luia basin</th>
<th>Zambezi Luia to Revúbuè</th>
<th>Revúbuè basin</th>
<th>Zambezi Revúbuè to Luenha</th>
<th>Luenha basin</th>
<th>Zambezi Luenha to Shire</th>
<th>Shire to Marromeu</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of Samples</td>
<td>7</td>
<td>2</td>
<td>5</td>
<td>2</td>
<td>2</td>
<td>4</td>
<td>8</td>
<td>4</td>
<td>34</td>
</tr>
<tr>
<td>Minerals</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pyroxene/Amphibole Group</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Green Hornblende</td>
<td>52</td>
<td>24</td>
<td>43</td>
<td>28</td>
<td>54</td>
<td>72</td>
<td>32</td>
<td>49</td>
<td>45</td>
</tr>
<tr>
<td>Others</td>
<td>4</td>
<td>14</td>
<td>6</td>
<td>35</td>
<td>8</td>
<td>7</td>
<td>6</td>
<td>6</td>
<td>8</td>
</tr>
<tr>
<td>Mica Group</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Muscovite</td>
<td>6</td>
<td>0</td>
<td>4</td>
<td>0</td>
<td>2</td>
<td>1</td>
<td>4</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Biotite</td>
<td>9</td>
<td>47</td>
<td>5</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>12</td>
<td>12</td>
<td>10</td>
</tr>
<tr>
<td>Garnets</td>
<td>6</td>
<td>2</td>
<td>8</td>
<td>5</td>
<td>6</td>
<td>4</td>
<td>7</td>
<td>5</td>
<td>6</td>
</tr>
<tr>
<td>Garnets</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Opaque minerals</td>
<td>9</td>
<td>11</td>
<td>22</td>
<td>21</td>
<td>20</td>
<td>7</td>
<td>33</td>
<td>20</td>
<td>19</td>
</tr>
<tr>
<td>Epidote</td>
<td>5</td>
<td>2</td>
<td>4</td>
<td>6</td>
<td>6</td>
<td>3</td>
<td>2</td>
<td>2</td>
<td>4</td>
</tr>
<tr>
<td>Others</td>
<td>9</td>
<td>0</td>
<td>8</td>
<td>4</td>
<td>3</td>
<td>4</td>
<td>4</td>
<td>3</td>
<td>5</td>
</tr>
</tbody>
</table>
see Table 53. On some filters the loading of certain minerals was too low to give an accurate result. Such values have been omitted from the table. Very low concentrations have been included for other samples because, in those cases, a larger volume of samples was filtered with the result that the load in the filter was higher. The total concentration of solids, determined earlier by gravimetric analysis, is also given in Table 53 for each sample. In a number of cases these values, which were known to contain errors, have been adjusted on the basis of the other results in the table. The changes were no greater than 30 ppm but in samples with low concentrations even small changes may involve large percentage errors. For this reason the mass of each element in the sediment particles has not be expressed as a proportion of the total load. Three filters (8, 14 and 19) were seen to have very high loadings. Under these circumstances the X-ray fluorescence spectrometer may give values for individual elements which are too low because the sediment particles are too closely packed. The sediment loading on the filters was an important factor in determining which of them were suitable for this form of analysis.

It is clear from Table 53 that silicon and aluminium are present in relatively large quantities. They are present in the form of various alumina silicates which form the bulk of the inorganic sediment load in most rivers. Since aluminium constitutes about 10% of the mass of most alumina silicates likely to be present, the concentration of aluminium may be used as the basis for estimating the total sediment load for samples in which the concentration of organic matter is thought to be insignificant. In the samples analysed above the ratio of aluminium to total load appears to be in the range 6 - 9%, see Table 54, indicating that there are probably appreciable quantities of organic matter present in the Zambezi's water as suggested by Hall and Valente Burholt.

For many purposes the ratio of the weights of two elements may be more revealing than their absolute values. These ratios can provide important information about the sediment characteristics of the basin and of its different tributaries. However, there are a number of factors which affect the chemical composition of sediment and which must be considered. Differences in composition may be found; firstly, in sediment
<table>
<thead>
<tr>
<th>Sample Number</th>
<th>River</th>
<th>Location</th>
<th>Date</th>
<th>Sampling method</th>
<th>Sample Volume (ml)</th>
<th>Total sediment loaded (ppm by wt.)</th>
<th>Mass of element on filter expressed as a concentration in the unfiltered sample (ppm by weight)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Luangwa</td>
<td>Mfwe br.</td>
<td>29.40.80 superficial</td>
<td>25</td>
<td>&lt;4</td>
<td>310</td>
<td>K 0.094, P 37.0, Al 18.8, Ca 1.17, Mn 11.6, Fe 0.138, Si 0.042, Ti 0.65, Cl 0.072</td>
</tr>
<tr>
<td>2</td>
<td>Luia</td>
<td>Bone</td>
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* Value adjusted as described in the text.
Table 54: Ratios of selected elements based on the results of Table 53, (%)

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originating from different parts of the basin; secondly, in sediment produced during different seasons of the year; thirdly, in samples obtained by different sampling methods; and fourthly, in different particle size fractions of a single sediment sample. Because of the complexity of these relationships it is difficult to draw firm conclusions from the results currently available.

The Si/Al ratios, given in Table 54, have been considered in some detail. On a global basis the mean value of the Si/Al ratio for river sediments is approximately 250%. Where the ratio lies in the ratio 300 - 400% a basin generally has an abundance of quartz. Conversely, where the ratio lies below 200%, as in the Zambezi basin, there is generally an abundance of laterite or bauxite. For the Zambezi, this conclusion is supported by available information about the basin's geology as well as by the study of bed material by the MFPZ discussed above.

Although Tables 53 and 54 include only two dry season samples (15 and 27) these appear to indicate that in the dry season an increase in the Si/Al ratio occurs. Other samples taken under flood conditions (1, 8 and 14) also appear to show increased Si/Al values whilst in another case (19) floods caused the ratio to fall. The processes which produced these variations are not clearly understood.

The effect of particle size on the Si/Al ratio may also be seen in Table 54. In general the ratio appears to fall slightly as larger particles are removed during sedimentation (2-4, 16-18 and 20-22). Changes of this nature may indicate that particles of a different size have different compositions. Alternatively, the composition may be uniform but if particles of a certain mineral present have a high specific gravity they will settle out in a sedimentation column faster than similar sized particles of other minerals. Thus, the concentration of that mineral will appear to decrease as the analysis proceeds to smaller particle sizes. In a natural river such processes will also be at work with the result that, in all but the most turbulent rivers, sediment composition analysis is likely to be influenced by the method by which samples are obtained.
With regard to other elements a large number of different ratios have been suggested as showing important characteristics of the sediment. However, the most common practice is to express other elements as ratios with either silicon or aluminium since these elements show fairly constant concentrations over a wide range of particle sizes. Comparison between Mn/Al and Mn/Si ratios in Table 54 suggests that there is little to choose between the two for the majority of cases but where the Si/Al ratio deviates significantly from the mean, as noted above, considerable differences may arise. In general it has been decided to use aluminium as the basis for these ratios in the present study.

It is beyond the scope of this work to consider the results obtained for each element individually. A brief discussion of the Fe/Al ratio is, however, included because of the possible implications for agriculture of high iron concentrations in sediment deposited in floodplains. Iron is the third most plentiful of the elements analysed and some will be present in the alumina-silicates discussed above. The remainder may be in the form of iron oxide. In general, if the Fe/Al ratio rises much above 50% excess iron oxide is likely to be present. Of the samples analysed, about half had values greater than 55%. It is these sediments which are likely to be agriculturally unproductive.

There appears to be no clear pattern as to which samples show high Fe/Al ratios in Table 54. Two of the highest were found in samples taken during floods (8 and 14) but another very high value was found in a dry season sample (15). Of the remaining samples taken in flood conditions, two (1 and 19) have relatively high Fe/Al values whilst others (2 - 7) have relatively low values. Clearly, a more detailed programme of sampling would be required before useful conclusions could be reached. The present work would be of some value in planning such a programme.

Hall and Valente Burholt also produced results from an analysis of the sediment which was obtained during their sampling programme, see Table 47b. The aluminium concentrations in this table are of the same order of magnitude as those of Table 53 and show similar variations between the wet and dry seasons. The ratios k/Al, Ca/Al, Fe/Al and Mn/Al may also be derived from Table 47b and compared with those of Table 54. Apart from the Shire in the wet season, which had a very low
aluminium concentration and, therefore, high values for those ratios, there appears to be broad agreement between the two sets of results. However, the Hall and Valente Burholt values show a marked increase in the k/Al ratio, in the dry season, as well as a marked decrease in the Fe/Al ratio. Such changes do not appear in the data of Table 54. Unfortunately neither set of results is sufficiently detailed for the origins of such differences to be traced.
Appendix 9

Survey of data from floods capable of causing major inundations in the lower Zambezi valley.

Four independent hydrological records were studied to identify the highest river discharges in the lower Zambezi since records began. Two of the records were the 'natural' discharge series at Cabora Bassa, prepared by RPT and the DNA, which were used in the flood frequency analysis in Chapter 3 of this thesis. For these, the criterion selected for a flood likely to cause a major floodplain inundation was a mean monthly discharge of over \(10 \times 10^3 \text{ m}^3/\text{s}\). This occurred in nine years of the RPT series and in six years of the DNA series. The other two records studied were the records of daily gauge levels at Marromeu and Luabo. Since the zero of these gauges was set at the level of a flood which caused a major inundation in 1925/6 it is convenient to use the gauge zero as the criterion for identifying large floods. The zero level was reached or exceeded on seven occasions in the Marromeu record and five occasions in the Luabo record. A flood event which satisfied the stated criterion in any of the records has been included in the present study. The twelve floods thus identified are shown in Table 55. Where an event has been identified as a flood in one record the details of the event in other records are also given even if it does not satisfy the criteria for those records. The results suggest that major inundations occurred in the lower Zambezi at a frequency of approximately five years although their severity is difficult to judge from the available data.

Detailed study of the data in Table 55 reveals a number of difficulties. Firstly, the records are not of equal length with the result that the twelve floods selected do not appear in all four series. Secondly, because two of the records are based on estimated mean monthly discharges whilst the other two are based on daily peak river levels, there is a possibility that a flood of relatively short duration may have produced high gauge levels in the floodplain which would not have appeared as a major flood in the discharge records. Thirdly, the discharge records for Cabora Bassa would not record floods generated in tributary basins downstream. Either of the latter factors might explain why floods in 1939/40 and 1943/4 were
Table 55: Major floods recorded for the lower Zambezi

Cabora Bassa 'natural' discharges:
One-month annual maximum flood series

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<th>Rank</th>
<th>Year</th>
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<th>Rank</th>
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Q = mean monthly flow (m³/s x 10³).

Gauge records, DNA files, Maputo

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Brackets indicate that the event is not part of the continuous data series.
relatively severe at Marromeu (and also Mutarara) but were much less severe in the Cabora Bassa data series. They may also explain the low ranking given to the 1925/6 flood in the RPT series. However, since the RPT series contained a large synthetic component in the initial years, the discrepancy may be due to errors in that series. Data errors are, therefore, a fourth factor which must be taken into account. They may account for the discharge recorded in the RPT series for 1952/3 which appears, from the other records, to have been too high. Finally, since the Marromeu and Luabo records are based on gauge levels they do not accurately represent discharges because the mobile river bed is subject to significant changes in profile in these reaches. Nevertheless, they provide a good indication of the extent of floodplain inundation.

Four of the twelve high floods occurred after the construction of the Kariba Dam and one was also after the completion of the Cabora Bassa Dam. Of these, the 1962/3 and 1977/8 floods may have been attenuated slightly by the dams but still caused major inundations in the floodplain. The other two, in 1968/9 and 1973/4, as indicated in the RPT and DNA data appear, from the Marromeu and Luabo records, to have been attenuated appreciably by the Kariba Dam. In particular the presence of the dam appears to have prevented a major inundation in 1968/9.
NOTES AND REFERENCES

Introduction

1. Cited in Institution of Civil Engineers (1978) p5.
3. For a more detailed discussion of climate see Griffiths (1972).

7. UN, World Trade Statistics, New York (various years).
12. See, for example, Torp (1979) p38.
13. For further details of the party's formation and development see Frelimo (1970).
15. See, for example, Frelimo (1978) p43.
16. A speech by Samora Machel in 1972, cited by Vail and White (1980) p372, emphasizes the importance which was attached to stimulating popular initiative during the armed conflict.
22. See note 18 above.
27. Speech by the Governor of Tete Province in reference, specifically, to salary levels in HCB: Tempo, Maputo, 538, 1 Feb, p5.
30. See Fonseca (1968) and Conselho de Coordenação do Decénio Hidrológico Internacional (1971).

Chapter 1

34. The provisions of this act, incorporating the five amendments made to it between 1933 and 1941, are reproduced in Clapp (1955) Appendix B.
35. Lilienthal (1944) p77.
38. Ibid.
39. Lilienthal (1944) p177, emphasis in original.

Chapter 2

43. For a more detailed account of prazo agriculture see Isaacman (1972) p64-9.
44. For further details see biographies of Livingstone, for example Jeal (1973) and Listowel (1974), which include important primary sources.
50. Ibid, p208.
51. See Rankin (1892 and 1893).

52. Esquema Geral, 17.2, p354-64. For example the principal commodities exported by river from Tete in the period 1907-1909 were groundnuts (200 t/yr), mapira - a local variety of millet - (100 t/yr), maize (40 t/yr), sesame seed (60 t/yr), timber (30 t/yr), cattle (500/yr), goats (1 000/yr) and sheep (150/yr). Figures for 1925 suggest that exports of most of these commodities had, in the interim, slowly declined.

53. Esquema Geral, 18, p2.
54. Relatório Preliminar, 2, section 4.2.
55. Ibid, section 4.10.

58. See, for example, the graphic account of the difficulties of navigation - including the frequent need to free vessels from sand banks or, at times, haul them over the sand banks using teams of African labourers - in Esquema Geral, 17.2, Ch. 6.
60. See Trapnell (1953) and Trapnell and Clothier (1957).
61. See, for example, Gale (1949).
62. An official report on navigation upstream of the Victoria Falls was prepared by Smart (1948).
63. Esson (1905) p957.
64. See Troost and Norman (1969) p177.
65. For further details see Metropolitan Vickers Gazette Manchester, 11(184), July 1928, p4-12; Legge (1970); and Olivier, Great Dams p71.
70. Olivier, Great Dams, p112.
71. After Anderson et al. (1960) p58.
72. Reeve and Edmonds (1965) p175.
74. Based on information drawn from reports in Water Power, 6, 1954 p205, 245 & 284 and 7, 1955, p42 & 280 and from the technical references cited in note 76 below.
75. See, for example, Anderson et al. (1960); Gibb and Partners (1958); Laborde-Milaa (1959); and Olivier (1975 and Great Dams).
76. See, for example, Balasubrahmanyam, S, and Abou-Zeid, S.M., 'The Kafue River Hydro-Electric Development', in Howard and Williams (1982) p31-5; Brown (1974); Corlin and Larsen (1979); Rosenstrom (1972); Williams (1977); and ZESCO (1977). Earlier designs for the Kafue Project may be found in Water Power, London, 5(4), 1953, p125-30 & 150; and de Rosenbaum (1953).
77. For further details see Appleton (1974a).
82. Ibid., documents 1.19, 1.20, 1.25 and 1.35.
83. Ibid., documents 1.26.
84. Ibid., documents 1.34.
85. Salazar to the Minister of the Colonies, 22 Mar. 1950, Ibid., document 1.29.
86. Ibid., document 1.28.
88. Debenham (1952).
90. See, for example, GPZ (1971a) and Falcão (1963) p56.
91. GPZ (1971a) writer's translation.
95. See, for example, Davidson (1972), Grohs (1974), Henderson (1972), Middlemas (1975), Programme to Combat Racism (1971) and Radman (1974a and b).

98. See, for example, Davidson (1972) p46.


101. See, for example, the accounts presented in the works by Middlemas (1975) and Olivier (1975).


107. For examples of information pamphlets produced in this campaign see Programme to Combat Racism (1971) and International Student Movement for the UN, The Cabora Bassa Scheme, Geneva, no date.

108. The lists are not identical but see Hofmann (1970) Table 1, Programme to Combat Racism (1971) p29 and Donque (1971) p100.

109. Hidrotécnica Portuguesa (1967a). In April of the previous year the report Hidrotécnica Portuguesa (1966) had given estimates of Cabora Bassa’s energy potential similar to those in the Plano Geral.


111. Derived from monthly operating data for the period supplied by HCB to DNA in Maputo.

112. One of the most comprehensive accounts is that of Rodrigues et al. (1973). Details of the civil engineering works are given by Appleton (1974b), Gonon and Lempérière (1975), Lempérière and Vigny (1975), Olivier (1975 and Great Dams) and Volland (1973). Details of electrical engineering works are given by de Rosenbaum (1972), Hofmann (1970) and Klein et al. (1974).

113. Olivier (1975) p127 and 139.


115. See Quintela et al. (1979).


117. His arguments were published in full at a later date, see Olivier (1973).

118. See, Notes on the Development (note 93 above), Overseas Companies in Portugal (1973) and GPZ (1971a).

119. See Lederer (1968) and Donque (1971)

120. The natural river channel downstream of Lupata contains no cataracts. Although its gradient is steep compared to that of many natural channels of the same capacity, it would, nevertheless,
be difficult to design artificial channels of the required capacity which would have gradients significantly smaller. For details of the natural channel characteristics see Chapter 5.

121. *Plano Geral, Texto*, p100-1.
126. Two dryland settlement projects covering a total of $30 \times 10^3$ ha, employing 400 Europeans and 800 Africans; two irrigated settlement projects covering $23 \times 10^3$ ha, employing 1 200 Europeans and 2 500 Africans; and two irrigated plantation projects covering $150 \times 10^3$ ha, employing 4 000 Europeans and 56 000 Africans.
129. See, for example, *Esquema Geral*, 26, p35.
140. Cited in Middlemas (1975) p201.
141. For an account of the negotiations see Mittleman (1978).
143. See note 18 above.
144. For the 1978/9 season the records of the Provincial Agriculture Directorate in Tete lists twenty-five agricultural co-operatives in operation, in the province, comprising 1 100 people and cultivating 1 600 ha.
150. For further details of labour recruitment practices in this period see Head (1978). Vail and White (1980) also show the harshness of the workers' conditions by quoting the words of their protest songs.

Chapter 3

160. Some examples of ancient dam failures during floods and of works abandoned because they failed to fulfil their design purpose are recorded by Smith (1972).
161. See Ven Te Chow (1964) Historical development, in Chow, (ed.) 1, p7-10.
162. See, for example, Linsley et al. (1958), Chow, (ed.) (1964), Bruce and Clark (1966) and Ward (1967).
163. Institution of Civil Engineers (1975a).
169. See, for example C.C. Parkman, contribution to discussion, in ICE (1975b) p91.
170. See, for example, C.L. Clarke, contribution to discussion in ICE (1975b) p99.
171. See Bass (1975).

172. See ASCE (1973) for an evaluation of American practice. Support for the adoption of economic criteria in Britain is given by Cole and Penning-Rowsell (1980). The application of probability theory in the estimation of flood risk to a project over a finite period (its 'economic life') is discussed by Yen (1970).

173. For its use on TVA reservoirs see Bowden (1949) and on Columbia River reservoirs see Whipple (1951).

174. A combined energy rule curve for the TVA reservoir system is given by Blee (1945), Bowden (1949) and by Brudenell and Gilbreath (1959).


177. See Pereira (1973). His work is also extensively quoted by Jackson (1977).


179. See Gregory (1969) who includes an analysis of data from Mozambique.

180. See Minderhoud (1978) for a brief description of the DHV studies.

181. See Esquema Geral, 22.1.

182. See Plano Geral, 55.1.


184. Reference to this work is made in the report by Hidrotécnica Portuguesa (1973) p 35ff.

185. The writer has been unable to study this work in detail but references to it are included in the report by SWECO (1982).


187. Reference was made in the thesis introduction to difficulties in obtaining reliable estimates of the catchment areas for the Kariba and Cabora Bassa Projects. The most comprehensive study available is that presented in the Relatório Preliminar, 2, Figure 2 but comparisons with data from other sources have been made.

188. Communications from the CAPC to the Portuguese authorities, many in the form of telegrams, are preserved in the file Cheias do Zambeze in the DNA offices in Maputo.


191. Ibid., (note 189).
192. On 1 Jan. 1977 the level was 323.25 m rather than 320.0 m and on 1 Feb. 1980 the level was 320.4 m rather than 320.0 m.

193. Contribution by A.C. Quintela, in Proc. 13th ICOLD Congress, New Delhi, 1979, 5, p563-40. The reason why partial openings must be avoided is not entirely clear in view of the fact that Rodrigues et al. (1973), p286, reported that six of the eight gates had been specially designed to operate at partial openings.

194. Sutcliffe (1980) p9 makes a similar assumption in comparing the flood frequency characteristics of various regions of the world without reference to differences in the duration of critical floods.

195. See Cunnane (1975) p44.


197. For details, see Jenkinson (1955).

198. See, Griffiths and Berry (1975) p4.3.

199. Ibid., p4.5.

200. The study of the Itaipu Dam undertaken by Moraes et al. (1979) indicated that a significant increase in design flood would result from full development of the hydroelectric potential of its catchment. However, the hydrological characteristics of the Parana are very different from those of the Zambezi.


202. Based on records in DNA, Maputo. However, the recorded zero elevation of the scale was found to be in error by approximately 0.5 m when a correlation was undertaken with the records of reservoir levels at Cabora Bassa in the period since 1975. Details of this study are recorded in P. Bolton, Um Estudo da Escala do Zumbo (EH 310)... 24 Nov. 1979, DNA, Maputo and the records quoted in the present study have been duly amended.


204. Plano Geral, 55.1, p1.

205. Noticías, Maputo, 5 Apr. 1978, 'Felizement que Cahora Bassa existe'.

206. See note 189 above.

207. Plano Geral, 55.1, p2.


Chapter 4

211. Quoted in Davidson (1966) p118.

212. Quoted in Lanning and Mueller (1979) p27.

No published source has been found to confirm the 1982 and 1990 figures. However, geologists working for the Direcção Nacional de Geologia e Minas, Maputo, have informed the writer of studies being undertaken to assess whether such outputs are feasible.

Falcão (1963) Table XIII.

Falcão (1963). Derived from Tables XVI and XVII.

Plano Geral, Texto, p64 and 67.

See Lanning and Mueller (1979) p190-1.

See, for example, Real (1966) and Thonnard (1971).

See Falcão (1963) p85-9, Middlemas (1975) p225-8 and GPZ (1971a) for summaries of the main proposals contained in the report of the MFPZ.

Esquema Geral, 26, p14.

Plano Geral, Texto, piv.

Ibid.

Plano Geral, Texto, p88.

Plano Geral, Texto, p89 and 209 and Table 44.

Esquema Geral, 26, p11.

Plano Geral, Texto, P117.

GPZ, Resumo de Actividade, March 1972.


GPZ, Resumo de Actividade, April 1972.


Lanning and Mueller (1979) p490. See also p270.

See, for example, McKinnon (1963).

Banks (1979) Table 7.3.

See, for example, Cliffe (1980) p242.

Esquema Geral, 26, p51.

See Middlemas (1975) p230.

GPZ (1973a) p43.

See Banks (1979) p47 and 141.


246. A short account of the development of the electrical power system in Uganda is given by Ogendo (1975) p135-7.

247. See Glentworth (1977) Ch. 4.


251. The policy is stated, with reference to the supply of energy, in papers by Moreno (1964 and 1967).


255. For further details see Moura (1968); de Rosenbaum (1972); Klein et al. (1974); and 'Report on joint meeting of CIGRE A.C. and D.C. Study Committees', Direct Current, London 8(8), 1963, p206-9.

256. See 'Report on joint meeting ...', op. cit. note 255 above.


259. Noticias, Maputo (17 Mar. 1980) reported that 'Energy from Cabora Bassa is being extended to Palmeira and Zinavane' (which lie approximately 100 km north of Maputo).


262. L. Kranendonk, DNA Maputo, Oct. 1979, pers. comm.


266. GPZ, Resumo de Actividado, June 1972.


268. Moura (1968) p95.


270. Da Silva (1964) p113.


272. The problem is discussed, with reference to 400 kV lines of similar length in the RSA, by Troost and Norman (1969).


276. Ibid., p211.


278. GPZ (1971b) p53.

279. Middlemas (1975) p211.

280. Figures presented by Middlemas (1975) p67 & 211 appear to imply that the credit had been provided by the governments of France, Germany and the RSA, respectively in the following proportions: 20%, 20% and 40%. An account contained in GPZ (1971b) p43 appears to suggest that the appropriate proportions were 35%, 35% and 10%.

281. Based on Middlemas (1975) p67. Other sources placed the value of the RSA's contribution even higher; Water Power, 23(1), 1971, p3, stated that the RSA provided two thirds of the total investment.

282. For a discussion of the creation of this company see Mittleman (1978) p8.


285. The failure to produce accounts is reported in To The Point International, Antwerp, 2 Mar. 1979, p18. The reason given in the report for this failure, implying obstruction by the Mozambican authorities, seems implausible.

286. RSA, House of Assembly Reports (Hansard), Pretoria, 3(5), 2 Mar. 1976, p6, qu. 441. Question from Mr C.W. Eglin to Minister of Economic Affairs.


290. This situation is reported to have occurred following the sabotage of the transmission line in the first two months of 1981 according to the Financial Times, London, 4 Mar. 1981.


297. For general accounts of the development of the electricity supply industry in Zambia see Mihalyi (1977) and Williams (1979a).
299. For details of the transmission lines referred to see de Rosenbaum (1959) and Engstrom (1975).
300. See Escom of Malawi (1971), Malawi's Hydroelectric Resources, Blantyre.
301. Stoneman, pers. comm., see note 296. An imminent decision to proceed with the North Bank Station was also indicated in Tempo Maputo, 528, 23 Nov. 1980, p7-8.

Chapter 5

302. The growing awareness amongst engineers of the need to consider more carefully questions related to the transport of sediment is indicated by the publication of a manual by the American Society of Civil Engineers, Vanoni (1975).
304. See, for example, Thomas and Prasuhn (1977) Emmett and Thomas (1978), Hammad (1972) and Bettess and White (1981).
305. See, for example, Khalh (1975).
306. See, for example, White, Paris and Bettess (1981).
307. The Hydraulics Research Station, Wallingford, has developed pump samplers for use in their investigations. Details of the apparatus and techniques are given in three undated mimeographed papers: 'Sampling of suspended sediment'; 'On-board treatment of pumped solids'; and, M.J. Crickmore and R.F. Aked, 'Pump samplers for measuring sand transport in tidal waters'.
308. See, for example, James (1969).
310. See, for example, Vanoni (1975) and Bolton (1979).
311. See Rankin (1889).
312. For Zimbabwe, see work cited by Hudson (1971); for Zambia, see Robinson (1978).
315. Rhodesia Hydrological Year Book 1974/5, Salisbury, Figure H 1902/1, 'Surface area/capacity relations for Kariba'.
316. Lane and Koelzer (1943). See also Koelzer and Lara (1958) and Vanoni (1975) p38-44.

317. See Balon and Coche (1974) p58 where work by G. Bond is cited which suggests appreciable quantities of sand particles may be present.

318. See Ministry of Water Development (1972).

319. Relatório Preliminar, 2, Figure 2.

320. An internal report by P.A. Muncaster, to this effect, is cited by Balon and Coche (1974) p83.

321. Details of the work, undertaken from the Department of Civil Engineering, University of Rhodesia and the Hydrological Branch of the Ministry of Water Development, Salisbury are recorded in the following reports and papers: Ward (1976, 1977 and 1980), Chikwanha (1980), Chikwanha and Ward (1979) and Ward and Chikwanha (1980).


325. See, for example, Elwell (1975 and 1980), Elwell and Stocking (1974), Stocking and Elwell (1973) and Stocking (1978).

326. Plano Geral, Texto, p190. The present arrangements for financing the project, based on the sale of power to Escom, envisage an 'economic life' of thirty years or less, see Chapter 4.

327. The principal tributaries are the Hunyani, the Angwa and the Musengesi. Catchment areas are derived from Ministry of Water Development (1972).


333. Samples are reported to have been obtained using a US D-49 depth-integrating sampler. Unpublished data were kindly provided by Dr T.C. Sharma of the National Council for Scientific Research, Chelston, Lusaka in April 1980 and February 1981.

334. Relatório Preliminar, 2, Figure 2.

Leopold, Wolman and Miller (1964) p291.

See Leopold and Wolman (1957).

See Chien (1961) who has proposed a relationship between the extent of the lateral movements and the discharge of the river.

Ibid., note 336.

Data from Plano Geral, 29.2.

GPZ (1974) Table 4.

ASCE (1965) Table 1.


See, for example, Vanoni (1975) p621-3, Leopold, Wolman and Miller (1964) p454-7 and Stanley (1951).

Plano Geral, Texto, p192.

The discharge was presented in two forms, the mean annual discharge and mean annual flood. Separate correlations were undertaken for each. For the Zambezi the values of these discharges are approximately 3.2 x 10^3 m^3/s and 8 x 10^3 m^3/s respectively. The sediment size variable was defined as the percentage bed material smaller than 74μ which, for the Zambezi, is probably about 1% from the results given in Appendix 8.

Plano Geral, Texto, p203 and Plano Geral, 54, Appendix. The Luenha 7 Project is also discussed in the report GPZ (1973b), v1.

See Buma and Day (1977) p279-80.

See Sykes (1937) part 1.


See McEwan (1961).


See Chen and Simons (1979).


Data on minimum channel depth is presented in various forms in the volumes Esquema Geral, 22.2, Plano Geral, 67 and GPZ (1974). See, for example, Plano Geral, 67, Fig. 9.

GPZ (1974) p5. It should be stressed that the values given are for navigation downstream. If fully laden vessels of this size were to travel upstream the depths required, according to Langbein (1962), would be 4.3 - 5.3 m.

Esquema Geral, 22.1.


See Hao Zhang et al. (1976).

See Robinson (1971) and Brown (1945).

Chapter 6

364. See various entries in Bibliography 2 under their separate and joint names.
367. References on the growth of aquatic weeds are given later in this chapter.
370. See, for example, Hawes (1951) and Foster (1953).
371. Quoted by Williams and Howell (1977) p95.
373. See Minderhoud (1978).
380. Ibid., p29-34.
381. Plano Geral, 35.1, p29-34.
382. Ibid., p1-2.
383. GPZ, Resumo de Actividade, July 1982.
384. See note 142 above.
385. Plano Geral, Texto, p50.
392. Esquema Geral, 26, p34.
394. See, in particular, Scudder and Colson (1972).
396. Plano Geral, Texto, p207.
399. For details see de Oliveira (1976) p31-50.
401. See GPZ (1972) p23.
405. GPZ (1972) p20.
406. Ibid., p34.
412. Ibid., (writer's translation).
413. Frelimo (1978) p43.
419. See Esquema Geral, 25.1.
421. Esquema Geral, 26, p85.
422. Plano Geral, 35.1, p12, writer's translation.
423. Esquema Geral, 26, p85.
426. Ibid., p220.


433. See Odingo (1979) p176.


435. See note 432, above, p218.


440. See note 432, above, p212-8.

441. See note 431, above, p222-5.


447. The minor tributaries are richer in nutrients, see Balon and Coche (1974) p73.


458. See Scudder (1965 and 1973a) and Scudder and Colson (1972).
466. See Hall and Davies (1974), Davies, Hall and Jackson (1975), Jackson and Rogers (1976) and Jackson and Davies (1976).
468. See Jackson (1975a) and Jackson and Rogers (1976),
472. M.I. Van der Lingen quoted in Davies, Hall and Jackson (1975) p193.
476. Ibid., 396.
480. See Jackson (1974b).
487. See Davies (1975a and b).
490. See Welcome (1975).
492. See Phélines et al. (1973).
493. See Davies, Hall and Jackson (1975), Tinley (1975), and Riney (1977).
496. Kinawy and El-Ghamry (1973) reached different conclusions from those of Orlova and Zenkovich (1974) on its effects.
503. CEA Fonseca to the Governor of the District of Tete, 18 Feb. 1959 in the file 'Cheias do Zambeze', DNA, Maputo.
506. MFPZ (Tete) to CAPC, 6 Aug. 1966, in Correspondence Files, SPA, Tete.
507. Esquema Geral, 22.1, Table 14 and Sheets 1-2.


511. UN Department of Economic and Social Affairs (1976) p107.


Appendix 6


515. Evidence of water level changes has, however, been provided from studies of Lake Malawi, see Crossley (1980), and of the overflow from the Okavango Delta into the Makarikari Depression, see Wellington (1950). The latter suggested that the period from 1925 to 1950 was unusually dry.


517. See Kraus (1955), Lamb (1975) and Winstanley (1973).

518. See Angus Paton, in ICE (1975b) p2.

519. Reeve and Edmonds (1965) p175.

520. For full details see Plano Geral, 29.2, p25-8.


525. See Water Power, 5(3) 1953, p81 and FAO (1968), 3, p37-8. In the FAO report it is estimated that, between 1927 and 1964, about 230 x 10^3 ha (2 300 km^2) of woodland was felled for timber and that the more damaging clear-felling for fuel wood reached a peak of 15 x 10^3 ha/yr in the 1950s.


527. The date is summarized as monthly discharge values in DNA (1980a), Table 6.

528. The data of Curve D are taken from the monthly totals published by RPT (1980), Appendix A. According to the text of this report the data were supplied to RPT by the CAPC in early 1980.

529. Livingstone data are derived from the published reports of hydrological data from the Hydrological Branch of the Ministry of Water Development in Harare.


532. Principal source: Department of Meteorology (1972). For the four longest records, recent data were added direct from the department's files.
533. For a general discussion of rainfall reliability see Gregory (1969). A study of these effects in Zambia has been published by the Department of Meteorology (1974).


537. Olivier, Great Dams, p71, suggested that the reservoir of the Mulungushi power station, on a tributary of the Luangwa, has only run dry on two occasions, in 1933-35 and in 1973.


Appendix 8

539. Plano Geral, 64, Tables 1 and 2, and Plano Geral, 67.


542. For details see Bolton (1979) p31-3.


544. Samples were injected by syringe through Nuclepore filters (produced by the Nuclepore Company of America). The pore size used was such that all particles greater than 0.4\(\mu\) would be retained.


547. Plano Geral, 63.

548. Much of the information on which the following interpretation of these results is based was provided by Dr Brian Price, Dept. of Geology, University of Edinburgh.
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