Nkula Falls hydro-elestric scheme initial development

R. S. ARNOT, D. D. A. PIÉSOLD & J. G. WILTSHIRE

Mr Piésold

One of the main surface features of Malawi is the extension of the great Rift Valley formed in the early cretaceous period 100 million years ago. Intrusions of syenite and granite in the mainly pre-cambrian rock formations of granitic gneisses, pyroxene granulites, quartzites and schists add much to the beauty of the country.

104. The climate is temperate, but Malawi is almost unique in the intensity and duration of its thunderstorms; the famous 'Zomba' storm lasted for 20 h out of 24. The consequences of such storms have been significant in relation to the Lake Malawi/Shire River complex described in the Paper and also, perhaps, to the operational problems resulting from the very wide variation in bed load, suspended load, floating debris, sudd islands, trees, etc., coming down the river at certain times of the year.

105. In the Paper the emphasis has been placed on three aspects: hydrology, technical design and limitations imposed on capital expenditure. For their later work on the hydrology the Authors found invaluable the results of the investigations undertaken in 1927 by Mr Anthony, in 1939 and 1945 by Dr Kanthack and in the 1950s by Sir William Halcrow & Partners.

106. The need for absolute economy at all stages of the Nkula Project was impressed on all concerned. For this reason dugouts were used for investigation work rather than motor launches; for instance, whilst on construction maximum use was made of natural materials and existing installations, the Liwonde bund served as a cofferdam for the construction of the barrage.

107. Whenever possible a maintenance approach was adopted instead of a capital intensive one. A good example of the best use of this philosophy is the design of a spillway for a mining company interested primarily in mineral production over a short period of time. In such circumstances we have known a client to say 'Allow the river to cut its own spillway. If the geological appreciation and design predictions are correct a spillway will be created at little cost. We will take the small risk involved.' Comparing two completed spillways designed for similar flood characteristics and known to be satisfactory in operation, the difference in the costs, £20 000 and £250 000, can be attributed solely to the approach to design.

Mr Wiltshire

The economic case for the Nkula Falls scheme, which was estimated in 1959 to cost only 18% more in capital expenditure than the equivalent thermal station, is clear-cut. Nevertheless, the £2½ million for the first stage of the scheme represented a considerable proportion of the current expenditure on development in Malawi, and the spending of the money was tightly controlled.

109. The comparison between the hydro-electric scheme and the equivalent thermal scheme was based on an annual system load factor of 50%. In fact, the present load factor is nearly 60%, which further improves the case for a hydro-electric scheme. The electrical distribution network is at present very compact, which contributes to the low cost of energy in the Southern Province of Malawi.

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110. The load in the Southern Province last year was close to the estimate, being just over 19 MW and 97×10^6 kWh generated. This represents a 15% increase in maximum demand over the previous year, and a 20% increase in units generated. The need for new generating capacity in 1971 at Tedzani is thus still urgent.

111. Plans exist for a transmission connexion to Lilongwe, in the centre of Malawi, where a new capital city is to be built. A logical next step will be to develop the hydro-electric power resources which exist in the north and to connect them to Lilongwe, thus creating the backbone of a transmission from north to south.

112. In conclusion, the Authors would like to pay tribute to the many people in Malawi whose foresight and determination made the Nkula Falls scheme a reality, and to the Contractors who accepted the emphasis on economy and completed the work on time.

Mr R. G. Taylor, Sir William Halcrow & Partners

I was particularly interested in the Paper because it is, to my astonishment, as long as 18 years since I was involved in some of the early investigations for the Shire River Project of which this is the first real beginning. I was also interested to note that, despite the 15 years of additional records since the Halcrow Report was published in 1954, no significantly different conclusions appear regarding the overall hydrological study.

114. Since 1954 the lake has fluctuated over a range of about 10 ft, which is not inconsiderable, and, so far as I can ascertain from the Paper, has exceeded the previously recorded highest level, which was in 1937, by something over 1 ft.

115. I would like to mention the position in 1954. At that time the lake had already fallen about 8 or 9 ft below the previously recorded highest level, which was, as far as we were concerned, a very sacred one indeed. Now that the 1937 level has been exceeded and the present control arrangements appear to allow for levels which are even higher, I would ask the Authors to explain what has occurred to make this possible. I am sure they will forgive me for emphasizing that everything depends on getting water out of the lake, and how much easier that task is if the lake can be maintained at a high level.

116. There are a number of other points which I find interesting, but one in particular is that when, in 1955, a decision was made to build the Liwonde bund, which had been devised as a very coarse form of lake control, the following two years contributed free water of no less than 6 ft. Following the construction of the barrage at Liwonde, which seems to have been in 1961, the free water in the succeeding two years was no less than 8 ft. This also emphasizes how very much wetter the last decade has been and how fortunate Malawi is to have a good supply of water at the present moment.

117. This leads me to ask the Authors if they can confirm that, since the barrage was built, apart from a short period in 1965 when gates were closed to assist construction at Nkula, the gates have not required to be closed to regulate the lake level. If that is so, perhaps they will forgive me if I ask a further question. Would it not have been possible, with the knowledge of hindsight, to have deferred construction of the barrage and perhaps spent the £350 000 on some other more deserving feature of the scheme, dredging, for instance?

118. The Halcrow Report scheme for controlling the lake levels was very much restricted by the need not to exceed the 1937 level, and I think that the Authors are fortunate in being able to consider higher levels for maximum and normal operation.

119. I would also ask them to clarify the range over which the present scheme is reckoned to control lake levels. It seems to me that their range is rather smaller than the 14 ft which we had estimated as being necessary if the upper lake level had to be maintained below 1556 ft. I am labouring this point perhaps, but it does come to my mind how very much we were, in 1957, involved in tremendous repercussions when

the lake level was approaching, but not exceeding the 1937 level. I would be interested to know how the present inhabitants of Malawi, and those responsible for its development, have been able to live with this higher level and to accept it, because whilst it must be a good thing for hydro-electric power, I trust that development of the lake shore has not been impaired.

120. I find remarkable the fact that a scheme completed in 1967 could be achieved at a cost somewhat less than that which was conceived in 1959. There must be some very good reason, quite apart from the extreme care and attention to economy at all stages which the Authors have so ably demonstrated.

Mr R. Casinader, Binnie & Partners

The hydrology of Lake Malawi and the Shire River is fascinating. However, in view of the detailed discussion that has taken place in the past on the subject and which, I am sure, will continue to take place, I shall confine my remarks to the purely hydro-electric aspects of the scheme.

122. The installed capacity of 24 MW is only a quarter of the potential of the Nkula Falls site itself, and only some 2½% of the estimated 1000 MW potential of the Middle Shire River. The scheme is therefore very much in the nature of a pilot scheme for the future development of hydro-electricity in the area. A pilot scheme, providing as it does valuable information on various design aspects and construction costs as well as construction and operating experience, can be of particular value before embarking upon much larger projects in the developing countries. It would be interesting to hear the Authors' comments as to how this factor might have affected the capacity chosen for the initial development.

123. According to § 7, the consulting engineers were given a financial target within which to design a scheme of 16 MW. We have already heard how this affected various design aspects, but it would be interesting to hear the Authors' comments on how the terms of reference affected the economic decisions on the project. For example, the size of a tunnel is often selected to give the lowest long-term cost/benefit ratio. What was the criterion in this case?

124. In § 98, the Authors rightly emphasize the importance of taking inflation of fuel costs and wages into account when comparing thermal and hydro-electric schemes. These factors can easily be allowed for if the discounted cash flow method of cost analysis is used, but it is rather more difficult if the method used is the annual charges method on which Table 6 appears to be based.

125. The intake works are extremely interesting, and it would add greatly to the value of the Paper if the Authors would describe the various designs tested by the Hydraulics Research Station. The design has apparently been very successful in excluding bed-load except during heavily laden floods. Fig. 10 suggests that by accentuating the effect of the bend it might have been possible to develop greater cross currents, but presumably there were practical difficulties in doing this. It would be interesting to hear more about it.

126. The design is apparently not quite so successful in dealing with suspended matter, 90% of which appears to pass into the tunnels. We have heard of the possibility of damage to the runners, and also why it was not possible to allow for sand traps. Was provision made for adding these at a later date?

127. Fig. 9 (d) and § 58 indicate that in the embankment section of the barrage, filter layers of gravel and small rockfill, between the earthfill and rockfill zones, are only 3 in. thick. How were these very thin layers placed, and was there any tendency for the layers to be pinched out?

Mr H. R. Bridger, W. & C. French Ltd

At the time these works were being constructed I was associated with them on behalf of the principal contractor, Messrs W. & C. French.

129. First, I thank the Authors for the Paper, which is of particular interest to me and, I am sure, will be of interest not only to all those who have been associated with work in Malawi and Africa generally, but also to all those who are interested in hydro-electric construction. The Authors should be congratulated on the fact that they have piloted this scheme through so many political changes. Mr Piésold referred to the fact that when they started they were working for the Nyasaland Protectorate; it then became part of the Central African Federation, reverted briefly to some form of Colonial status and eventually emerged as an independent country. Governments may come and go but engineers seem to go on for ever.

130. Mr Piésold also referred to the economy with which the scheme was designed and was kind enough to say that the enthusiasm for economy was shared by all who took part. I must add, however, that some of that enthusiasm was a little difficult to discern at certain points of the contractor's organization.

131. The first part of our task was construction of the Liwonde barrage. We were given the opportunity to tender through the good offices originally of Kennedy and Donkin, with which firm we had been associated in Uganda. We were rather strange to Malawi but we had not anticipated any particular difficulty in acclimatizing ourselves, and did not do so; with the co-operation of both client and consultants the job went very smoothly.

132. The first and most important part was construction of the radial gates and the piers in which they were built. This involved working within an existing bund. The bund first had to be flattened off at the top to allow piling equipment to come in. Then the piles were sunk to bed level. The cofferdam was formed with sheet piles, and excavated material from the cofferdam was put outside to form a blanket. Theoretically, by taking material out of the middle and putting it on the sides you achieve a cofferdam. Unfortunately the slopes of the sides had to be a good deal flatter than we had hoped, and we had to get a great deal of borrow material to hold the slopes outside the cofferdam. We thought we would be faced with the problem of removal, but we were helped by the consultants in experimenting with the removal of blanketing materials by regulation of flow through the radial gates, and this solved the problem.

133. The closure structure presented no particular difficulty. The central core was made of broken stone, and then the filter layers were tipped down the sides of the central core and raked to the required thickness.

134. A point was made that it might have been possible to do without this barrage. That may be so, but there is one aspect to which the Authors did not refer; it has provided an invaluable bridge and link between the south and the centre of Malawi. Prior to this, the crossing of the Shire was by an old ferry pulled along on a wire. Here they have a first class bridge complete with a control structure at what I think is a rather low cost—lower than that of a bridge of somewhat similar dimensions elsewhere in Malawi. So there was great value in that bridge, which has opened up the road from Zomba and Blantyre to Lilongwe, where the new capital is to be.

135. The first part of the main work was the intake. There, the necessity of having the control at Liwonde became apparent. It would, I think, have been impossible to build the cofferdam lower down the river; it could only have worked provided at the same time there was some upstream river control. So, quite apart from its value as a bridge, the barrage made possible the intake works and to some extent the work in the power station itself.

136. I believe that when the scheme was originally proposed there was to have been some form of control work on the left fork at the intake.

137. The next part of the work was the tunnel; this was constructed by International Contractors, a company associated with Roberts, the well-known South African contractors. The main thing we were concerned with there was our hope that excavated material would provide us with the aggregate needed for concrete

construction. Owing to the variable nature of the materials which came out of the tunnel it did not work, and we had to buy most of the material from elsewhere.

138. In the excavations for the power station, the anchor blocks and pavings under the penstocks and the surge tower, the principal problem was one of the nature of the rock. It was fairly heavily fissured, and we had a great deal of over-break. It varied a great deal in texture and we were not able to trim it to anything like the fine limits we would have liked, particularly in the power station.

139. As Mr Piésold said, the cofferdam formed from excavated material proved extremely effective. When we started the work it was intended to have two sets; during the course of the work the decision was made to have the third one and that decision was of a little assistance to us.

140. One of the problems which one always faces in East and Central Africa is labour, but Malawi men are good workers. Indeed, they form the basis of much work in the South African mining industry, in which they have to have many skills useful also in civil engineering construction. We finished with a force that consisted of supervisors drawn from England, Rhodesia and South Africa, foremen from Italy and India, and workmen from Portugal, Kenya and Malawi. We had this miniature United Nations down in the middle of the bush in Malawi at a time when there was a good deal of political awareness because of the coming of independence, and at no time did we have the slightest difficulty with labour. That was due I think mainly to the fact that they were kept well employed, well paid, well housed, and also to the great assistance we had from the Government at all levels. On one occasion President Banda himself came to the job, lined up the supervisory staff on one side and the workers on the other and said, 'I have brought these men to do a job of work for our country; you must do what they say. If these men do not work properly I shall send them home. If you do not work properly I shall punish you.' We had no trouble with labour.

141. In conclusion may I say how grateful we were for the assistance we got at every stage of the job not only from the employing authority, the Electricity Supply Commission, but also from the Consulting Engineers.

Mr H. Headland, Consultant, Kennedy & Donkin

Undoubtedly the experience implicit in this Paper must not be overlooked in the Shire River developments foreshadowed in § 101; in particular the effect of debris and silt on plant operation point to the need to tackle potential troubles at the source rather than in the plant itself. In small schemes where investment targets, as mentioned in § 7, must be met, some initial savings must inevitably emerge as false economies. Paragraph 67 is perhaps an understatement, and the Authors may have done themselves less than justice on such topics. For example, the sediment analysis given in § 62 could have been coupled with concentration and petrological data. Concentrations of 2500 p.p.m. are not unusual and on occasions rise to 5000–6000 p.p.m., some of which is high on Mohr's hardness scale. Plant design endeavoured to take care of this, first by using special easily weldable and erosion resistant stainless steel in the runners, as mentioned in § 85. This was the first occasion this newly developed material, emanating from seawater corrosion and erosion studies, was employed, but it is now commonly adopted for turbine runners, Pelton buckets and in other fields. Secondly, facilities for runner withdrawal without machine dismantling via the removable draft tube section, as shown in Fig. 15, were provided, and thirdly a spare runner was provided.

143. The effect of sand and silt on the runners, as distinct from limited and unusual cavitation damage, approaches that encountered in stations using water from glacial and alpine rivers. There is need for research in this field on basic materials, but three papers[1-3] on protective coatings to the International Association of Hydraulic Research Symposium in 1968 are potentially encouraging as inexpensive maintenance techniques.

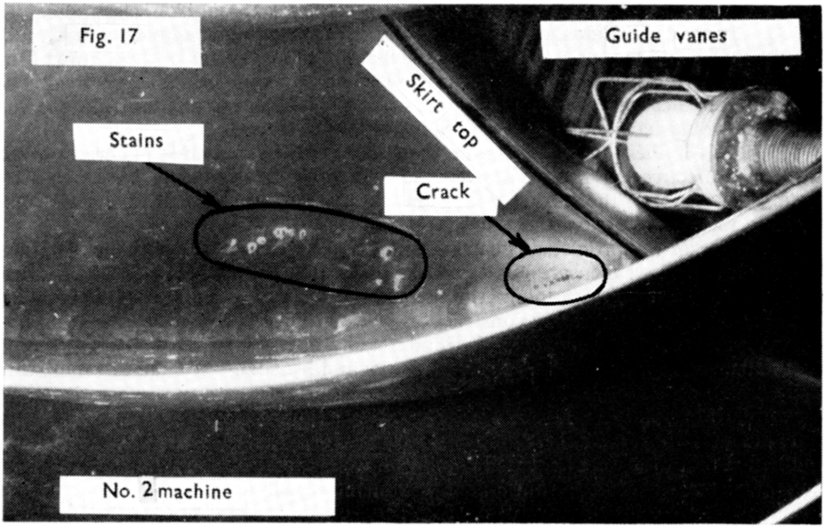

Fig. 17. Typical runner damage

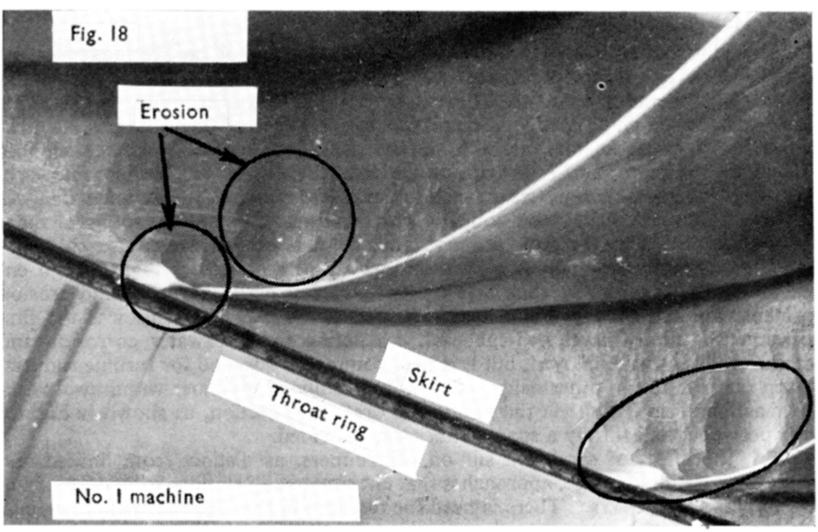

Fig. 18. Runner blade edge thinning

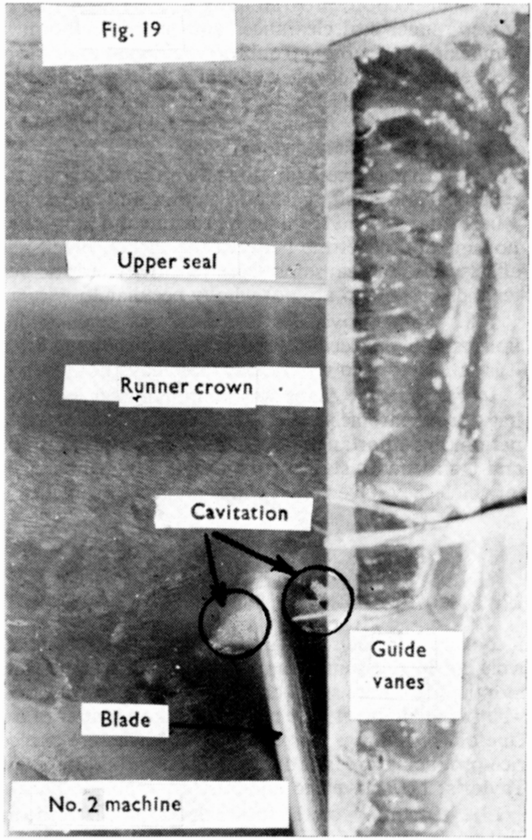

Fig. 19. Runner inlet cavitation at blade/crown junction

144. Figs 17 and 18 illustrate the nature of the damage sustained by two runners after several thousand hours' operation; the effect of the sand and silt carried through the runner passages will be seen to resemble ripples on the bed of a river. Fig. 18 also shows pronounced blade edge thinning. This material has high erosion resistance; the damage gives some idea of the abrasive action of the river water. Figs 17 and 19 also reveal incipient cracking in the vicinity of the blade outlet cavitation at the blade inlet/crown junction, which is a rather unusual location for this type of damage.

145. There are two items in the text which perhaps need clarification. The first is the reference in § 74 to surge chamber characteristics and dimensions, which seems to fail to discriminate between large load change effects and small load variation stability where machine, governing and electrical network considerations determine the Thoma area margin. Secondly, the butterfly valves mentioned in § 85 are opened under balanced pressure via an oil system but close by weight operation in an emergency via over-velocity paddles for pipeline failure or protective devices on turbine overspeed or major machine faults.

146. Small low-cost station design and construction is often more demanding than that for major plants, and the need for meticulous attention to manufacture,

works inspection, programming and erection was evident throughout. Upper and lower runner seal clearances and instrumentation were particularly relevant in this connexion. Teething troubles resulting in multiple guide vane breaking link rupture, heat exchanger blockage and gland leakage difficulties had their origin in water-borne silt and debris, the latter two emphasizing the need for automatic rather than manually operated strainers for coarse vegetable matter and separate fine filters for sand and silt, albeit at some additional cost.

147. Experience has also shown that too little is known about the integration of carbon gland shaft seal construction and operation with turbine design, especially where sand and silt from both pressure and tailrace water can at times enter the gland housing and penetrate between the carbon block and shaft interfaces; among other effects these can cause pressure sensitivity, erratic performance, wear and high maintenance costs, and are not wholly peculiar to Nkula.

148. Some novel features such as semi-outdoor station construction (§ 79), unusually high specific speed Francis turbines (§ 85) and others were introduced, and it is satisfactory to report that these have not given rise to operating difficulties.

149. Since the plant was commissioned in 1966, operating time and conditions have been extremely severe, and much valuable experience has been acquired in this nationally important station. It is appropriate to pay tribute to Escom's operating and maintenance staff for the exemplary manner, both technical and administrative, in which they have coped with operation problems, often under arduous conditions.

Mr F. H. Russell, Sir William Halcrow & Partners

I, too, am very interested in this project, because part of my time in Africa was spent working in the same country and on the same Shire River project. My first six months there were spent carrying out a survey around the shores of the lake to assess what would happen if we raised the lake a matter of 6 ft to above the sacred 1937 level. One of the findings was that if that level were exceeded by 6 ft, the majority of the rice-producing areas around the lake would be drowned. So I add my plea to Mr Taylor's; how have the administrative people been able to get over that?

151. Secondly, on the future development of the middle Shire, it is mentioned that Tedzani would probably be the next site to be used. Further on it is mentioned that there is the possibility of large requirements of up to 200 MW if big industrial developments take place. The only site to my knowledge at which such a large amount can be produced is Mpatamanga, which, if developed to capacity, would drown out Tedzani. Was that taken into account?

152. The other fact is that the original scheme was to put a main control at Matope at the top of the falls. Here, the idea was to raise the level right back to the lake so that there would be less uncontrolled flow coming down the Shire. Several quite large tributaries come into the Shire between the outlet from the lake and Matope, which, as has been pointed out, can bring down large flash floods. With control at Matope the whole flow is much more regulated.

153. The exercise we were carrying out was not purely for hydro-electric power but also for reclamation of the marsh in the lower river and for irrigation there, which is one reason why we were more interested in regulation perhaps than pure hydro-electric considerations.

154. If we had been able to allow the lake to go above the 1937 level it would have made conditions easier. Allowing for the fact that that was our permitted maximum, the only way to get sufficient water down to produce this regulated flow was either to carry out dredging—and there was some 38 000 000 cu. yd of material to be moved—or construct a bund at the outlet of the lake and pump the water over.

Mr H. A. McLean, Watermeyer, Legge, Piésold & Uhlmann

I was concerned with the early stages of the project and I thought that Members might be interested in one or two points relating to the civil works. First, I consider Liwonde barrage, and I assure you that there is nothing really wrong with the barrage despite what you may have been led to believe by looking at Fig. 9 (e). The level of the roadway is RL 1560 and not RL 1538 as you will have guessed by looking at Fig. 19.

156. Mr Bridger has covered a number of the points I had planned to put. He mentioned that the barrage structure itself was constructed within the confines of the bund. The bund was, in the main, soft material, although I recall that at least one bicycle frame was excavated. There was one major obstruction, a block ship, which was placed by the engineers when closing the original bund. This must have been a frightening task during construction of the bund itself, but of course this problem did not reappear when constructing the bund, as it was not a question of closing the whole of the river flow. The flow could be diverted from the embankment section and passed through the gate openings as these were completed.

157. We fully expected that extensive pumping from the excavation would be necessary. In fact it was arranged for the structure to be completed in compartments, two sections at a time, and for the contractor to put in temporary bulkheads. These were to be double timber bulkheads with puddled clay cores, the bulkheads to be attached to the piers and to be moved back progressively as the gated sections were completed. Also, we thought there might be problems of uplift before the superstructure could be completed, and arrangements were made for flooding completed sections as necessary. In the event, as sometimes happens, our fears were not realized and very little pumping was necessary.

158. To construct the embankment we did not have to stop the flow but merely to divert it. Of course the material for the embankment has to be placed basically

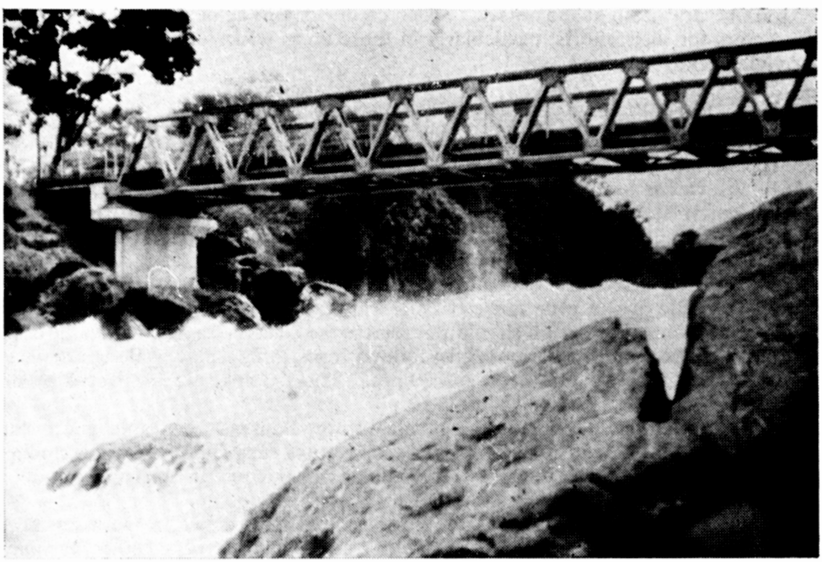

Fig. 20. Callender-Hamilton Bridge over the Shire river

under water. A previous speaker raised the point of how the 3 ft thick layers of filter material could be placed. They were deposited very much as Mr Bridger has said.

159. Fifty miles downstream the work on the Nkula power scheme had started about four months after commencement of the Liwonde barrage. Access to the site during the investigation stage was confined to the Matope bridge crossing of the Shire River upstream from Nkula, which was the nearest crossing to the site. There is a good road from Blantyre to Matope and a lesser road from Matope to Simon, a small village on the other side. It was not difficult to construct an access track to the site from Simon. It was planned that this would be developed for the main construction access for the project. At the time it was envisaged that the main road link south from Blantyre due to be started soon would pass very near the Nkula scheme, and consequently a crossing would be provided gratis. However, a closer look at the Nkula site indicated that some form of bailey-type bridging could perhaps be squeezed in if we linked to the access road already available to Walker's Ferry. This would cut the distance from Blantyre to the site by 20 miles. We spent £40 000 and thereby saved £100 000.

160. Fig. 20 shows that getting it across the river was something of a 'cliff-hanging' operation. Great credit is due to the erector who, as the Authors have said, had very few aids and certainly no skilled labour to assist him. But also credit is due to the engineers and contractors whose measurements were proved to be right the first time. The bridge has a main span of 120 ft, with two side spans on each side of about 15 ft.

161. Now, I would like to mention construction times. The Liwonde barrage was started in early 1964, and the structure itself was very nearly complete by March 1965. It took about four months thereafter to complete the embankment. Meanwhile work at Nkula was proceeding, the two programmes being linked only in so far as it was necessary to operate the completed barrage so that all work at Nkula on the intake and tailraces would be executed in dry conditions as much as possible.

162. Overall, the first machine was commissioned about 2¼ years after the main contracts were placed, and this was exactly in accordance with the implementation programme drawn up at the outset. Much credit for this achievement is due to the contractors for their efforts, particularly in those areas where electrical, mechanical and civil work overlapped.

Mr M. H. Rees, Watermeyer, Legge, Piésold & Uhlmann

I wish to refer to two areas, apparently disconnected: the cost/benefit of power station design, and barrage operating policy.

164. Much has been said of cost/benefit studies for hydro-electric waterways but less for power stations. It is not always recognized that total power house cost depends on the interaction of civil, mechanical and electrical requirements. The total power house cost may be a large percentage of total cost (at Nkula over 40%) and the ratio of mechanical (M) and electrical (E) costs to civil cost for the power house is variable over a wide range from less than unity to 4 or more. It is clear, therefore, that machine design should not dictate the structure as is so often the case, but that the best total power house cost follows from an interplay of design requirements between the two (or three) disciplines. These points are illustrated by an analysis of the Nkula costs in Tables 7–10.

165. The plant/civil ratio for the Nkula 'power house' is 2·6, and reflects the nature of the total design, namely 170 ft head, vertical sets, surface water-excluding structure of massive lower construction, cellular upper construction, and out-door overhead crane.

166. The plant/civil ratio is, I submit, of general importance in the assessment of power house total design. It will vary with head, machine type, whether machines are vertical or horizontal, extent of power station tailwater inundation and whether of underground or surface type. Elsewhere[4] the probable pattern of the ratio is

Table 7. Costs of hydro-electric scheme only

Civil (C) only	%	*Mechanical (M) and electrical (E) only*	%
Intake	13	Turbines and valves	31
Tunnel	45	Generators	31
Valve house/penstock	14	Cranes and pumps	5
Surge chamber	10	Switching, transformers	19
Power station/switchyard	18	Transmission	14
	100		100
Preliminary + C + M + E	%	*Breakdown 'power house' and rest*	%
Exploratory and preliminary	8	'Power house'	41
C	49	The rest	59
M and E	43		
	100		100

Table 8. Cost of barrage only

	%
Structure	70
Bank	22
Gates and hoists	8
	100

Table 9. Cost of whole scheme

	%
Exploratory and preliminary	7
C (hydro)	42
C (barrage)	14
M and E	37
	100

Table 10. 'Power house' only (= power station + valve house)

	%
C.	26
M and E plant	68
Cabling, etc.	6
	100

$$R = \frac{\text{M and E plant}}{\text{C}} = 2{\cdot}6$$

described; it is shown to vary proportionately with the logarithm of head and the effects of tailwater flooding, underground siting and shaft attitude are indicated.

167. Coming now to barrage operating policy, the Liwonde policy allows flexibility in operation. This flexibility must be the starting point for the hydrologist of the African lakes in his attempted projections of the water balance. In the case of Lake Malawi (as applies, indeed, for Lakes Victoria and Tanganyika) the water balance has variously been described as 'delicate' and 'precarious'. This results, of course, from the small percentage of free water derived from the difference between large quantities, primarily rainfall and evaporation, themselves variable, and, in the case of evaporation and of rainfall over the lake, having a historical record possessing limited data and, in many cases, of doubtful interpretation.

168. As a result of these difficulties, it comes as no surprise that three different authorities in recent years have produced rather different water balances for Lake Malawi, in some cases the free water of similar years being attributed with different signs.

169. However, the main difficulty for the hydrologist is the anticipation of climatic conditions. The dilemma is whether he should project on the basis of the historical record or accept a meteorological view associated with the names of Kranz, Lamb, Bargman[5] and others, that the climate of the Eastern part of the African continent is reverting to the Victorian phase of greater extremes.

170. In this respect, prehistoric evidence is of little value in the case of all the African lakes, since the tectonic movements associated with the formation of the African Rift continued into recent geological time, the lowest of the raised beaches and lacustrine deposits dating from this period. It is probable,[6] however, that Man did not reach this part of the Rift valley before the last major subsidence occurred. If so, it is worth while recalling the discovery[7] of Bushmanoid artefacts in the sands at Monkey Bay which had waterworn facets only below a level given as '5 ft higher than the 1937 maximum level'.

171. Taking the wider view, it is worth recognizing that, for the Nyasaland section of the Great Rift valley 'the presence of hot springs along the lines of the youngest faults and the frequent occurrence of earth tremors indicate that the activities connected with the formation of the Rift valley have not entirely subsided'.[6]

172. In the face of all these problems one must recall the words of an engineer[8] whose name is also connected with Lake Malawi: 'I am not planning the millennium but the next few decades.' It is in this context that the Liwonde operating policy must be viewed.

Mr J. G. Pike, *Partner, Raikes and Partners, Rome*

The Authors are to be congratulated on their concise quantitative presentation of the details of a project that marks the first real step in the development of the Shire valley of Malawi, which has been the subject of intensive study and investigation over nearly two decades. The section dealing with hydrology is a useful summary of previous detailed work by Cochrane[9] and Pike,[10,11] and additional extensions by the Authors brings the hydrological situation up to date.

174. The control of Lake Malawi and the regulation of the Shire River is an intractable problem to which there is no ideal solution, but it is pertinent to examine the decision to effect partial control of the lake and river by a barrage at Liwonde. This barrage has, of course, the important function of a road crossing for one of the country's main arterial roads, and being able to effect closure of the river for short periods to facilitate development work further downstream. Nevertheless, in the long term it is arguable from hydrological considerations whether in fact the structure is warranted, and secondly, whether it will perform its function. It is perhaps axiomatic that no barrage on the upper river can control the fluctuations of lake level because the range in free water in the lake is so much greater than the capacity of the channel; it can only minimize them by some 25%. Apart from the short-term difficulties associated with forecasting of future lake levels and the barrage operation, the major difficulty would appear to lie in the unsatisfactory nature of the channel between the lake outlet and Liwonde, which is readily recognized by the Authors in reference to long-term planning.

175. The capacity of the upper river channel depends upon the presence or absence of natural obstructions in the form of bars, reed growth and sudd. Because the gradient is so flat (1:100 000) and the velocity so low at periods of low lake level, these obstructions readily form and are not easily removed until the lake rises to an appreciably higher level and erosion can take place. The characteristic of the stage/discharge curve at the Liwonde gauging station, just downstream of the barrage, is

an instructive example of the effects of bank and channel accretion. The flow at Liwonde, being controlled by the level of the lake, shows a steady rise and fall throughout the year, and minor tributary floods have little effect on this steady annual cycle. The rating curve displays, however, a hysteresis shape, with rising and falling limbs, but these are converse to those normally observed, which is that the lower limb represents rising stage conditions associated with increased slope (i.e. greater discharge for lower gauge height), and the upper limb represents falling stage. In the case of Liwonde the upper curve represents the *rising* stage, and investigations made by Pike in 1960 showed that this was due mainly to an increased value of Manning's n arising out of rank reed growth and sudd that had accumulated along the river margins during the previous dry season. Once discharge reaches its annual maximum, usually in April–May, and starts to decline to its minimum, normally reached in early December, the value of n decreases, as the bank roughness elements are no longer a factor as vegetation follows the water level down. For a given gauge height the difference in flow between rising and falling stages is as much as 20% in this case. As there is a probability that the cumulative lake level will at some future date decline, it is clear that obstructions will readily form and the channel become progressively less efficient, and, under such circumstances, the Liwonde barrage could be deprived of its function. Cochrane[9] emphasized this point when he maintained that no barrage could operate on the upper river over the full range of expected regulated levels without recourse to (*a*) dredging the upper river, or (*b*) building a bund and pumping station at Fort Johnston, or (*c*) raising the level of Lake Nyasa 6 ft above a level of 1556·4, in which case (*a*) and (*b*) would not be necessary. The first alternative would impose an unreasonable burden and the last would be economically and politically undesirable, but the second alternative has considerable merit.

176. As the stabilization of the lake and the control of the river are incompatible, the effect of sealing the outlet and controlling it by a bund and pumping station immediately renders the behaviour of the lake independent of the river, the ultimate goal. As it is possible that the pumping station at Fort Johnston will be required to keep the channel open if the lake level entered a period of decline, it would perhaps have been better therefore to build the bund and pumping station at Fort Johnston in the first instance and dispense with the barrage. The amount of power required for pumping would be of the order of 6–10 MW, which is insignificant compared with the gain in assured hydro-electric power in the middle Shire cataracts which would result from a fully controlled outlet. The advantages of a pumping station over the barrage would have been the severing of the river from the lake, thus providing a greater degree of control and flexibility, probable lower initial cost of an earth bund and low head pumping units as compared with the present structure. Such an installation would not have had to be built for a number of years, thus reducing the initial capital cost of the present Nkula Falls project. Although the present barrage serves also as a highly important and necessary road-crossing, a bridge at this site could have been built for approximately one third of the cost of the barrage by utilizing longer spans.

177. The problem of forecasting future lake levels has been the subject of considerable investigations and these have centred on seeking relationships between sunspot numbers,[12] and the rate of change of sunspot numbers.[9] Pike[11] has put forward a possible explanation for the relationships found to exist and concluded that as a practical means of predicting lake levels any such relationships were however limited. Recent work by Lamb[13] has now focused attention on apparent abrupt changes in rainfall pattern related to a change in general wind circulation affecting most parts of the world, and suggests that since 1960 circulation patterns seem to represent a recurrence of a régime that prevailed over long periods before 1895. Without sufficiently long-term data these conclusions must be tentative at this stage, but a repetition of pre-1895 conditions in the Lake Malawi region would indicate a steady decline in lake level over a long period.

178. Pike[10] found that during the period 1930–1965 inferred run-off into the lake steadily increased from 18% to 25% of the rainfall, and this is seen to be directly related to a rapid increase in population, augmented by immigration, all of whom gain subsistence from the land and who have considerably altered the natural conditions of the catchment. As such a trend would tend to increase available free water in the lake, this would alleviate somewhat the possibility of a long-term overall decrease in lake level. However, this in turn is nullified to some extent by the fact that the bed level at the outlet of the lake at the Fort Johnston 'bar' has been shown by Latham[14] to have risen from a level of 1536 to 1541 ft during the period 1900–1926 and has not been eroded under the influence of high lake levels since then. This implies that flow into the Shire River would cease at a higher lake level than on the previous occasion in 1915.

179. The mean value of free water of 0·95 ft for the years 1900–1965 is noted to be almost identical to Pike's value of 0·97 ft obtained from water balance methods for the period 1921–1964. In attempting to extend the record further back the paucity of data precluded anything but the crudest estimates. In extending the record from 1915 back to 1900 by using the Liwonde rating curve, had the Authors taken into account the fact that the Fort Johnston bar had risen and that the present rating curve is related to a level of 1541 and not to the gradually increasing bed level between 1900 and 1915?

180. A minor error is contained in Fig. 9 (e), where the deck level of the roadway is shown as 1538 ft 0 in., which should clearly read 1560 ft 0 in.

Mr D. J. Dalton, General Manager, Electricity Supply Commission of Malawi

I congratulate the Authors on an extremely interesting and readable Paper. It is obvious that it was necessary to omit many interesting but comparatively unimportant points in order to contain the Paper to a reasonable length. In general the scheme has operated well; the Liwonde barrage, designed to regulate the flow in the Shire at low lake levels, has been used to reduce the flow to assist in river works of other projects, and because of this a certain amount of damage has occurred to the bed of the river below the downstream apron. Some damage was expected, but not to the extent that has occurred, and it is hoped to be able to carry out repairs during the construction of the next hydro-electric scheme. The stability of the barrage has not been affected.

182. The difficulties that have arisen are attributable to the nature of the river and the water conditions; it was known that the river had a high silt loading and that trash could be expected, but not, however, in the density that has been experienced. As seen from the Paper, the silt problem was appreciated, and the materials for the runners, throat ring, etc. were specially selected. The trash problem, however, was not appreciated, and at present is a major one. There are three main types of trash; in the early part of the season dry leaves washed down by the first major rains up-river cause substantial clogging of the screens. Later rains causing flood water conditions bring down quantities of maize stalks, papyrus reeds complete with roots and aquatic weed and grass. Throughout the year there is also the problem of water-logged trees, complete with branches and roots. The nature of the channel ensures that the sudd islands emanating from the Fort Johnston–Liwonde section are broken up and, just upstream of the intake, a series of rapids causes relatively even distribution of trash throughout the depth of the water. In the interests of economy, trash raking equipment was omitted from the design of the intake, on the basis of past experience of run of the river schemes in Central Africa where hand-raking has proved adequate. However, it is quite obvious that the river Shire does not conform to other rivers—the influx of debris is too great to be coped with by hand-raking. This was suspected in 1967 and realized early in 1968, and a prototype movable trash rake was designed, constructed and commissioned. In November–December 1968, at the

start of the rains, the trash rake proved adequate for normal quantities of trash, but inadequate to cope with the major influx of debris under flood conditions and a regulated river flow, and it has been decided that it will be necessary to have mechanical trash rakes operating on each of the six screens. The worst occurrence of the blocking of the intake occurred in December 1968 when the intake was completely choked in $1\frac{1}{2}$ h. The matter was so thick that it was possible for staff to sit on it and load it into drums for disposal. The head loss across the screens required the shut down of the turbines, thus relieving the water pressure on the trash and allowing the mechanical rake and the hand-rakes to operate.

183. It will be appreciated that a certain amount of trash gets through the screens at the intake and, while it is obvious that the majority passes through the turbines without damage, on dewatering it has been noticed that considerable quantities of reeds wrap themselves around the stay vanes. It is thought that these accumulations of trash have resulted in temporary inexplicable reductions in power output, particularly in the case of No. 1 machine, which generally seems to collect more trash than the other two machines. The cooling water is tapped from the spirals of the machines and passes through duplex filters before entering the heat exchangers. At times of dirty river conditions it is necessary to have an operator on each machine whose sole duty is to clean the filters, switching from one to the other as soon as the cleaning is complete. Despite these filters, small quantities of leaves and grass pass through to the heat exchangers and block some of the tubes. A very careful watch has to be kept on the cooling water pressure in the heat exchangers, and when this rises the machine has to be shut down for about 1 h to remove the debris. It will be appreciated that when this occurs and one of these machines is out for maintenance purposes, thermal generation has to be resorted to, and it is necessary to keep boilers under pressure during the rainy season.

184. As I stated previously, the silt loading of the river was known; however, it was not appreciated that the silt, when deposited under static water conditions, would become solid and have to be chipped out. The outflow pipe from the pressure valve fitted to the heat exchanger normally has static water and has been found to be blocked solid with silt, rendering the valve inoperative. It has also been found that tubes in the heat exchangers become blocked following a temporary blockage by vegetable matter. If not too many tubes are affected the slight increase in cooling water pressure is not noticed. Modifications are being carried out to the by-pass pipe, which, it is hoped, will prevent it blocking up. However, the problem of the blocked tubes remains, and it can only be solved by ensuring a matter-free supply of water to the heat exchanger. There are several solutions to this problem, and it is really a matter of deciding on the simplest, cheapest method that can be installed with the minimum of shut down time.

185. Trouble has also been experienced with the glands due to silt; it is essential at all times while the machine is flooded that an adequate pressure of clean water should be maintained to prevent the ingress of silt below the bottom carbons. The silt lifts the carbons sufficiently for the gland water pressure to fall, leading to the rapid failure of the gland.

186. One further point I would like to mention; again in the interests of economy, stop logs were designed for the intake instead of gates. These have been used on occasion to reduce the flow in an intake bay to assist in the removal of a log jammed in the screen. Invariably the stop log itself gets jammed and recourse is made to the local Sub-Aqua Club to free it. It has also been necessary to use the divers on jammed draft tube gates, and I feel that the frustration and time wasted when this happens will soon offset the original economics effected. It is essential in any hydroelectric scheme that the final river works, intake and tailrace, which cannot be constantly maintained, should be 100% reliable.

187. In conclusion, I should like to mention that the main civil and plant contractors were under considerable pressure to commission the first set at Nkula on

time. The thermal station in Blantyre was loaded well over its safe capacity and it was essential to commission before the onset of the cold season. The main Civil Contractors gave clear clean access to the Plant Contractors on schedule, and the hard work of the erection staff of the Plant Contractors enabled the first set to be commissioned in June 1966. The Commission was able to meet all the demands for electricity in the Southern Region.

Mr W. E. Shackleton, Sir Alexander Gibb and Partners

I should like to congratulate the Authors on their most interesting Paper and ask a few questions about Liwonde barrage.

189. It is implied in § 51 that the choice of site for the barrage depends firstly on the foundation conditions and secondly on the existing bund. Would it not have been fairer to say that the obvious site for the barrage was at the existing bund and that the sub-surface investigations confirmed this choice? Were boreholes, apart from the eight through the bund, drilled in the locality of Liwonde?

190. I would also be interested to hear how the rockfill embankment was designed. Presumably the slopes are controlled by the materials' angles of repose under water. Is Fig. 9 (d) incorrectly dimensioned? The two filter layers do not appear to be of adequate thickness to prevent the earthfill being washed into the rockfill. Would the Authors give the particle size grading or the Unified Soils Classification of the earthfill material and state whether or not it differs from the river-deposited alluvium?

Mr D. D. A. Piésold

Mr Taylor is correct in stating that the 1937 high level has been exceeded by something over 1 ft. The new high levels are acceptable since they have been produced entirely by natural causes, i.e. high rainfall and run off, before regulation.

192. The barrage was completed in 1965 and not in 1961. However, the last decade has been wet not only in Malawi but in other major catchments of Central Africa.

193. Operation of the gates has been required in terms of the rule laid down by the hydrological sequence. Lake level control by barrage follows a policy based upon the historical record and is not related entirely to individual high levels. A barrage was essential as a positive measure to safeguard the investment; dredging is normally a continuous and indeterminate requirement and presupposes the availability of funds at unspecified times in the future.

194. The range of levels would be approximately 1548·4–1558 ft. As mentioned earlier, the lake has approached the high level following heavy seasonal rainfall, and conditions along the shore are therefore known and acceptable.

195. The estimates have been maintained by the stability of labour on the one hand and by the attention to detail by all concerned with the scheme on the other hand.

196. **Mr Casinader** has raised interesting and important points, several of which are answered by Mr Wiltshire.

197. The terms of reference and the financial constraints determined the main dimensions. The tunnel diameter does not give the lowest long-term cost–benefit ratio. The economic study was carried out, and the desirability of a larger tunnel was considered but ruled out on grounds of known availability of capital.

198. Various designs of intake were considered and evaluated, including a 'scoop' type facing directly into the current. At low stage when the first rains introduce high concentrations of surface soils, the bend is in fact accentuated by the presence of the low weir and the channel left of the island in Fig. 10.

199. The costs of arranging sand traps would have been disproportionate, and it was agreed by the engineers that the most durable materials would be used in the turbine runners and, further, that the replacement of the latter from time to time would be an acceptable feature.

200. The filter layers are 3 ft thick not 3 in.

201. **Mr Bridger** has drawn attention to some interesting problems which arose during construction. The material used for blanketing the cofferdam at Liwonde tended to slough away, causing some anxiety. However it stabilized at flatter slopes, and fortunately suitable borrow material was readily available.

202. In the early designs provision was made for a control work at the intake, but this second 'string' was abandoned on grounds of cost.

203. **Mr Russell** refers to the possibility of extremely high lake levels and the adverse effect upon rice-producing areas. The historical record and proposals for barrage operation suggest that in the unlikely event of the lake rising to 6 ft above the 1937 level this would be primarily attributable to high rainfall and limitations imposed by the upper river channel, not to the barrage control.

204. It is agreed that better control can be effected at Matope but at a cost too high to be sustained by initial hydro-electric development.

205. The presence of the barrage greatly reduces the amount of dredging required to make possible full regulation. The combination of barrage plus limited dredging provides a lower cost approach than pumping over a bund at the lake outlet.

206. **Mr McLean** is thanked for his valuable contribution in amplifying specific aspects of interest, and also for drawing attention to certain corrections required.

207. **Mr Rees** comments upon the variations in hydrological results prepared by different authorities. Differences year by year are due to the particular hydrographic year selected and whether the calculations are done monthly, quarterly or annually. Of importance, however, is the very close agreement on the average free water available over the reliable period of the historical record.

208. **Mr Pike** refers to the desirability of sealing the outlet from the lake and controlling the flow by bund and pumping station and suggests, further, that such an installation could be deferred for some years. This approach assumes that the capital needed would be available as and when required. Unfortunately this is not normally the case. If the installation were required after a few years due to falling levels, the costs of low lift pumps capable of discharging over 2000 cusec would be high in relation to the costs of Nkula. The costs of the transmission system to serve such a pumping station would also be formidable in the early years of development. However, in the very long term, it may be advantageous to use a pumping system and perhaps even manage the lake at lower levels, thereby reducing evaporation and increasing the yield.

209. Mr Pike has correctly drawn attention to the paucity of data prior to 1921. Unfortunately this is a feature of the records on major rivers in Central Africa. Rainfall records frequently go back to the 1900s, but hydrographic work tends to become more reliable only in the 1920s.

210. There is justification for using the rating curve retro-actively over the period 1900–1915. The Authors do not believe that there was significant slow build-up of bed level in these years, but that the Upper Shire was closed by a combination of low lake levels and a local injection of silt and coarse granular material by the Nkasi and Nkangai.

211. **Mr Shackleton** inquires as to the selection of site for the Barrage. The old road bridge site downstream of Liwonde where the river changes grade is probably somewhat better than the Liwonde site from the viewpoint of foundations. However, the existing bund at Liwonde available for cofferdam work tipped the scales. Boreholes were placed along the banks at the road bridge site and at other points in the Liwonde area.

Table 11. Preferred material available for earthfill zone of closure embankment

BS sieves	Percentage finer than
$\frac{3}{4}$ in.	100
$\frac{3}{8}$ in.	98
$\frac{3}{16}$ in.	94
No. 7	87
No. 14	79
No. 25	71
No. 52	62
No. 100	52
No. 200	42
Particle size:	
0·05 mm	33
0·04 „	30
0·03 „	27
0·02 „	25
0·01 „	22
0·005 „	20
0·002 „	18

Table 12. Alternative material available for earthfill zone of closure embankment

BS sieves	Percentage finer than
$\frac{3}{4}$ in.	100
$\frac{3}{8}$ in.	99
$\frac{3}{16}$ in.	98
No. 7	96
No. 14	95
No. 25	90
No. 52	81
No. 100	68
No. 200	48
Particle size:	
0·05 mm	40
0·04 „	36
0·03 „	34
0·02 „	32
0·01 „	29
0·005 „	25
0·002 „	24

212. Fig. 9(d) is incorrectly dimensioned; the filter layers are 3 ft not 3 in. thick. The upstream slopes were controlled by the materials' angle of repose under water; this point has been touched upon by Mr Bridger.

213. The earthfill material does differ from the river-deposited alluvium as the former is partly derived from the decomposition in situ of the gneissic rock. The particle size grading is shown in Tables 11 and 12.

Mr J. G. Wiltshire

Mr Casinader refers to the initial development as being in the nature of a pilot scheme. While he is correct in assuming that much has been learned which will be invaluable in the planning of future schemes, the size of the initial development was determined almost entirely by the need to limit capital expenditure whilst meeting the immediate load requirements.

215. The discounted cash flow method of cost analysis enables a simple economic comparison to be made between two or more development programmes, but it does not automatically take account of inflationary trends, nor for that matter does it allow for variations in the value of capital over a long period as expressed in the rate of interest used for discounting. This method was one of those used in choosing Tedzani as the next site for development. One of the main reasons why inflation is often not taken into account in comparing alternative thermal and hydro-electric programmes is the difficulty in putting a fair inflation rate on the various aspects involved. The Authors suggest that inflation can be taken into account when comparing schemes on the basis of annual charges by appropriately inflating the capital cost of each project and by taking an average figure for the cost of fuel, wages, etc. over the life of the plant.

216. **Mr Headland,** who was responsible for the machine design, has commented on erosion damage to the runners which has been caused by suspended silt, and the Authors are very grateful for his valuable contribution on this and other aspects.

217. Mr Russell refers to Mpatamanga, which is one of the six sites on the Middle Shire which were considered for future development, and he wonders whether Tedzani would be flooded out by a full development at Mpatamanga. This line of thought tended to overshadow Tedzani as a potential site, but a study indicated that the most economic solution is obtained by developing the head provided by the Tedzani and Mpatamanga Falls in two stages rather than one. The power output of the two Falls is in this way slightly increased with a marginal reduction in storage capacity, which is only significant from the point of view of flood control at Mpatamanga.

218. **Mr Dalton's** contribution is most valuable and particularly so as it represents the views of the user. His suggestion that the variation in output of machines could be caused by reeds on the stay vanes is one possible solution to a problem which is still being investigated. The Duplex filters in the cooling water system have not been able to deal with the extreme conditions which occur for a small proportion of the year, and the Authors would have preferred more sophisticated and more expensive arrangements which would have more easily handled the removal of trash and which would have gone some way towards preventing the accumulation of silt at the heat exchanger pressure relief valves; Mr Headland also commented on this point. The Commission has since agreed to the trial installation of an automatic self-scouring filter for No. 1 machine.

219. Mr Dalton also refers to the troubles experienced with the carbon glands. These glands are perhaps more susceptible to variations in the pressure of the clean water than was expected, but after a number of modifications the number of outages from this cause appears to have diminished.

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