NATURALISATION OF LAKE MALAWI LEVELS AND SHIRE RIVER FLOWS
Challenges of Water Resources Research and Sustainable Utilisation of the Lake Malawi-Shire River System

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1. Introduction

The Lake Malawi and Shire River basin lies in southern part of the Great East African Rift Valley system, which has significantly influenced its shape and morphology. The entire basin area of Lake Malawi/Shire River system is about 150,000 km^2 and is a tributary of Zambezi River. The lake itself has a catchment area of 126,500 km^2 square kilometres that is in the territories of Malawi with 87,530 km^2, Tanzania with 26,600 km^2 and Mozambique with 12,370 km^2, including the lake surface. Its rift faulting formation has resulted in an unusually low land/lake catchment ratio of 17 to 5 and relatively deep lake with an average depth of about 250 metres and deepest point that is 702 metres below surface. The lake surface is about 28,750 km^2, 590 kilometres long and a maximum width of 80 kilometres, with average observed water level of 474.15 metres a.s.l, as of 1998/99 water-year. It is the eleventh and third largest lake in the world and Africa, respectively.

The rift faulting resulted in having tributaries of the lake relatively small compared to the lake itself. The largest tributary is Ruhuhu River in Tanzania with a catchment area of 14,070 km^2. The second largest is South Rukuru in Malawi with 12,110 km^2. The Bua and Linthipe rivers, all in Malawi, are also significant tributaries with 10, 700 and 8,560 km^2, respectively. The other tributaries include Songwe, Kiwira and North Rukuru rivers and others, which are all less than 5,000 km^2 each. The nature and size of tributary catchment show that a single tributary cannot dominate the lake catchment hydrology, whether with regulated or natural flows.

The Shire River is the outlet of the lake and flows approximately 410 km from Mangochi to Ziu Ziu in Mozambique, where it drains into Zambezi River. Its reach can be divided into the upper, middle and lower sections. The Upper Shire is between Mangochi and Matope, with a total channel bed drop of about 15.0 m, over a distance of 130 kilometres. However, within this reach the upper most reach from Mangochi to Liwonde is almost flat with the channel bed dropping to about 1.5 m over a distance of 87 km. The physiography of Upper Shire has offered opportunities for regulating river flows and subsequently lake levels, with possible expansion. The Middle Shire is about 80 km and steep. It is characterised or marked by the rock bars and outcrops right from Matope to Chikwawa. It has a total fall of 370 m providing a significant hydropower potential.

The Lower Shire is the stretch below the bottom of the Chikwawa escarpment where the river has an elevation of about 80 m a.s.l. This section can also be divided into upper and lower sections. The upper Lower Shire is 80 kilometres long and is occupied by the Elephant Marsh. It is relatively gentle dropping to 45 metres a.s.l at Chiromo. This is where the Elephant Marsh ends and the Ruo River tributary joins the river. The lower section of Lower Shire runs along a distance of about 120 kilometres from Chiromo to the confluence with Zambezi, where river levels are around 30 metres above sea level. The hydrology of the Ruo and that of Zambezi rivers sometimes take advantage of the gentle profiles of Shire River to significantly influence its temporal flows, particularly during the floods and when Zambezi River flows are regulated.

1.1 Water Balance of Lake Malawi

The levels in Lake Malawi have shown considerable variations over the period of continuous record starting in 1896. The Lake was at such low levels during the early years of this century that it reached lowest level of 469.94 m above sea level and that the outflow ceased, in 1915. The result was a complete absence of outflow in the period 1915 to 1935. The high levels in 1935 to 1937, however, progressively breached the sand bars and debris, cleared and opened the river channel at its mouth and along its reaches in the top middle half of the Upper Shire. Fig 1.1 shows the hydrograph of lake levels.

The sudden drop of water levels in both the Lake Malawi and Shire River was the subject of many speculations in the 1920s through 1940s[1]. These speculations included suggestions that *techtonic* movements, evidenced by recorded tremors in the rift valley, had lowered the lake basin thereby lowering the lake levels. It is now known that the low rainfall in the catchment during the period prior to 1915 was responsible for the lowering of lake levels. The resulting and continued lack of outflow at lake levels above the datum and threshold of the outlet flows was blamed on channel blockage. The vegetation overgrowth and piling of sedimentation from small tributaries near the lake blocked water flow.

In recent years the rainfall or drought periods of 1949 and 1992, have had similar effects on lake levels, particularly in their impacts on annual lake levels rises. The lake level rises were 0.08 and 0.32 metres in 1948/49 and 1991/92 water-years, respectively. These are very low rises compared to 1915 to 1999 average annual lake level rise of 0.99 metres and annual recessions average 0.9 metres, with standard deviation of 0.34 and 0.17, respectively. The impacts of droughts on the lake levels, therefore, can be very significant.

The lake has had periods of high lake levels, too. The worse period was from 1979 to 1984, where a record rise of 1.83 m during the wet season of 1978/79 was registered. The rise was mainly due to the two consecutive and exceptionally high annual rainfalls in 1977/78 and 1978/79. This record annual peak rise was followed, in 1980, by a further record lake level of 477.16 m a.s.l. (The older reports on Lake Malawi levels sometimes quote the levels using Shire Valley Datum, which is 1.37 m below those, obtained from Surveyor General's datum). The peak lake levels were accompanied by peak monthly flows in the Shire River of about 963 m^3/s against an average of 401 m^3/s recorded over the last 50 years. Recently the lake levels have been dropping since 1991 due the persistent droughts that have been prevalent in southern Africa. The lake levels reached 472.96 m in November 1997, the lowest levels since 1931.

The above observations introduce the complexity of the Lake Malawi water balance, which is further complicated by lack of adequate data for its computation. The inflows are not recorded in all the tributaries and those gauged have inadequate or short duration data, rainfall is not measured on the lake but only land rainfall is recorded and the lake level and Shire River flow data are influenced by regulation of Shire River flows. The lake levels and Shire River flows have been influenced by regulation or Shire River flow control by human activities over the years.

A comprehensive water balance analysis was, however, made in 1983[2] and offers a better understanding of the input, output and storage relationships. The analysis examined the data and computed water balance for the lake during the period 1954/55 to 1979/80. This was the period considered to have reasonable good quality data. The analysis included modelling and filling gaps that facilitated computation of water balance equation parameters. The result of this showed that the 110 mm change in lake level was explained by the input of average direct rainfall of about 1410 mm plus the tributary inflow equivalent to 1,000 mm and ground water inflow of 380 mm minus the output or losses from the lake system. The losses were the computed average annual evapo-transpiration of 2260 mm and the observed average annual out flow equivalent to 420 mm, through the Shire River flow. The computed annual evapo-transpiration, which was computed from pan evaporation records and its values more than pan figures themselves, is questionable. It is exceptionally high and cannot be explained reasonably. The ground water discharge, which was

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[1] Pictures copied from Annex of Ref. # 1

[2] The work of Dr. Kidd in *A water Resources Evaluation of Lake Malawi and Shire River*, Ref. # 2

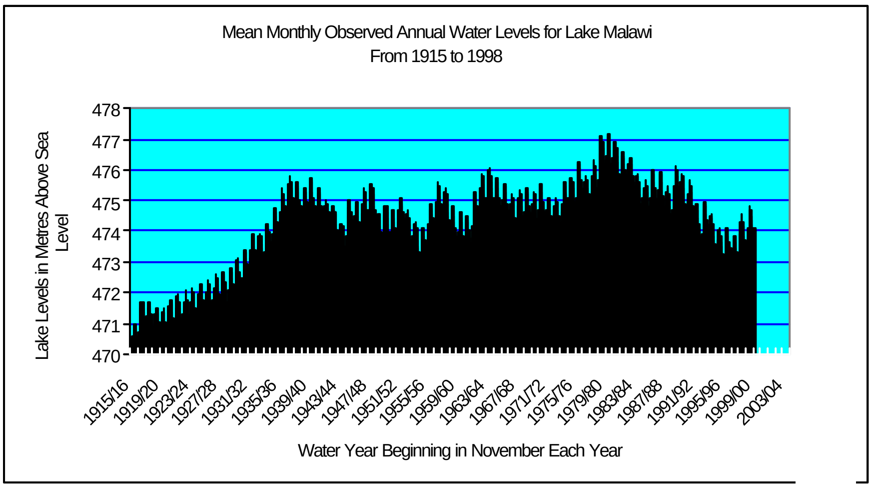
computed as the figure that balances the water balance equation or explaining the ground discharge into the lake, is also exceptionally high. From the pan evaporation records and ground water studies these parameters should be about 1,900 and 10 mm, respectively.

The disputes in the water balance parameters underscore the challenges of hydrological analysis with inadequate and influenced data. The data series used in the water balance equation and computation of the parameters were not corrected for reduced flows or the effects of these on lake levels. Thus, the water balance explains what the system respond from natural processes as well as the intervention made on the Shire River flows and lake levels. Besides, the data range, too, could not be extended further as there were no outflow measurements or adequate evapo-transpiration and rainfall data prior to 1954/55 water-year. The absence of rainfall measuring stations over the lake is also a serious set back, as seen from the water balance parameters. The water balance of the lake has demonstrated that the lake levels are very sensitive to climate and the periods of droughts or high rainfall have significant impact on the hydrology of Lake Malawi and Shire River, besides the flow regulation activities.

1.2 Lake Malawi and Shire River Hydrology

The hydrology of Lake Malawi and Shire River, like other tropical *savanna* catchments, is dominated by distinct dry and wet seasons. The rainfall or wet season starts in October to November and ends in April or May in the following year. The rainfall season starts early in southern part and ends by April. The northern part receives rains latter and gets dry beginning in May. The catchment receives an average rainfall of 996 mm but the distribution is uneven. The northern half of the catchment receives an average of 1,110[3] mm while further northern areas particularly in eastern lakeshore areas and escarpments in Malawi and northern escarpments in Tanzania receive higher than 1,540 mm annually on average. The rainfall over the lake averages about 1,410 mm (estimated from land rain gauges a long the shore). Both the land catchment and the lake rainfall peak up in March, with monthly totals of about 220 and 300 mm, respectively.

Fig.1.1 Lake Malawi Observed Hydrograph.



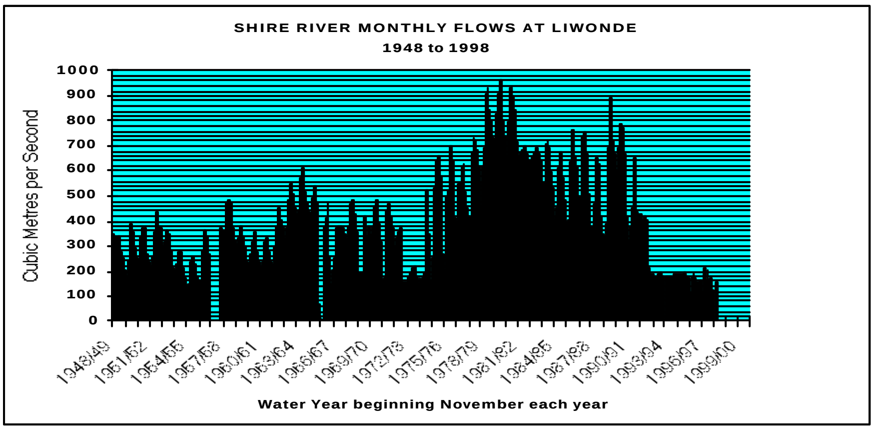
The tributary flows are gauged in Malawi and Tanzania and records show that they respond to the trends of rainfall pattern. The inflows average about 910 m^3/s or 1,000 mm depth over the lake per year and are highest in April, with an average monthly flow of 2,080 m^3/s equivalent to a total monthly depth of 7.8 mm. This is much lower than the lake level depth gain from the direct average monthly rainfall total of 300 mm mentioned above. The high influence of inflows from Tanzania explains this delay in inflow peaking, as compared to that of rainfall. The tributaries from Tanzania discharge about 52 % of the total inflow into the lake and rainfall in that part of the catchment

[3] Rounded off from figure computed by Dr. Kidd's in Ref. # 2

peaks in April.
The lake levels have the richest record of data. They have been observed since the turn of the 20th century, as the first levels were recorded in 1896. However, daily records have been kept since 1915 and are observed from stations at Chilumba in the north, Nkhata Bay in the middle and Monkey Bay in the southern part. For all practical purposes, the mean over the three stations is being used in this paper. There are insignificant seasonal differences of a few centimetres, however, between the three stations throughout the year. The wind set up from south-easteries and monsoons appear to be the main cause of this difference. The differences in daily inflow or rainfall over the lake have also been observed to cause these fluctuations between the guages. Fig. 1.1 is the observed lake level hydrograph, which shows lake level fluctuations since 1915

The lake levels peak in May and crest in November or December. In contrast, the lake peaks up a month after average catchment rainfall peaks up. The levels themselves have displayed a variation of 7.38 metres since records started. The lowest recorded monthly lake level was 469.94 m a.s.l recorded in December, 1915 while the maximum of 477.16 m a.s.l was recorded in May 1980. (The maximum daily highest was actually 477.32 m a.s.l.). The early fluctuations between 1915 and 1936 are largely responsible for the relatively high variation in the lake hydrograph. In fact the variation was only 4.35 m in the last 63 years compared to the 5.81 metre variation during the first 22 years of record (1915/16 to 1936/37). The "damming" effect caused by the Shire River blockage during the lowest levels in 1915 appear to be the main cause of the rapid rise of lake levels during the period.

Figure 1.2 Shire River Flow Hydrograph at Liwonde



The Shire River originates at the southern end of the Lake Malawi. It draws its main flows from the lake itself and its hydrology is influenced by lake levels. The river has continued to serve as an outlet of the lake since the flows got re-established in 1935 or thereabouts. The outflow begins at lake levels of 471.5[4] m a.s.l or thereabouts and is, for all practical reasons, measured at Liownde, where the catchment area is 3,700 km^2 below the Lake Malawi. The flow regime follows that of lake levels, with peaks being established in May and minimum flows in November or December, unless appreciable rainfall occurs early in the catchment below the lake. The outflows average monthly flows have been as low as 50 m^3/s in December,1997 to as high as 963 m^3/s in May1980. The daily values have been as high as 1,000 m^3/s and as low as 40 m^3/s during the same respective periods. It should be noted that these minimum observed flows refer to the periods when there were no complete obstructions of flow in the Shire River. The actual minimum flows were zero, observed in November 1956 when an earth bund was put across the Shire River at Liwonde to allow Kamuzu Barrage foundation investigations. Figure 1.2 is the observed historical hydrograph for Shire River flow at Liwonde.

4 This is a ridge of lake sand bar across the Shire River mouth, which appears to have been formed as a beach during 1915 to 1935. The channel bed itself drops to about 469 m a.s.l. immediately downstream

The Shire River flows increase gradually as the river runs down into the Middle and Lower Shire. Its annual average flow measured at Matope, with catchment area of 7,200 km^2 below the Lake Malawi, is 405 m^3/s. The minimum monthly flows at this point were about 1.5 m^3/s, where as they were 6.3 m^3/s at the bottom of Chikwawa escarpment (catchment area of 11,300 km^2. below the lake), during the periods when blocked flows at Liwonde were zero. These minimum flows occurred during dry season and increased to 22 m^3/s at Chiromo where Shire River catchment area below the Lake is 18,000 km^2.

The Shire River flows increase to an annual mean of about 480 m^3/s at Chiromo, where the total catchment is 144,800 km^2. The flows increase quite considerably during wet season, as the tributaries in the area are flooded with runoff from relatively wet escarpment catchment. In fact the area is prone to floods as tributary rivers, particularly the Ruo, can carry as much as 3,000 m^3/s into the Shire during peak floods. The flood levels become worse when the Zambezi River levels are high from floods and back up Shire Rivers for several days. The operations of Cabora Bassa and Kariba, too, should have some influence on the river flow regime in Lower shire. The information on flooding and backwater effects is scarce due to lack of appropriate measuring stations, techniques and institutional frameworks.

1.3 Land Use Changes and Hydrological Regimes

The lake level and Shire River flow regimes have been influenced by several activities and one of these are the land use changes taking place in the catchment. These changes have had gradual as well as dramatic effects. The silting up and “damming” of Shire River, when the lake levels or Shire River flows were much lower that the sediment ridden tributaries was attributed to the heavy cultivation along the streams and upland areas. Recently[5] an accumulation of more that one million cubic metres of silt in Nkhula Barrage reservoir in middle Shire, which cost about US $ 3 million to dredge, is attributed to poor and intensive deforestation and cultivation along the banks and catchments of tributary streams and rivers feeding into Shire River.

Changes in land use have manifested themselves in the hydrological regimes of rivers and lake levels. For example, a study[6] of assessing the impact of land use changes on water resources or water levels of Lake Malawi showed that the lake levels gained from the rapid rate of deforestation taking place in the lake land catchment. The study showed that the lake levels would have been one metre lower than the lake levels observed during the 1992 southern African drought, if the catchment vegetation or forest cover had not decreased from 64% in 1967 to 51% in early 1990s. These and other undocumented influences of the natural hydrological regimes are interesting and important to understand in the use of the data and the strategic planning and sustainable management of water resources in Lake Malawi and Shire River. The lack of adequate data and information on the land use and resulting hydro-meteorological processes often impend comprehensive intervention analysis, let a lone naturalisation of lake levels or river flows from such changes. However, some information and data is available on the physical developments and control of Lake Malawi and Shire River and associated hydrological processes for reasonable analysis and naturalisation of lake levels and Shire River flows.

1.4 Control and Development of Lake Malawi and Shire River

The quest to control the hydrological regimes of Lake Malawi and Shire River started at the turn of 20th century when very low lake levels and Shire River flows hampered navigation. Both the Lake Malawi and Shire River were major transport routes for passengers and cargo in the then land locked Nyasaland. However, all passenger and cargo transport services or commercial navigation came to a halt soon after 1903 and have not been re-opened. Another study was done in 1942, which

5 Section on “Water related social, economic and environmental costs and conflicts” in Ref. # 3
6 Staff of Institute of Hydrology UK and Water Resources Dept., Malawi, collaborated in study referenced as Ref. # 6

investigated and proposed plans for stabilisation of lake levels and Shire River flows and restoration of navigational services in the Shire River. In mid 1950s, another study called "Control and Development of Lake Nyasa and Shire River" was carried out. The study came up with a blue print plan for construction of flow regulating barrages, locks and gates, dams, hydropower plants and harbours on Shire River. The control and development scheme was intended to benefit flood protection, irrigation, hydropower generation, inland navigation and support for industrial development in Lower Shire. This scheme was not implemented, except a small portion, due to break up of the Federation of Rhodesia and Nyasaland in 1959.

The main flow control and regulating facility on Shire River is the Kamuzu Barrage constructed in 1965 and is situated at Liwonde. This was part of the proposed control and development scheme for Lake Malawi and Shire River and is intended to regulate Shire River flows to facilitate development and operation of hydropower plants in middle Shire. The other structures are Nkhula and Tedzani barrages constructed by Electricity Supply Commission of Malawi, ESCOM. The operations of these two barrages only affect flows downstream and not lake levels.

The operation of the Kamuzu Barrage has also benefited irrigation in Lower Shire Valley. It has also, indirectly, facilitated the maintenance of relatively high lake levels that have supported navigation, fisheries development, etc. Some further discussions on the economic stakes hinging on Lake Malawi and Shire River would advance the appreciation of the challenges in naturalisation of hydrological regimes and water resources research and sustainable utilisation of Lake Malawi and Shire River system.

Despite lake level fluctuations, the waters of Lake Malawi/Shire River system are probably the most important natural resources for Malawi. Hydropower plants of about 200 MW generation output, based on a firm flow of 170 m^3/s, have been developed on Shire River. These were developed after the construction of Kamuzu Barrage at Liwonde, in 1965, which can only operate at lake levels of between 473.2 and 475.32 m a.s.l. The hydropower generated provides 98% of electricity produced and used in Malawi. Although a small percentage (3-4%) of the country's energy needs, this electricity is undoubtedly the primary source of energy driving the economic and industrial infrastructure and services in the country. The further hydropower potential of 400 to 500 MW in the Shire River accounts for the major share (80%) of the total potential within Malawi.

An estimated 20 to 25 m^3/s of water is abstracted the Lake Malawi and Shire River for irrigating more than 20,000 hectares of land in the Lower Shire Valley and along the lakeshore. Plans are underway to abstract a further 40 m^3/s of water for planned irrigation in Lower Shire Valley. Blantyre City abstracts about 1 m^3/s from Shire River for its water supply. It is important to note that there are no significant alternative sources for water supplies to satisfy these irrigation and urban water supply demands. Besides, the waterworks and pumping stations for all these schemes were constructed to operate with specific range of water levels or flows in the Shire River, which are dependent on stable lake levels.

It can also be stated that the unique relationship between the upper Shire riverine and southern end of the lake makes it an ideal and very important ecosystem for fish breeding and fisheries development. The fish catch is up to 48,000 tonnes per annum from Lake Malawi and Shire River system alone. This has made fisheries a very important sector in Malawi's economy and is accounting for about 60% of the animal protein consumed in the country, apart from employment opportunities the fish industries offer. It should be noted that Lake Malawi, besides numerous other aquatic lives, has the largest fish species with about 600 species identified and more than 200 of these species are endemic to the lake. The lake is, therefore, is a major depository of rich bio-diversity. In recognition of this, there is Lake Malawi National Park, which is already on World Natural Heritage list of UNESCO. These bio-diversity reaches should be preserved and stable lake levels should be among the requirements for conserving the appropriate habitat. Naturalised lake levels and Shire River flows should be the basis for designing facilities that can conserve the bio-diversity habitat and support other services requiring stable lake levels.

At present the lake is used as a major transport route benefiting Malawi particularly, but also Mozambique and Tanzania. The total annual average handling services have been as high as 200,000 passengers and 100,000 tonnes of goods, accordingly. The harbours and ports have been designed and constructed to operate within lake levels of 475.00 m or thereabouts, but the lake has been below these levels several times. Several communities along the lakeshore and on Islands are dependent on this service for their personal transport and for marketing of their produce.

The LMSR system, therefore, can be described as the lifeline of Malawi and the hinterland of Mozambique and Tanzania within the vicinity of the lake. The adverse effects of lake level and Shire River flow fluctuations have, therefore, far reaching social and economic consequences now than in the early days when the Shire River dried up. Despite these observations and a number of proposals for stabilising LMSR, no attempts have been made to reconstruct natural lake levels and flows for strategic planning and sustainable management of Lake Malawi and Shire River system. This is necessary for the protection of investments dependent on effective control and regulation of lake levels and Shire River flows. The infrastructures, both in the Lake Malawi and Shire River, are planned, developed and management using the influenced lake levels and Shire River flows instead of natural ones. The importance of naturalised lake levels and Shire River flows cannot, therefore, be over emphasised.

2. Naturalised Lake Levels and Shire River flow.

2.1 Lake Levels and Shire River Flow Records

The ministry of Water Development keeps records of lake levels and Shire River flow, including some information on the operation of Kamuzu Barrage. As has been said before, the records between 1896 and 1915 were maximum and minimum annual lake levels. No daily values were observed and recorded. The quality of this data is also questionable, as there were no regular gauging stations established in the lake. The records beginning December 1915 were observed from regular gauging stations and are considered of good quality. Not all these observed lake levels are natural, however, as some have been affected by blockage of Shire River and its flow regulation. Unfortunately, there is no information on what have been the effects and how much the lake levels appreciated or depreciated from these interventions. This information is also difficult to detect from visual inspection of observed lake level data or hydrograph in Fig. 1.1. However, the inventions are documented on Shire River flows.

Prior to the construction of the Kamuzu Barrage, the flows were blocked in 1956 to 1957 and 1965. In 1965 another bund was constructed across Shire River at Liwonde, about 400 metres upstream of the gauging station, during the construction of the barrage. The barrage has been the main facility for regulating flow releases for Lake Malawi, since its construction. In the late 1960s, 1970s and 1980s the flows were regulated to reduce Shire River water levels during turbine installation or servicing at Nkhula and Tedzani power stations on Shire River. The barrage was also regulated to carry out test runs in 1978 and the period 1982 to 1983. The barrage has only been used to conserve water for hydropower generation from 1992 to present. The influences on the outflow, therefore, have been documented and can be used in naturalisation of data. For this reason and other considerations mentioned in the introduction, the naturalisation of lake levels and Shire river flows is concentrating on lake itself and its outflow.

The Kamuzu Barrage, as mentioned before, was constructed to conserve and control lake releases or outflow and appropriate control curves or operational rules, for its proper operation, were also adopted. These include a formula that uses critical parameters and lake levels to determine the required releases depending on the observed and forecasted lake levels. The formula is:

$$\begin{aligned} Q_{cf} &= Q_{fsr} && \text{if LL} > 475.32 \text{ m a.s.l,} \\ &= 237\,(LL - 471.37) - 411 \text{ m}^3/\text{s} && \text{if } 473.82 < LL < 475.32 \text{ m a.s.l} \\ &= 170 \text{ m}^3/\text{s} && \text{if } 473.22 < LL < 473.82 \text{ m a.s.l} \\ &= Q_{fsr} && \text{if } LL < 473.22 \end{aligned} \quad (1)$$

Where Q_{cf} is controlled daily flow at Liwonde
Q_{fsr} is the free daily flow or no control at Liwonde
LL is the forecasted daily mean lake level

Kanthack developed these rules in 1942[7] in his feasibility studies for stabilisation of Lake Malawi and Shire River and reintroduction of navigation in the Shire River. The rules were adopted in 1965 after commissioning the barrage. The reasoning behind this simple operational rule is not completely understood, except the convenience and physical limitations of the barrage. There were no models to simulate conditions requiring lake level control and determine optimal control curves nor are there any models now because of various factors, including lack of up-to-date necessary data. The limitations on the range of lake levels where the barrage can operate relate to its inability to control lake levels below 473.22 m a.s.l. and dangers of being over topped when operated at lake levels above 475.32 m a.s.l.

The operational rules, for the purpose of seriously conserving water latter release, were only invoked in 1992. This was necessary when the hydropower generation was threatened by the drought and forecasted flows during the dry season 1992 could not meet the demand without conserving and controlling releases at Liwonde. The operational rules also contained instructions that include forecasting two-week lake levels, which are used in the operation. Besides, the operations themselves have to be announced two weeks in advance.

However, the severity of the lake level recession made the ministry of Water Development in Malawi adopt a temporary operational rule where only the flows required for generating hydropower could be released at Liwonde. Thus the Shire River flows have been controlled between 155 to 200 m^3/s whenever the lake levels were above minimum level of 473.22 m a.s.l., otherwise the gates were opened. Departures for this range have also been observed when the head behind the barrage due to local rains and thereby increase the flow without adjusting the gates.

The effects of the above obstructions in the river and operations of the barrage are captured in the observed Shire River flows recorded at regular gauging station at Liwonde. The historical hydrograph for monthly mean flows are shown in Fig. 1.2. The various interventions in the flows can be detected by visual inspection of the graph. Using this hydrograph and the notes mentioned above, a set of free Shire River monthly mean flow data and respective monthly lake levels were screened and identified from the 1948 to 1999 records. That is the monthly mean flows that were not influenced by river obstructions or operations of Kamuzu Barrage. This was the set of data used in establishing the lake level and outflow relationship or rating curve. The documentation presented above should facilitate the understanding and appreciation of the nature of data and relevant information used.

2.2 Lake Levels and Outflow Relationship

The research on data and relevant information documentation was followed by the attempt to generate naturalised lake levels and Shire River flows. The establishment of lake level and outflow mathematical relationship was undertaken first. With the history of interference with Shire River flows at Liwonde, all relevant information on the obstructions and barrage operations that influenced Shire River flows were t used to screen out all monthly lake levels and Shire River flows that might have been controlled. The range of data period was also restricted to that where both reliable lake levels and Shire River flows could be found. Thus only data from 1948, when flow data recording commenced at Liwonde, to present was examined. However, the data from 1956 to 1958, 1964 to 1975, 1882 to 1983, May1992 to present and some months in 1975 to 1978, was

[7] Dr Kidd report quotes *The Hydrology of Nyasa Rift Valley* by F.E. Kanthack, in Southern Geological Journal, Vol. 24, 1942 and makes reference to it.

not included as explained above. The result was a set of 794 monthly lake levels and corresponding Shire River flows were considered to be natural data set i.e. not influenced by closure or regulation of Shire River flows.

The trial fitting of equations to establish mathematical relationship between Lake levels and Shire River flows was carried using the natural data set of lake levels and corresponding Shire River flows. The assumption was that the outflows were a function of lake levels of relationship:

$$\mathbf{q = a\ h^{c}} \qquad 2$$

which is a typical form of equation for open channel flow, with **q** as flow, **h** as head and **a** and **c** coefficients. The coefficients can be determined empirically, using linear regression analysis if sets of **q** and h are available. In this case the **q** and **h** are monthly Shire River flows and **h** is the effective depth of water at the mouth of Shire, above lake level below which there is no out flow. The first assumption was that this zero flow lake level was the lowest point at mouth of the lake, which is about 471.5 m a.s.l. This was the first choice in iterative determination of **a** and **c**, with logarithmic linear equation:

$$\mathbf{\ln q = \ln a + c \ln h}$$
$$\mathbf{= \ln a + c \ln (WL_{LM} - WL_{0})}$$

where $\mathbf{WL_{LM}}$ = water level in Lake Malawi
$\mathbf{WL_{0}}$ = effective lake level where Shire River ceases to provide outflow.

The statistically best fit was considered the theoretical value of $\mathbf{WL_0}$. After several trials, $\mathbf{WL_0}$ was found to be 470.8 m .a.sl. and had a maximum correlation coefficient, $\mathbf{r}^2$ = 0.9782. At this value, **a** and **c** are 24.257 and 2.027, respectively. These compare well with those found by Kid (1983): 470.37, 20.4 and 2.03, respectively. The earlier work does not have correlation coefficient to compare and the difference in **a** may be as a result of using data that has controlled flows as well. Thus the Shire River flow at Liwonde can be represented by lake levels and computed using the equation

$$\mathbf{Q_{SR(i,j)} = 24.457(W_{LM(i,j)} - 470.8)^{2.027}} \qquad R^2 = 0.9782 \qquad 3$$

Where $\mathbf{Q_{SR(i,j)}}$ = Monthly Mean Shire River flow (outflow) for month j in the year i
$\mathbf{W_{LM(i,j)}}$ = Monthly Mean Lake Malawi Levels) for month j in the year i

2.3 Naturalisation of Lake levels and Shire River Flows

The process of computing what would have been the lake levels and Shire River flows without the obstructions in 1956 to 57 and 1964 to 65 and the subsequent barrage operations between 1965 to present, has been duped naturalisation of lake levels and Shire River flows. The lake level/Shire River flow relational equation found in section 2.2 or equation 3 and observed lake levels and Shire River flows were used to simultaneously naturalise the lake levels and Shire River flows. The generating flows were first computed using lake levels at the start of Shire River flow regulation in 1956. The method of naturalising the Shire River flow and lake levels was achieved by substituting equation 3 into the control-volume or continuity equation. The control-volume equation was simplified to the lake level filling rate or changes in lake levels due to control, changes in observed lake levels and the losses through Shire River whenever, during a period of controlled flows. Thus the filling rate of the Lake between period t and (t-1) when the system is constrained or flows are obstructed or regulated. Thus the control-volume of the lake filling is:

$$W_{LM(t)} - W_{LM(t+1)} = LL_{(t-1)} - LL_{t} + (Qsr_{(t-1)} - Qof_{(t-1)})_{f} \qquad 4$$

where W_{LM} is the lake level or water level of lake Malawi due to flow control

LL is observed lake level at respective times t and (t-1) while

Qsr is the natural flow

Qof is the observed controlled flow in Shire River

$_f$ is the constant for converting flow in m^3/s into equivalent depth over the lake surface between the period t and (t-1).

It is assumed that changes to lake levels from inflows and evaporation or ground water losses or gains have resulted into the state of the lake levels at any time. This state does not change whether the outflow is controlled or not, especially that the lake area is considered constant or changes insignificantly with changes in lake levels. The filling rate, therefore, is equal to change in lake level between the two periods, which is as a result of change in storage caused by the difference between the controlled flow and what would have been the natural flow. Since $Qof_{(t-1)}$ should always be less than the natural flow during partial or complete closure of the barrage, the lake can only appreciate, and not reduce, as a result of barrage operation. Following the above equation and arguments, the lake level at time t should be as follows

$$\mathbf{W}_{LM(i,j)} = \mathbf{W}_{LM(i,j-1)} - \ddot{e}(\mathbf{Q}_{SR(i,j-1)} - \mathbf{Q}_{OF(i,j-1)}) - (\mathbf{W}_{OL(i,j-1)} - \mathbf{W}_{OL(i,j)}) \quad \text{if } (Q_{SR(i,j-1)} - Q_{OF(i,j-1)}) > 0 \qquad 5$$

$$\text{or} \quad = \mathbf{W}_{LM(i,j-1)} - (\mathbf{W}_{OL(i,j-1)} - \mathbf{W}_{OL(i,j)}) \quad \text{if } (Q_{SR(i,j-1)} - Q_{Os(i,j-1)}) < 0$$

Where i = year

j = month and in this case time t,

ë = a constant for converting Shire River flows (m^3/s) to equivalent depth of water over the lake for each month

$\mathbf{W}_{LM(i,j)}$ = Generated lake levels for year i and month j

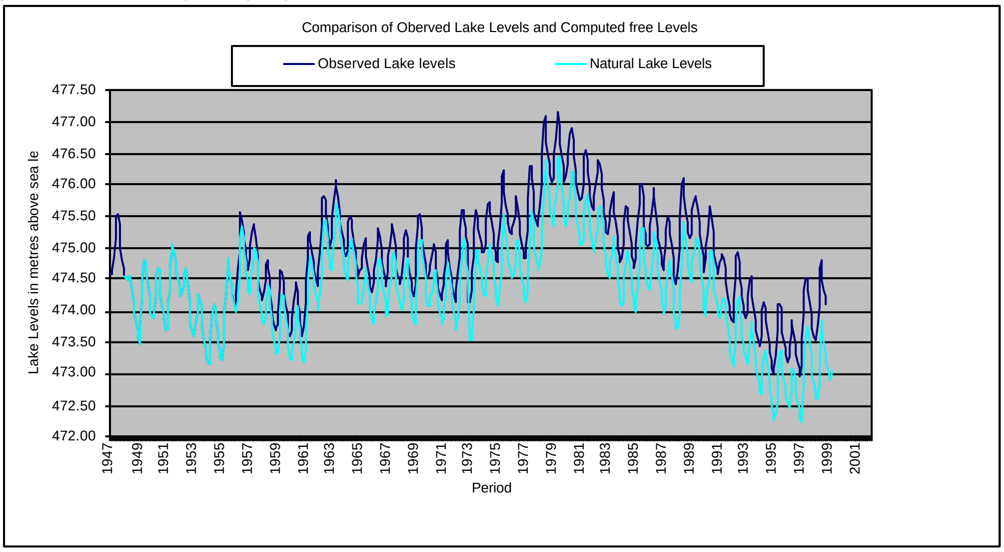
$\mathbf{W}_{OL(i,j-1)}$ = Observed lake levels in year i and month j-1

$\mathbf{Q}_{SR(i,j-1)}$ = Generated Shire River flows for year i and month j-1

$\mathbf{Q}_{OF(i,j-1)}$ = Observed Shire River flows in year i and month j-1

The $\mathbf{Q}_{SR(i,j-1)}$ is the flow of Shire River computed from the equation 3 above, using the lake level observed in or computed for the previous month. In an iterative process, the lake level for the next month are computed using equation 5 and then the Shire River flows for the present month are computed using equation 3. This process was done for all the months beginning from 1956 to 1998, where complete records of flow at Liwonde are available. Fig. 2.2 is the hydrograph of naturalised lake levels as compared to observed lake levels hydrograph similar to that in Fig. 1.1.

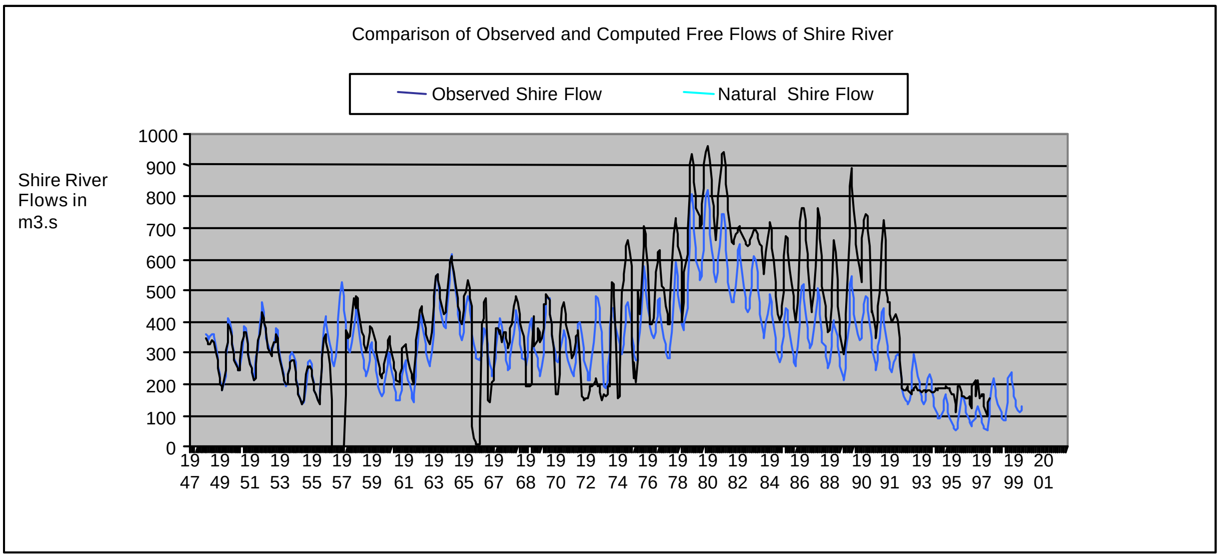
Fig. 2.2 Hydrographs of Naturalised and Observed Levels of Lake Malawi



The naturalisation of lake levels show that Lake Malawi has gradually risen since 1956, as a result of obstructions and operations of Kamuzu Barrage. The naturalised lake level series show an annual average of 473.85 m a.s.l, some 0.30 m below that of the observed lake levels for the same period 1915 to 1998. The results further show that the lake levels would have been significantly lower than what has been observed, since 1956. Notable events on lake levels, like crests and peaks are significantly lower than those observed. For example, the lake would have been lower by 0.77 m in December 1997 when it registered the lowest observed lake level of 472.96 m a.s.l since 1931. Its peak would have been 496.46 m a.s.l, 0.60 metres lower than in May 1980!

The naturalised Shire River flows are more dramatic and significantly different from the observed, as can be seen from Fig. 2.3 that compares the hydrographs of naturalised and observed Shire River flows. The naturalised Shire River flow series show an annual average of 343 m^3/s, some 62 m^3/s or more than 15% below the observed flows for the same period 1948 to 1998. The naturalised hydrograph is smoothened and, unlike lake levels, show that natural flows could have been below or above the observed flows. After the 1956 to 57 obstructions, the naturalised flows almost caught up with observed flows in early 1960s but the gap widens soon after closure of 1965. They fluctuate between the observed wild flow fluctuations caused by intermittent and often severe closures between 1965 and 1975. The naturalised flows then lie below the observed from 1979 but crosses above and fluctuates around the observed after 1992. The naturalised peak flow of 822 m^3/s coincides with that of lake levels and is lower by almost 140 m^3/s from that observed. The lowest natural flow would have been 50 m^3/s in December 1997, just like the lake levels.

Fig. 2.3 Comparison of Naturalised and Observed Hydrographs of Shire River Flows



6. Sustainable Utilisation of Lake Malawi and Shire River

6.1 Existing and Planned Water Resources Developments

The significance of these results is the influence on the sustainable utilisation of Lake Malawi and Shire River. The results show that regulation of the Shire River flows cannot be ignored in the planning and operation of water related infrastructures a long the lake and Shire River. The relevance of this statement can be seen in the problems of navigational facilities designed to operate at 475 m a.s.l. The monthly lake levels, however, have been below this level with 70.3 % probability of not being exceeded or 708 out of 1008 months of observed records. They also been below 474 m a.s.l with 34.5 % probability of not being exceeded or 348 out of 1008 months of observed records being below 475 m a.s.l. The analysis of naturalised lake levels show even higher degrees of failures to maintain lake levels at 475 m a.s.l required for navigational purposes. Its shows that lake levels would have been below this level with 84.6 % probability of not being exceeded or 832 out 1008 months of observed records.

Another good example is the so-called firm flow of 170 m^3 /s for generation of hydropower in middle Shire River. The analysis of observed Shire River flows shows that, between 1965 and 1998, the firm flow has not been exceeded in 34 months out of 384 observed months or with 8.6 % probability of not being exceeded. If the Shire River flows were not controlled, this would have been 51 months out of 384 computed natural monthly flows or 13.50% probability of not being exceeded. Thus the degree of failure to satisfy 170 m^3/s required for the generation of hydropower is high without regulation. Some of the failures during the regulation period 1965 to 1998, however, were artificially or deliberately done and could have been controlled, especially between 1965 and 1978. The indispensable failures are the ones after 1994.

The two examples given above just high light the inherent problems of operating the existing infrastructure as designed because of the inadequacies of information used in their designs. One of these inadequacies is the direct use of influenced lake levels and Shire River flows in determining design parameters for the said infrastructures. This should be avoided in future planning, design and operation of the infrastructure dependent on Lake Malawi and Shire River.

6.2 Future Designs and Sustainable Water Resources Utilisation

There are plans of constructing and installing “Shire River Flow Augmentation Scheme”, an Integrated Water Resources Development Scheme for Lake Malawi and Shire River system and many other plans on Lake Malawi and Shire River. The Shire River augmentation scheme aims at constructing a barrage and installing pumps at the mouth of Shire River. These pumps would lift water form Lake Malawi into Shire River to maintain 170 m^3/s flow in case the lake levels recede to levels that cannot yield this amount of water to flow naturally in Shire River. This would require modelling and analysis of lake levels and Shire River flows to come up with design parameters. Naturalised data should be used otherwise the observed data would wrongly influence the design parameters. The Integrated Water Resources Development scheme for Lake Malawi and Shire River would, among other things, come up with strategies and designs for stabilising lake levels and Shire River flows for the benefit of navigation, electricity, irrigation, water supply, tourism, etc. Infrastructures necessary for support of existing and planned facilities for navigation, hydropower, irrigation, etc., among others, would also be designed and constructed to achieve the sustainable utilisation of Lake Malawi and Shire River. Note that the project has regional elements. It would involve the three riparian states and, if need be, the Zambezi basin states as well. Unless these interventions consider and use the naturalised data for lake levels and Shire River flows, the designed infrastructure will fail to provide sustainable utilisation of Lake Malawi and Shire River system.

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