# Working Paper

## Multiobjective Operation of Zambezi River Reservoirs

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WP-90-31
July 1990

IIASA

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# Foreword

A three-year study on the development of decision support tools for management of large international rivers was conducted by the *Water Resources Project* of the Environment Program at IIASA. Main focus of the study was the Zambezi river basin in Africa, which is shared by eight riparian countries. One of the many problems that those countries are facing at present is that of the operation of large reservoirs. Reservoirs are used primarily for the generation of hydroelectric power, which for some of the countries in the region is the main source of energy. Hence, efficient operation of the reservoirs is vital from the economic point of view. With the operation formulations of such reservoirs the study also attempts to incorporate directly environmental objectives.

I hope that results of the study will be found interesting not only by those of the scientific community dealing wth problems of reservoir operation, but also for those practicing water management in African countries.

Professor B.R. Döös
Leader
Environment Program

# Multiobjective Operation of Zambezi River Reservoirs

*C. Gandolfi and K.A. Salewicz*

## 1. Introduction

The Zambezi is situated South of the Equator between 12° and 20° latitude and is the largest of the African rivers flowing into the Indian Ocean (see Fig. 1). Its length is in the order of 2500 km from its source in the Central African Plateau to the Indian Ocean (Balon and Coche, 1974; Balek, 1977). Its total catchment is about 1,300,000 km$^2$, and it is shared by eight countries, for some of which the river constitutes the main water resource. The total population within the river basin is about 20 million (UNEP, 1987). Although the catchment possesses large development potentials, the main water uses have been limited to the construction of three large hydroelectric schemes: Kariba and Cabora Bassa on the Zambezi itself, and Kafue Gorge–Itezhitezhi on the Kafue river, one of its main tributaries. Zambia and Zimbabwe rely for more than 70 per cent of the generating capacity of their interconnected electricity supply system on Kariba and Kafue Gorge–Itezhitezhi schemes (Williams, 1984; ZESA, 1986), whereas the operation of Cabora Bassa has been considerably jeopardized by the intense activity of guerrilla groups in Mozambique. The creation of large man-made lakes brought along several consequences on the socio-economical and environmental conditions of the Zambezi Valley. For example since the creation of Lake Kariba, fishery on the lake has grown rapidly in importance.

In 1985 the total catch of sardines was of nearly 25,000 t and was estimated to be worth about 10,000,000 US dollars (Marshall, 1987). On the other hand, the middle part of the Zambezi is now almost completely regulated and the variations of the natural flow regime caused by the operation of the schemes endangers the ecological equilibrium of some unique ecosystems (e.g. the Kafue Flats between Itezhitezhi and Kafue Gorge, and Mana Pools downstream of Kariba dam) as well as those economical activities which are most related to the natural flooding and drying cycle (e.g. fishing, cattle grazing, flood water agriculture) (see, for example, Mepaham, 1982; Obrdlik et al., 1989, Rees, 1978; White, 1973; Attwell, 1970; Magadza, 1981; Nyschens, 1982; Du Toit, 1983). While concerns about the ecological and socio-economic costs of the construction of large dams and other physical infrastructures have been growing in recent years (Scudder, 1989), the issue

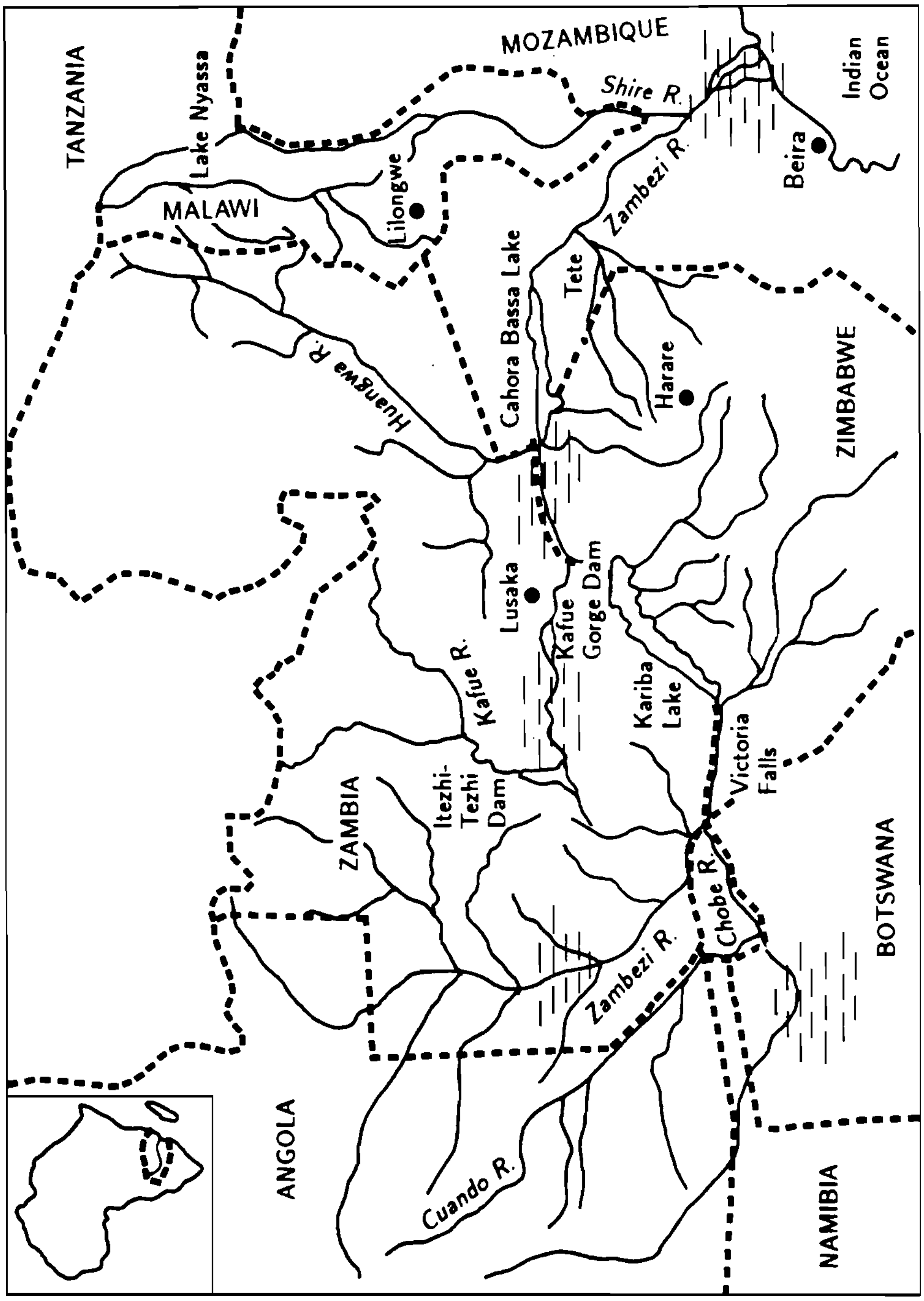


Figure 1. Layout of the Zambezi river basin.

of the multipurpose operation of the existing schemes, in order to minimize the undesired impacts, has not achieved the same relevance. Also in the agreement on the action plan for the environmentally sound management of the Zambezi (UNEP, 1987), signed in 1987 by five of the riparian countries, such issue is not taken into due consideration.

This paper presents a multiobjective analysis of the management of Kariba and of Kafue Gorge-Itezhitezhi schemes. A heuristic approach is applied to the problem of improving the control policy of the two schemes (see Guariso *et al.*, 1986). In the first part the Kariba scheme is considered. The first section describes the main characteristics of the hydrology of the Zambezi upstream of Kariba. Section 2 presents the main objective of Lake Kariba management, together with the basic physical characteristics of the system. In Section 3 the multiobjective problem is formulated and solved as a multiobjective mathematical programming problem with a heuristic method. In Section 4 a particular operating rule is selected within the set of efficient operating rules, and its performances are shown in comparison with the historical ones. The four sections constituting the second part present the same kind of analysis for the Kafue Gorge-Itezhtezhi scheme. In the last part the results and the practical implications of this study are summarized.

## 2. The Kariba Scheme

When Kariba filled to capacity in 1962, it was the largest man-made lake in the world. Currently it is the fourth largest. At the maximum retention level the lake covers an area of more than 5600 km$^2$ and has an active storage of about 70 cubic km. The first stage of the Kariba hydroelectric scheme was completed in March 1962 when the last of six 111 MW turbo generators was brought into service in the South Bank power station. Stage two called for four 150 MW turbo generators to be installed on the North Bank. The works for this stage started in 1970, and the last of the generators was eventually commissioned in May 1977.

### 2.1. Hydrology

The catchment area upstream of Kariba Gorge is approximately 664,000 km$^2$ (Santa Clara, 1988). The river flows from Kalene hills in the high plateau between Zambia and Zaire (about 1500 m a.s.l.) to the Kariba dam (maximum retention level 489.5 m a.s.l). Rainfall over the catchment is seasonal in character. The rainy season normally extends from November to March. From April to October the area is influenced by a zone of high pressure, and warm sunny conditions prevail. The rainfall distribution on the catchment shows a decreasing trend from North to South, with average annual totals ranging from 1440 mm at Hillwood (at the head of the basin) to 760 mm at Sesheke (in the southern portion). On the contrary rainfall variability decreases from South to North (Sharma and Nyumbu, 1985). The Zambezi has been gauged at Livingstone, near Victoria Falls, some 400 km upstream of Kariba Gorge, as early as 1905, and since 1924 daily readings have been taken at Livingstone pump station. It is convenient therefore to divide the total catchment into the Upper Catchment of 507,200 $km^2$, upstream of Victoria Falls, and the Lower Catchment of 156,600 $km^2$, lying between the Falls and Kariba (Santa Clara, 1988). The flow regime of the Zambezi at Victoria Falls is markedly influenced by the presence of the Barotse Plain and of the Chobe Swamps, two large swamp areas bordering the river for almost 300 km (see Fig. 1). In fact, the flood regulation by these natural reservoirs is considerable, as the Barotse Plain alone is calculated to be capable of about 8 cubic km storage at normal annual flood levels and up to 17 cubic km at the peak of high floods. One of the effects of this storage is to delay the flood waves. The river's peak discharge occurs normally at the end of March at Chavuma, in the second half of April at Senanga, and it reaches Victoria Falls at the beginning of May (Sharma and Nyumbu, 1985). The discharge at the Falls returns to base flow in October or November and persists until January, when the rising limb of the hydrograph starts. The Lower Catchment has very different characteristics. No major river system is present, but several secondary tributaries, with catchments ranging in size from few hundreds $km^2$ to the almost 50,000 $km^2$ of the Gwaai, run a relatively short way before entering Lake Kariba. The river gradients are generally quite steep and, since there is no natural storage, most of them are characterized by erratic discharges and short duration flood peaks. Almost 60 per cent of the $9 * 10^9$ $m^3$ of average annual flow from the lower catchment is concentrated between January and March. Over the last decades a number of tributaries have been gauged, and more recently an hydrological model was used to obtain meaningful records of the runoffs from the ungauged areas (CAPC, 1978).

### 2.2. Main Objectives of Lake Kariba Management

Since its construction, Kariba scheme has been the main source of energy for Zambian-Zimbabwean interconnected electricity supply system. Since 1977, when the North Bank power station was fully commissioned, the scheme has supplied a monthly average of about 600 GWh, with an almost constant distribution throughout the year. In the control of the lake level, a balance has to be maintained between the need to maximize the hydropower output and that to have a safe capacity at the beginning of the rainy season to avoid peak discharges through the floodgates. Since the main objective of the management is to maintain a fixed level of energy production, a good indicator of the performance of the reservoir operation was considered to be the difference between such desired level and the energy actually generated. Thus, for each month $t$ the energy deficit $d_t$ is defined as:

$$d_t = \begin{cases} 0 & \text{if } e_t \geq E \\ E - e_t & \text{if } e_t < E \end{cases} \tag{1}$$

where $e_t$ is the energy output in month $t$, and $E$ is target output. Opening of the floodgates is, on the other hand extremely inconvenient because of three main reasons: first, from the power generating point of view, the rise in tailwater level with the opening of one floodgate reduces the net head of about 5 m, and thereafter of about 3 m with every additional gate that is opened; second, from the dam safety point of view, the vibrations induced by very high discharges through the floodgates should be avoided as far as possible; third, extremely large releases may endanger the population living downstream and create problem to the Cabora Bassa dam. Therefore it was assumed as a second indicator, related to to the risks associated with peak discharges, the value of the total monthly release $r_t$, both through the turbines and the spillgates.

Finally, the attitude of the dam management towards both objectives is strongly averse to the risk of large failures. In fact, the main concern related to power production is to avoid large values of $d_t$ which would cause severe shortages in the electricity supply to both Zambia and Zimbabwe. Similarly, relatively small discharge through the floodgates for few months are rather accepted than an extremely high discharge in one single month. The risk averse attitude of the management was taken into account by a min-max formulation of the objectives, i.e they are assumed to be the minimization of the maximum value $D$ of the monthly energy deficit $d_t$ and of the maximum value $F$ of the total monthly release $r_t$,

$$\min \,(D, F)$$

where

$$\begin{aligned} D &= \max_t \,[d_t] \\ F &= \max_t [r_t] \end{aligned} \tag{2}$$

### 2.3. The Kariba Management Problem

An heuristic approach was applied to the problem of determining the control policy of the Kariba scheme (see Guariso *et al.*, 1986). The main feature of the method is that the solution is strongly dependent upon the characteristics of the past management.

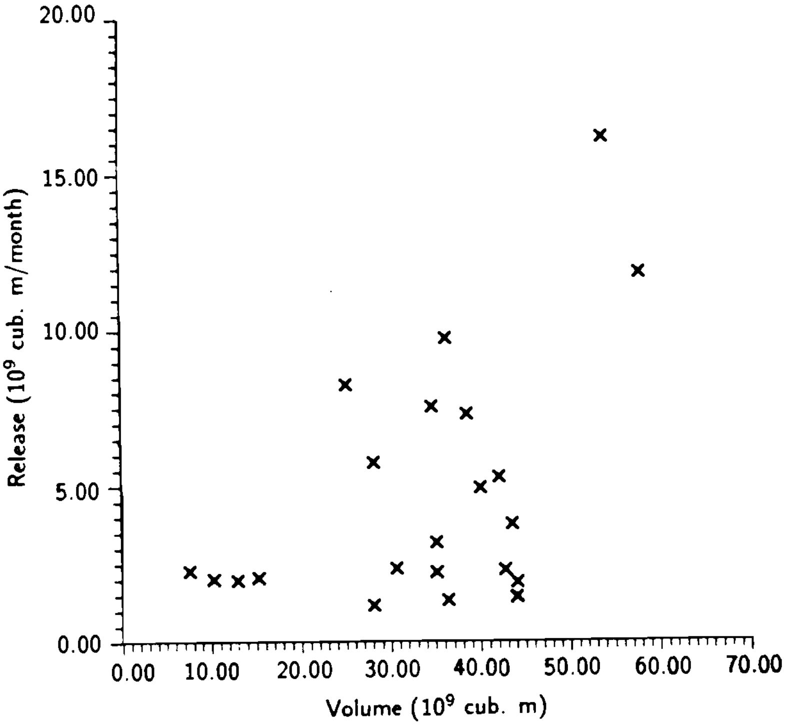


**Figure 2.** Historical relationship between storage and release from Lake Kariba as recorded for February – beginning of the flood season.

The management of the Kariba scheme has been based on a rule curve, which gives the *a priori* pattern of the desired storage values in every month of the year. According to such curve the storage should gradually drop down between July and January, to provide sufficient storage for the annual flood, which is expected to fill the reservoir in the following months. The analysis of historical time series of reservoir storage values shows frequent deviations from that *a priori* pattern. In particular, it is apparent that the decision on the release volume $r_t$ in month $t$ is strongly influenced by the reservoir storage $s_t$ at the beginning of the month. Figures 2 and 3 show in the plane storage–release the historical values of $s_t$ and $r_t$ for the months of February (beginning of the flood season) and of June (beginning of the dry season), respectively. It can be seen that the active storage can be roughly divided into two zones: a lower zone where release is almost constant and determined by the satisfaction of the energy demand; an upper zone where release sharply increases in order to avoid excessive filling of the reservoir, thus preventing the risk of extremely high releases in the following months. The boundary $S_t$ between the two zones varies during the year.

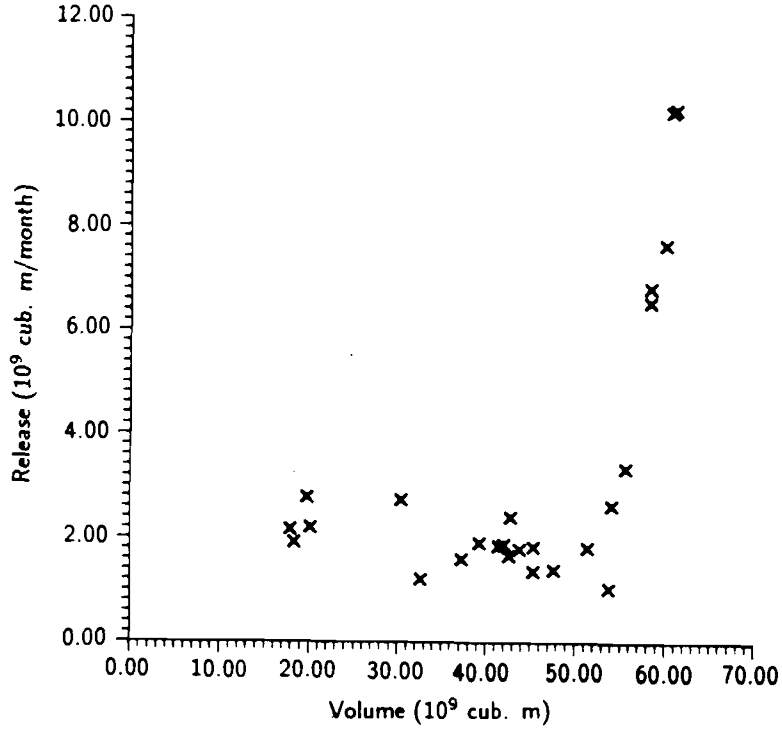


**Figure 3.** Historical relationship between storage and release from Lake Kariba as recorded for June – beginning of the dry season.

As it is to be expected, it is lower when the probability of high inflows is higher (compare Figures 2 and 3), showing a pattern similar to that of the rule curve. Therefore it was assumed that the past management can be described by operating rules of the kind shown in Figure 4, with the boundary $S_t$ varying with $t$ according to the law shown in Figure 5. Such operating rules are of the form

$$r = r(t,s_t,r_L,r_U S_L,S_U) \tag{3}$$

and are uniquely identified by the four parameters $(r_L,r_U,S_L,S_U)$.

In order to formulate the management problem, let us now consider the equation describing the reservoir balance

$$s_{t+1} = s_t + i_t - v_t - u_t \tag{4}$$

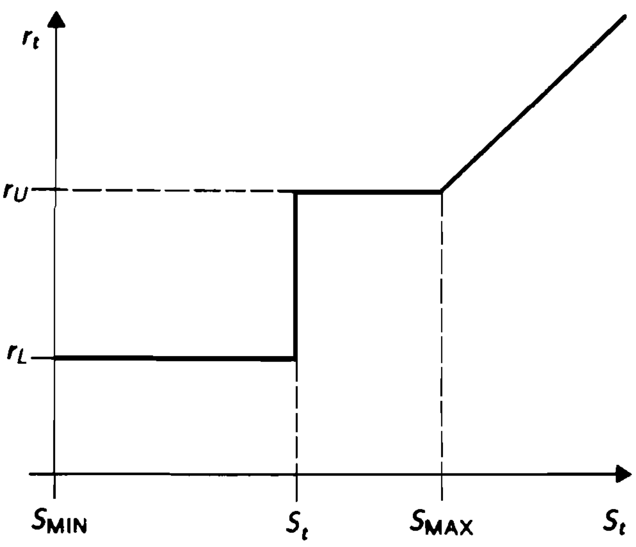


Figure 4. Storage–release operating rule proposed for Lake Kariba.

where

$i_t$ is the volume of inflow in month $t$;

$v_t$ is the volume of evaporation in month $t$;

$u_t$ is the volume of release in month $t$.

The evaporation from the reservoir was assumed to be proportional to the reservoir surface $A$, which, within the operational range of storage values, can be approximated by a linear function of the storage. Therefore, the average value $A$ of the reservoir surface in month $t$ is given by

$$A_t = a * (s_{t+1}+s_t)/2 + b \tag{5}$$

while evaporation loss volume $v_t$ is given by

$$v_t = k_t A_t \tag{6}$$

The coefficients $k_t$ are periodical with respect to $t$ and were calculated based on the available time series of evaporation from the reservoir (CAPC, 1978). Substituting eq. (6) for eq. (4) we obtain the reservoir equation in the form

$$s_{t+1} = c1_t * s_t + c2_t * (i_t - u_t) + c3_t \tag{7}$$

in which $c1_t$, $c2_t$ and $c3_t$ can easily be obtained for known $a$,$b$ and $k_t$.

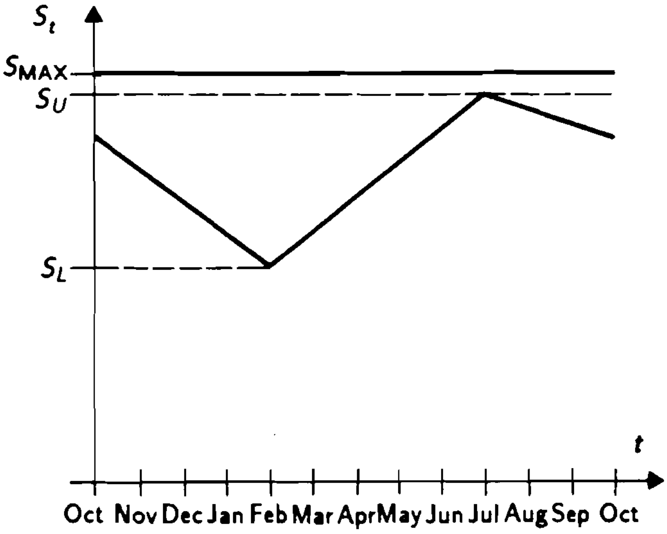


**Figure 5.** Time dependent boundary $S_t$ separating two storage zones of Lake Kariba hydropower scheme.

Moreover, a distinction must be made between the release $u_t$ in eq. (7) and the release $r_t$ given by the operating rule (3). In fact, since the decision $r_t$ is taken when the values of $i_t$ and $v_t$ are unknown, it cannot be *a priori* guaranteed that $r_t$ is feasible. The volume of release $u_t$ is given by

$$u_t = \min\left[\max\left[r_t \, , \, R(S_{MAX},s_t,i_t)\right] \, , \, R(S_{MIN},s_t,i_t)\right] \tag{8}$$

where $S_{MAX}$ and $S_{MIN}$ are the maximum and minimum value of the storage, and

$$R(s,s_t,i_t) = \frac{c1_t}{c2_t}\, s_t - \frac{1}{c2_t}\, s_{t+1} + i_t + \frac{c3_t}{c2_t} \tag{9}$$

gives the volume of release that has to be made to obtain storage $s_{t+1} = s$, starting from storage $s_t$ with inflow $i_t$.

The management problem could then be formulated as a two objective optimization problem as follows:

$$\min_{\{r_L, r_U, S_L, S_U\}} [D,F] \tag{10}$$

subject to

- the continuity equation (7);
- the operating rule (3);
- the feasibility condition (8);
- the rule determining the division of $u_t$ between turbines and floodgates discharge ($u_t^A$ and $u_t^B$, respectively):

$$u_t^A = \min\left[u_t, M_t\right]$$
$$(11)$$
$$u_t^B = \max\left[0, (u_t - M_t)\right]$$

  where $M_t$ is the volume discharged in month $t$ if all the turbines are fully operating for 90% of the time;
- the equation relating the net head on the turbines to the storage and the release; and
- the objective functions defined by equations (1) and (2).

The solution of problem (10) is not unique (see, for example, Cohon and Marks, 1975).

A set of efficient (in the Pareto sense) operating rules can be determined. Each of them is identified by a particular quadruple ($r_L$, $r_U$, $S_L$, $S_U$) of parameters, and has the property that none of such parameters can be varied without weakening at least one of the two objectives. From a computational point of view the efficient solutions can be found by simulating the system for a sufficiently long period of time with a large number of different operating rules (i.e. of quadruples ($r_L$, $r_U$, $S_L$, $S_U$)). In the case at hand, the simulations were carried out using the inflow data of the period from 1950 to 1984. A random search algorithm (Karnopp, 1963) in the space ($r_L$, $r_U$, $S_L$, $S_U$) was used to limit a region around the optimum, and then a deterministic method (Himmelblau, 1972) was applied for the refinement of the result. The target power production $E$ was set equal to the historical value of 600 GWh per month.

The efficient solutions in the space of the two objectives $D$ and $F$ are shown in Fig. 6. Several interesting considerations can be drawn from its analysis. First, the minimum value of $F$ is $5 * 10^9$ m$^3$/month, and is quite close to the maximum turbine discharge, which, assuming a plant factor of 0.9, is equal to $3.82 * 10^9$ m$^3$/month. Therefore the maximum discharge through the floodgates can be reduced to less than $1.2 * 10^9$ m$^3$/month. Obviously this implies accepting an extremely high value of the deficit $D$. Fig. 6 shows also that the present level of target energy production can be completely

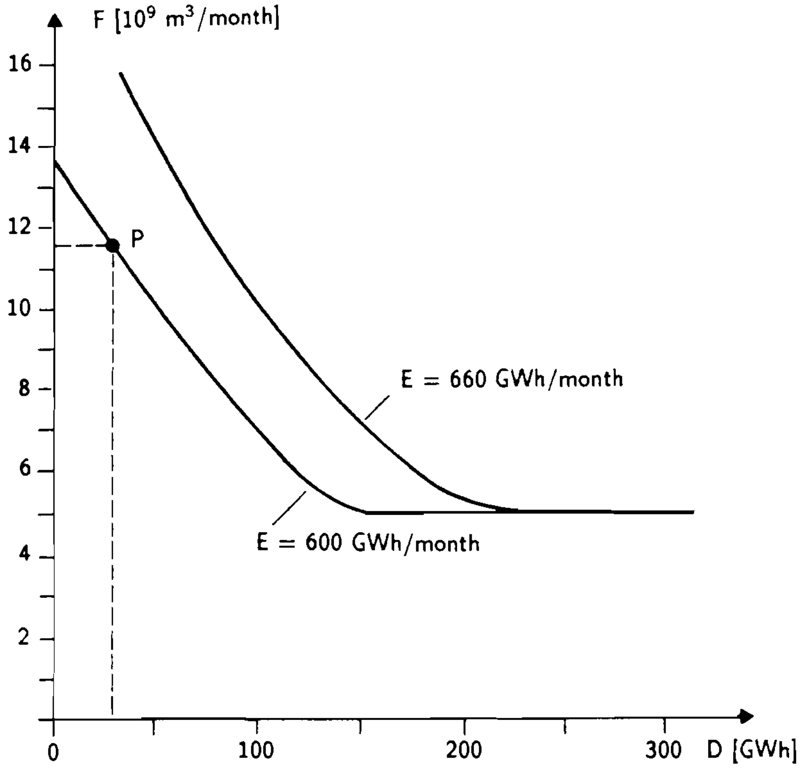


**Figure 6.** The efficient set of solutions of Lake Kariba management problem in the space of energy deficit *D* and the maximum total monthly release *F*.

satisfied if a maximum release of 13.5 $*$ $10^9$ $m^3$/month is considered to be acceptable. The effects of an increase of the target power production *E* were also analyzed. The efficient points corresponding to a 10 per cent increase of the historical target are also shown in Fig. 6.

The results obtained for available hydrological data demonstrate that the maximum monthly production which can still be achieved with no failures is 610 GWh and the corresponding maximum release is more than 15 $*$ $10^9$ $m^3$/month.

## 2.4. Analysis of a Particular Operating Rule

In order to verify its reliability one of the efficient operating rules has been analysed in more detail. In particular any proposed operating rule, besides giving good performances in terms of the maximum values of the objectives, should also be proved to be acceptable with respect to their average values. Point P (D=38 GWh, F=11.6 $*$ $10^9$ $m^3$) in Fig. 6 was selected for the analysis. Fig. 7 shows the average values and the standard deviations of the monthly power production, if the proposed operating rule, identified by $r_L = 2.754 * 10^9 10\ \mathrm{m}^3/\mathrm{month}$, $r_U = 11.333 * 10^9\ \mathrm{m}^3/\mathrm{month}$, $S_L = 37.762 * 10^9\ \mathrm{m}^3$, $S_U = 67.947 * 10^9\ \mathrm{m}^3$, were implemented in the period 1950-1984. It can be seen that all the values are well above the 600 GWh target, giving an average annual total of 8300 GWh. Moreover, the standard deviations are quite small, indicating a high reliability of the production, as it could be expected given the small value of $D$.

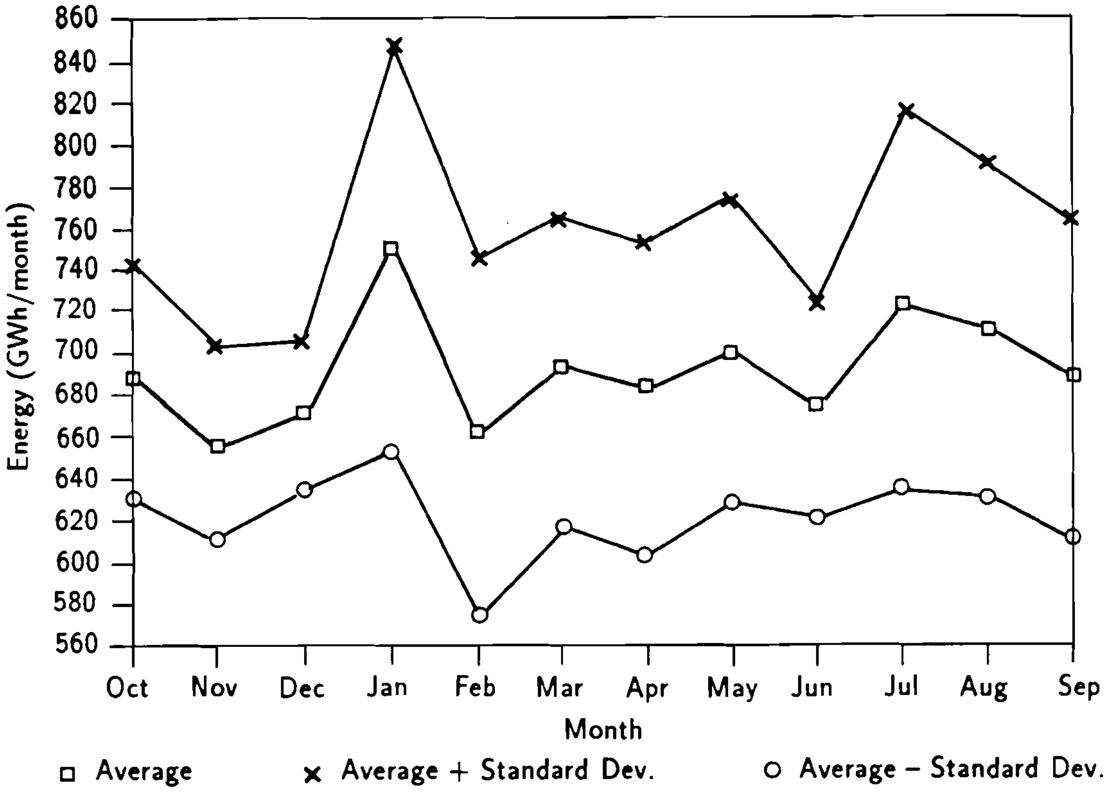


**Figure 7.** Values of the average monthly power production at Lake Kariba calculated for the historical record flow covering the period 1950–1984 and resulting from the proposed operating rule.

The performances of the proposed operating rule were compared with the results of the historical management in the years from 1977 to 1984, in which Kariba station was fully in operation. Fig. 8 shows the values of the yearly energy production in the two cases.

It turns out that the proposed rule is superior both in terms of average annual production (8000 against 7200 GWh) and of minimum monthly production (562 against 428 GWh). Moreover, the maximum monthly release decreases from $17.1 * 10^9\ \mathrm{m}^3$ to $11.6 * 10^9\ \mathrm{m}^3/\mathrm{month}$ and the number of months in which the floodgates had to be opened from 22 to 12.

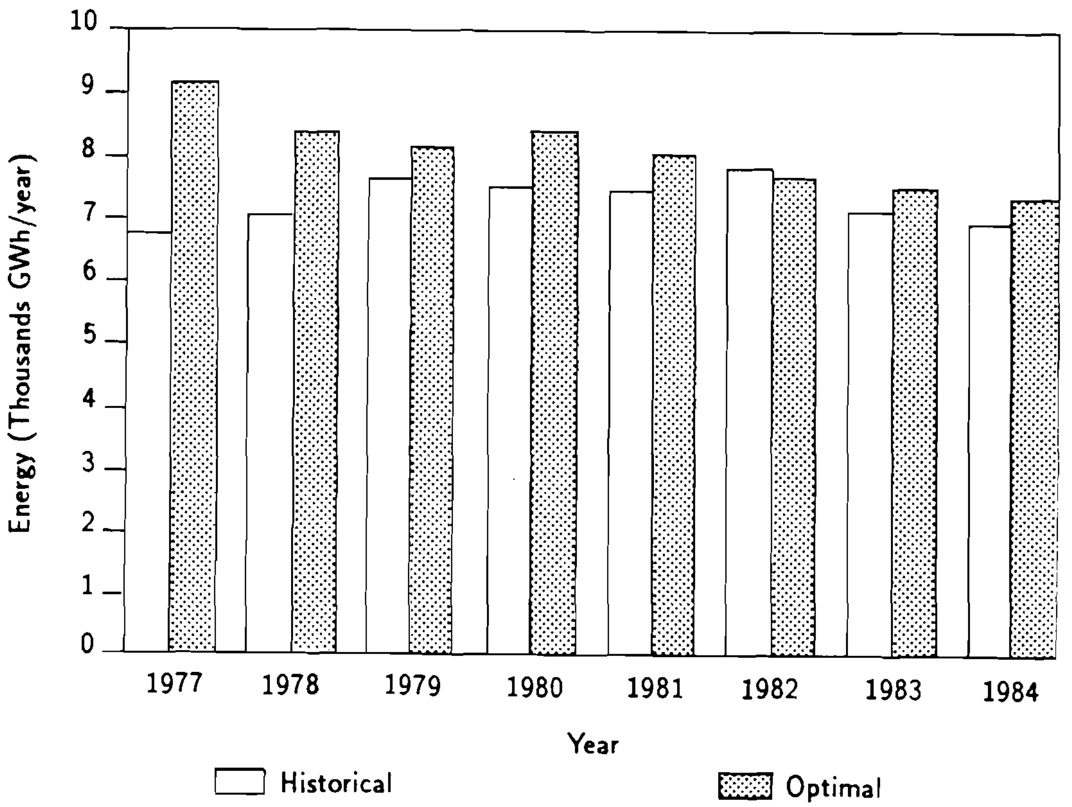


**Figure 8.** Energy production pattern of Lake Kariba: comparison of historical and optimal management strategies.

It must be pointed out, however, that the proposed rule causes a more significant alteration of the natural flow regime downstream of the dam than the historical management. It produces, in fact, an almost flat hydrograph with an anticipated and sudden peak in January. The impact of such a regime on the downstream areas (e.g. Mana Pools) should be thoroughly analyzed before implementing the proposed rule.

Finally, to verify the robustness of the proposed operating rule, the reservoir operation was also simulated using the inflows to the lake for the period 1924-1949. The following performances were obtained: a minimum monthly production of 569 GWh, an average annual production of 8000 GWh, and a maximum monthly release of $11.6 * 10^9$ $m^3$. The results were, therefore, comparable to those of the period 1950-1984 and can be considered completely satisfactory.

## 3. The Kafue Gorge-Itezhitezhi Scheme

The most important waterway for Zambian national economy is the 1500 km long Kafue river (Obrdlik *et al.* 1989). Its catchment (see Fig. 9), which lies entirely in Zambian territory, covers one fifth of the country area and houses one third of the Zambian population (Sharma, 1984). The major mining installations, towns, agricultural farms, and industrial plants are situated in the Kafue basin. The enormous hydropower potential of the river led to the realization of the Kafue Hydroelectric Scheme. In 1972 a dam was closed at Kafue Gorge, equipped with a 600 MW power station. In 1976, in order to increase the storage capacity of the scheme to enable more power generation, a second dam with an active storage of 5.7 cubic km was completed at Itezhitezhi, and early in 1977 two additional 150 MW groups were installed at Kafue Gorge power station.

### 3.1. Hydrology

The Kafue river rises from the watershed between the Zambezi and the Congo basins, flows southward through the copper belt of Zambia, and skirts the Lukanga Swamps before reaching Itezhitezhi. Here the river breaks through a range of low hills, and then meanders for more than 400 km across the Kafue Flats. After the floodplain, the river plunges 670 m, as it flows through the less than 30 km long Kafue Gorge, and finally enters the Zambezi some 80 km downstream of the Kariba Dam. The rainfall regime on the 154,000 $km^2$ of the Kafue catchment has the same characteristics described for the whole Zambezi basin (see Section 2.1). Flow records at Itezhitezhi and Kasaka (just upstream of the Kafue Gorge) have been kept since the early twenties (FAO, 1968) and more recently reviewed by the British Institute of Hydrology (Institute of Hydrology, 1981). The almost 100,000 $km^2$ of the catchment above Itezhitezhi provide an average annual runoff of about $10 * 10^9$ $m^3$, while the average contribution of the catchment between Itezhitezhi and Kasaka (more than 50,000 $km^2$) is only $1 * 10^9$ $m^3$ per year. The already mentioned decrease of precipitation from North to South, as well as the important evapotranspiration which occurs in the Kafue Flats account for such difference in runoff contribution. The influence of the Kafue Flats on the natural (i.e. before the construction of Itezhitezhi dam) flow regime of the river is also apparent from the analysis of the monthly runoff (see Fig. 10).

Runoff at Itezhitezhi is very low between July and November, it sharply increases from December and normally peaks in March. The high flows from the upper catchment, as well as direct rainfall and runoff from the local tributaries account for the flooding and waterlogging of the Kafue flats. The natural hydrological cycle of the flats is quite

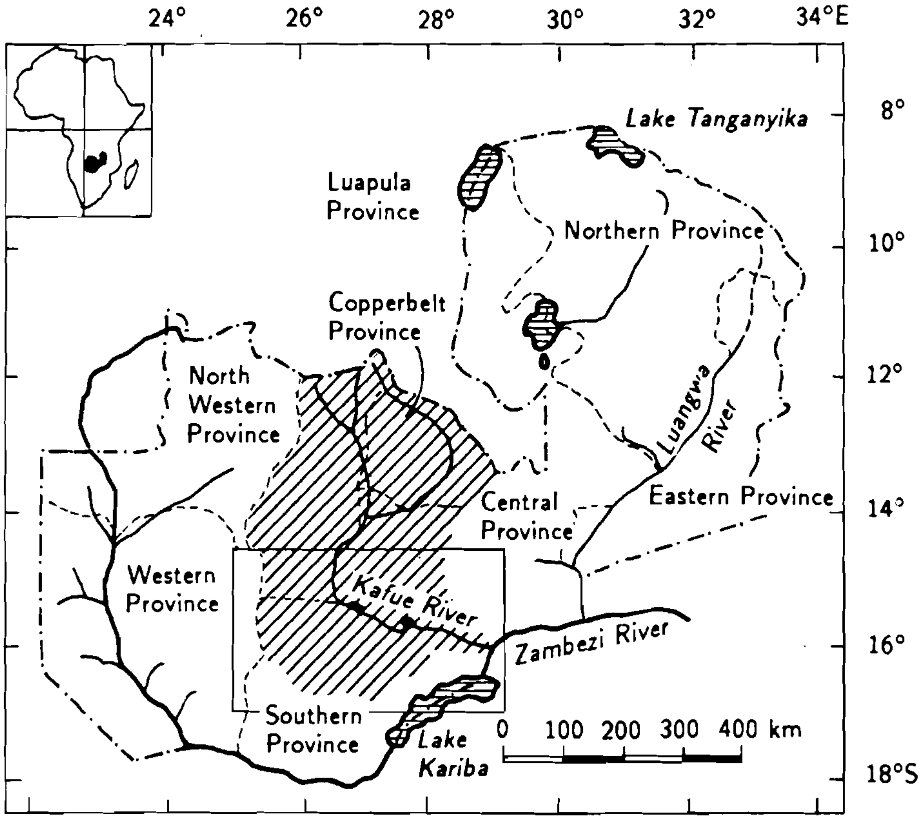


Figure 9A. Layout of the Kafue river catchment.

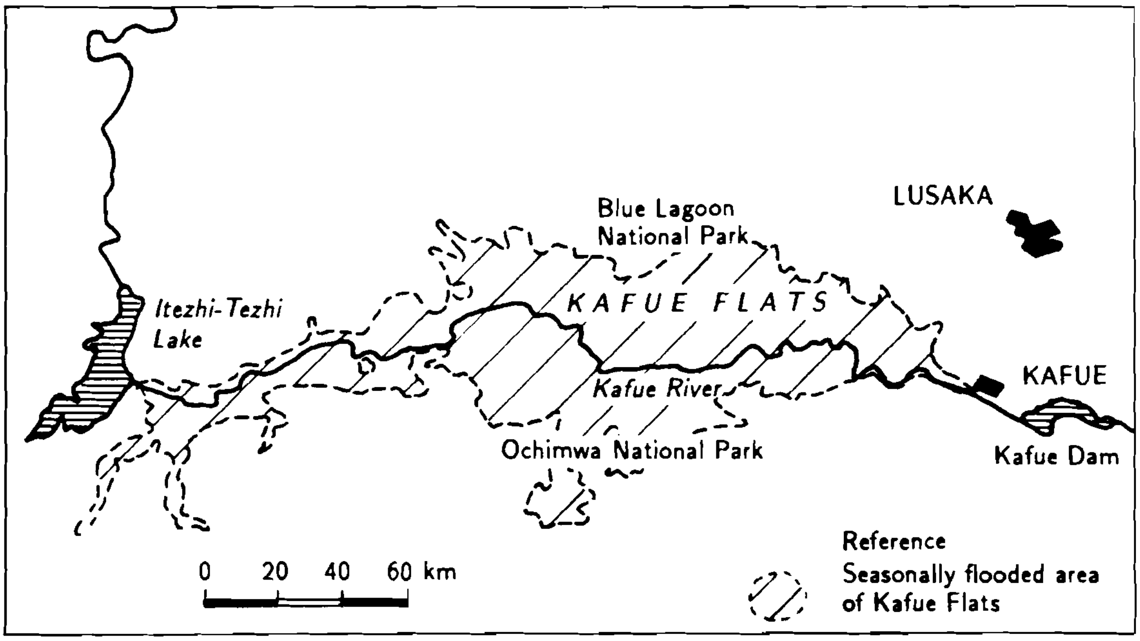


Figure 9B. Kafue dams and flats.

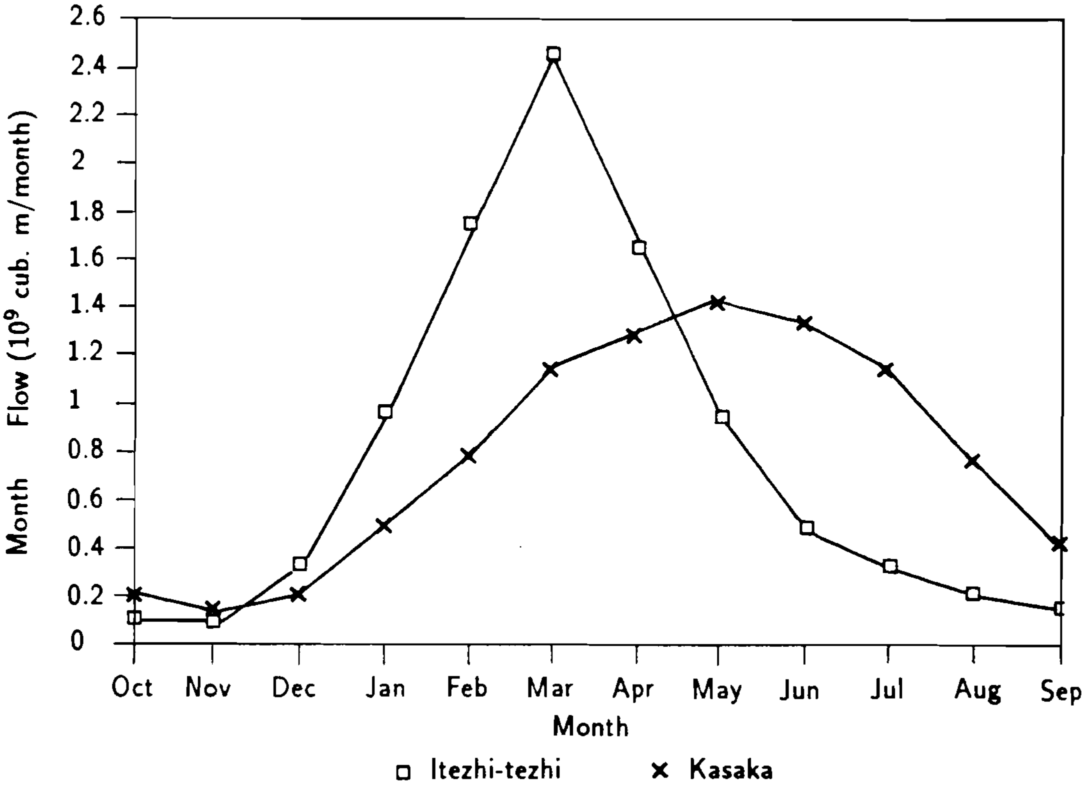


**Figure 10.** Average monthly flow patterns at Itezhi-tezhi and at Kasaka in the vicinity of the Kafue Gorge dam.

dramatic. Fully three quarters of the flood plain can change from an aquatic to a terrestrial environment within a season. At the eastern end of the flats, a shallow area of more than 1,000 km$^2$ is flooded more or less permanently. From December this area is extended westward and in wet years over 5,500 km$^2$ may be inundated by April or May (Mepham, 1982). Then the water slowly recedes from the floodplains until October. Thus, the flats create a natural buffer for the floods from the upper part of the catchment. In fact, the natural hydrograph at Kasaka is characterized by a relatively smooth increase of the runoff from December to May, when the peak is normally reached with a delay of about two months and a reduction of more than 40 per cent with respect to Itezhitezhi (see again Fig. 10). Between June and October the contribution from the upper part of the catchment is very small, and the runoff is mainly sustained by the water stored in the floodplains.

### 3.2. Main Objectives of the Kafue Gorge–Itezhitezhi Scheme Management

The main purpose of the combined storage of the Itezhitezhi and Kafue Gorge reservoirs is to maintain a constant power output of 440 GWh per month at the Gorge power station, corresponding to a turbinated flow of about $442 * 10^6$ $m^3$/month (Balasubrahmanyam and Abu-Zeid, 1982; Obrdlik *et al.*, 1989). At present only regulated releases to meet such power generation requirements are made monthly from Itezhitezhi, except in March when $780 * 10^6$ $m^3$ are released to maintain at least partial flooding of the flats (Balasubrahmanyam and Abu-Zeid, 1982; White, 1973). From the point of view of power generation, two indicators were taken into account. Given the target value $E$ of production, we define the monthly deficit $d_t$ as

$$d_t = \begin{cases} 0 & \text{if } e_t \geq E \\ E - e_t & \text{if } e_t < E \end{cases} \tag{12}$$

and the monthly surplus $g_t$ as

$$g_t = \begin{cases} 0 & \text{if } e_t \leq E \\ e_t - E & \text{if } e_t > E \end{cases} \tag{13}$$

where $e_t$ is the energy output in month $t$. Based on the analysis of the available data on the historical management, it was assumed that the effort of the management is towards the achievement of the best performances in a long term perspective. This led to a formulation of the objectives of the management in terms of the minimization of the expected value $D$ of the monthly energy deficit $d_t$ and the maximization of the expected values $G$ of the monthly surplus $g_t$, where

$$\begin{aligned} D &= E[d_t] \\ G &= E\,[g_t] \end{aligned} \tag{14}$$

Moreover, the possibility of including in the formulation of the management problem some aspects related to the effects of the management on the Kafue flats was considered. The impacts of the Kafue river regulation on the unique floodplain ecosystem and on the human activities in the flats were outlined by Handlos (1982) and Mepham (1982). The most unfavourable changes manifested themselves in floodplain fishery and biology of the wild herbivorous animals. With more than 5500 tons of fish caught in 1970, the Kafue Flats fishery ranked among the most important for fishery of Zambia (Muyanga and Chipungu, 1982). The main reason for the reduced fish production is not clear on the basis of today's data and knowledge (Hayward, 1984). It is proved, however, that seasonal flooding of the Kafue Flats provided an extension to fish habitats for about six months of the year, including the reproduction period of most fish species (Williams, 1971; Lagler *et al.*, 1971). Moreover it was pointed out that the changes in the flood regime may be the main cause of the observed reduction in the number of wild herbivores. According to Wunschmann (1988), for example, the population of the endemic Kafue lechwe has been reduced by about 50 per cent in the last ten years. Although the complex processes behind such impacts are not completely understood, it seems to be accepted that it would be beneficial to maintain the release pattern from Itezhitezhi reservoir as close as possible to the natural regime. A good indicator of the performance of the system with respect to this objective was assumed to be the difference $f_y$ between the peak flood discharge in March and the average monthly flow during the dry season, from June to December, in year $y$, i.e.

$$f_y = r_{Mar} - \frac{1}{7}\sum_{Jun}^{Dec} r_t \qquad (15)$$

Finally, it was assumed that also with respect to such indicator, the optimization criterion is long-term efficiency, i.e. it can be formulated as the maximization of the value of $F$, where

$$F = E[f_y] \qquad (16)$$

### 3.3. The Kafue Gorge-Itezhitezhi Management Problem

The same approach applied to Lake Kariba was followed to solve the Kafue Gorge-Itezhitezhi control problem. The operating rule for Itezhitezhi was assumed to be of the type shown in Fig. 11. The release decision $r$ is kept constant between June and December, and presents in the remaining five months a triangular flood wave peaking in March. The operating rules of this type are uniquely identified by two parameters: the value of the release in any of the months and the total annual release. Since the latter was assumed to be equal to the average annual natural runoff at Itezhitezhi in the period 1924–1969 minus the estimated average annual evaportion losses from the lake, the number of parameters reduced to one ($r_A$) in Fig. 11).

Therefore the considered operating rules are of the form

$$r_t = r(t, r_A) \qquad (17)$$

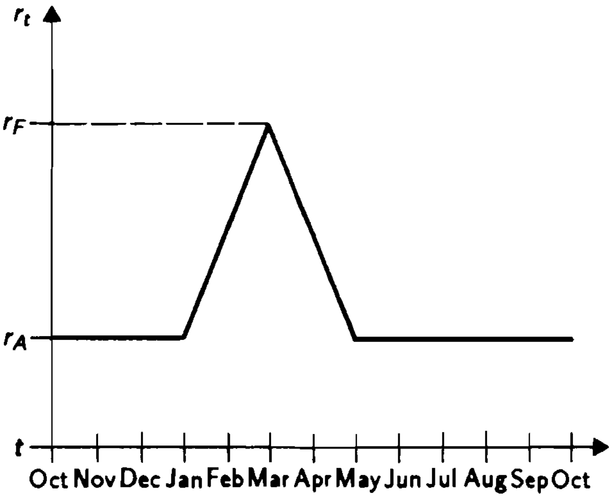


**Figure 11.** Release policy proposed for Itezhi-tezhi dam.

The present operating rule can obviously be represented by eq. (17), but also the natural pattern of runoff can be fairly well reproduced by eq. (17) itself.

Based on considerations analogous to those exposed for the Kariba scheme, the operating rule of the Kafue Gorge reservoir was assumed to be of the type shown in Figs. 12 and 13. The release in the upper zone of the storage is fixed and equal to the volume discharged in one month if all the turbines are fully operating for 90% of the time. The considered operating rules are therefore of the form

$$r = r(t, s_t, r_L, S_L, S_U) \tag{18}$$

and are uniquely identified by the parameters $(r_L, S_L, S_U)$.

The management problem was then formulated as a multiobjective optimization problem as follows:

$$\min_{\{r_A, r_L, S_L, S_U\}} [D]$$

$$\max_{\{r_A, r_L, S_L, S_U\}} [G, F] \tag{19}$$

subject to

- the reservoir equation of the form (7) for each reservoir;
- the operating rules (17) and (18) for Itezhitezhi and Kafue Gorge, respectively;

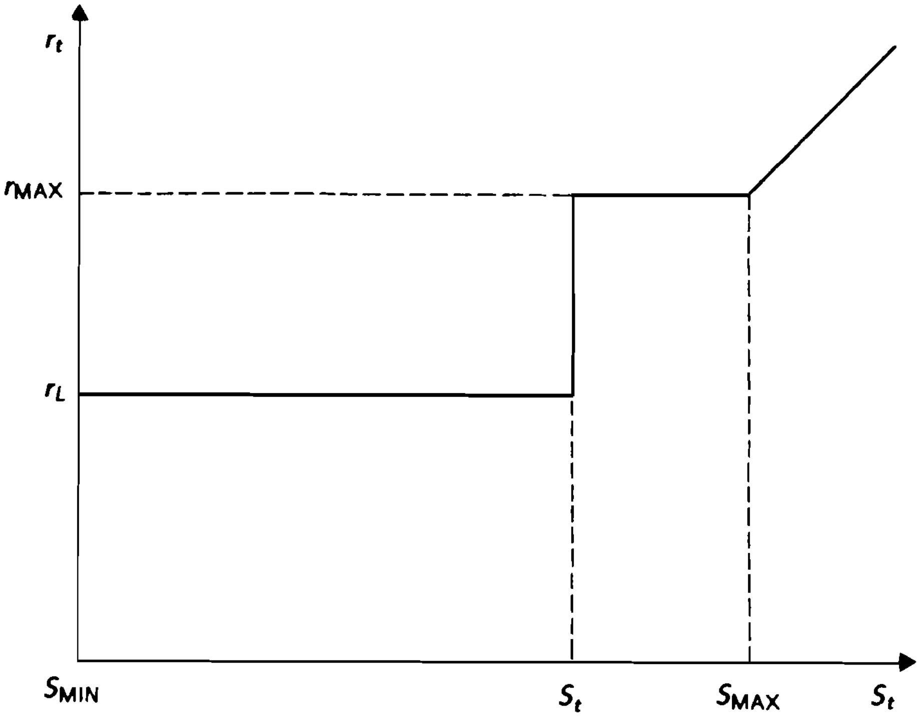


**Figure 12.** Storage–release operating rule proposed for the Kafue Gorge reservoir.

- the equation of the model relating the inflow into Kafue Gorge to the release from Itezhitezhi (as explained below)
- the feasibility condition of the form (11) for each reservoir;
- the equation relating the net head on the turbines to the storage and the release for Kafue Gorge reservoir;
- equations (12)–(16).

The routing of the flow in the river stretch between Itezhitezhi and Kafue Gorge was described by a linear first-order autoregressive scheme with the flow at Itezhitezhi as exogenous input. Several tests were carried out and the performances of the selected model proved to be satisfactory for the scope of the present study.

Problem (19) was solved using the same method applied to the lake Kariba management problem (see Section 2.3). The results are reported in Fig. 14, which shows the efficient solutions as contour lines of the surplus energy production $G$ in the space ($D$, $F$) of the other two objectives.

The analysis of the results suggests some comments. First, the values of $D$ are generally very small compared to the target production. Considering for example the curve corresponding to G = 60 GWh, the range of variation of $D$ is between 4.14 and 14.14

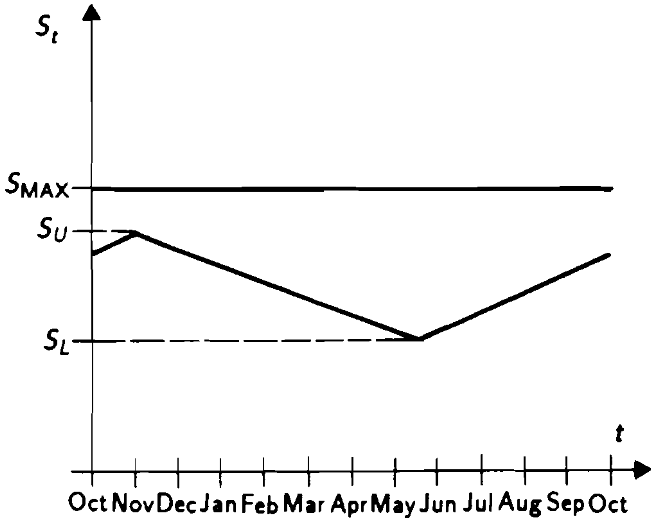


**Figure 13.** Time dependent boundary $S_t$ separating two storage zones of the Kafue Gorge reservoir.

GWh, which means between 0.9 and 3.2 per cent of the target production. The respective values of $F$ are $2.02 * 10^9$ $m^3$/month and $0.692 * 10^9$ $m^3$/month. Therefore, there appears to be a vast set of solutions which can guarantee a flow regime downstream of Itezhitezhi fairly close to the average natural conditions and still good performances with respect to hydropower production at Kafue Gorge. Moreover both $F$ and $D$ are quite sensitive to variations of $G$. Considering, for example, point $A$ in Fig. 14 it can be seen that by reducing $G$ of 30 GWh the value of $F$ can be doubled and the value of $D$ halved (points $B$ and $C$ respectively, in the same figure).

### 3.4. Analysis of a Particular Operating Rule

Several studies are available on the impacts on the Kafue Flats of the changes in the flow regime due to the operation of Itezhitezhi reservoir (see Section 3.2). To the authors' knowledge, however, no research has been conducted to assess which are the flow conditions that can reduce such impacts. The selection of a particular solution for a more detailed analysis was, therefore, based on some indications extracted from the published literature and on common sense. Point $P$ ($D = 12.5$ GWh, $G = 59$ GWh, $F = 1.94 * 10^9$ $m^3$/month) in Fig. 14 was considered to represent a good compromise among the different objectives. Fig. 15 shows the average values of the monthly release from Itezhitezhi if the proposed operating rule, identified by $r_A = 321 * 10^6$ $m^3$/month, is implemented. It can be seen that the timing and shape of the natural hydrograph are fairly well maintained by the adopted release pattern. The flow in the flood period (January to May) is 82 and 77

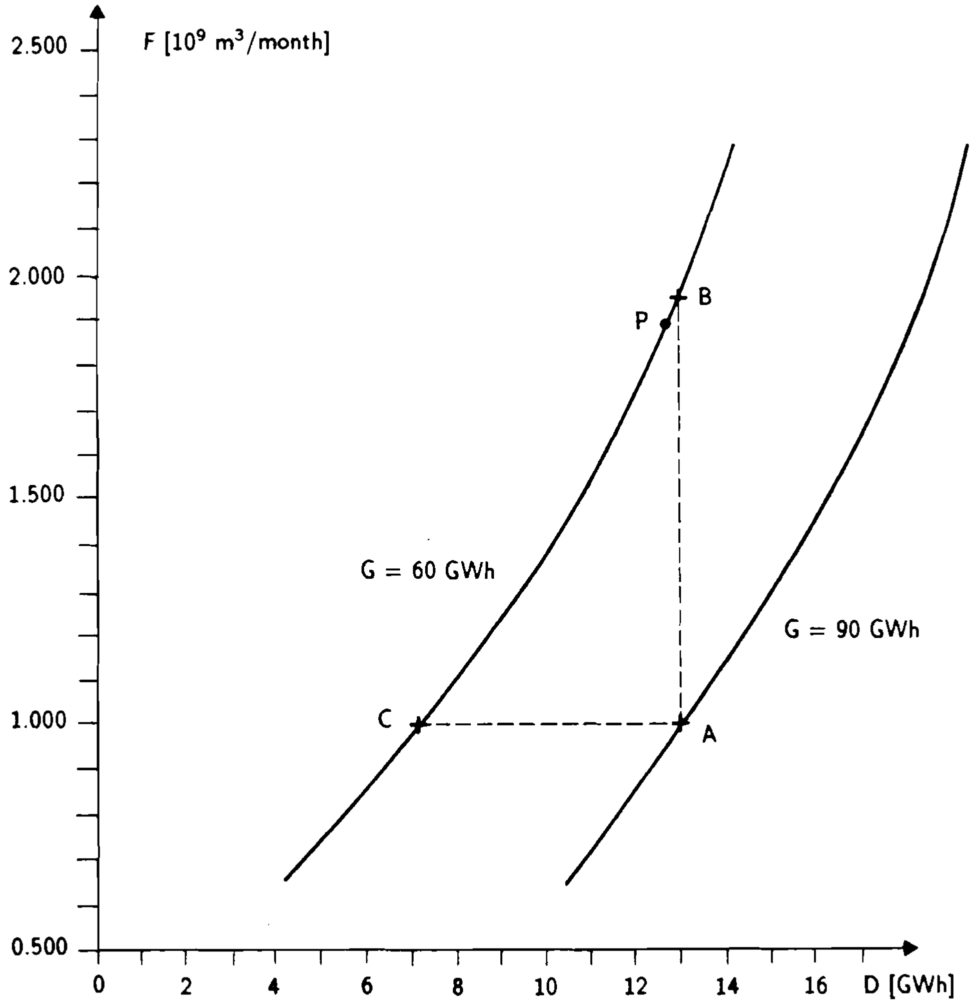


**Figure 14.** Efficient solutions of the Kafue Gorge–Itezhitezhi management problem in the space of objectives $(D,F)$.

per cent of the annual total in natural conditions and following the proposed regulation, respectively.

On the other hand, the standard deviations of all the monthly flows considerably decrease after the proposed regulation. Therefore the main effect of the regulation is not the reduction of the variations of the flows within the year, but of the variability of flows in the same month of different years. Turning to the power generation issue, Fig. 16 shows the values of the average monthly production together with their standard deviations obtained adopting the proposed solution ($r_L = 455.3 * 10^6$ m$^3$/month, $S_L = 1258 * 10^6$ m$^3$/month, $S_U = 1754 * 10^6$ m$^3$/month).

It can be seen that the target production is always achieved, apart from the months from November to January (i.e. at the end of the dry season) when the production is slightly below the target. In the same three months the reliability of the production is

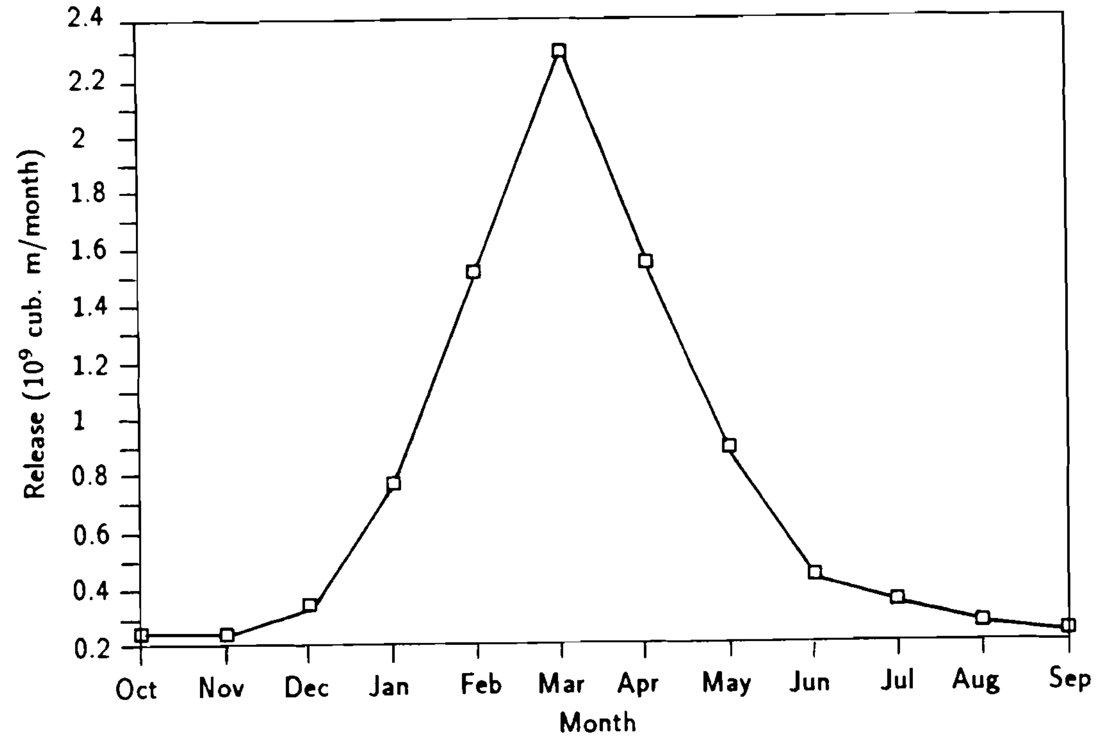
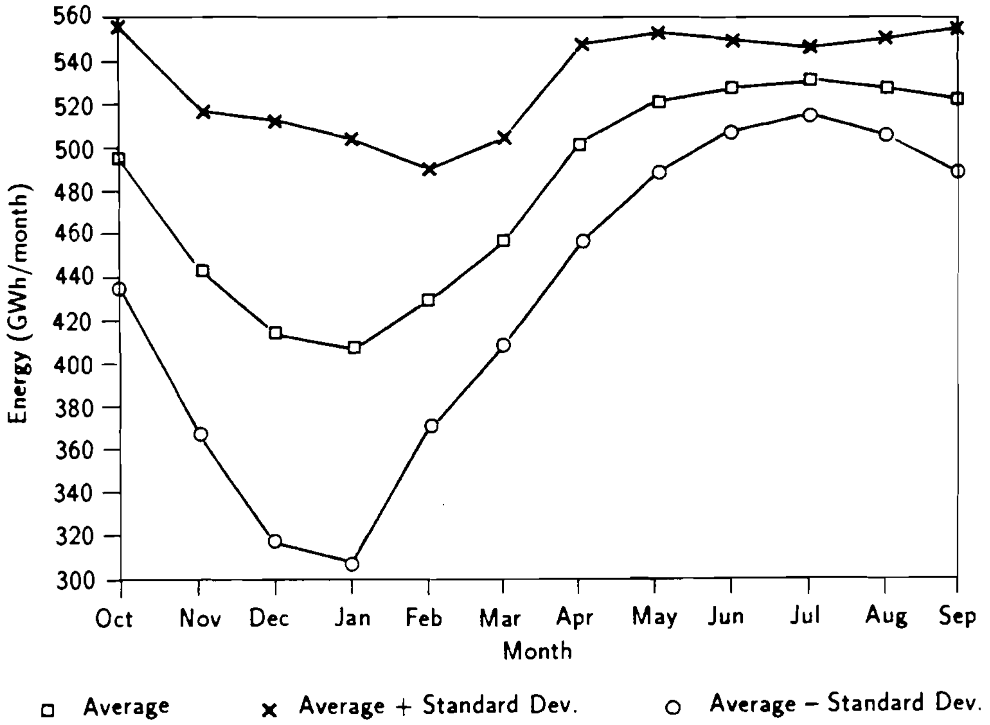


**Figure 15.** Average monthly releases from the Itezhi-tezhi reservoir obtained for the optimal release policy.

also lower, as shown by the high values of the standard deviation. Unfortunately the available data were not sufficient to carry out a thorough comparison of the historical management with the proposed operating rule. An almost complete set of data was available only for the years from 1982 to 1986.

Fig. 17 shows a comparison of the natural flows at Itezhitezhi in this period, with the historical releases and the releases given by the proposed rule. It is apparent that the latter follow much better than the historical releases the natural flow pattern. It can be noticed that since the considered years were particularly dry, the proposed rule even magnifies the flow peak by partly depleting the water stored in the reservoir at the beginning of the period. Turning to power generation, the average monthly production and the patterns of annual productions are almost coincident in the two cases, showing that the modified inflow regime at Kafue Gorge does not penalize the global performances of the plant. It must be pointed out, however, that the proposed management produces few very high, though isolated, values of the monthly deficit, which are considerably smaller in the historical management. To reduce this undesired effect, the authors are analyzing the possibility of slightly changing the formulation of the energy related objectives, and



**Figre 16.** The average monthly energy production at Kafue Gorge plant obtained for the optimal operating rule.

the first results seem to be encouraging.

## 4. Concluding Remarks

In this paper a multiobjective analysis of the management of two very large hydroelectric schemes in the Zambezi basin has been presented. The main purpose of the analysis was to determine the sensitivty of the hydropower production performances of the schemes to the variations of some suitable indicators related to the satisfaction of other objectives. In particular it has been shown that in the case of the Kariba scheme, a rather strict limitation of the maximum discharge from the lake can be achieved, even maintaining a high level of satisfaction of the hydropower demand. Moreover, an operating rule has been proposed that proved to be superior to the historical management with respect to all the considered performane indicators. In the case of the Kafue Gorge-Itezhitezhi scheme, the analysis has shown that the present level of average energy output can be maintained even adopting a release policy at Itezhitezhi which explicitely aims at

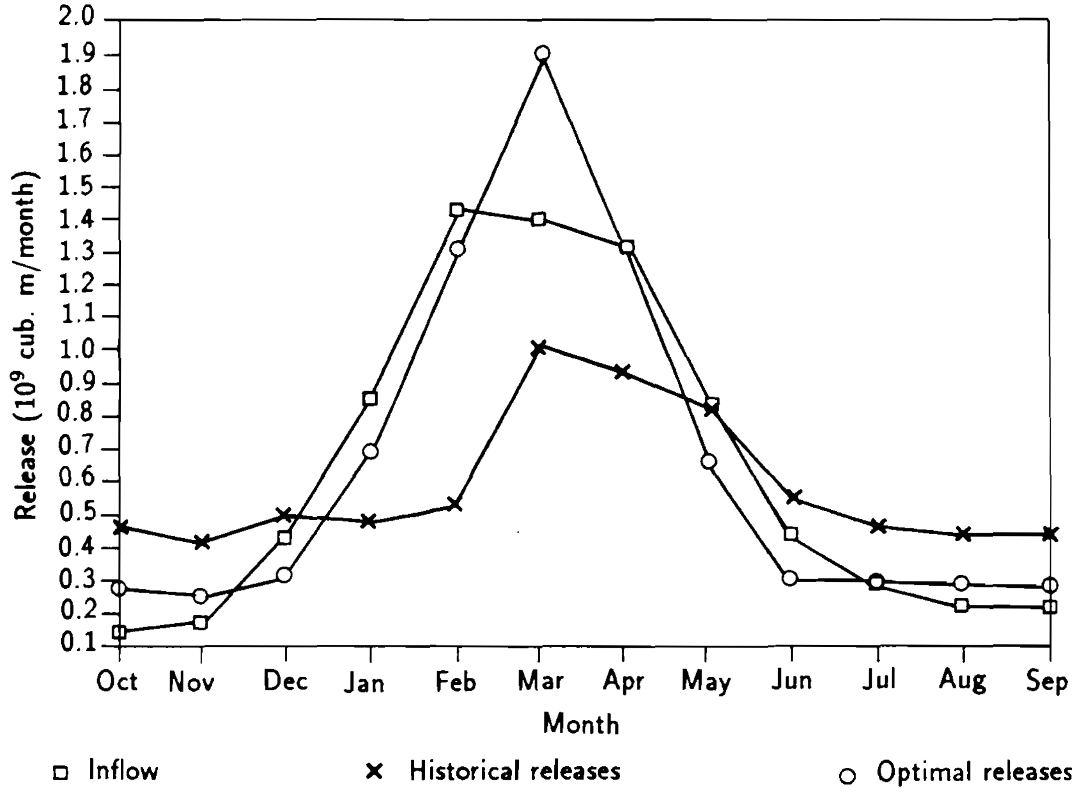


**Figure 17.** Average inflows to Itezhi-tezhi reservoir and sequence of historical and optimal releases.

preserving the size and timing of the annual flow fluctuations of the natural regime. Also in this case a particular operating rule was analyzed im more detail and the results confirmed the expectations, showing, however, an increase of the risk of occurrence of low values of hydropower production with respect to the historical management. For both schemes more research is needed to determine the degree of variation of the natural flow regime which can be tolerated by the affected ecosystems and which is best suited for the most relevant human activities in order to determine the most convenient tradeoff within the set of efficient solutions.

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## REFERENCES

References

Attwell, R.J. (1970) Some effects of Lake Kariba on the ecology of a floodplain on the mid-Zambezi valley of Rhodesia. *Biol. Conserv.*, 2(3), 189-196.

Balasubrahmanyam, S. and Abu-Zeid, S.M. (1982) The Kafue river hydroelectric development. *Proc. Nat. Sem. on Environment and Change: the Consequences of Hydroel. Power Development on the Utilization of the Kafue Flats.* University of Zambia, Lusaka, 1978, 63-67.

Balek, J. (1977) Hydrology and water resources in tropical Africa. *Development in Water Science*, 8, Elsevier, Amsterdam, 208 p.

Balon, E.K. and Coche A.G. (1974) Lake Kariba: on man-made tropical ecosystems in Central Africa. *Monographiae Biologicae*, 24, W. Junk. Publisher, 767p.

Central African Power Corporation (Santa Clara, J.M.A.) (1978) Reappraisal of the power generation potential of the Zambezi at Kariba. Parts I, II and III (1981), Salisbury.

Cohon, J.L. and Marks, D.H. (1975) A review and evaluation of multiobjective programming techniques. *Wat. Resour. Res.*, 11(2), 208-219.

Du Toit, R.F. (1983) Hydrological changes in the middle-Zambezi system. *The Zimbabwe Science News*, 17(7-8), 121-125.

FAO (1968) Multipurpose Survey of the Kafue River Basin, Zambia. Final Report, FAO, Rome.

Guariso, G., Rinaldi, S. and Soncini-Sessa, R. (1986) The management of lake Como: a multiobjective analysis. *Wat. Resour. Res.*, 22(2), 109-120.

Hayward, P.B. (1984) Status report on the Kafue fishery. In: Handlos, W.L. and Willimas, G.J. (Eds.) *Development on the Kafue Flats - The Last Five Years*, KBRC, University of Zambia, Lusaka, 58-73.

Himmelblau, D.L. (1972) Applied Nonlinear Programming, McGraw Hill, New York.

Karnopp, D.C. (1963) Random Search Techniques for Optimization Problems, *Automatica*, Vol.I.

Institute of Hydrology (Plinston, D.) (1981) A review of the hydrology of the upper Zambezi. Wallingford, England.

Lagler, K.F., Kapetsky, J.M. and Stewart, D.J. (1971) The Fisheries of the Kafue River Flats, Zambia, in Relation to the Kafue Gorge Dam. FAO-UN, University of Michigan, 161p.

Magadza, C.H.D. (1981) Editorial-Mana Pools. *Zimb. Science News*, 15, 110.

Marshall, B.E. (1987) Catch and effort in the lake Kariba sardine fishery. *J. Limnol. Soc. South. Afr.*, 13(1), 20-22.

Mepaham, R.H. and Mepham, J.S. (1982) Wetlands of the Zambezi basin and the lowlands of Mozambique. In: Burgis, M.J. and Symoens, J.J. (Eds.) *African Wetlands and Shallow Water Bodies: Directory. Inst. Francais de Recherche Scientifique pour le Devloppment en Cooperation*, Paris, 650pp.

Muyanga, E.D. and Chipungu, P.M. (1982) A short review of the Kafue flats fishery, from 1968 to 1978. *Proc. Nat. Sem. on Environment and Change: the Consequences of Hydroel. Power Development on the Utilization of the Kafue Flats*, University of Zambia, Lusaange: the Consequences of Hydroel. Power Development on the Utilization of the Kafue Flats, University of Zambia, Lusaka, 1978, 63-67.

Nyschens, I.R. (1982) Mana Pools is dying. *Zimb. Science News*, 16, 241-243.

Obrdlik, P., Mumeka, A., Kasonde, J.M. (1989) Regulated rivers in Zambia – the case study of the Kafue river. *Reg. Riv.: Res. and Manag.*, 3, 371-380.

Rees, W.A. (1978) The ecology of the Kafue lechwe: as affected by the Kafue Gorge hydroelectric scheme. *J Appl. Ecol.*, 15, 205-217.

Santa Clara, J.M.A. (1988) The hydrological operation of the Kariba hydroelectric scheme: past, present and future. Presented at 16th Congress on Big Dams, San Francisco.

Scudder, T. (1989) Conservation vs. development - river basin projects in Africa. *Environment*, 31(2), 4-32.

Sharma, T.C. (1984) Characteristics of runoff processes in the upper Kafue basin. NCSR/TR 51, *Wat. Resour. Res. Rep.* WR 25, Lusaka, Zambia.

Sharma T.C. and Nyumbu, I.L. (1985) Some hydrologic characteristics of the upper Zambezi basin. In: Handlos, W.L. and Howard, G.W. (Eds.) *Development Prospects for the Zambezi Valley in Zambia*. Kafue Basin Res. Comm., University of Zambia.

UNEP (1987) Agreement on the action plan for the environmentally sound management of the common Zambezi river system – final act. Harare, 26-28 May 1987.

White, E. (1973) Zambia's Kafue hydroelectric scheme and its biological problems. In: W.C. Ackermann, G.F. White, and E.B. Orthington (Eds.) *Man-Made Lakes: Their Problems and Environmental Effects*, 620-628.

Williams, R. (1971) Fish ecology of the Kafue river and floodplain environment. *Fish. Res. Bull. Zambia*, 5, 305-330.

Williams, G.J. (1984) Problems of a shared resource: hydropower on the middle-Zambezi. *Swansea Geographer*, 21, 17-26.

Wunschmann, A. (1988) Naturstützung statt Raubbau. *World Wildlife Fund Journal*, Federal Republic of Germany, 1, p. 30-31.

ZESA (1986) Annual Report and Accounts. Zimbabwe Electricity Supply Authority, Harare.