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Foreword

Within IIASA's Enironment Program, one of the objectives of the *Water Resources Project* is to investigate the impact of environmental and economic changes on water resources management. The climate/water resources problem raises a number of scientific questions that must be addressed to answer policy needs reflecting potential effects of global climatic change on regional water management, and possible adaptive measures that could be taken. Historically water resource systems hae been designed on the assumption that future climatic and hydrologic variations might be expected to be similar to those observed during the last century. However, man's activity may cause significant influence the hydrological regime in various parts of the earth.

The paper by Professor Z. Kaczmarek concerns the possible impacts of long-term hydrological non-stationarity on design and operation of water reservoir systems. As man-made lakes are essential tools in controlling the effects of hydrological variability, the paper considers the relationship between storage capacity, water demand and various performance criteria of reservoir management for a number of scenarios. It may be expected that the impact of climatic change can be detected particularly well in those elements of water systems that accumulate climatic impacts over long periods, such as groundwater, lakes and reservoirs. It may be seen from the conclusions of the paper that even relatively small changes in the stochastic characteristics of the inflow to the reservoir may be amplified into much larger changes in reliability and other operational criteria.

The application of methodological tools presented here is illustrated by the Lake Kariba case study. This man-made impoundment, one of the largest in the world, is located in the Zambezi river basin. In the past three years, *Water Resources Project* has been deeply involved in studying water-oriented policy problems in southern Africa in close cooperation with the United Nations Environment Program (UNEP) and the Southern African Development Coordination Conference (SADCC). This shows not only IIASA's interest in problems of the developing countries, but also reflects the interconnection between global environmental processes and regional economic and technical problems.

B.R. Döös
Leader
Environment Program

IMPACT OF CLIMATIC VARIATIONS ON STORAGE RESERVOIR SYSTEMS

*Zdzislaw Kaczmarek**

1. INTRODUCTION

Scientists and politicians are faced with an unusual problem, in that mankind is going to change the global environment due to increased population stress, agricultural and industrial development and often unwise resource management. Dramatic disturbances in climatic processes may be expected during the next century due to increased concentration of greenhouse gases in the atmosphere and related changes in the radiation balance of the Earth. In spite of all the uncertainties associated with the climate issue, the world scientific community is expected to evaluate possible consequences of climatic changes on economic activities, standard of living, and even on global environmental security. This paper is concerned with possible impacts of climate variations on water resources systems, and, in particular, on the efficiency of large storage reservoirs.

During the last 40 years a number of huge reservoir systems were constructed in various parts of the world, the best known are the Aswan (Sadd-El-Aali) reservoir on the River Nile, the Kariba dam in southern Africa, the Bratsk reservoir on the Angara-Yenisey river in the USSR, and many others. Such systems are expensive, usually of vital importance for a given country or economic region and their life-time is in most cases of the order of one hundred years or more. Their role is obvious: to cope with the *variability* of runoff in order to increase water supply reliability for meeting agricultural and urban demands, as well as for energy production. All these large-scale hydraulic investments were planned and implemented under the assumption that future climate and hydrology will be similar to the past. The basic concept of *runoff stationarity* is still widely accepted as the foundation of planning techniques, independent on the level of their sophistication, and for calculating performance criteria of water schemes, such as risk, reliability, resilience or robustness. The question arises as to how *existing* water storage systems will react on changes in runoff processes. Or, what we can do to make new hydraulic struc-

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tures accommodate changes in hydrologic processes, or how planning and design procedures should take into account the uncertainties concerning the magnitude of the impacts of climatic shifts on hydrology.

The problem of sensitivity of water storage systems to climate changes has been recently raised in a number of papers [4, 9, 11, 19]. On the basis of model calculations some authors claim that water reservoirs designed and operated under present hydrologic conditions may be severely affected by climatic changes, and that largely increased storage capacity may be needed to cope with the effects of such changes. Unfortunately, the methodological background for evaluating possible consequences of shifts in hydrological processes on planning and operation of water reservoirs is far from being adequate to the needs. To obtain more firm and comprehensive results a new methodological approach should be developed and applied. This concerns both the future structure of runoff processes and methods allowing the evaluation of storage systems response to changes in the hydrological regime. This paper is concerned mostly with the latter problem, although some discussion on the climate/water resources transfer functions will also be presented.

The possibility of application of the *stochastic storage* theory to analysing the effects of non-stationarity on reservoir performance will be examined. This theory introduced by mathematicians and hydrologists many years ago [7, 12, 14, 24] is mostly because of some computational difficulties not very popular among water resources engineers. Its potential, however, to analyse stochastic structure of storage processes is high and for this reason we shall use it for detecting impacts of changes in runoff properties on probability-based performance criteria of the reservoir. The Kariba lake on the Zambezi river has been selected as a case study for showing the practical applicability of proposed methodology.

2. NON-STATIONARITY OF HYDROLOGICAL PROCESSES

For a number of reasons the runoff process may differ from a stationary regime. Land-use changes, deforestation, development of hydraulic infrastructure and many other forms of human economic activity may substantially modify the soil-vegetation-water-atmosphere interrelations. It may be surprising that in spite of existing and expected disturbances the traditional water management techniques, based on historical hydrology as a basis for designing future water systems, are still prevailing in practice. The fundamental concept of a stationary hydrology is commonly accepted by water resource planners and decision makers.

Only during the last decade the growing awareness of potential implications of climatic change on various fields of human activities influenced the way of thinking in the area of water resources. This *per se* should be seen as important positive result of the "greenhouse debates", irrespective of the intensity of hydrological transformations due to climate variations. The potentiality of climate change not only heightens the need to review planning techniques, but at the same time creates favourable conditions for reevaluations of legal and institutional procedures for managing water resources in a more flexible way. Since the World Climate Conference in 1979 a growing from year to year amount of papers were published on the impact of climate variability on water resources. Although the progress in scientific understanding of the problem seems to be not very impressive, the general concept of non-stationary future is now accepted by a growing circle of water specialists.

Unfortunately, there is still a long distance to overcome between the general understanding of the problem and development of realistic and scientifically acceptable future hydrologic scenarios. The key problem is that to make such scenarios useful for water resources analysis they have to reflect not only the average changes in runoff characteristics, but also give adequate information on changes in hydrological variability. As stated in [9]

> "... majority of water resource problems are located in tails
> of the distributions of hydrological and meteorological processes that
> eventually decide on water shortage or water excess."

Also, in a Statement on the Hydrological and Water Resource Impacts of Global Climate Change, the WMO Commission for Hydrology [27] claims

> "... In the foreseeable future the information that will be derivable from a
> paleoclimatic reconstructions or from GCMs will relate to mean annual and
> seasonal values of primary climatic variables. *Water resources exists to cope with departures from mean values and spatial variability ...*"

It is clear that models able to represent average hydrological characteristics and their changes may be interesting from purely scientific point of view, but are of limited value for water resources management.

In this paper *climate* is defined as a *stochastic process*, the realizations of which are the *states of the atmosphere* (often called weather) at a point or over a given area, described by means of a set of quantifiable attributes $w_1, w_2, \ldots, w_r$. *Hydrology* in turn is defined as a *stochastic process*, the realizations of which are the *states of the hydrosphere* at a point or over a given area, described by quantifiable attributes $h_1, h_2 \cdots h_s$. The two processes may be linked by a number of functional relations, which will be called a *transfer operator* or a *transfer function*. Changes in climate or in the transfer operator will be of course reflected by changes in hydrology.

Due to seasonality, climate and hydrology are *not stationary*. However, they may be called semi-stationary, if the joint probability distribution associated with realizations

$$\begin{bmatrix} w_{1t_1} \\ w_{2t_1} \\ \cdot \\ \cdot \\ \cdot \\ w_{rt_1} \end{bmatrix} \begin{bmatrix} w_{1t_2} \\ w_{2t_2} \\ \cdot \\ \cdot \\ \cdot \\ w_{rt_2} \end{bmatrix} \begin{bmatrix} w_{1t_3} \\ w_{2t_3} \\ \cdot \\ \cdot \\ \cdot \\ w_{rt_3} \end{bmatrix} \cdots \begin{bmatrix} w_{1t_m} \\ w_{2t_m} \\ \cdot \\ \cdot \\ \cdot \\ w_{rt_m} \end{bmatrix}$$

made at any set of times $t_1, t_2, t_3, \ldots$, is the same as that associated with m realizations made at times

$$t_1 + k\Delta t\ ,\quad t_2 + k\Delta t\ , \ldots ,\ t_m + k\Delta t$$

where Δt is a time interval of one year. For a climate to be semi-stationary, the joint distribution of any set of (multivariate) realizations must be unaffected by shifting all the observation times by *any number of years*. The same may be said for hydrology.

Functional operators developed for relating climate and hydrology should describe physical processes of the soil–water–atmosphere cycle and may be presented in the form of mathematical models of various level of sophistication. A simple example may be found in [6], where a model for calculating average water temperature in a well mixed lake has been described. The driving forces for the temperature regime are energy fluxes between water surface and the atmosphere Q_c and between the water body and its bed Q_b

$$\rho c_w h \frac{dT_w}{dt} = Q_c + Q_b \tag{1}$$

where ρ is density of water, c_w its specific heat, h is the mean depth of the lake and t denotes time. The energy exchange between water surface and the atmosphere may be approximated by a quadratic formula

$$Q_c = \alpha + \beta T_w + \gamma T_w^2 \tag{2}$$

where parameters α,β and γ depend on incoming short-wave radiation Q_{sr}, albedo, air temperature T, air humidity e and the wind speed u. After integration Jurak [6] obtained the formula for calculating the average water temperature in the time interval $<0,t>$

$$\bar{T}_w = -\frac{\beta}{2\gamma} - \frac{\rho c_w h}{2\gamma t}\left[\ln\frac{(1-\Theta)^2}{\Theta} - \ln\frac{(1-\psi)^2}{\psi}\right] \qquad (3)$$

where the right-side functions depend on α,β and γ, i.e. on a vector of climatic variables. Schematically the result may be shown in Figure 1.

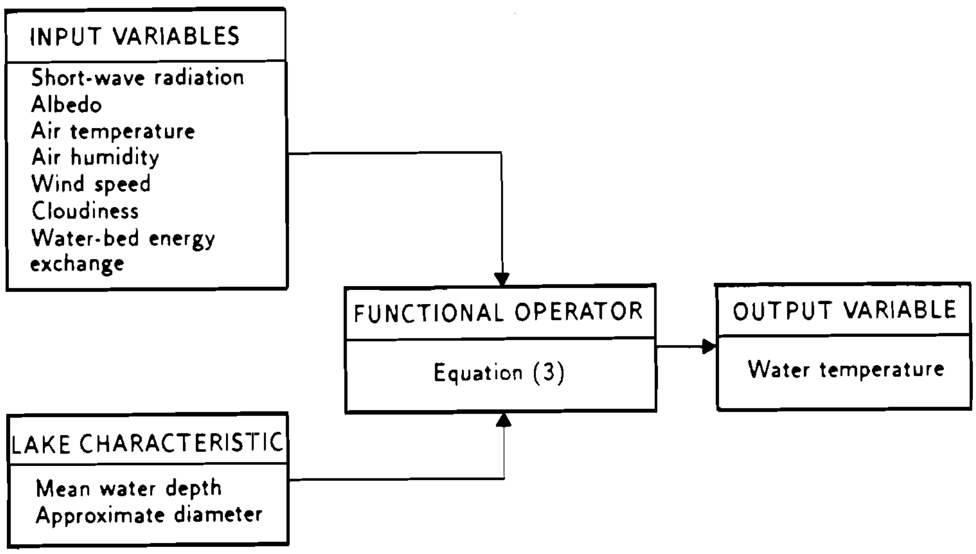

Figure 1. Input–output system for calculating water temperature.

In the case of rainfall/runoff models the complex relations between climate, soil characteristics, vegetation and hydrology should be reflected. An interesting example of catchment transfer functions may be found in the paper by Bultot *et al.* [2], where sensitivity of water balance components to changes in climatic inputs have been examined for three river catchments in Belgium. It is clear from this and other papers on runoff modelling that in order to get realistic results a great amount of climatic and soil characteristics is needed, such as radiation fluxes, cloud cover, air temperature and humidity, wind speed and others. If oversimplified, the transfer operators usually contain some parameters of no clear physical meaning which have to be estimated on the basis of historical data.

In [25] Schaake and Kaczmarek observed that there are three factors influencing the validity of climate/hydrology transfer functions:

- the inherent accuracy of models,
- the degree to which model parameters depend upon the past climatic conditions for which the model was calibrated, and
- the accuracy of available input data.

The stationarity of transfer functions dependent on past data deserves particular attention. As long as the stationarity, i.e. independence of climatic conditions, of the model parameters has not been proved, such a model cannot be effectively used for evaluating hydrological consequences of changes in climatic processes. This is particularly important for simple empirical relations such as Langbein's diagrams [13] or Turc formula [26].

It was said earlier that key input elements for evaluating hydrological processes are precipitation, air temperature, air humidity, energy balance, wind speed, vegetation resistance, soil moisture and permeability, hydrodynamic conditions of the surface, etc. All of them may be influenced by changes in the chemical composition of the atmosphere, but unfortunately only few may be adequately represented in the present generation of General Circulation Models. If some authors claim that impacts of climate change on water resources may be decided on the basis of changes in temperature and (eventually) precipitation they are simply wrong. At least, if they are interested in something more than in multiyear averages of water balance components. For example, in the interesting work of Nemec and Schaake [19], the authors were forced *to assume*, instead of calculating the possible changes in evapotranspiration values because of insufficient climatic information used as input data for their Sacramento Runoff Model.

In such circumstances a key question which has to be answered rings: how to build hydrological scenarios for uncertain future, useful for water resources planning and analysis? Today, the following alternative solutions may be suggested:

1. Application of complex, physically based hydrologic models with some input variables based on paleoclimatic analyses or GCMs outputs, and others assumed as reasonable guesses.
2. Application of such comprehensive models together with a climate scenarios approach (e.g. temperature rise of +2,0 K or +4.0 K, precipitation increase or decrease by 10 or 20 per cent, etc.).
3. Scenario approach applied ***directly to hydrological processes by assuming*** reasonable changes in their stochastic structure.

From the scientific point of view, the first approach seems to be the most attractive. Unfortunately, the accuracy of GCMs predictions and of climate/hydrology transfer operators is still too low to meet the needs of water resources analysis. For example in

[16] L. Mearns *et al.* estimate that by CO_2 doubling the regional precipitation may change from −20 to +20 per cent and expect that time needed for research leading to consensus may vary from 10–50 years. In the recently published paper [23] Ramanathan *et al.* discuss interactions in geosphere/biosphere processes and conclude that "No current model accounts for these interactions, and we are perhaps decades away from developing one that does. In the meantime, we face the unenviable task of judging the seriousness of the anthropogenic effect with a very limited comprehension of the climate system."

The scenario approaches are less ambitious, but at least allow to investigate how sensitive are water resource systems to anthropogenic changes in hydrological processes. Of the above-mentioned techniques of creating hydrological scenarios, the third one seems to be the most rational. The often presented in the literature an *indirect* approach, based on a number of climate scenarios transferred through functional relations to get hydrological variables, may be seen as an interesting scientific exercise, but gives no more information for the water resources analyst than he may get from direct runoff scenarios.

In this paper, focused on sensitivity analysis of storage reservoirs, we will follow the direct scenario approach. If, for example, the inflow to a reservoir is described as a stochastic process

$$Q(c_1, c_2, \ldots, c_r, t_1, t_2, \ldots, t_N) \tag{4}$$

where c_i are parameters and t_j denote discrete time intervals, then through reasonable changes in parameter values a number of inflow scenarios will be determined. The *reasonable* assumptions about the range of possible c_i values may be based on:

- temporal analogues of hydrological characteristics for specific N-years climatic situations, e.g. warm periods,
- preliminary climate/hydrology sensitivity studies done, for example, for one or more small catchments located inside a larger water resources region,
- regional analysis of differences in climatological and hydrological regimes.

The final goal is to get a number of *feasible* runoff scenarios containing sufficient information needed for water resources impact studies.

3. ROLE OF STORAGE RESERVOIRS IN WATER MANAGEMENT

It is clear from previous considerations that water resource planners are facing high uncertainty in evaluating future hydrologic conditions. Recognizing this Dooge [3] offers the following advice:

> "The best strategy may be to return to the classical procedure of allowing for a safety factor to cover possible changes and then work through research and accumulated experience to reduce over time the degree of uncertainty, thus allowing the use of a lower safety factor."

Such an iterative strategy may be well illustrated by analyzing the sensitivity of water storage systems to climate-induced changes in the hydrological regime.

If water resources management exists to cope with runoff variability, then storage reservoirs are probably the main tools for assuring high reliability of meeting various water demands. The usual practice is to design water resource systems in such a way that this reliability be equal or higher to some value accepted by water users, e.g. 90 percent. A great number of large reservoir systems of vital importance for national and regional economy have been designed in the past. The well known examples are:

- a group of reservoirs in the Alpine region of Austria, Italy and Switzerland used for energy production and urban water supply,
- the huge storage reservoir system (Kariba, Itezhi-tezhi, Kafue Gorge, and Cahora Bassa) in the Zambezi river basin with the overall volume of more than 230 billion cubic meter,
- the hydropower system on the Volga river with a number of large flow regulating reservoirs,
- the system of 42 reservoirs operated by the Tennessee Valley Authority to provide navigation, flood control and power generation,
- the system of reservoirs in the Amazon basin, used mainly for the energy production.

All these reservoir systems may be badly affected by changes in runoff characteristics, caused by global (climate) or regional (land use, deforestation) processes.

Several authors studying the interrelation between climate and hydrology suggest a magnification of precipitation and evapotranspiration changes when they are transferred into changes in runoff. Because of a cumulative effect, similar non-linearities may be expected in storage behaviour in relation to the hypothetical inflow changes. For example, on the basis of some case studies Nemec and Schaake [19] conclude that in humid regions a decrease of 25 percent in precipitation gave a more than 400 percent increase in storage needed to maintain the required reliability of water supply. The conclusions of Klemes [11] are less categorical and show that the reliability differences under various inflow scenarios vary in accordance with the target release and storage capacity.

The basic problem in storage theory is to find the relationship between inflow process $Q(t)$, target release D, capacity of the reservoir W and reliability R of meeting demands

$$R = f[Q(t)\ ,\ D, W] \tag{5}$$

when the mass balance equation of the reservoir

$$\frac{dV}{dt} = Q(t) - Q_0(t) \tag{6}$$

is satisfied. V means the current storage volume, and $Q_0(t)$ is a release function, usually dependent on $Q(t)$, D and V. The complexity of multipurpose reservoir systems requires the release function to be determined on the basis of some optimization procedures. Both $Q(t)$ and D may fluctuate according to changes in climate, but to simplify the problem we shall first assume that the target release is constant. The relationship (5) may be presented in an alternative form

$$W = f[Q(t)\ ,\ D, R] \tag{7}$$

defining the necessary reservoir capacity needed to secure the target release with a given level of reliability.

The reliability criterion is commonly used in water resources practice. Roughly speaking it may be defined as the *probability of success*

$$R = \text{Prob}(S) \tag{8}$$

where S is defined in various ways, but generally means meeting desired demands. It should be, however, remembered that some other performance criteria suitable to characterize the efficiency of water resource systems have been proposed. Among them are such performance measures as resiliency, robustness and system vulnerability. Referring to Hashimoto *et al.* descriptive and formal definitions of some of these criteria follow.

Resilience is a measure describing how quickly a reservoir will recover from a failure, independently how it would be defined, once failure has occurred. Let F denote failure and S represent a success. Then according to [5] the resilience criterion is defined as probability of recovery from the failure in a single time interval

$$\text{RES} = \text{Prob}(S \mid F) = 1 - \text{Prob}(F \mid F) \tag{9}$$

Resilience is an important criterion. If the "recovery" of a water system will be too slow, this may seriously affect its operational efficiency.

A number of ***robustness*** measures has been offered in the water resources literature. Most of them, however, seems to be difficult to adapt for evaluating climate impacts on storage reservoirs. An alternative robustness criterion will be formulated below, directly reflecting the influence of hypothetical changes in climatic and hydrological processes. Let:

- $[D, W]$ be the vector of design parameters,
- $Q_0(t)$ represent the inflow process estimated for present climatic conditions on the basis of runoff data, and
- $Q_i(t)$, $i = 1,2,...$ is a set of plausible inflow scenarios, to which subjective probabilities (or wages) P_i may be attached

An optimal design vector $[D_{opt}, W_{opt}]$ for current hydrological conditions, which maximize some objective function, may be found. If, for example, the reservoir manager wants to maximize supply reliability, then

$$R_{opt} = R(D_{opt}, W_{opt} \mid Q_0(t)) \tag{10}$$

For other inflow scenarios the reliability

$$R_i = R(D_{opt}, W_{opt} \mid Q_i(t)) \tag{11}$$

will generally differ from (10). The inverse of the waged deviation

$$WD = \sqrt{\sum_i P_i (R_i - R_{opt})^2} \tag{12}$$

may be used as robustness criterion

$$RBS = \frac{1}{WD} \tag{13}$$

It may happen that some design vector $[D_k, W_k]$ will assure a smaller reliability

$$R_k = R(D_k, W_k \mid Q_o(t)) < R_{opt} \tag{14}$$

but at the same time the reservoir's robustness (13) will become higher.

Many other performance criteria may be used to study the impact of changes in physical processes on water storage systems. In general, water reservoirs are suitable tools for analysing the seriousness of such impacts if proper analytical methods for relating input characteristics to storage and output processes are used. One such methodology which will be presented in the next chapter seems to be very promising.

4. STOCHASTIC STORAGE THEORY REVISITED

The designing of storage systems has been the subject of water resources management for many years. But only during the last 40 years a rigorous mathematical theory of such systems has been developed employing *stochastic* inflow process to find the probability distribution of storage levels and reservoirs outflow. A number of mathematicians were working in this field developing an elegant theory that became a part of "pure" mathematics. At the same time the applied stochastic storage theory appears to provide suitable basis for solving practical problems in the field of water resources. Although some papers [12, 24] were published in the Russian literature in fortieth, the main stream of work started with the Moran's paper [17], in which a stationary probability distribution of storage levels was found for independent and stationary inflows. Kaczmarek [7] and Lloyd [14] used different methods for extending Moran's model to the case of correlated and seasonally distributed inflows. An excellent summary of the stochastic storage models was given by Klemes [10] and Phatarfod [21]. Most of the work in the applied stochastic storage theory has been done for infinite reservoirs and discrete inflows. Such somehow unrealistic assumptions may be however avoided as it was shown in [8]. In this paper we shall use an *annual stochastic storage model* subject to first-order Markovian inflows having log-normal probability distribution. Its mathematical formulation may be easily extended to the seasonal or monthly case and to other forms of probability distributions.

Let us consider a water reservoir such that the relative storage level

$$0 \leq z(t) \leq 1 \quad , \quad z(t) = \frac{V(t)}{W} \tag{15}$$

where W is the maximum allowable storage capacity. The inflow $Q(t)$ forms the first-order Markovian process (stationary) subject to a bivariate log-normal probability distribution. The water balance equation may be written in the form

$$W\frac{dz}{dt} = Q(t) - Q_0(t) \tag{16}$$

where the release function $Q_0(t)$ will in most practical situations depend on current storage level, inflow to the reservoir and on number of parameters

$$Q_0(t) = Q_0(t,z,Q,c_1,c_2,...) \tag{17}$$

The c_i values may be optimized to meet the objectives of flow regulation. The release function (17) should fulfill two important conditions. First, it should not allow the storage level go beyond the boundaries (15). Second, it should belong to a class of functions for which, after integrating (16), the storage function

$$z(t) = g[z(t-1)\ ,\ Q\ ,\ c_1, c_2\ ,...] \tag{18}$$

and its unique inverse transformation

$$Q = g^{-1}[z(t)\ ,\ z(t-1)\ ,+c_1, c_2\ ,...] \tag{19}$$

exist for all values of parameters (Q is assumed to be constant in the time interval $<t-1,t>$). If these conditions are met, and inflow $Q(t)$ is the first-order Markov process, then storage levels $z(1)$, $z(2),\ldots,z(t-1)$ will form the second-order Markov process (see [1]). In the author's paper [8], the following release function, fulfilling the above conditions, has been used

$$Q_0(t) = D(1-\frac{\alpha}{z(t)}) + Q\frac{\alpha}{1-z(t)} \tag{20}$$

It may be proved that using (20) the relative storage levels will be kept within the limits α, $(1-\alpha)$.

Some additional comments are necessary before going into computational details. *First*, the *annual* storage model will be developed. It may be extended for a reservoir operated on a seasonal or monthly basis, but for the purpose of this paper it is not necessary. *Second*, both the target release and the reservoir inflow will be averaged over each time-interval (in this case – over each year), what may be acceptable only if the capacity W is relatively large in comparison with the yearly inflow.

For a given year let z_1 denote an initial level of storage, z_2 – storage at the end of the year and Δt – length of the time interval (in sec if Q is done in m^3/sec). Assuming that $Q(t) = Q$ and substituting release function (20) into (16), the following relationship will be received after integration from z_1 to z_2 and from 0 to Δt

$$0.5(1+\frac{b}{c})\ln\left|\frac{(a+bz_2+cz_2^2)}{(a+bz_1+cz_1^2)}\right| - (z_2-z_1) +$$

$$+\ 0.5(b+\frac{b^2-2ac}{c})\cdot\frac{1}{\sqrt{\Delta}}\ln\left[\frac{(b+2cz_2+\sqrt{\Delta})(-b-2cz_1+\sqrt{\Delta})}{(-b-2cz_2+\sqrt{\Delta})(b+2cz_1+\sqrt{\Delta})}\right] + \frac{c\Delta t}{W} = 0 \tag{21}$$

where

$a = \alpha D, \quad b = (1-\alpha)Q-(1+\alpha)D, \quad c = D - Q,$

$\Delta = \quad b^2 - 4ac, \quad$ and $z_1 \neq z_2$

Equation (21) may be solved for z_2 if z_1, Q, D, α, W and Δt are known, but it can also be used for calculating the inflow to the reservoir if the initial and final storage levels are determined.

The final goal in the stochastic storage theory is to find probability distribution of storage levels, and use it for evaluating all necessary performance criteria of the reservoir. It is clear that such distribution depends on characteristics of the inflow process, on the release rule, and on design parameters. Because $Q(t)$ may be affected by climatic change, the storage distribution and operational criteria can reflect the sensitivity of the reservoir to the departures from the stationary climatic regime. It may be expected that both natural and man-made lakes are excellent indicators of changes in atmospheric and hydrological processes. The well-known dramatic decrease of the Lake Tchad level is a good illustration of this.

We shall now discretize the storage space by dividing the total capacity of the reservoir into r layers (Fig. 2). The probability that the reservoirs level will move from the state s_i to the state s_j during the n-th year will be denoted as p_{ij}^{n}, and

$$\mathbf{P}_{ij}^{(n)} = [p_{11}^{(n)} p_{12}^{(n)} \cdots p_{rr}^{(n)}] \tag{22}$$

is a vector, whose elements are all values of $p_{ij}^{(n)}$. Let us now introduce a conditional, or transition probability

$$p_{ij',j''k}^{(n)} = \mathrm{Prob}\,(s_j s_k \mid s_i s_j) \tag{23}$$

which for $j' = j''$ will be denoted as $p_{ijk}^{(n)}$, and for $j' \neq j''$ is equal zero. The quadratic matrix of transition probabilities includes r^3 non-zero elements

$$\mathbf{P}_{ijk}^{(n)} = [[\, p_{ij',j''k}^{(n)}]] \tag{24}$$

For the annual model the symbol n in (24) may be dropped.

The basic equation in the stochastic storage model is based on matrix operations and may be written in the form

$$\mathbf{P}_{ij}^{(n+1)} = \mathbf{P}_{ij}^{(n)} \cdot \mathbf{P}_{ijk} \tag{25}$$

or

$$\mathbf{P}_{ij}^{(n+m)} = \mathbf{P}_{ij}^{(n)} (\mathbf{P}_{ijk})^{m} \tag{26}$$

If, for example, in the first year ($n = 1$) the reservoir is empty, the initial vector will be $\mathbf{P}_{ij}^{(1)} = [1,0,0\ ,\dots]$. The recurrence equation (26) allows to determine storage distributions after one, two, three or more years. It should be added that knowing all elements of the vector $\mathbf{P}_{ij}$ we may obtain

$$p_i = \sum_j p_{ij} \text{ , or } p_j = \sum_i p_{ij} \quad . \tag{27}$$

In water resources applications, in particular for analysing the efficiency of river flow regulation, the steady-state (ergodic) probability distributions are desired. It is known from the Markov chain theory that ergodic probabilities may be found by solving – under certain conditions – a non-homogeneous system of linear equations

$$\mathbf{P}_{ij}^{erg} = \mathbf{P}_{ij}^{erg} \cdot \mathbf{P}_{ijk} \tag{28}$$

by replacing one of the equations (28) by

$$\sum_i \sum_j p_{ij}^{erg} = 1 \tag{29}$$

Another possibility for receiving ergodic probabilities is based on an iterative procedure consisting in successive application of formula (25).

The key computational procedure, which for the annual storage model must be repeated r^3 times, is connected with calculation of transition probabilities p_{ijk}. Omitting technical details the following algorithm may be recommended (see Figure 2):

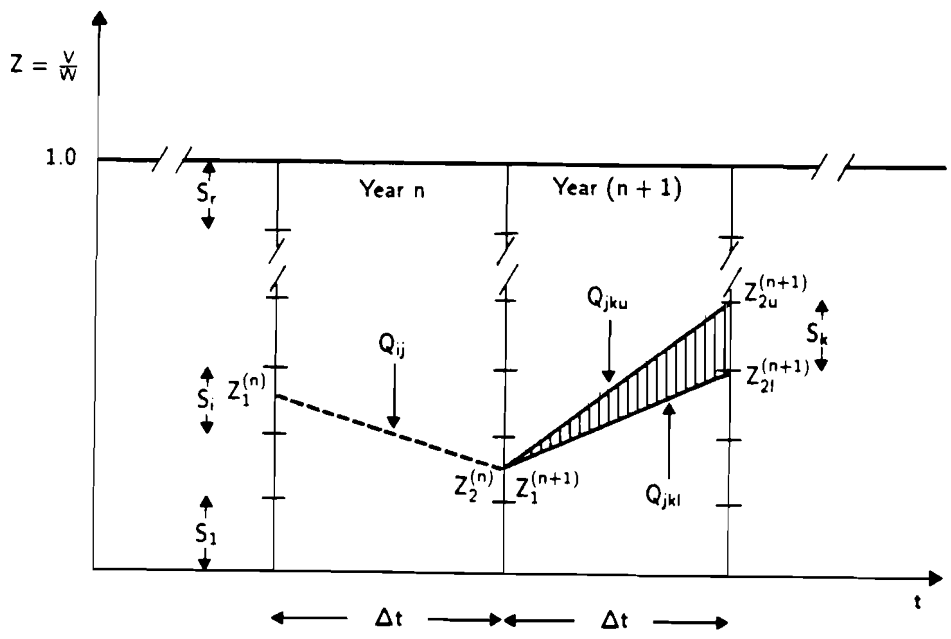

Figure 2. Schematic representation of changes in the storage level.

1. On the basis of inflow data calculate parameters of bivariate log-normal distribution m_x, s_x and $r_{x,x}$.

2. For each combination of storage states s_i, s_j, s_k find z_1^n, z_2^n, $z_1^{n+1} = z_2^n$, z_{2u}^{n+1} and z_{2l}^{n+1} according to symbols used in Figure 2.

3. Solve equation (21) for calculating inflow values

$$Q_{ij} = g^{-1}(z_1^n\ ,\ z_2^n\ ,\ D\ ,\ \alpha\ ,\ W\ ,\ \Delta t)$$

$$Q_{jkl} = g^{-1}(z_1^{n+1}\ ,\ z_{2l}^{n+1}\ ,\ D\ ,\ \alpha\ ,\ W\ ,\ \Delta t)$$

$$Q_{jku} = g^{-1}(z_1^{n+1}\ ,\ z_{2u}^{n+1}\ ,\ D\ ,\ \alpha\ ,\ W\ ,\ \Delta t)$$

and their logarithms.

4. Find parameters of conditional log-normal distribution

$$m_{\text{cond}} = m_x + r_{x,x}(x_{ij} - m_x)\ \ ,\quad x_{ij} = \ln Q_{ij} \tag{30}$$

$$s_{\text{cond}} = s_x\sqrt{1 - r_{x,x}^2} \tag{31}$$

5. Calculate the transition probability

$$p_{ijk} = \text{Prob}\,\left(\frac{\ln Q_{jkl} - m_{\text{cond}}}{s_{\text{cond}}} \le t < \frac{\ln Q_{jku} - m_{\text{cond}}}{s_{\text{cond}}}\right) \tag{32}$$

6. Form the matrix $\mathbf{P}_{ijk} = [[\,p_{ij',j''k}]]$.

If a set of inflow scenarios is considered, then this algorithm has to be repeated for each scenario.

After somehow exhausting mathematical considerations we may conclude this part of the paper with comments on practical usefulness of the stochastic storage theory. Phatarfod (21) comparing analytical (probabilistic) models with widely used simulation techniques makes an interesting remark that "The area where the mathematical theory can play a part is in providing an insight into the reservoir operation, thus enabling the engineer to have a better feel of the situation." This is particularly true in the case of changing operational conditions. Knowing the probabilistic structure of storage it is relatively easy to calculate various characteristics, such as mean storage level, probability of failure, reliability of supply, etc. These characteristic values may be compared for a number of hydrologic scenarios what is essential for any climate sensitivity study. We shall now try to do this for the Kariba Lake, one of the largest man-made water impoundments in the world.

5. THE KARIBA LAKE CASE STUDY

There is no other way to study the impact of climate on water resources than to draw lessons from a number of case studies. Water problems and related policy options are strongly site-specific, depending on the structure of economy, the demographic stress, hydrological regime and many other factors. Because in this paper we are concerned with the sensitivity of storage systems to climatic variations, the case study approach will be illustrated by assuming various hydrological scenarios for the Kariba reservoir in Southern Africa. There are several reasons for such a selection: ***first***, the Kariba hydro-power system is of great importance for two African countries – Zambia and Zimbabwe; ***second***, the lake is big enough to be studied on an annual operational basis, and ***third***, the IIASA Water Resources Project is strongly involved in studying water management problems in the Zambezi river basin.

The Zambezi river system is situated south of the equator between 12° and 20°S (Figure 3). More than 90 percent of inflow to the Kariba reservoir is generated in the upper part of the catchment, which may be defined a warm temperate region with dry winter season between May and September [22]. The average yearly precipitation in the Upper Zambezi is about 1100 mm and the mean annual temperature is 20°C. The annual and seasonal runoff variation is rather high: the ratio of extreme monthly flows in Livingstone (Victoria Falls) is 60:1. Such variability is a cause of difficulties in water management, but is also important for ecological dynamics of the river. A large part of the Zambezi river is now regulated by man-made lakes constructed for the purpose of hydroelectric power generation, but posing some serious environmental problems.

The Kariba reservoir is the largest impoundment in the Zambezi river basin and one of the largest in the world. Its operational capacity W is 70.10^9 cum., i.e. 50 percent larger than the average annual inflow to the lake. The capacity of Kariba power plant is 1200 MW, exploited jointly by Zambia and Zimbabwe. Operation of the reservoir is submitted to the optimal energy production with the additional goal to minimize the floodgate discharge. Generally, however, the Kariba lake managers try to keep the storage level as high as possible. From time to time, e.g. in the eighties, the upper Zambezi catchment is facing with droughts causing serious problems for the management of the reservoir. It may be added that the role of evaporation in the water balance of the lake is important. It can be estimated that average annual evaporation rate is equivalent to 256 m^3/sec, that is about 16 percent of the total inflow from the upper and middle parts of the catchment. Although the seasonal differences in the water balance components and in the level of storage are substantial, they are relatively small in relation to long-term inter-annual fluctuations. This allows to focus the analysis of reservoir

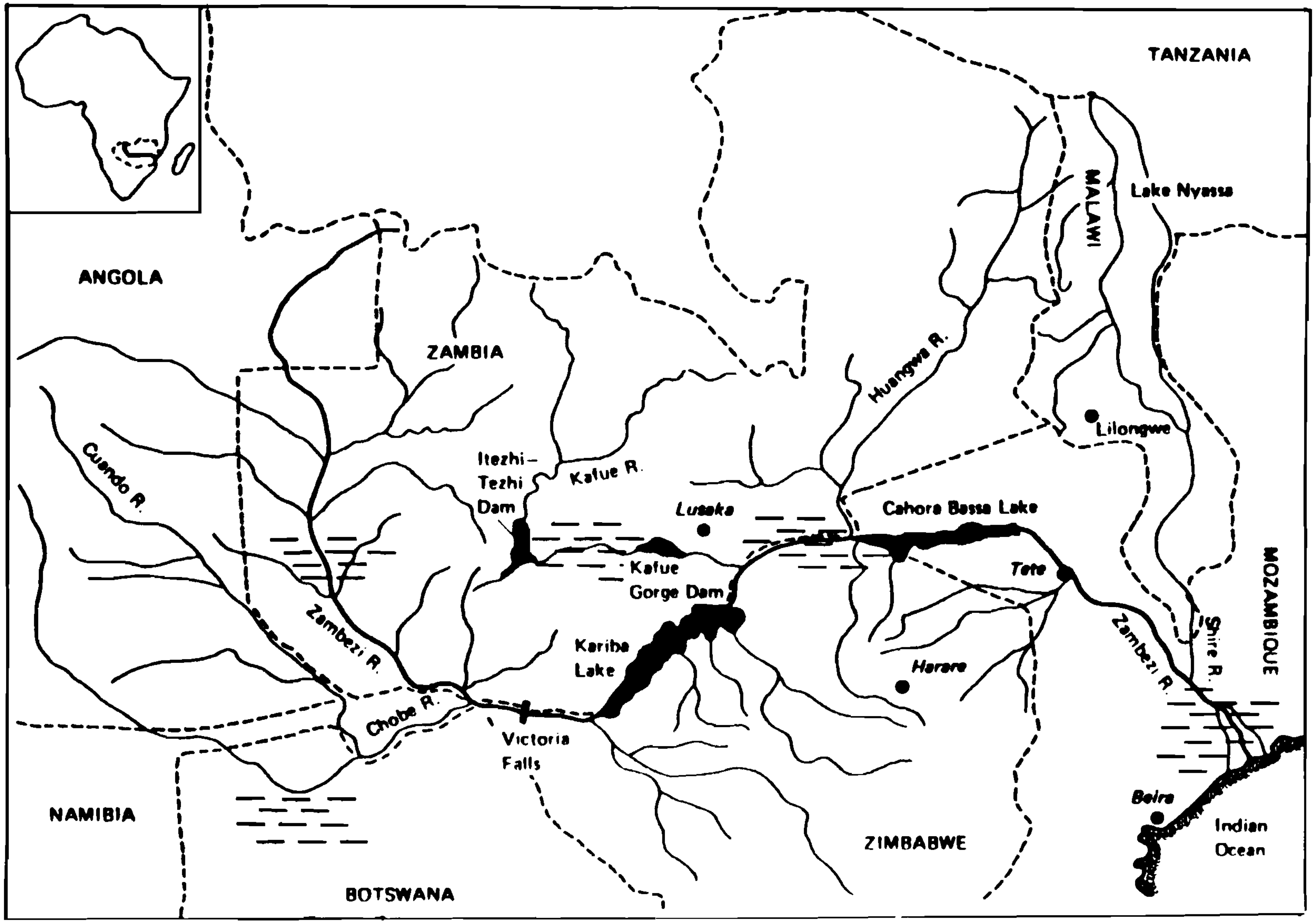

Figure 3. The Zambezi river basin with Kariba reservoir.

management on multi-year flow regulation.

The mean annual inputs to the system were calculated for the years 1924–1984 as the sum of upper and middle catchment inflows and the precipitation on the lake surface, minus evaporation losses (Table 1). The average characteristics are estimated to be:

- the average input $\bar{Q} = 1458$ m^3/sec,
- standard deviation $s_Q = 578$ m^3/sec, and
- the correlation coefficient for consecutive years $r_Q = 0.24$.

The statistical analysis of historical data leads to the conclusion that the input to the Kariba reservoir may be represented as the first-order Markov process with bi-variate log-normal probability distribution.

Table 1. Yearly inflows to the Kariba reservoir in m^3/sec.

Year	...0	...1	...2	...3	...4	...5	...6	...7	...8	...9
192.	-	-	-	-	2445	1361	1102	944	929	893
193.	1034	1334	770	1295	1173	990	1359	983	1883	1699
194.	1299	712	979	1567	1120	1124	1251	2062	517	1189
195.	1335	2199	2337	1287	2186	2042	1620	2978	1320	1246
196.	1648	1948	2695	1163	1122	1390	1100	1827	2433	1757
197.	1330	1251	596	2290	1906	1990	1355	2813	1621	1522
198.	1778	629	620	658	970	-	-	-	-	-

The question may be asked how the present hydrological regime of the Kariba reservoir will be affected by changes in climate. Very few climate impact studies were done for the African continent and some of the known results are highly controversial. The GCM outputs show a one–two degrees increase of annual temperature by the CO_2 doubling for the mid-latitude Southern Hemisphere. For the precipitation and soil moisture changes the picture is very unclear with results of different direction obtained from various models. Much of the intellectual and computational work is still to be done before a consensus on climate-induced hydrological changes in Africa can be reached. In this situation, the only possible way to study the sensitivity of water resource systems to hydrological non-stationarities is to investigate the present structure of runoff processes and to make assumptions about possible changes in their statistical characteristics. The range of assumed scenarios should reasonably reflect the existing knowledge on possible variations of water balance components and their sensitivity to at least main climatic characteristics, such as air temperature and precipitation.

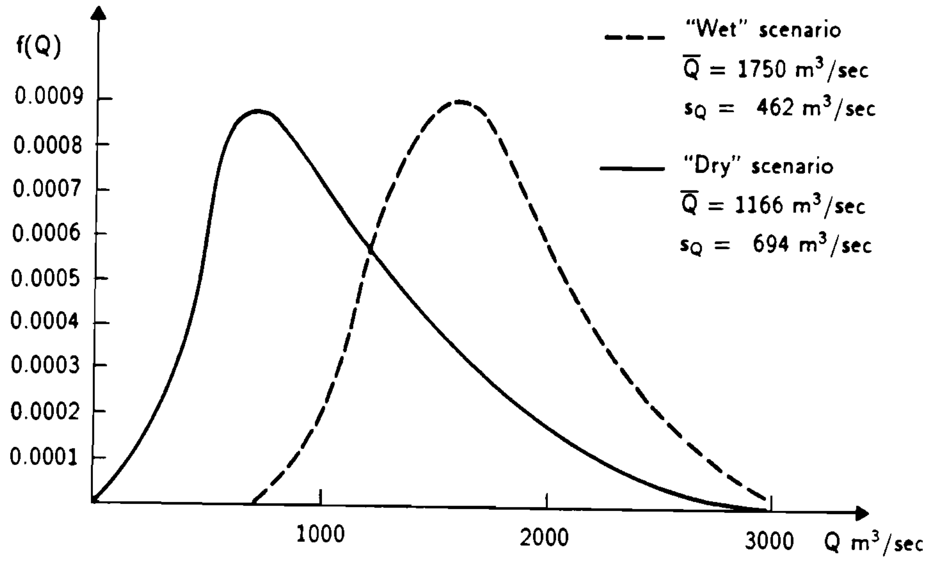

Figure 4. Log-normal inflow distributions for extreme scenarios.

On the basis of past hydrological and meteorological observations and taking into account hypothetical changes in the temperature and rainfall patterns it may be expected, that by the CO_2 doubling the average input to the Kariba reservoir will differ no more than $\pm$ 20 percent from the past 60 years. Similar range of changes will be assumed in relation to the standard deviation s_Q. On the basis of these assumptions 25 input scenarios and their impact on management of Kariba reservoir will be investigated. The parameters for the log-normal distribution for each scenario are given in Table 2, and, as examples two distribution functions for extreme situations are shown in Figure 4. The correlation coefficient for the bivariate distribution is assumed to be unchanged by climatic variations.

Methods developed in the framework of stochastic storage theory will be employed to show the consequences of various scenarios on the efficiency of reservoir management. The storage space of total operational capacity $W = 70.10^9$ m^3 will be divided into five layers, which seem to be sufficient in order to get the necessary information on probabilities p_i and p_{ij}. It may be added that on the basis of some experience a heuristic inequality

$$r \geq 1.5 \frac{W}{D \cdot \Delta t} \tag{33}$$

Table 2. Parameters of the log-normal distribution of the inflow to the Kariba reservoir.

s_Q [m^3/s]		$\bar{Q}$[m^3/s] 1166	1312	1458	1604	1750
462	m_z	6.988	7.121	7.237	7.340	7.434
	s_z	0.382	0.342	0.309	0.282	0.260
520	m_z	6.971	7.106	7.225	7.330	7.425
	s_z	0.426	0.382	0.346	0.316	0.291
578	m_z	6.951	7.091	7.212	7.319	7.416
	s_z	0.469	0.421	0.382	0.349	0.322
636	m_z	6.931	7.074	7.198	7.307	7.405
	s_z	0.510	0.459	0.417	0.382	0.352
694	m_z	6.910	7.056	7.183	7.294	7.394
	s_z	0.551	0.497	0.452	0.414	0.382

can be suggested to determine the minimum number of intervals (or storage states) to get reasonable results. The release function (20) will be used with the parameters $\alpha = 0.01$ and $D = 1\,100$ m^3/sec, what means that the target or guaranteed release should be close to 70 percent of the multiyear input to the reservoir.

The performance of Kariba reservoir operated by such a rule, under various hydrological scenarios, will be evaluated by means of probability distributions of storage states and by a number of additional criteria. The mean level of storage is

$$m_z = W \sum_j p_j \frac{j\text{-}0.5}{r} \tag{34}$$

The reliability criterion (8) will be defined as the ergodic probability of storage level being in the upper two layers during the given year

$$R = p_{4,4} + p_{4,5} + p_{5,4} + p_{5,5} \tag{35}$$

and the risk of failure as

$$\text{Risk} = p_{11} \quad . \tag{36}$$

In accordance with (9) the resilience criterion may be calculated by means of the formula

$$\mathrm{RES} = 1 - \frac{p_{11}}{p_1} \quad , \tag{37}$$

if failure means that the reservoir is in the state s_1. An additional criterion called "time of recovery" will be introduced now.

Let us assume that at the beginning of the first year the reservoir is in the state s_1 (empty), and that the initial $\mathbf{P}_{ij}$ vector is of the form $[1,0,0,...]$. Applying equations (26) and (27) we may calculate the vectors $\mathbf{P}_{ij}^{1+m}$ and $\mathbf{P}_{j}^{1+m}$ for successive years $m = 1,2,...$ Let

$$\mathrm{TREC} = 1 + m_{\mathrm{rec}} \tag{38}$$

be the *first year in the sequence*, for which $p_s^{1+m}\mathrm{rec} \geq 0.5$. We shall call (38) "time of recovery" or "time of filling up" the reservoir. All these criteria m_z, R, Risk, RES and TREC will be estimated for assumed input scenarios.

Calculations were done for 25 input scenarios on the basis of formulae (21)–(32) and following the algorithm described in the previous chapter. Three examples of matrices of transition probabilities for the base (historical) scenario and two extreme cases are presented in Tables 3, 4 and 5.

The differences are significant so it can be expected that also the ergodic probabilities and selected performance criteria will strongly reflect the impact of changes in hydrological processes on operational characteristics of the reservoir. The results are given in Tables 6, 7, and 9.

The dependence of reliability and resilience criteria on the input parameters are shown in Figures 5 and 6. The results are self-evident. In spite of the fact that only moderate changes in inflow characteristics were assumed, the values of the performance criteria are highly differentiated. It shows a very high sensitivity of the Kariba reservoir management to departures from the current hydrological regime for which the reservoir has been designed.

Table 9. Matrix of conditional probabilities $p_{ij',j''k}$ for base scenario ($\bar{Q} = 1458$ m^3/s, $s_Q = 578$ m^3/s).

$j''k$ / ij'	1.1	1.2	1.3	1.4	1.5	2.1	2.2	2.3	2.4	2.5	3.1	3.2
1.1	0.504	0.306	0.126	0.044	0.020	0	0	0	0	0	0	0
1.2	0	0	0	0	0	0.089	0.347	0.308	0.158	0.098	0	0
1.3	0	0	0	0	0	0	0	0	0	0	0.000	0.073
1.4	0	0	0	0	0	0	0	0	0	0	0	0
1.5	0	0	0	0	0	0	0	0	0	0	0	0
2.1	0.638	0.251	0.080	0.023	0.008	0	0	0	0	0	0	0
2.2	0	0	0	0	0	0.130	0.395	0.286	0.125	0.064	0	0
2.3	0	0	0	0	0	0	0	0	0	0	0.000	0.098
2.4	0	0	0	0	0	0	0	0	0	0	0	0
2.5	0	0	0	0	0	0	0	0	0	0	0	0
3.1	0.887	0.093	0.016	0.003	0.001	0	0	0	0	0	0	0
3.2	0	0	0	0	0	0.220	0.441	0.230	0.078	0.031	0	0
3.3	0	0	0	0	0	0	0	0	0	0	0.001	0.144
3.4	0	0	0	0	0	0	0	0	0	0	0	0
3.5	0	0	0	0	0	0	0	0	0	0	0	0
4.1	1.000	0.000	0.000	0.000	0.000	0	0	0	0	0	0	0
4.2	0	0	0	0	0	0.515	0.374	0.090	0.017	0.004	0	0
4.3	0	0	0	0	0	0	0	0	0	0	0.003	0.236
4.4	0	0	0	0	0	0	0	0	0	0	0	0
4.5	0	0	0	0	0	0	0	0	0	0	0	0
5.1	1.000	0.000	0.000	0.000	0.000	0	0	0	0	0	0	0
5.2	0	0	0	0	0	1.000	0.000	0.000	0.000	0.000	0	0
5.3	0	0	0	0	0	0	0	0	0	0	0.024	0.507
5.4	0	0	0	0	0	0	0	0	0	0	0	0
5.5	0	0	0	0	0	0	0	0	0	0	0	0

If $j' = j''$ then $p_{ij',j''k} = p_{ijk}$; if $j' \neq j''$ then $p_{ij',j''k} = 0$.

We have analysed the existing water resource system for which no changes in design parameters may be made (of course, we may always change the operational rules). To show, however, the possible influence of storage capacity W on the performance criteria, additional calculations were done for the base scenario with W changing from 50.10^9 m^3 to 130.10^9 m^3. The results are given in Table 8. It may be seen that the influence of the design capacity on the reliability of operation is rather inconsiderable. It may mean that to cope with climatic and hydrological variations by extending water resource systems will probably require high investment costs, not easy to be secured under all the uncertainties accompanying the climate issue.

Table 3. contd.

3.3	3.4	3.5	4.1	4.2	4.3	4.4	4.5	5.1	5.2	5.3	5.4	5.5
0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0
0.308	0.317	0.302	0	0	0	0	0	0	0	0	0	0
0	0	0	0.000	0.000	0.061	0.290	0.649	0	0	0	0	0
0	0	0	0	0	0	0	0	0.000	0.000	0.000	0.061	0.939
0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0
0.349	0.307	0.246	0	0	0	0	0	0	0	0	0	0
0	0	0	0.000	0.000	0.079	0.322	0.599	0	0	0	0	0
0	0	0	0	0	0	0	0	0.000	0.000	0.000	0.075	0.925
0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0
0.393	0.283	0.179	0	0	0	0	0	0	0	0	0	0
0	0	0	0.000	0.001	0.106	0.360	0.533	0	0	0	0	0
0	0	0	0	0	0	0	0	0.000	0.000	0.000	0.096	0.904
0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0
0.432	0.226	0.103	0	0	0	0	0	0	0	0	0	0
0	0	0	0.000	0.001	0.153	0.403	0.443	0	0	0	0	0
0	0	0	0	0	0	0	0	0.000	0.000	0.001	0.125	0.874
0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0
0.360	0.089	0.020	0	0	0	0	0	0	0	0	0	0
0	0	0	0.000	0.004	0.244	0.437	0.315	0	0	0	0	0
0	0	0	0	0	0	0	0	0.000	0.000	0.001	0.171	0.828

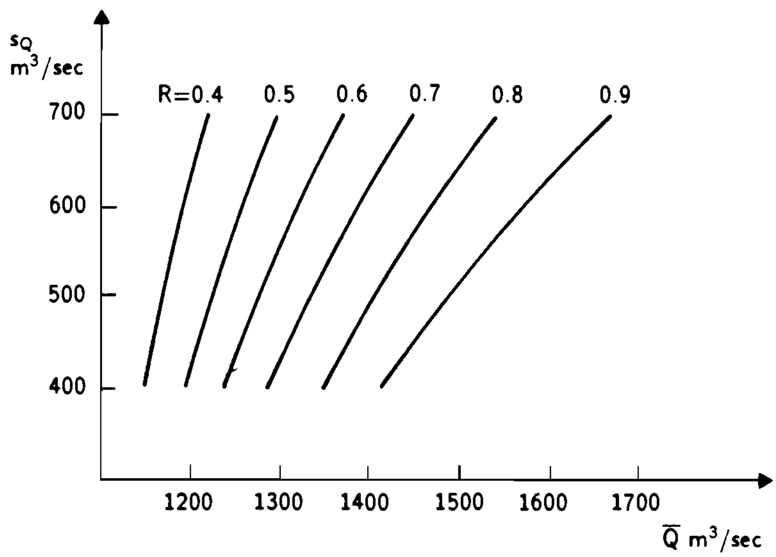

Figure 5. Relation between reliability and inflow parameters.

Table 4. Matrix of conditional probability $p_{ij',j''k}$ for dry scenario ($\bar{Q} = 1166$ m^3, $s_Q = 694$ m^3/s).

$j''k$ / ij'	1.1	1.2	1.3	1.4	1.5	2.1	2.2	2.3	2.4	2.5	3.1	3.2
1.1	0.667	0.182	0.081	0.037	0.033	0	0	0	0	0	0	0
1.2	0	0	0	0	0	0.305	0.318	0.188	0.096	0.093	0	0
1.3	0	0	0	0	0	0	0	0	0	0	0.022	0.257
1.4	0	0	0	0	0	0	0	0	0	0	0	0
1.5	0	0	0	0	0	0	0	0	0	0	0	0
2.1	0.748	0.150	0.059	0.024	0.019	0	0	0	0	0	0	0
2.2	0	0	0	0	0	0.361	0.319	0.170	0.080	0.070	0	0
2.3	0	0	0	0	0	0	0	0	0	0	0.029	0.290
2.4	0	0	0	0	0	0	0	0	0	0	0	0
2.5	0	0	0	0	0	0	0	0	0	0	0	0
3.1	0.896	0.072	0.021	0.007	0.004	0	0	0	0	0	0	0
3.2	0	0	0	0	0	0.456	0.306	0.138	0.058	0.042	0	0
3.3	0	0	0	0	0	0	0	0	0	0	0.041	0.338
3.4	0	0	0	0	0	0	0	0	0	0	0	0
3.5	0	0	0	0	0	0	0	0	0	0	0	0
4.1	1.000	0.000	0.000	0.000	0.000	0	0	0	0	0	0	0
4.2	0	0	0	0	0	0.674	0.225	0.068	0.022	0.011	0	0
4.3	0	0	0	0	0	0	0	0	0	0	0.069	0.405
4.4	0	0	0	0	0	0	0	0	0	0	0	0
4.5	0	0	0	0	0	0	0	0	0	0	0	0
5.1	1.000	0.000	0.000	0.000	0.000	0	0	0	0	0	0	0
5.2	0	0	0	0	0	1.000	0.000	0.000	0.000	0.000	0	0
5.3	0	0	0	0	0	0	0	0	0	0	0.172	0.513
5.4	0	0	0	0	0	0	0	0	0	0	0	0
5.5	0	0	0	0	0	0	0	0	0	0	0	0

If $j' = j''$ then $p_{ij',j''k} = p_{ijk}$; if $j' \neq j''$ then $p_{ij',j''k} = 0$.

Another interesting problem arises when the water resources manager is asking for possible impact of changes in hydrological parameters on the firm (reliable) release from a reservoir. The storagy-yield-reliability relationship (5) should then be transformed into

$$D = f[Q(t), W, R] \tag{39}$$

Table 4 contd.

3.3	3.4	3.5	4.1	4.2	4.3	4.4	4.5	5.1	5.2	5.3	5.4	5.5
0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0
0.307	0.198	0.216	0	0	0	0	0	0	0	0	0	0
0	0	0	0.000	0.021	0.238	0.304	0.437	0	0	0	0	0
0	0	0	0	0	0	0	0	0.000	0.000	0.020	0.239	0.741
0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0
0.311	0.186	0.184	0	0	0	0	0	0	0	0	0	0
0	0	0	0.000	0.026	0.263	0.310	0.401	0	0	0	0	0
0	0	0	0	0	0	0	0	0.000	0.000	0.024	0.260	0.716
0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0
0.309	0.167	0.145	0	0	0	0	0	0	0	0	0	0
0	0	0	0.000	0.034	0.296	0.313	0.357	0	0	0	0	0
0	0	0	0	0	0	0	0	0.000	0.000	0.030	0.286	0.684
0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0
0.295	0.135	0.096	0	0	0	0	0	0	0	0	0	0
0	0	0	0.000	0.048	0.341	0.311	0.300	0	0	0	0	0
0	0	0	0	0	0	0	0	0.000	0.000	0.038	0.318	0.644
0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0
0.215	0.068	0.032	0	0	0	0	0	0	0	0	0	0
0	0	0	0.000	0.076	0.405	0.295	0.224	0	0	0	0	0
0	0	0	0	0	0	0	0	0.000	0.000	0.051	0.358	0.591

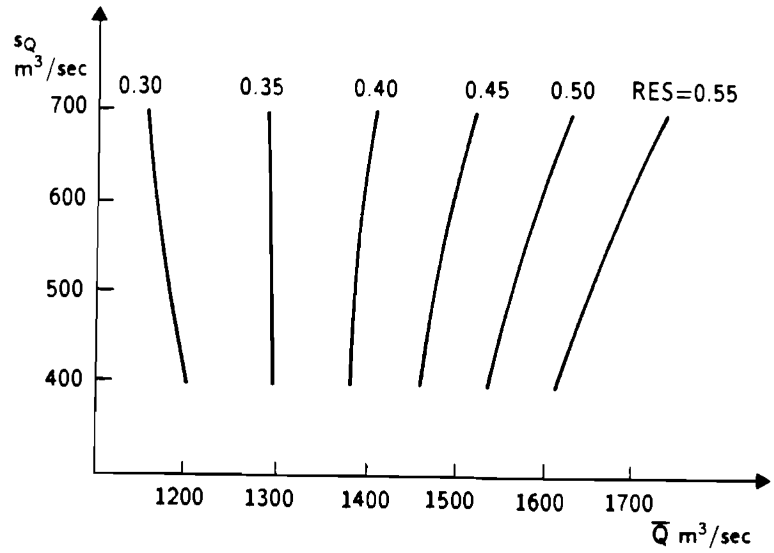

Figure 6. Relation between resiliency and inflow parameters.

Table 5. Matrix of conditional probability $p_{ij',j''k}$ for wet scenario ($\bar{Q} = 1750$ m^3, $s_Q = 462$ m^3/s).

ij' \ $j''k$	1.1	1.2	1.3	1.4	1.5	2.1	2.2	2.3	2.4	2.5	3.1	3.2
1.1	0.259	0.477	0.207	0.048	0.009	0	0	0	0	0	0	0
1.2	0	0	0	0	0	0.004	0.181	0.435	0.273	0.107	0	0
1.3	0	0	0	0	0	0	0	0	0	0	0.000	0.003
1.4	0	0	0	0	0	0	0	0	0	0	0	0
1.5	0	0	0	0	0	0	0	0	0	0	0	0
2.1	0.443	0.428	0.110	0.017	0.002	0	0	0	0	0	0	0
2.2	0	0	0	0	0	0.010	0.274	0.453	0.205	0.058	0	0
2.3	0	0	0	0	0	0	0	0	0	0	0.000	0.005
2.4	0	0	0	0	0	0	0	0	0	0	0	0
2.5	0	0	0	0	0	0	0	0	0	0	0	0
3.1	0.868	0.124	0.008	0.000	0.000	0	0	0	0	0	0	0
3.2	0	0	0	0	0	0.036	0.445	0.395	0.106	0.018	0	0
3.3	0	0	0	0	0	0	0	0	0	0	0.000	0.013
3.4	0	0	0	0	0	0	0	0	0	0	0	0
3.5	0	0	0	0	0	0	0	0	0	0	0	0
4.1	1.000	0.000	0.000	0.000	0.000	0	0	0	0	0	0	0
4.2	0	0	0	0	0	0.273	0.600	0.117	0.009	0.001	0	0
4.3	0	0	0	0	0	0	0	0	0	0	0.000	0
4.4	0	0	0	0	0	0	0	0	0	0	0	0
4.5	0	0	0	0	0	0	0	0	0	0	0	0
5.1	1.000	0.000	0.000	0.000	0.000	0	0	0	0	0	0	
5.2	0	0	0	0	0	1.000	0.000	0.000	0.000	0.000	0	0
5.3	0	0	0	0	0	0	0	0	0	0	0.000	0.292
5.4	0	0	0	0	0	0	0	0	0	0	0	0
5.5	0	0	0	0	0	0	0	0	0	0	0	0

If $j' = j''$ then $p_{ij',j''k} = p_{ijk}$; if $j' \neq j''$ then $p_{ij',j''k} = 0$.

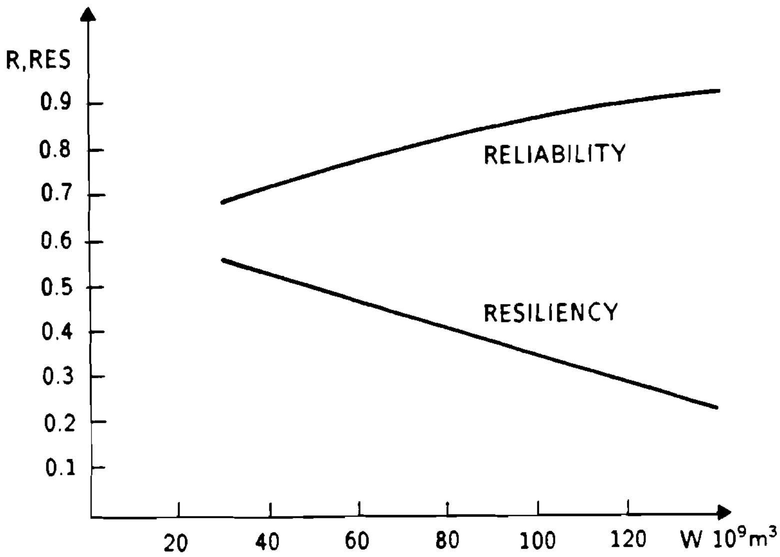

Figure 7. Reliability and resilience as functions of storage capacity.

Table 5 contd.

3.3	3.4	3.5	4.1	4.2	4.3	4.4	4.5	5.1	5.2	5.3	5.4	5.5
0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0
0.131	0.406	0.460	0	0	0	0	0	0	0	0	0	0
0	0	0	0.000	0.000	0.002	0.110	0.888	0	0	0	0	0
0	0	0	0	0	0	0	0	0.000	0.000	0.000	0.002	0.998
0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0
0.189	0.441	0.365	0	0	0	0	0	0	0	0	0	0
0	0	0	0.000	0.000	0.003	0.148	0.849	0	0	0	0	0
0	0	0	0	0	0	0	0	0.000	0.000	0.000	0.003	0.997
0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0
0.287	0.452	0.248	0	0	0	0	0	0	0	0	0	0
0	0	0	0.000	0.000	0.006	0.211	0.783	0	0	0	0	0
0	0	0	0	0	0	0	0	0.000	0.000	0.000	0.005	0.995
0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0
0.452	0.388	0.116	0	0	0	0	0	0	0	0	0	0
0	0	0	0.000	0.000	0.015	0.311	0.674	0	0	0	0	0
0	0	0	0	0	0	0	0	0.000	0.000	0.000	0.010	0.990
0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0
0.583	0.116	0.009	0	0	0	0	0	0	0	0	0	0
0	0	0	0.000	0.000	0.048	0.470	0.482	0	0	0	0	0
0	0	0	0	0	0	0	0	0.000	0.000	0.000	0.020	0.980

which may be used in order to calculate the target release D for a postulated value of reliability level R and for given $Q(t)$ and W. In the case of Kariba study we will assume $R = 90\%$, $W = 70.10^9$ cum and analyse the 25 hydrological scenarios characterized by the parameters shown in Table 2. The results obtained by a trial-and-error method from the stochastic storage model are given in Table 10 and are also presented in Figure 8.

The results indicate that a 20 percent decrease of mean inflow to the Kariba reservoir is amplified into slightly larger decrease of the reliable release by a factor from 1.06 to 1.10, depending on the standard deviation s_Q. Similar amplification takes place in the case of inflow increase with the factor varying from 1.04 to 1.06.

Table 6. Ergodic probabilities p_{ij} for selected scenarios.

ij	SCENARIOS		
Q	1166 m^3/s	1458 m^3/s	1750 m^3/s
s_Q	694 m^3/s	578 m^3/s	462 m^3/s
1,1	0.172	0.008	0.000
1,2	0.042	0.004	0.000
1,3	0.018	0.002	0.000
1,4	0.008	0.001	0.000
1,5	0.007	0.000	0.000
2,1	0.065	0.006	0.000
2,2	0.050	0.015	0.000
2,3	0.025	0.009	0.000
2,4	0.012	0.004	0.000
2,5	0.010	0.002	0.000
3,1	0.009	0.000	0.000
3,2	0.060	0.017	0.000
3,3	0.050	0.037	0.001
3,4	0.026	0.023	0.001
3,5	0.022	0.014	0.000
4,1	0.000	0.000	0.000
4,2	0.010	0.001	0.000
4,3	0.064	0.042	0.001
4,4	0.055	0.092	0.013
4,5	0.052	0.088	0.019
5,1	0.000	0.000	0.000
5,2	0.000	0.000	0.000
5,3	0.011	0.001	0.000
5,4	0.081	0.103	0.019
5,5	0.150	0.531	0.945

6. CONCLUSIONS

The global climate is going to change due to man's activity. This may strongly affect regional water resource systems on the supply and demand size and influence both the design strategy and future operational decisions. Novaky *et al.* [20] are right claiming that "A climate-induced increase and decrease of water resources takes on value only in terms of the actual or potential benefits and hazards to humans."

Table 7. Ergodic probabilities p_j for various inflow scenarios.

Scenario Q [m^3/s]	Scenario ^{s}Q [m^3/s]	p_1	p_2	p_3	p_4	p_5
1166	694	0.247	0.162	0.168	0.182	0.241
1166	636	0.228	0.164	0.173	0.190	0.245
1166	578	0.208	0.165	0.178	0.198	0.251
1166	520	0.187	0.164	0.183	0.208	0.258
1166	462	0.166	0.163	0.188	0.217	0.266
1312	694	0.113	0.118	0.161	0.227	0.381
1312	636	0.092	0.109	0.159	0.236	0.404
1312	578	0.072	0.098	0.154	0.243	0.433
1312	520	0.054	0.085	0.146	0.248	0.467
1312	462	0.036	0.069	0.133	0.249	0.513
1458	694	0.036	0.061	0.118	0.234	0.551
1458	636	0.024	0.049	0.106	0.231	0.590
1458	578	0.015	0.036	0.091	0.223	0.635
1458	520	0.008	0.025	0.072	0.207	0.688
1458	462	0.003	0.014	0.052	0.182	0.749
1604	694	0.008	0.022	0.065	0.195	0.710
1604	636	0.004	0.014	0.051	0.178	0.753
1604	578	0.002	0.008	0.036	0.154	0.800
1604	520	0.001	0.004	0.023	0.124	0.848
1604	462	0.000	0.002	0.012	0.090	0.896
1750	694	0.001	0.006	0.027	0.133	0.833
1750	636	0.000	0.003	0.018	0.110	0.869
1750	578	0.000	0.001	0.011	0.083	0.905
1750	520	0.000	0.000	0.005	0.057	0.938
1750	462	0.000	0.000	0.002	0.033	0.965

This paper examines the possible implications of altered hydrological regime on the operation of the large water storage system in southern Africa. In spite of impressive progress in climate research it is difficult to expect that meteorologists will expand their understanding of the climate system fast enough to be able, in a short span of time, to identify regional consequences of global atmospheric processes in a way which allows hydrologists to use comprehensive runoff models. The scenario approach will be during the next decade the main technique adequate to study the impact of climatic changes on hydrology and water resources.

Table 8. Storage parameters for various capacity of the reservoir

$$\bar{Q} = 1458 \; [m^3/sec], \; s_Q = 578 \; [m^3/sec].$$

W	Reliability	Risk of failure	Mean storage	Resilience	Time of filling
$[10^9 m^3]$	–	–	$[10^9 m^3]$	–	Years
50	0.753	0.015	38.1	0.494	5
70	0.815	0.008	54.9	0.433	6
90	0.847	0.007	71.9	0.367	8
110	0.878	0.005	89.6	0.302	9
130	0.906	0.004	108.0	0.241	10

Owing to their cumulative effect, the storage reservoirs are excellent tools for detecting consequences of non-stationarity of hydrological processes on the efficiency of water resources systems. The results of Lake Kariba case study are very encouraging for undertaking similar investigations for major world water reservoir systems. Both traditional simulation technique and more elegant stochastic storage models may be used to analyse the economic sensitivity of these systems to climatic change.

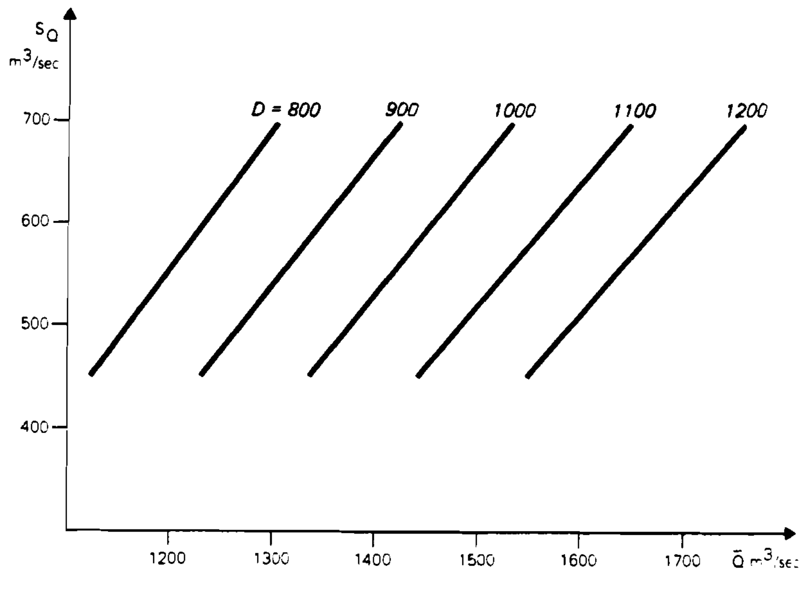

Figure 8. Relation between target release and inflow parameters.

Table 9. Storage parameters for various inflow scenarios.

Scenario $\bar{Q}$ [m³/s]	s_Q [m³/s]	Reliability –	Risk of failure –	Mean storage [$10^9 m^3$]	Resilience –	Time of filling [Years]
1166	694	0.338	0.172	35.1	0.304	INF
1166	636	0.353	0.159	35.8	0.303	INF
1166	578	0.371	0.146	36.7	0.298	INF
1166	520	0.392	0.131	37.6	0.295	INF
1166	462	0.414	0.118	38.6	0.287	INF
1312	694	0.527	0.073	44.0	0.359	INF
1312	636	0.565	0.059	45.5	0.361	INF
1312	578	0.606	0.046	47.1	0.362	INF
1312	520	0.653	0.034	48.9	0.361	INF
1312	462	0.709	0.023	50.9	0.359	15
1458	694	0.725	0.021	51.9	0.422	8
1458	636	0.769	0.014	53.4	0.428	7
1458	578	0.815	0.008	54.9	0.433	6
1458	520	0.861	0.005	56.6	0.438	6
1458	462	0.907	0.002	58.2	0.442	6
1604	694	0.870	0.004	57.1	0.489	5
1604	636	0.904	0.002	58.2	0.499	5
1604	578	0.934	0.001	59.4	0.510	4
1604	520	0.960	0.000	60.4	0.521	4
1604	462	0.980	0.000	61.3	0.533	4
1750	694	0.950	0.000	60.1	0.559	4
1750	636	0.968	0.000	60.8	0.574	4
1750	578	0.982	0.000	61.5	0.590	4
1750	520	0.991	0.000	62.0	0.606	4
1750	462	0.997	0.000	62.4	0.625	4

Table 10. Firm release (R = 0.900) from the Kariba reservoir for various hydrological scenarios.

s_Q \ $\bar{Q}$	1166	1312	1458	1604	1750
462	832	970	1108	1245	1383
520	791	925	1059	1195	1331
578	752	884	1016	1148	1280
636	715	844	973	1104	1235
694	679	806	934	1062	1191

In this paper a set of scenarios has been created through direct changes of runoff parameters. It is necessary not only to get more and precise information from the General Circulation Models, but also to expand research on operators transferring this information into hydrological variates, with the understanding that for water management the knowledge of possible changes in the stochastic structure of these variates is of crucial importance.

It should be stressed in conclusion that the climate change issue makes it necessary to integrate the efforts by scientists of various disciplines. Interdisciplinary research is needed for better understanding the problems facing today water resource scientists and decision makers.

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