Sequential optimization of multiple non-monetary objectives in the operation of multiple reservoir systems
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A thesis submitted in partial fulfillment of the requirements for the degree of DOCTOR OF PHILOSOPHY ' in Civil Engineering
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Abstract:
Management of multi-purpose, multi-reservoir systems using the techniques of optimization received considerable attention in recent years. However, most of the studies reported involved optimization of an economic objective function, which presumed that the multiple uses of water can be evaluated through a common measure of effectiveness —usually dollars. Non-monetary uses were either ignored or monetized through subjective assumptions to make them compatible with the rest of the uses. Lately it is realized that certain non-monetary uses have to be considered earnestly in determining reservoir operation policies. However, quantitative techniques involving non-monetary optimization are rare. In certain cases, it may be necessary to optimize multiple objectives in the same time frame sequentially in an order of preference. Also different sets of objectives may have to be considered at different times.

An algorithm has been developed in this dissertation to solve this problem of sequential optimization of multiple non-monetary objectives. The algorithm has been used in developing two models, which were used in conjunction with each other for the case study of the integrated operation of three reservoirs in the Musselshell Basin in Montana. Two objectives namely, maximization of diversions for irrigation and maximization of reservoir storage for enhancement of recreation have been considered in that order of preference. Three conditions, namely, satisfying existing demands for irrigation, meeting increased demands and minimum flow requirements at a specific point were tested. The results of the case study establish the applicability of the algorithm in such cases.

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ABSTRACT

Management of multi-purpose, multi-reservoir systems using the techniques of optimization received considerable attention in recent years. However, most of the studies reported involved optimization of an economic objective function, which presumed that the multiple uses of water can be evaluated through a common measure of effectiveness --usually dollars. Non-monetary uses were either ignored or monetized through subjective assumptions to make them compatible with the rest of the uses. Lately it is realized that certain non-monetary uses have to be considered earnestly in determining reservoir operation policies. However, quantitative techniques involving non-monetary optimization are rare. In certain cases, it may be necessary to optimize multiple objectives in the same time frame sequentially in an order of preference. Also different sets of objectives may have to be considered at different times.

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Chapter I

INTRODUCTION

Since water is basic to human existence, man tried to put this gift of God to his best use, from the early days of Indus Valley civilization to this present space age. The history of this important human endeavor is the history of water resources engineering. In the early days of civilization, the major use for water, apart from sustenance of life, was for irrigation to raise crops. This has continued to be the major use until almost the turn of this century. In the modern world, water is put to many uses, apart from irrigation and navigation. It is essential for generation of power, industrial processes, recreation, and many more uses. With this multitude of demands on a limited resource came the need for conservation and regulation through law. Increased municipal and industrial use of water brought with it the problems of pollution and the need to protect the quality of water.

At present, water is being studied from many points of view by scientists in the disciplines of biology, ecology, chemistry, hydrology, meteorology, etc., apart from economists, politicians, public administrators, and lawyers. With this explosion of specialists interested in the same subject of water came the need for efforts at inter-disciplinary understanding. One of the earliest and most important attempts in this direction was the formation of the Harvard Water Group. In their well known publication, Maass et al. (1962) of the group laid somewhat of a foundation for the now well formulated subject of water resources systems engineering. This is essentially the branch of water resources engineering which attempts to use the techniques of systems analysis and operations research and the modern high-speed digital computer for efficient solutions to the hitherto unsolved complex problems of water resources planning, development and management.

One of the important problems which received considerable attention was the operation of multi-purpose, multi-reservoir systems. Until about a decade ago, the only way this problem was 'solved' was by the intuition and judgement of experienced operators. The variables involved and the possible solution space were too complex to attempt an 'optimal' solution. Now, with the use of the techniques of systems analysis and operations research and the use of computers, it is indeed possible to put the water in reservoirs to the 'best' use achieving 'optimal' benefits.

Chapter II considers some of the techniques available and applied in the context of reservoir management. Most of the techniques discussed in that chapter assume--true to the classical optimization theory--that the various uses of water can be evaluated through a common measure of effectiveness, usually dollars, and the 'best' solution is the economically most profitable. However, it is widely recognized that operation of a reservoir system does involve multiple objectives, and then evaluation through a common measure of effectiveness is not all that easy. Chapter III discusses some approaches to the solution of the multiple objective optimization problem. Also discussed in this chapter is an algorithm developed during the research leading to this dissertation, to achieve sequential optimization of multiple non-monetary objectives in the operation of reservoir systems. Briefly, this algorithm addresses itself to the evolution of a quantitative technique to achieve optimum solutions in situations where it is impossible or unrealistic to specify monetary measures of effectiveness. Also, contrary to the usual optimization problem, in water resources operation, the same objective will not hold good at all times. Even in a given time frame, there will be more than one objective to be satisfied, perhaps in a given preferential order. The algorithm referred to above attempts an 'optimal' solution in such situations also. This algorithm is applied to the operation of a system of reservoirs in the Musselshell basin of Montana. Chapter IV describes the Musselshell System and states the problem. Two models to solve this problem are developed in Chapter V. Chapter VI presents the computer program developed and the data compilation for the case study. Chapter VII discusses results from some runs of these models under different conditions. Chapter VIII summarizes some important conclusions from this study and gives suggestions for future work.

Even though the Musselshell basin is chosen for the case study, the principles of sequential optimization of multiple non-monetary objectives can be used in the solution of other problems in the management and planning of water and other important resources, where monetary optimization is not realistic and sequential optimization is needed.

Chapter II

RESERVOIR MANAGEMENT: A REVIEW

River control structures have existed almost from the beginnings of human civilization. The early structures were, perhaps, temporary obstructions of earth and tree branches (bundhs) constructed across the rivers before the arrival of floods to divert the flood waters on to the neighboring fields which were later cultivated, after the subsidence of floods. Thus, irrigation was the motivation behind the earliest river regulating structures. Surprisingly, in spite of tremendous developments in the scientific world beginning with the industrial revolution of medieval Europe to the great advances of modern technology, until about a century back irrigation remained the major use, apart from navigation. It is only at the turn of this century that the great potential for generation of hydropower has been recognized and exploited, leading to the giant hydropower generating stations. Thus, river control structures, like dams which in yesteryears were known to be irrigation projects, have no more remained so and serve a multitude of uses making reservoir operation a very complex task--many times a "rope trick" balancing between conflicting demands.

The classical reservoir operation policy is conspicuous by its absence. Most reservoir managers never had a fixed policy for operating reservoirs in their control. This was so because sufficient quantification of the considerations involved was not available. Moreover, most reservoirs were single purpose reservoirs and, hence, the only guiding principle was to release water whenever needed, if available.

Determination of reservoir capacity for a certain assured water supply was studied for the first time by Rippl (1883). He developed the still widely used mass-curve technique, wherein the cumulative historic inflows were plotted against time on graph paper. On the same graph, the cumulative discharge required was also plotted. The largest difference between the two was taken as the reservoir capacity needed to assure the desired draft. This method was widely followed and was perhaps the best of the available techniques. Even today it can serve as a good check to the work done by other methods. However, the method has the following limitations:

a) The method assumes that the future inflow pattern will be a repetition of the historical pattern.

b) The highest possible flood and the lowest possible drought in the future are not expected to be different from those that occurred in the past.

Neither of these assumptions is true and, hence, the validity of the results of this analysis is limited. These limitations will be more serious if the length of record available is short, which is the case with many projects.

Once the required capacity was decided and the dam was constructed creating the reservoir, the operation was a simple matter of releasing water, if available, to satisfy the demand (mainly for irrigation). During inflow periods, the reservoir was filled to the full reservoir capacity and any further inflows were surplused over the spillway, which was normally designed to pass the maximum historical flood. This was more or less the methodology involved in the design and operation of most systems, until recently.

EVOLUTION OF MODERN TECHNIQUES FOR RESERVOIR OPERATION

The limitations mentioned above in the classical operation policy led many researchers to work towards a more satisfactory solution to the problem. Study of modern developments will be better understood if the problem is divided into two major parts:

a) Estimation of inflows into the reservoir, and

b) Working out optimum policy of reservoir operation.

Estimation of Inflows

Introduction. As mentioned earlier, the classical concept has been to look at the history of flows for having an idea of future inflows. While certainly an important way to read into the future will be to start with looking into the historical record, it is not correct to expect the same historical sequence to repeat. Also, the assumption of historical floods as limits of future possibilities does not stand to reason. To work on these assumptions is more risky, if the data available is for a short length of period, which is usually the case. In answer to this problem, a number of techniques to synthesize flow sequences have been developed. This new branch of hydrology is known severally as operational hydrology, synthetic hydrology, and stochastic hydrology. All these names refer to the process of using some statistical parameters like mean, standard deviation, etc., from the historical data to generate sequences of likely flows. The general algorithm is as follows:

a) Collect the available historical data

b) Estimate statistical parameters like mean and standard deviation from the historical data

c) Develop a methodology to synthesize sequences of flows, based on the statistical parameters of the historical data.

The number of sets to be generated depends on the particular problem under consideration and the statistical confidence desired. Also, the length of record to be generated depends on the problem.

Synthetic Hydrology. The earliest attempts made to synthesize flows was by Sudler (1927). He wrote the annual volumes of stream flows on cards, shuffled, and dealt them to produce several sequences of flows. This method, though it produced different sequences, suffered from the same limitations as the classical method in that the maximum flood expected cannot exceed the known historic flood. Also, this shuffling game does not have much meaning with short lengths of data.

A small variation to the above procedure produced somewhat better results. After one card is dealt, the value was noted on a piece of paper and that card was mixed with the rest in the deck before dealing the next card. Dealing without replacement is justified if there is reason to believe that once a historical flow has occurred, it won't repeat again. This improvisation in no way removes the basic objection; and hence, further efforts were made at improving the techniques of synthesis.

Although several efforts were made towards streamflow synthesis, the one organized effort brought before the largest audience was that of Thomas and Fiering in Maass et al. (1962) of the Harvard water program. In this work, the monthly streamflow volumes were considered to belong to a bivariate normal distribution. Time dependence between flows of succeeding months was also considered. The general model presented was of the following form:

$$Q_{i+1} = \overline{Q}_{j+1} + b_j \ (Q_i - \overline{Q}_j) + t_i \sigma_{j+1} \ (1-r_j)^{\frac{1}{2}}$$

Q_{i+1} = the streamflow volume being synthesized.

$\overline{Q}_{j+1}$ = The mean of historical flows for the j + 1st month being synthesized.

b_j = Regression coefficient (derived from the historical record or estimate thereof) between the time period currently being synthesized and the time period immediately preceding.

Q_i = Streamflow synthesized for the preceding time period.

$\overline{Q}_j$ = The mean historical streamflow for the preceding time period.

t_i = A random normal deviate.

σ_{j+1} = Standard deviation abstracted from the historical record for this time period.

r_j = The correlation coefficient (derived from the historical record or estimate thereof) between events in the time period currently being synthesized and events in the time period immediately preceding.

Thomas and Fiering also considered the spatial dependencies of flows at several points. Streamflow at one point was correlated to the streamflow at another point and a random variable.

The Hydrologic Engineering Center of the Army Corps of Engineers also made significant contributions to the knowledge of streamflow synthesis. They approximated the logarithms of monthly streamflow volumes to a gamma distribution. The gamma distribution approximation used is a Pearson Type III. The model developed was of the following form:

$$X = \mu_x + \sigma_x \ (K + 0.16 \ g \ (K - 1))$$

X = Logarithm of streamflow volume being generated.

μ_x, σ_x = Estimates of mean and standard deviation of logarithms of historical streamflow

g = An estimate of the skew factor of the distribution.

K = Synthesized standard normal deviate.

The above relationship was later modified by the Corps of Engineers in 1967, to be as follows

$$X = \mu_x + \sigma_x \left[\frac{g}{6} \left(k - \frac{g}{6} + 1\right)^3 - 1 \right] \frac{2}{g}$$

Fiering (1964) has developed another procedure using principal component analysis. Matalas (1967), Young and Pisano (1968) worked on a different model using residuals.

Other models. The models described above mostly use the idea of randomness of streamflows and work with the statistics of historical streamflows. Meanwhile, some work was also done on the traditional ground of correlation between rainfall and runoff. Some of the references at the end of this paper, particularly Fiering (1967) and Fiering and Jackson (1971) are recommended for further study of this area of hydrologic synthesis.

Reservoir Operation Procedures

Introduction. The classical operation policy was, as mentioned earlier, designed mostly to serve a single purpose. Hence, the obvious guideline is to meet the target demand if sufficient storage is available. In the inflow season, the inflows are stored to the full reservoir level and any surplus beyond this is discharged over the spillway. This standard policy is expressed in mathematical terms as follows:

$$D_i = \begin{cases} X_i + S_i & \text{if } X_i + S_i \leq T \\ T & \text{if } T \leq X_i + S_i \leq T + S_m \\ X_i + S_i - S_m & \text{if } X_i + S_i \geq T + S_m \end{cases}$$

D_i = Discharge volume during time interval "i"

X_i = Inflow during time interval "i"

S_i = Storage at the beginning of time interval "i"

T = Target discharge for the time interval "i"

S_m = Maximum storage (storage at full reservoir level)

The above standard policy is illustrated graphically in Figure 1.

Moran (1959) applied queuing theory to find the stationary probability distributions of D_i, S_i, and $X_i + S_i$, given, T, S_m and f, probability function for the inflow. Prabhu (1964) summarized this queuing theory approach of Moran and outlined later findings. It can be seen that the conventional policy, as well as the mathematical statement of Moran and Prabhu, are bereft of any economic considerations.

With the advent of multi-purpose reservoirs in comlex integrated systems of projects, the above theories were found to be inadequate. There arose a necessity to compare the various uses on a common economic scale, to find the economically optimal policy. The method of approach in general is as follows.

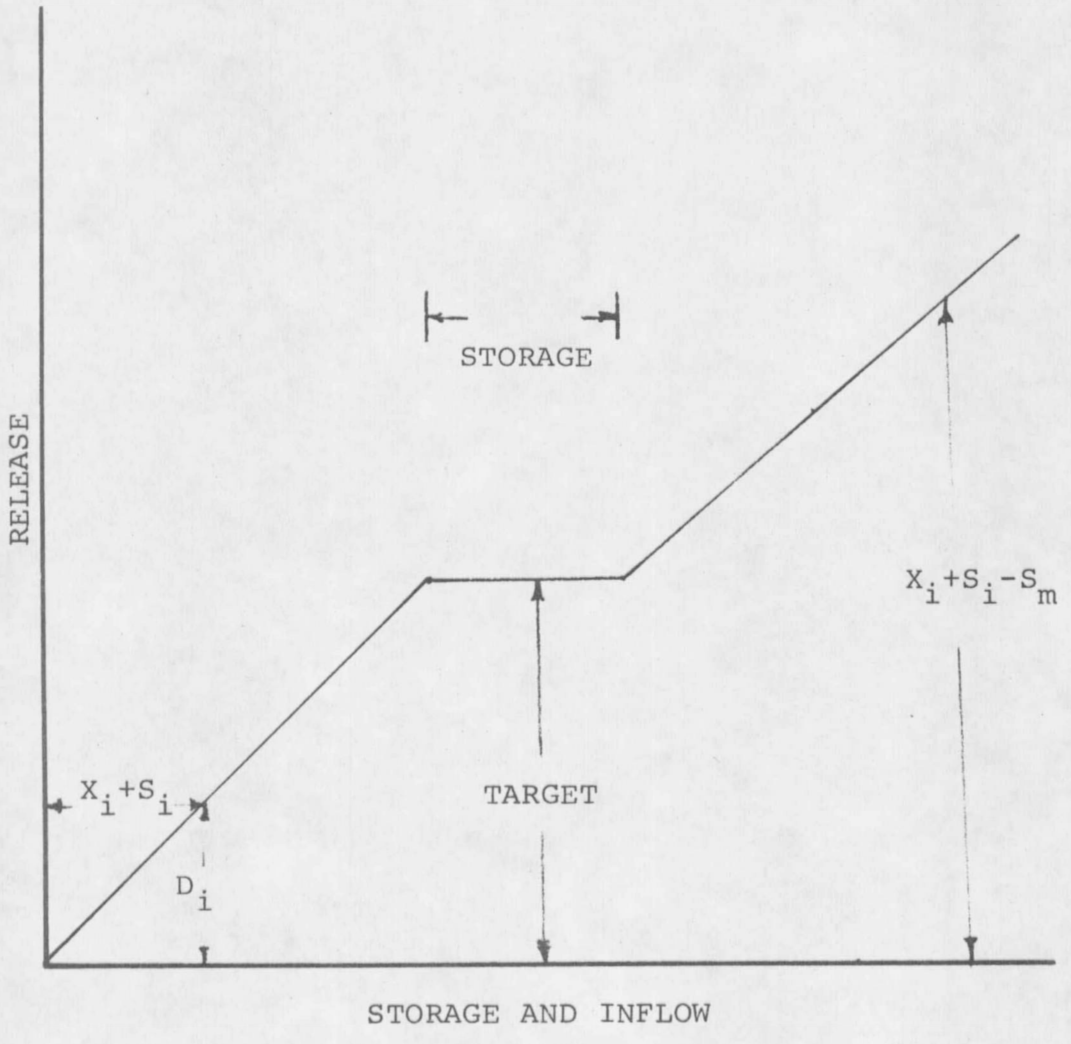

Figure 1. Classical operation policy.

Mathematically speaking, Buras (1963) states that the design of water resource systems involves making decisions concerning: (a) the determination of the physical dimensions of the system, (b) the optimization of the target outputs, and (c) the establishment of an optimum operating policy. This implies that the benefit "B" is a function of $\vec{X}_1$ = the physical dimensions of the system, $\vec{X}_2$ = the scale of development, and $\vec{X}_3$ = the operating procedure.

Thus, $B = B\ (\vec{X}_1, \vec{X}_2, \vec{X}_3)$

Buras further states that B is a response surface in a four-dimensional space, and its maximum in the domain of admissible values of $\vec{X}_1$, $\vec{X}_2$, and $\vec{X}_3$ must be found. Given $\vec{X}_1$ and $\vec{X}_2$, the loss function is found from typical benefit and cost functions. The development of benefit and cost functions for various uses involves interaction of political, governmental, and economic considerations. General approaches to the development of such functions are discussed in Maass et al. (1962), Marglin (1967) and Hall and Dracup (1970).

<u>Genesis of optimization models</u>. So far discussed are the procedures for estimating inflows into a reservoir system. Also considered are the early

attempts to give a mathematical solution to the problem of operation of a single reservoir. However, where integrated systems of multi-purpose reservoirs are involved, there arose the need to compare the various purposes involved on a common economic scale as defined by benefit cost curves. Now consider the procedures to define the optimum policy of operation, using the above information. The general steps involved in this are:

a) Generate several sets of streamflows

b) Define a set of operational rules

c) Test the defined set of rules against each set of generated flow data to find the returns, using the benefit cost curves already developed.

d) Repeat steps 2 and 3 several times

e) Compare the benefits and choose the best policy of operation.

In this neatly drafted procedure, the practical difficulty will be that there are a large number of sets of rules that can be defined and that the above procedure becomes cumbersome and time consuming. This procedure is called "simulation". A schematic representation of this procedure is given in Figure 2. Next consider an alternative procedure, involving slight changes to the above.

a) Generate a set of streamflows

b) Find the optimal set of operation rules for that streamflow set and save the results

c) Repeat steps a and b several times

d) Perform a regression analysis in which storage and inflow are the independent variables and the release is the dependent variable.

A schematic diagram of this procedure is given in Figure 3. The common techniques used in the procedure for optimization are linear programming and dynamic programming.

Linear programming models. Linear programming is a tool which provides solutions to a system of linear relationships (both equalities and inequalities can be solved) in which the number of variables is equal to or greater than the number of relationships, so that a linear function of any number of the variables greater than zero is maximum. In case of problems having inequalities, they can be transformed into equalities by the addition of slack variables. It is not proposed to go into the mechanics of the

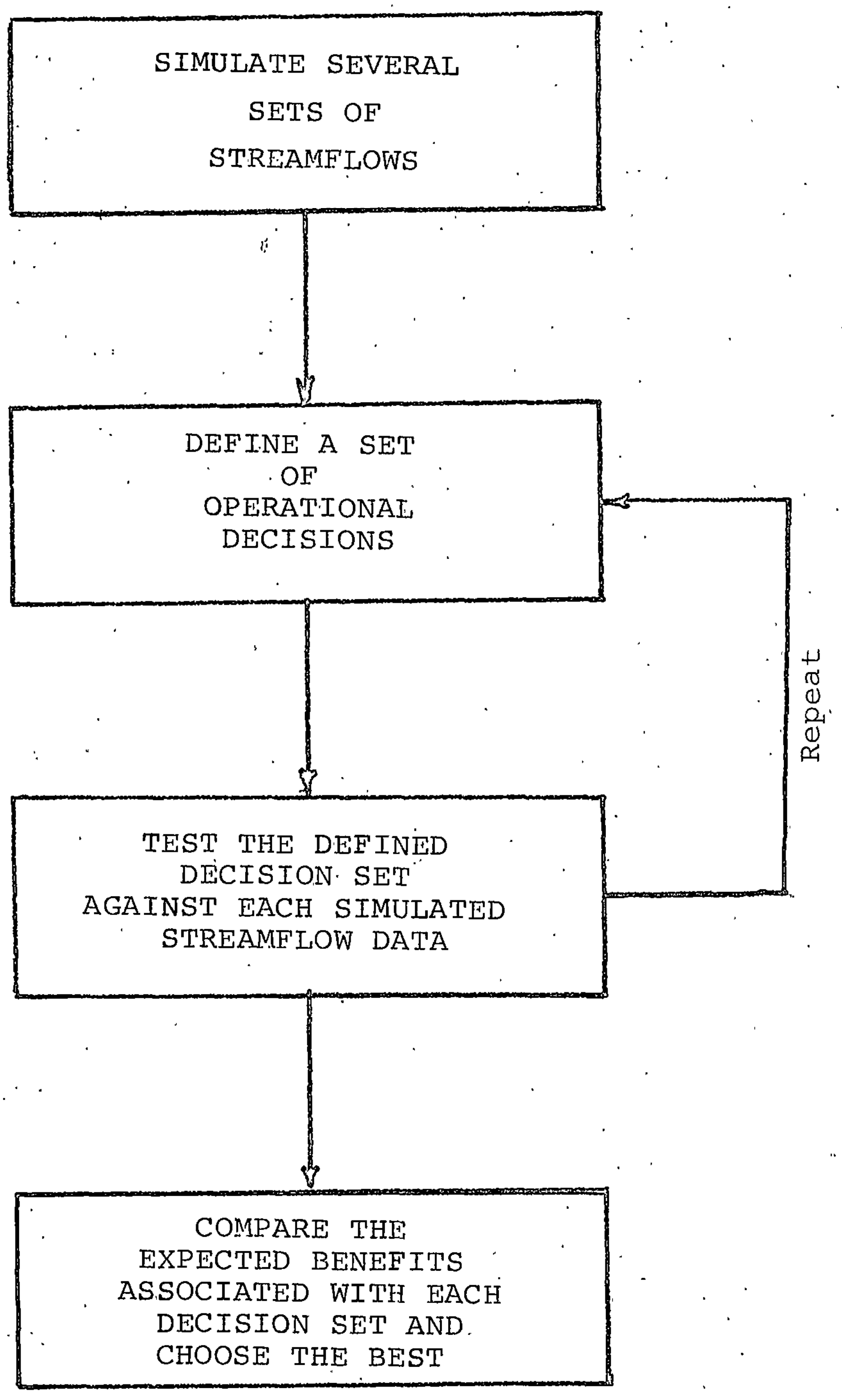

Figure 2.
Simulation

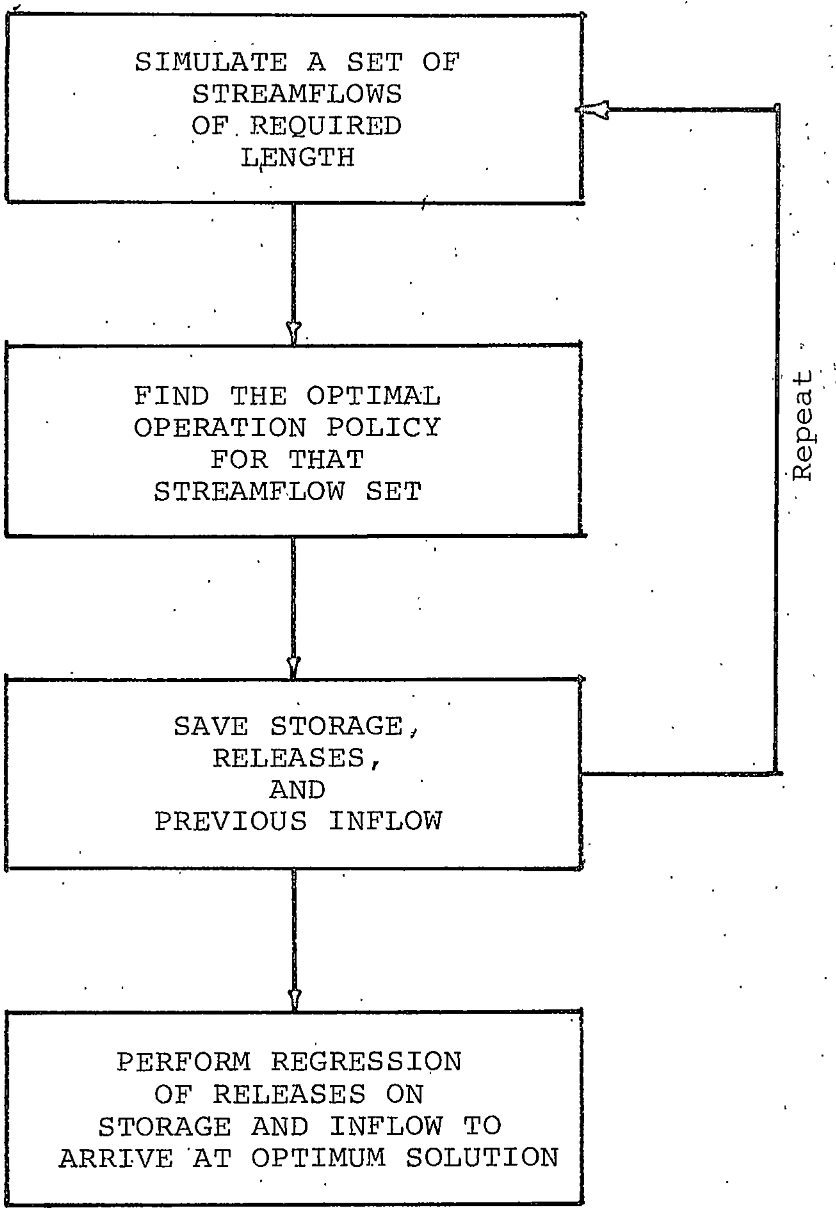

Figure 3. Simulation-optimization.