THE CALCULATION OF WATER RELEASE POLICY FOR BALOG-BALOG (PHILIPPINES) SINGLE MULTIPURPOSE RESERVOIR SYSTEM USING DDDP ANALYTICAL TECHNIQUE: I. MODEL DEVELOPMENT

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ABSTRACT

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The monthly water release operating policy for a single multi-purpose reservoir system at each stage of development of the service area was defined using Discrete Differential Dynamic Programming (DDDP) optimization analytical technique and simulation model developed in a master program for a mainframe computer type. Irrigation and flood control were the primary and secondary purposes, respectively, of the reservoir system with hydroelectric power generation as the by-product of the system's operation.

The recorded (historical) monthly streamflow data used in the study was subjected to the following analyses prior to generating a number of sequences of 50-year monthly streamflow data, namely: identification of probability distribution that best described the recorded streamflow data, and the determination of trend and periodicity using the 3-Parameter Log-Normal (3PLN) probability distribution function (pdf) and power spectrum analysis, respectively. The Thomas-Fiering streamflow model was used to generate the sequences of 50-year monthly streamflow data.

KEYWORDS: DDDP. Optimization. Power spectrum analysis. Reservoir system. Simulation model. Streamflow data. Thomas-Fiering model. Water release policy. 3PLN.

INTRODUCTION

Sound technical design of a single or multiunit multipurpose reservoir system operates within the confines of an optimum operating procedure. To arrive at such optimum procedure involves basically following either or both of the general approaches, namely: analytical and simulation method.

Of the analytical method, the Dynamic Programming (DP) technique is commonly used owing to its ease of treatment of non-convex (policy space), non-linear (objective functions and constraint), discontinuous objective and constraint functions, making it a very appropriate method in dealing with the analysis of water resource system and related problems involving definite sequential decision characteristics both in time (operational) and space (allocational) (Bellman, 1957; Hall and Dracup, 1970). This method has been used extensively in formulating an operating policy for a single multipurpose reservoir system (Hall and Buras, 1961; Hall, 1964; Hall and Roelfs, 1966; Meier and Beightler, 1967; Hall*et al.*, 1968; Harboe *et al.*, 1970; Mobasheri and Harboe, 1970; Sottimai, 1973).

A modified DP technique, known as DDDP, was developed by the University of Illinois. It is basically a DP method with a search technique. As an iterative method, it can considerably overcome the two normally encountered major difficulties in the optimization of the operating policies of any water resources system using the DP through high speed digital computers,*i.e.*, memory and computer time requirements. The method has proved to be particularly effective in the case of invertible systems. In short, the method starts with a trial trajectory satisfying a set of initial and final conditions and applies Bellman's recursive equation in the neighborhood of this trajectory. At the end of each iteration step, a locally improved trajectory is obtained and used again as the trial trajectory for the next step and so on until the procedure terminates, in which case the final optimum trajectory has been derived (Chow and Cortes-Rivera, 1974). Thisparticular technique has been used widely for multiunit, multipurpose reservoir systems (Chow and Cortes-Rivera, 1974; Meredith, 1975; Samaratunge, 1978; Carriaga, 1982).

Other analytical methods used in defining the optimum operating policy of a single multipurpose reservoir system are linear programming (LP) methods (Lott, 1964; Thomas and Revelle, 1966; Revelle*et al.*, 1969; Loucks, 1969), based on the theory of queue and Monte Carlo technique (Fiering, 1961; Thomas and Watermeyer, 1962; Askew *et al.*, 1971) and decision theory (Russel, 1974), linear decision rule (LDR) (Eastman and Revelle, 1973; Loucks and Dorfman, 1975), deterministic and stochastic optimizing models (Jacoby and Loucks, 1972), sequential unconstrained minimization technique (SUMT) (Muspratt, 1973), alternate stochastic optimization (ASO) (Croley, 1974), and reliability programming (Colorni and Fronza, 1976).

On the other hand, simulation as an optimization technique was first used by the water resources team of the Harvard University in the operation of a simplified river basin system with flood control, irrigation release and hydroelectric power generation as the primary objectives. Sequences of generated (or synthetic) streamflow were used in place of the short-period historical streamflow record as the input data. A four-step guideline was suggested in using simulation as a method of water resources system analysis which is composed of objective(s) identification, objective-to-design criteria transformation, devising a strategy satisfying the design criteria and strategy evaluation (Maass *et al.*, 1962). Simulation had been used in analyzing various cases of water reservoir system (from a single reservoir with a source of input and a demand or service area to a multisource, multiunit reservoir system serving a number of areas) primarily for irrigation purposes (Carr and Underhill, 1974), in the study of the interaction between irrigation and power sectors (Van, 1975) and in the determination of the behavioral characteristics of a single multipurpose reservoir prior to the formal optimization analysis in order to identify and reduce the magnitude of choice of alternatives as inputs to optimization procedure (Franco, 1978).

The only work combining simulation and analytic methods to come up with an optimized operating policy for a single reservoir system encountered in the author's review of literature was that of Young (1967) when simulation and deterministic DP were combined to identify the optimal reservoir operating rules of a single reservoir system with the objective of setting an annual operating policy with the minimum expected economic loss of each draft rate.

There has been no investigation combining the techniques of analysis of historical (observed and recorded) streamflow data, generation of synthetic streamflow data, optimization and simulation, to formulate an initial policy for the operation of a single multipurpose reservoir system primarily for irrigation and secondly for flood control, with hydroelectric power generation as by-product of the system's operation, hence this study.

THEORETICAL CONSIDERATIONS

Analysis of recorded monthly streamflow data

Identification of probability distribution for recorded monthly streamflow data. In most situations, monthly streamflows have non-symmetric marginal distributions. The 3PLN pdf often can approximate conveniently skewed monthly streamflow marginal distribution (Hoshi *et al.*, 1978). From the point of view of operational application, the 3PLN pdf provides good approximation and is quite satisfactory (Sangal and Biswas, 1970; Lettenmaier and Burges, 1977). Computational constraints imposed in the choice of pdf model preclude the use of the generalized gamma pdf (Lettenmaier and Burges, 1977; Hoshi and Burges, 1979), although it can be used for unimodal skewed distribution (Burges,*et al.*, 1975; Fiering and Jackson, 1971). These factors led to choosing the 3PLN pdf to describe the monthly streamflow marginal distribution.

The fitting of 3PLN pdf to the observed data is quite sensitive to estimated skew coefficient outliers in the data, although few can have substantial effects. The simplest way to test if a sample of data can be described or used as a basis for curve-fitting the observed data by this pdf, is to compute the skew of the transformed data; if the effects of outliers have been appropriately removed, the skew of $y=ln(x-a)$ is close to zero (Hoshi*et al.*, 1978).

The smoothening of such outliers depends on the purpose of the study. The use of the threshold value of $x + 2s$ to replace the value of the outliers for a particular month (Hoshi *et al.*, 1978) should be exercised with caution in order not to alter too much, by overuse of this 'replacing of value,' the basic structure of the original data.

The Quantile-Quantile (Q-Q) plot, a very powerful diagnostic check on the presence and impact of outliers, serves as the primary tool in the initial examination of any flow time series data to determine if it fits the 3PLN distribution (Hoshi*et al.*, 1978). The linear invariance property and plotting done commonly on ordinary linear graphing paper are the major advantages of the Q-Q plot.

In this study, the Q-Q plot is constructed by plotting the ordered observations of $ln(x-a)$ against the quantities of a standard normal distribution. The Weibull plotting formula was used to determine the empirical cumulative distribution while the corresponding quantiles of a normal distribution were computed after Hasting. The straight lines were defined by the first two theoretical moments in the transformed domain (Hoshi *et al.*, 1978).

Time series analysis. A time series being a sequence of values collected over time on a particular variable may be observed at discrete times, averaged over a given time period or recorded continuously with time (Haan, 1977). Continuous records sampled at discrete periods oftentimes provide a finite set of observations over any arbitrarily set length of time. The study had been limited to discrete type which was extended to time series observed at equally spaced time intervals.

The monthly streamflow data is composed basically of trend, periodicity or frequency and random components which can act singly or in combinations. Trend, periodicity or their combinations are deterministic components superimposed with stochastic component--the basic parts of any hydrologic time series.

The initial impression for the presence or absence and the type of trend was determined by plotting the streamflow data with time as abscissa and the streamflow values as the ordinate on an ordinary graphing paper. Any detected trend can be removed by using log transformation of the streamflow series (Roesner and Yevyevich, 1966), by adding irrigation diversion to observed flow, the result called the "virgin" flow (Sekhararidhi, 1971) and by using log first difference for linear trends in log form (Bolch and Huang, 1974).

The periodic component of any natural hydrologic time series is due to astronomic cycles. This component is composed of one or more harmonics describable by the Fourier series. However, only those significant harmonics should be considered, since most occur by chance alone. Only when corrections on the apparent trends on the streamflow data have been made that computations for Fourier coefficients which are independent for equally spaced observed data, and phase lag can be done (Haan, 1977).

The power spectrum analysis is used to identify the frequencies and approximate the variances derived from each of the effect-causing factors which can occur in either cyclic or random manner. It is a valuable tool for isolating periodicities and exhibiting the presence of a cycle (and its corresponding frequency) in a time series. An estimate of the power spectral density was obtained following these steps: determination of the mean and its square; formation of the autocorrelation function appropriate for the considered time series; Fourier transformation of the autocorrelation function from time to frequency domain for smoothing any fluctuation that may be present in the function; and second weighing computation to smoothen some degrees of distortion of the spectrum that resulted from the analysis of a single record (Chi, 1975). This study adopted the use of Parzen lag window for the discrete finite Fourier cousine series transformation of the autocorrelation function since its use facilitated the expression of the spectral density simply in terms of frequency than the usual variance per interval of frequency (Haan, 1977). The plots of the values of the autocorrelation function against time, *i.e.*, correlogram and spectrum density against frequency or the distribution of variance on the frequency scale, had been made.

Generation of synthetic monthly streamflow data: Thomas-Fiering model

The primary objective of data generation is to extend the available recorded (historical) streamflow data, normally of short duration, up to 50 years, the assumed life span of the reservoir system. The model that should be used for data generation should be stochastic, since streamflow is stochastic in nature, and must preserve the basic statistical properties of the historical streamflow data. These requirements will assure the generation of any desired number of equally likely streamflow sequences which could be used in place of the historical streamflow record. The most commonly used streamflow data-generation model is the Markov regressive model. This model preserves the lower order moments (*e.g.* mean, standard deviation and skewness) and the higher order moment *i.e.*, autocorrelation coefficient. A comparative study conducted by Burges and Lettenmaier (1975) on stochastic streamflow generators showed that the annual streamflows are summative carry-over effects in the surface storage not extending significantly for one year period. This finding made the Markov model appropriate for practical purpose.

The water resources research team of Harvard University (Maass *et al.*, 1962) postulated a lag-one linear regressive model for streamflow data-generation using the Markov model where the streamflow in the previous month under consideration is a linear function of the streamflow in the previous month. This modified Markov model was actually developed by Thomas and Fiering (1962) which took into account the seasonal and monthly variations of streamflow. It was then known as the Thomas-Fiering Model. This particular model for streamflow data generation was used in this study. The algorithm for generating the monthly streamflow data using the Thomas-Fiering Model is presented in Fig. 1. Independent studies made by Phongprapaphan (1977) and Bat (1977) using this model for generating streamflow data showed its property to preserve the first and the second moment. However, for historical streamflow data with very significant values of monthly serial correlations and skewness, the data should be subjected to log transformation to avoid generating negative values or moment transformation to fit the 3PLN or gamma pdf (Matalas, 1967).

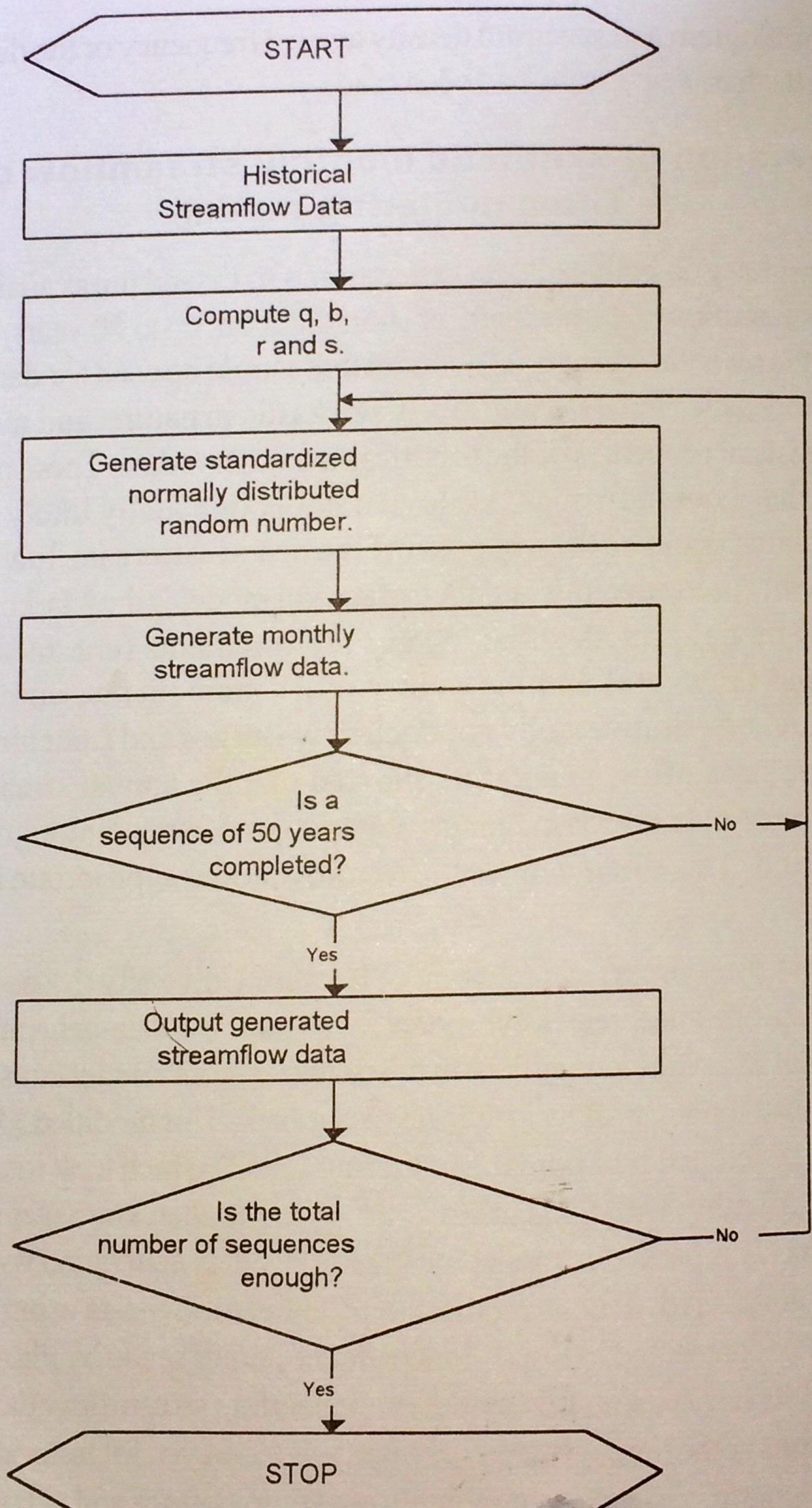

Figure 1. Algorithm for the Thomas-Fiering Model.

Twelve linear regression equations are used to provide a full account of the serial correlation of streamflows throughout the whole year with the last regression equation relating the streamflow for January to the streamflow in the immediate preceding December. There are 48 parameters required to describe the 12 regression equations, *i.e.*, 12 values each for the mean monthly streamflow (q), slope for the regression equations (b), serial correlation coefficient (r) and the standard deviation of the monthly streamflow (s).

Discrete differential dynamic programming (DDDP) analytical technique

The DDDP is a computational technique and not a modification of the basic principle behind DP. It uses the recursive equation of DP to search for an improved solution (trajectory) within the confines (corridor) of the previously specified trial solution. At the end of each iteration, an improved solution is obtained which then is used again as the trail solution for the next iteration. This procedure is repeated until a sufficiently near-optimal solution is found. Hence, instead of searching for the optimal solution over the entire state-stage environment (as in DP), DDDP converges successively to the optimal solution saving a considerable amount of computer time and memory requirements when using high speed digital computers (Chow *et al.*, 1975). The algorithm for DDDP analytical technique is presented in Fig. 2.

For this study, the optimization procedure started from the first month of the critical period (the starting month of the dry season) up to the end of the last month of the critical period (the ending month of the wet season), the stages when the reservoir was assumed to be at full storage capacity. Hence, the analysis took place for 37 stages. The critical period was the three-consecutive-year period with the lowest total volume of annual streamflow among the number of years of observations. The ith stage in the 37 stages was the start of the (37-i)th month in the critical period, used in backward DP.

The range between the maximum (full) and minimum (dead) storage levels, *i.e.*, active storage level, was divided into increments of storage levels (states) for a particular stage. The state transformation function (or mass balance equation) relates the state variables of each of the stages. To determine the appropriate number of states in order to increase the overall accuracy of the reservoir operating

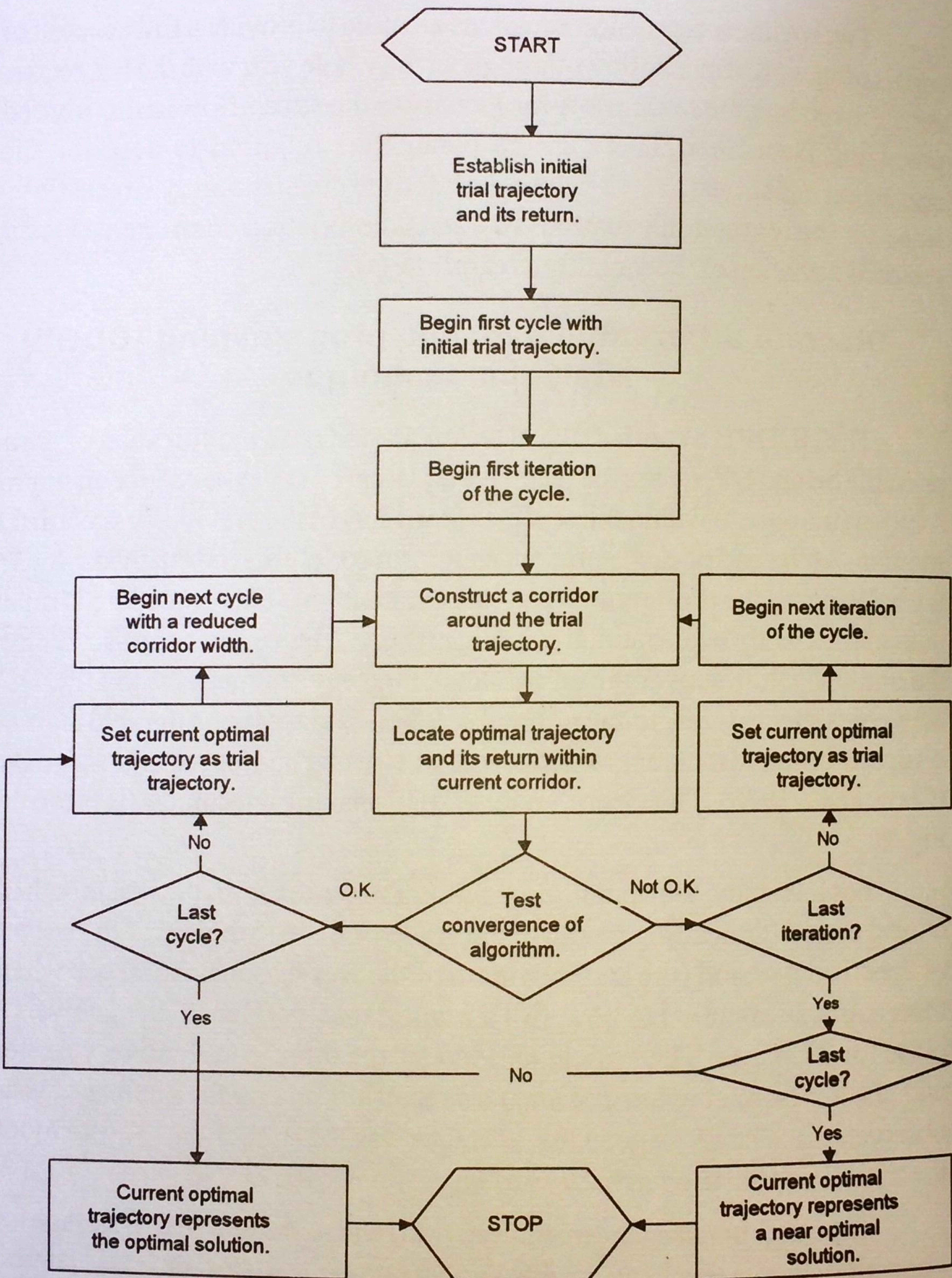

Figure 2. Algorithm for DDDP analytical technique.

policy to be defined, one should note that there is a linear relationship between the number of states and the reservoir storage capacity (Bat, 1977). At each of the stages (times or periods), *t*, when the reservoir was assumed to be at full storage capacity, the state (reservoir storage level), *i*, is one and equal to that capacity of the reservoir.

The initial optimum solution established by the previous DP optimization technique will be refined further by DDDP procedure to identify the most optimum solution. The series of iterations for each cycle are made to solve the recursive equation within the confines (width) of the assumed set of values (corridor) of the state variable until convergence towards an optimal solution is reached, *i.e.*, computation cycle is complete when the iteration process converges to the optimum trajectory. DP technique still determines the optimal trajectory within a given corridor for each cycle. In case the convergence criteria will not be met, the allowable maximum number of cycles throughout the procedure and the number of iterations per cycle should be defined in advance. Therefore, DDDP procedure will operate depending on the pre-set number of iterations per cycle or convergence criterion. Note that any intermediate optimal trajectory determined after a certain number of times of iteration for a certain cycle will serve as the trial trajectory for the next cycle and so on until the process terminates.

The initial trial trajectory established by DP represents the set of state variables which satisfies (or as near as possible) feasibility and optimality requirements for all the stages of operation. Such conditions assure a shorter computation period to reach the most possible optimum since at least one of the alternative trajectories (the initial trail trajectory) to be examined has satisfied already the feasibility, optimality and constraints as imposed by the problem on hand. Hence, the formulation of the initial trial trajectory was one of the most crucial aspects of the procedure.

In the construction of the corridors, the following were considered: a) the starting and immediate width values, *i.e.*, initializing and incrementing corridor widths; and b) design around the trial trajectory of the corridor.

The total number of state variables associated with each stage variable was kept as small as possible to minimize computer memory requirement. The most satisfactory value for state variables for each stage is 3 (Tauxe *et al.*, 1973; Chow and Cortes-Rivera, 1974). The corridor width is the difference between adjacent values of a state variable. Coarse-grid technique was used in initializing (large width for the first cycle) and incrementing (smaller widths for the following cycles) the corridor width. The larger the corridor for the first set of cycles, the lesser the number of iterations is needed for that particular cycle to arrive at the convergence to the optimum trial trajectory (Meredith, 1975). Chow and Cortes-Rivera (1974) reported that the most appropriate number of iterations per cycle should be at least six, with the corridor width of any given cycle ranging from 50 to 70% of the preceding cycle.

A corridor of three values for each state variable in each stage was constructed around the trial trajectory for this particular study. Specifically, the upper and lower values were symmetrical with respect to the trial trajectory for each iteration. With C as the corridor, $C = [Vnmt(s)]$, where $Vnmt(s)$ is the set of periodic m-state variables for n-time periods of the nth iteration.

The construction of the corridor proceeded as follows: for state variables, let $V^n_t(s)$ be the trajectory for the nth iteration for N-time periods (t=1,..., N; n=1,...) and let $\Delta V^n_t(s)$ be the uniform incremental nth value for the trajectory $\Delta V^n_t(s)$ for a period of N. This incremental value decreased as the number of iterations increased. Hence, the corridor of each period *t* and for each and every iteration included the following:

a) Upper Bound Limit (UBL)

$$UBL \begin{cases} = V^n_t(s) + \Delta V^n_t(s) = V^n_{3t}(s) \\ = SC \text{ iff } [V^n_t(s) + \Delta V^n_t(s)] \geq SC \end{cases}$$

where: SC = full storage capacity of the reservoir;

b) Trial Trajectory (TT)

$$TT = V^n_t(s) = V^n_{2t}(s)$$

where: t = 1, ..., N

n = 1, ...; and

c) Lower Bound Limit (LBL)

$$LBL \begin{cases} = V^n_t(s) - \Delta V^n_t(s) = V^n_{1t}(s) \\ = SD \text{ iff } [V^n_t(s) - \Delta V^n_t(s)] \leq SD \end{cases}$$

where: SD = dead storage capacity of the reservoir.

The corridor width was $2\Delta V^{n}_{t}(s)$ uniform for a particular state variable for N-periods for a particular cycle (Carriaga, 1982). The optimization procedure within a corridor was through the conventional DP limited to the values of stage variables set by the corridor.

The cyclic operation continued until there was no significant difference that occurred between the current and the previous values of the objective function, and at such point of the iterative convergence procedure, another cyclic operation was initiated but at a reduced corridor width. The process converged to the optimum thus, terminating the operation which depended on two considerations, namely:

1) Iterative Procedure. The number of iterations made to search for the optimum objective function in a given particular cycle was dependent on whether the following inequality was met:

$$(r_i - r_{i-1})/r_{i-1} \leq \alpha \qquad \text{for } i=2, \ldots, I$$

where: r_i, r_{i-1} = returns evaluated from the objective function at the i^{th} and $(i-1)^{th}$ iterations, respectively; and

α = arbitrary convergence parameter which, for the purpose of this study assumed a value of 0.001 though its selection was a function of one's objective to be close to the optimum; and

2) Cyclical Operation. This procedure terminated (indicative that convergence to the true optimum value of the objective function had been reached) upon reaching the following condition:

$$SLI \leq f\ (SA)$$

where: SLI = reduced state level increment decreasing cyclically at a given rate;

f = arbitrarily pre-set percentage factor; and

SA = active storage, *i.e.*, SA = SC - SD.

When these two conditions were satisfied by the trajectory, the optimum solution for this particular problem employing DDDP procedure was defined already, giving the optimum return r_i. The algorithm for DDDP analytical technique used in this particular study is presented in Fig. 3 under subroutine DDDP.

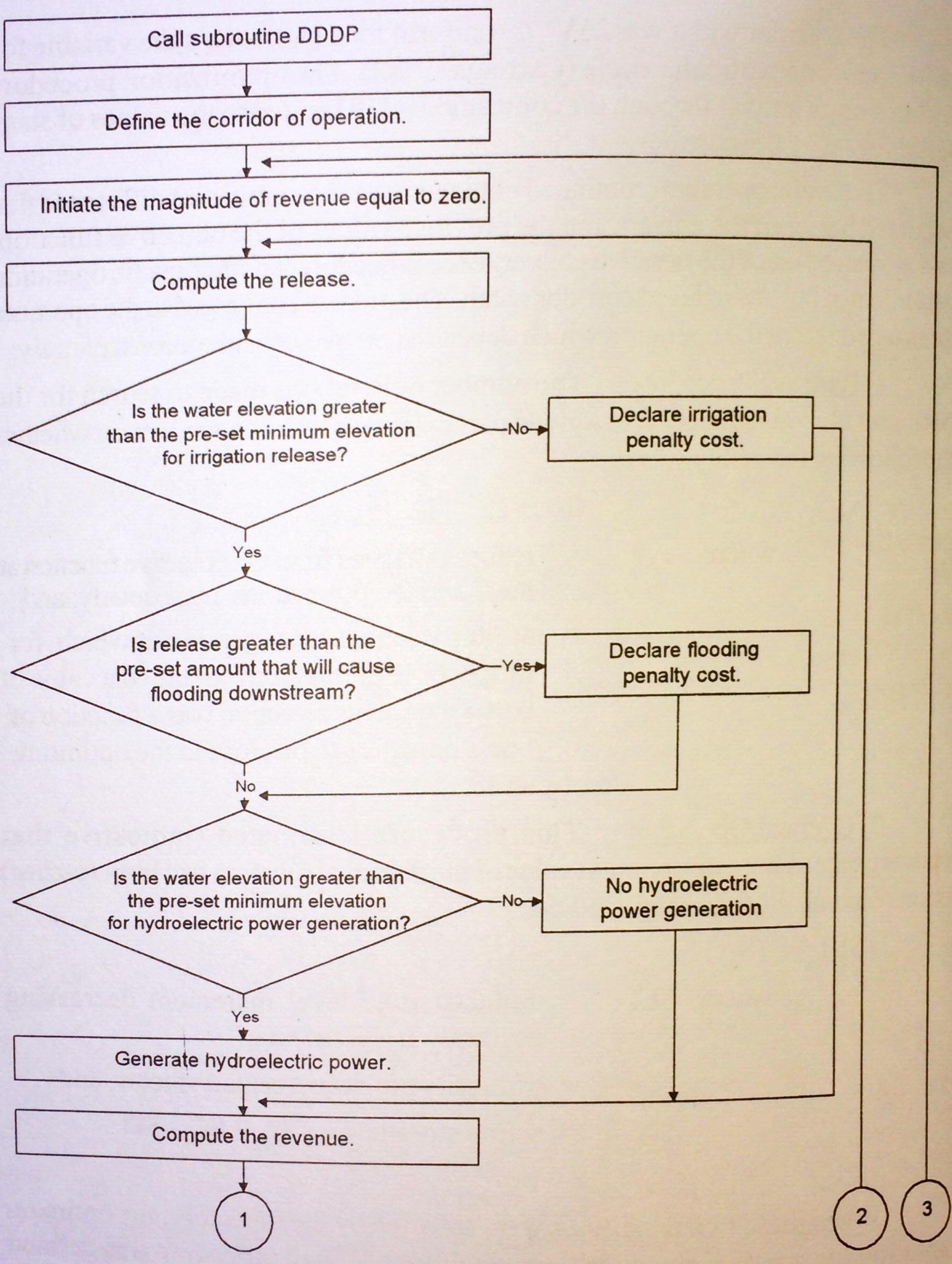

Figure 3. Algorithm for subroutine DDDP.

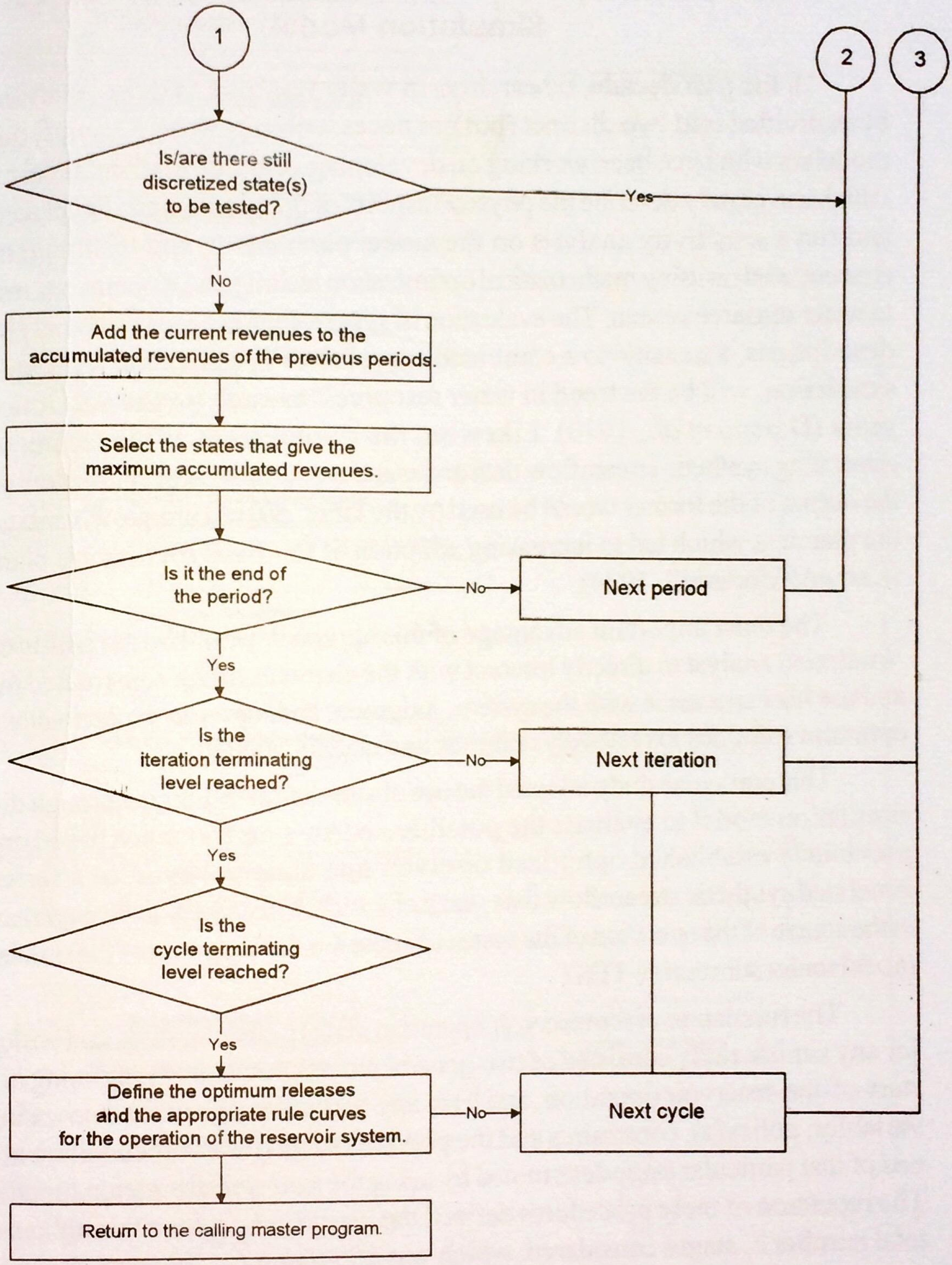

Figure 3. Algorithm for subroutine DDDP (continued).

The system's performance evaluation procedures: Simulation Model

In the past decade, researchers in water resource systems analysis have been divided into two distinct (but not necessarily opposing) groups, namely: modelers who have been working on developing complex mathematical models which can closely describe the physical aspects of the system on a digital computer and run a sensitivity analysis on the model parameters; and techniquers who concentrated on using mathematical optimization techniques of operations research to water resource system. The evaluation of system studies based on sound physical descriptions, amenable to a combined approach of optimization technique and simulation, will be the trend in water resources research for the next following years (Dracup *et al.*, 1970). Likewise, the combination of the techniques of generating synthetic streamflow data and water resource system simulation, where the output of the former would be used by the latter, offered unique advantages for the planners which led to increasing adoption of this basis for systems planning (Carr and Underhill, 1974).

The most important advantage of this approach would be the ability of the simulation analyst to directly interact with the elements of the constructed model and use his experience with the system, judgment and intuition to obtain close-to-optimum solutions to relatively complex and realistic models.

This particular study adopted the use of simulation technique through digital simulation model to evaluate the possible system's performance based on the previously established optimized reservoir operating policy from a series of generated synthetic streamflow data, each of which is just likely to be experienced in the course of the operation of the system. Figure 4 is the algorithm of the simulation model under subroutine TEST.

The simulation of the reservoir operation in this particular study and basically for any similar study consisted of two general procedures, namely: a) fixing of the start-of-the-reservoir operation; and b) at any particular stage with known input variables, policy(s), constraints and the previous stage (reservoir condition at the end of that particular stage determined by using the state transformation function). The repetition of these procedures defined the reservoir operation throughout the total number of stages considered, which was 600 stages,*i.e.*, 50 years, assuming the time period chosen for the simulation was the month.

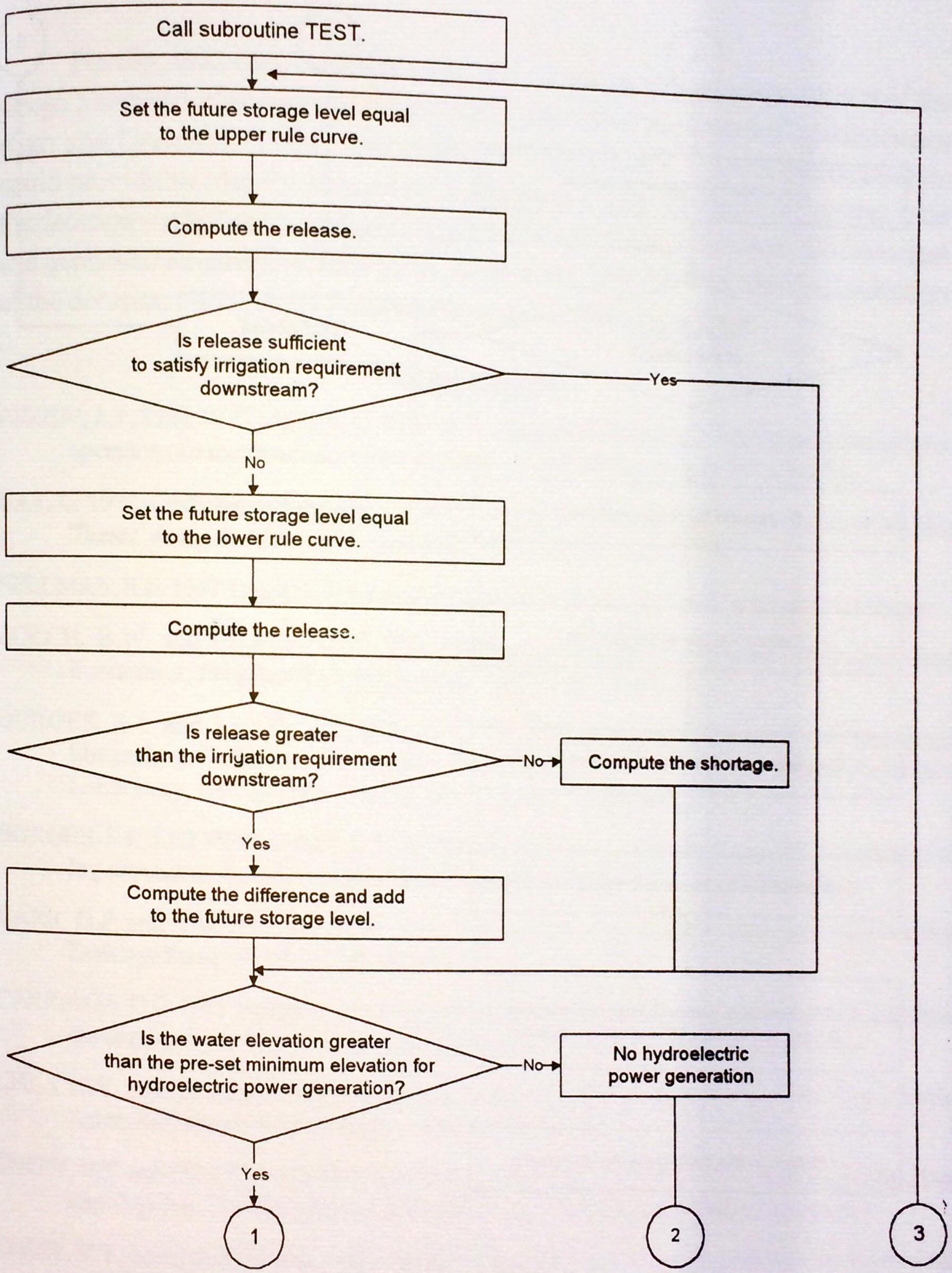

Figure 4. Algorithm for subroutine TEST.

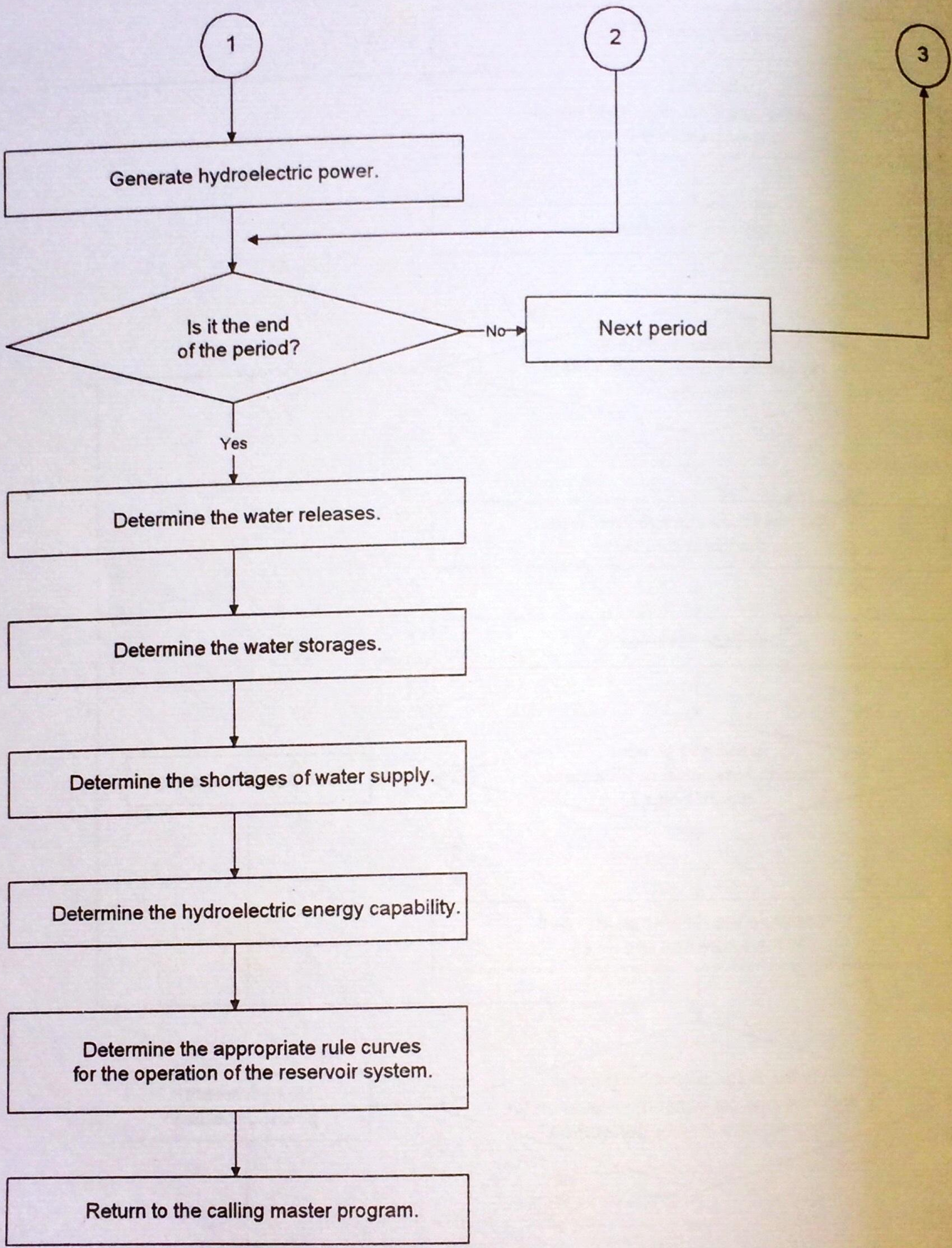

Figure 4. Algorithm for subroutine TEST (continued).

Finally, the output variables, *i.e.*, the response of the system on one of the design's alternative expressed in terms of a chosen measure of system's performance (Carr and Underhill, 1974), was evaluated in this study. This output evaluation could provide an idea for the system's planner on how the reservoir system (and the decision variables) would possibly behave in the future for both the historical and generated streamflow data as the input series, and facilitate the final selection of the decision variables in the operation of the reservoir system.

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