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DISSERTATION

MODELING OF RESERVOIR OPERATION WITH SEDIMENTATION CONTROL

Submitted by

Iwan K. Hadihardaja

Department of Civil Engineering

In partial fulfillment of the requirements

for the Degree of Doctor of Philosophy

Colorado State University

Fort Collins, Colorado

Summer, 2000

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COLORADO STATE UNIVERSITY

May 5, 2000

WE HEREBY RECOMMEND THAT THE DISSERTATION PREPARED UNDER OUR SUPERVISION BY IWAN K. HADIHARDAJA ENTITLED MODELING OF RESERVOIR OPERATION WITH SEDIMENTATION CONTROL BE ACCEPTED AS FULFILLING IN PART REQUIREMENTS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY.

Committee on Graduate Work

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Adviser

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Department Head

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ABSTRACT OF DISSERTATION

MODELING OF RESERVOIR OPERATION WITH SEDIMENTATION CONTROL

Operational planning management of reservoir systems becomes increasingly important when the water inflow from streams and watershed delivers a potentially high sediment rate. The amount of incoming sediment associated with stream flow or surface runoff entering the reservoir is crucial with respect to the reduction of storage capacity. Therefore, an appropriate model for enhancing reservoir system operation is an essential part of a decision support system model in relation to extending life expectancy of the reservoir. Reservoir operation modeling is a challenging problem as compared to a longer range of management operational planning. The modeling of reservoir operation has been studied widely using optimization models. However, studies focusing on sustainable reservoir operational planning due to sedimentation control have not been developed. The purpose of the proposed research is to develop a method of reservoir sediment-control operation by minimizing sediment deposition in the reservoir and maximizing other beneficial uses, especially for hydropower. When the dead storage has been completely filled with the sediment load then the reservoir is inundated forever. The model may provide a better management approach especially in maintaining the sustainability of a reservoir due to an unpredicted and underestimated sedimentation problem. In this study, the developed model will be implemented for a multipurpose single reservoir. The reservoir-sediment control model will be formulated and solved using Iterative Non-Linear Programming based on a multi-objective measure to perform

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the optimal release decision for the sediment control strategy and hydropower. The benefits of the proposed methodology in this research include its applicability, flexibility, and simplicity for practical applications. This model may correspondingly lead to improvements in future reservoir design and construction for sediment control management and sustainability while meeting downstream demands.

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DEDICATION

To the Almighty Allah, the Cherisher and Sustainer of the World,

My parents,
Joetata Hadihardaja and R.A. Enny K. Diponegoro

My parent in-law,
Mochamad Tuis and Anny S. Nuraini

My lovely wife,
Lisa Adhia Garina

My beautiful daughters,
Almira Kridarahmanda and Elita Kridavirmata

My brothers,
Andy, Herry, Doddy, Boma, Rinta, Ronny, and Suluh

My brother and sister in-law,
Dien, Rico, and Jenny

My aunt,
Dewi T. Muryati

In memorial,.......
Prof. Ir. Sosrowinarso, Ph.D.,
Prof. Ir. Martono Martodiputro,
Ir. Suweko Wirayasudarma,
Dr. Ir. Suhardjito Pradoto

Hydrology, Irrigation, Water Resources Management, ...

And We send down water from the sky according to (due) measure and We cause it to soak in the soil; and We certainly are able to drain it off (with ease).

(Holy Quran, 23;18)

Have they not seen how We lead the water to the barren land and therewith bring forth crops whereof their cattle eat, and they themselves? Will they not then see?

(Holy Quran, 32;27)

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LIST OF SYMBOLS

$\beta_{sediment\ t}$ = Dynamic value of release index during period t

$\alpha_{turbine}$ = Static value of release index

$R_{td\ t}$ = Volume of water release for power generation and water supply during period t

$R_{so\ t}$ = Volume of water release for sediment through outlet system during period t

$V_{si\ t}$ = Water equivalent volume of sediment inflow into reservoir during period t

$V_{so\ t}$ = Water equivalent volume of sediment outflow from reservoir during period t

η = Efficiency of turbine

γ_{mix} = Mixed water and sediment specific weight

$\Delta S/\Delta t$ = The change in storage volume (S) with respect to time (t)

ρ_{wi} = Density of water inflow

ρ = Water density

a = Coefficient

A_{ave} = Average of water surface area

A_t = Water surface area at the beginning of time interval Δt

$A_{t+\Delta t}$ = Water surface area at the end of time interval Δt

b = Exponent

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B = Width of the channel

C_{si} = Sediment inflow concentration

C_V = Coefficient of Correlation

D_{50} = Median diameter of bed load sediment

e = Coefficient of 1.06×10^5

E_r = Erodibility coefficient

e_t = Net evaporation rate

E_t = Net evaporation during period t

f = Constant of 0.02

g = Acceleration due to gravitation

H = Head of reservoir elevation

H_{ave} = Effective head

H_t = Head at the beginning of time interval Δt

$H_{t+\Delta t}$ = Head at the end of time interval Δt

I = Inflow rate at instant time t

I_t = Stream inflow into reservoir during period t

J_{bs} = $S_{bs} \times 10^4$

k = Constant of 1.6×10^{-6}

m = Rank of the data sort from the highest to the lowest or vice versa

n = Number of data set or point = 1, 2, 3, ..., N

N = Total number of data sets

O = Outflow rate at instant time t

O_{max} = Maximum outflow capacity associated with turbine or sediment outlet

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P = Power

P_o = Probability of occurrence

Q = Discharge through turbine

Q_s = Stream discharge

$Q_{s(ave)}$ = Average of stream discharge

Q_{si} = Rate of sediment inflow into reservoir

Q_{so} = Rate of sediment outflow through outlet system

Q_{wi} = Discharge of water inflow into reservoir

Q_{wo} = Discharge of water outflow through outlet system

Q_{wo} = Water outflow discharge for releasing sediment

$Q_{wo(max)}$ = Maximum water outflow discharge for releasing sediment

R_D = Discrepancy Ratio

$R_{D(AVE)}$ = Average of Discrepancy Ratio

R_t = Total water release during period t

S_{bs} = Bed slope of the river

S_t = Total storage (water and sediment) content at the end of period t

S_{t-1} = Total storage (water and sediment) content at the beginning of period t

S_{ws} = Slope of water surface

t = Time period = 1, 2, 3, …, T = 12 associated with the month in a year

u = 1, 2, 3, …, U = 30 associated with the total year of measurement

V_{si} = Volume of sediment inflow into reservoir

V_{wi} = Volume of water inflow into reservoir

X_{ave} = Average of computed sedimentation

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X_n = Computed sedimentation

Y_{ave} = Average of measured sedimentation

Y_n = Measured sedimentation

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CHAPTER I
INTRODUCTION

1.1. Background of Research

A major recent development in the water sector is the gradual introduction of integrated water management. Integrated water management presents a way of considering the entire water-related environment. This involves various interests, each of which has own specific demands.

An essential element of integrated water management as it relates to a reservoir management is the water release strategy. This strategy considers various interrelated elements and their interactions. For instance, reservoir storage is necessary to use the highly variable water resources of a river basin for beneficial purposes such as municipal and industrial water supply, irrigation, and hydroelectric power generation. In addition, public recreation, water quality, erosion and sedimentation, protection and enhancement of fish, wildlife, and other environmental resources are very important considerations in managing a reservoir and river basin system.

However, there is a difficult problem in specifying how to take all elements of the system into account. This is related to a social-economic issue and a technical issue. The social-economic issue is how to determine the boundaries of a water management strategy that will serve the elements best. The technical issue is how to realize this strategy in the regular operation of the water system works.

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Reservoir system analysis models are applied for different purposes in a variety of settings. In developing and implementing reservoir system analysis models, it is important to evaluate comprehensively the operation of existing reservoirs to obtain better management, water resource allocation, response to demands within priorities and environment characteristics. Modeling in practice deals with investigations performed specifically to reexamine reservoir operation policies. Recurrent examination may be actualized to guarantee system responsiveness to current conditions and to the objectives of the model. Therefore, in modeling, reservoir operation studies become increasingly important since the human demand and the natural supply may change with time. The studies are carried out annually in several reservoir systems to determine the next year's operating strategies.

Erosion and sedimentation are severe problems in streams, rivers, and reservoirs in many countries. Recently, problems associated with natural environmental phenomena such as land and stream erosion are receiving intensifying attention due to reservoir sedimentation in river basin systems. Sediments associated with stream inflow entering into reservoir encourage sedimentation deposition. The higher the inflow coming through the reservoir, the larger the amount of sediment deposits in the reservoir storage. This is true especially during flood events. The reliable location of reservoir provides nonrenewable resource in which it implies the one completed with silt, then that certain location is commonly irremediable (Eckholm, 1976). The United States Environmental Agency (USEPA) has noted that sediment as the source of water quality impairment produces impacts such as diminished reservoir capacity as a result of stream and river

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erosion (USEPA, 1998). In general, the reduction of capacity is quite significant and is estimated to be about 1% annually (Mahmood, 1987).

There are many studies focusing on operating plans of reservoir systems. However, there are no studies considering reservoir-sediment control operation through optimizing between sediment release operation and the beneficial uses of water supply, flood control, and power generation. In 1979, Quesada-Mateo investigated a methodology to evaluate the sedimentation effect in reservoir and stream flow modification for the hydroelectric firm power generation.

1.2. Statement of Problem

In general, very little attention has been given to the consequences of sediment deposition, or to ways in which minimizing the deposition and maximizing beneficial uses especially for hydropower may be incorporated in reservoir operation model formulation. Several studies have been carried out related to sedimentation in reservoirs, and reservoir operation; however, most of them were developed independently.

The main problem addressed in this research will be the development of a reservoir operation model minimizing sediment deposition and maximizing hydropower and water supply for a multipurpose reservoir system. The model is named the "Reservoir Sediment-Control Operation Model."

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1.3. Purpose of Research

The purpose of this research is to develop an easily applicable mathematical modeling (i.e. Decision Support System (DSS) model) of optimal multi-purpose reservoir operation minimizing sediment deposition in reservoir and maximizing other beneficial uses, especially for hydropower purposes.

1.4. Objectives of Study

There is a need to develop a reservoir operation model that is applicable at comprehensive scales and linked to maximizing the objectives of multipurpose reservoir systems and minimizing the deposition of sediment, which reduces the storage capacity. The research is targeted at developing a reservoir sediment-control operation model framework that potentially affects management policy in operating reservoir systems, enhancing sustainability and allowing better management strategies based on the optimal release decision. The specific objectives of the proposed research are:

- To develop a formulation of the optimization model incorporating effect of sediment deposition in the reservoir and downstream demands.
- To apply a Non-Linear Programming (NLP) model in order to determine the optimal planning policy for reservoir operation, especially for the conflicted objectives of sediment control operation and hydropower demand.
- To evaluate five different equations of sediment outflow rate due to the optimal planning policy.

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- To study changes in the pattern of reservoir operation due to the effects of inflow and outflow of sediment in term of planning decisions for reservoir operation.
- To assess the downstream sedimentation impact due to the reservoir sediment-control operation.
- To evaluate the release efficiency of continual sediment release operation in minimizing sediment deposition.
- To evaluate the static and dynamic value of release index due to objective measure to determine the optimal planning for reservoir operation.
- To evaluate the different operation based on the total annual energy production and the annual firm energy target.
- To establish the optimal operational planning based on the dry, normal, and wet year operation for yearly operation and long-term operation

1.5. Research Benefit

The benefit of this research is its contribution to reservoir operation modeling by incorporating the sediment control and other limitations such as hydrologic conditions and physical characteristics of the reservoir interacting in the system. By considering sediment inflow and outflow consequences in the formulation, it is expected that the lifetime expectancy of the reservoir can be extended; thus this model may enhance reservoir sustainability. In addition, this study will make recommendations which may motivate greater attention to the design of outlet systems, and to the reliability of the water-sediment measurement associated with reservoir-sediment control operation.

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1.6. Scope of Study

A possible way in order to increase the efficiency of reservoir operation is to adapt the management strategy of the reservoir system in such way that the requirements of all interests, elements, and boundaries are combined adequately. In this study, a single multi-purpose reservoir that has a potentially high sediment rate entering the reservoir has been selected for the model development.

The mathematical model used in developing the formulation associated with the sedimentation effect on the reservoir operation model is Non-Linear Programming (NLP). The spreadsheet model corresponding with the mathematical model contains an input range, graphical windows, a graphic user interface (GUI), hydrological range, physical reservoir limits, sedimentation and computation range. These are presented as a Decision Support System module.

The research will consist of analyses based on a reservoir sediment-control operation model of the multipurpose reservoir system within the multi-objective measure. Analyses and discussions of the case study will contain the scientific and practical recommendations and suggestions for further study.

1.7. Research Method

A wide application of computer modeling and analysis technique is used for developing quantitative information for use in evaluating sediment rate, storage capacities, water allocations, and release policies. The developed sedimentation inflow

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model and expended water-sediment outflow relation are taken into account in order to modify the common mass balance equation. The results are linked to a mathematical programming framework in which a formal algorithm is used to compute a set of decision variable values by maximizing the beneficial uses and minimizing sediment deposition subject to the constraints, such as hydrological conditions, physical reservoir boundaries and demands. The optimization method and multi-objective measure automatically search for the optimal release decision policy of the reservoir sediment-control operation.

1.8. Support

The successful solution to this problem may be introduced by applying the Non-Linear Programming (NLP) tool built into Microsoft Excel and known as a solver package software. A Graphic User Interface (GUI) is developed in this research to make an easily applicable tool to run the DSS model. Macro application is initiated in order to provide easy application of the DSS model and accelerate the process of repetition for NLP application with iterative fashion.

1.9. Location of Study

The case study for the research is associated with the single reservoir named Sanmenxia Reservoir, located on the lower part of the middle reach of the Yellow River, Republic of China. Sanmenxia Reservoir is a multi-purpose reservoir and serves especially for flood control, controlling a drainage area of 684,000 km^2, which is 92% of the whole Yellow River catchment area (Yuqian and Qishun, 1987).

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CHAPTER II
LITERATURE RIVIEW

2.1. Introduction

The reservoir operation model is established based on mathematical models that optimize inflow, storage and release of water in a reservoir associated with river reaches. In general, the specific model is developed based on certain purposes by providing evaluation of storage allocations and water release policies. Therefore, most reservoir system analysis models deal with quantities of water (Wurbs, 1996).

In order to develop a mathematical model for a reservoir system, it is essential to have sufficient knowledge of the interrelated functions of the system and its environment processes that are relevant for building the model. The description of fundamental knowledge associated with interrelated elements acting on reservoir systems is given in Linsley and Franzini [1979], Wurbs [1996], and Morris and Fan [1998]. Further existing research and studies (journals and proceedings) related to the reservoir operation and sedimentation are reviewed to support in establishing this research study.

2.2. Reservoir Systems and Purposes

A reservoir is specifically built in order to meet demands of water users. Single or multiple reservoir systems in parallel or in series should be operated and managed based on single-purpose or multi-purpose downstream demands (Wurbs, 1996). This proposed research deals with a single reservoir for multi-purpose demands.

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2.2.1 Reservoir Operation

Release decisions of multiple reservoirs are prepared in order to meet downstream demands that can alternatively be served by two or more reservoirs. The decision rule for a single reservoir is more simply established compared to decision rules for multiple reservoirs. In multiple reservoirs, decision rules are developed based on the adjustment of the reservoir pool, such that each reservoir is as the same zone of operation as far as possible at a specified time. The decisions affecting each reservoir are intended to minimize spills and other disadvantages (Wurbs, 1996).

A downstream reservoir may catch spills from an upstream reservoir. However, in order to minimize spills from the downstream reservoir, it is necessary to maximize the storage of the upstream reservoir. In addition, the downstream reservoir would be exhausted before utilizing water from the upstream reservoir to satisfy the downstream demands. The advantage of operating multi-reservoirs is considerably intensifying reliabilities compared to operating each individual reservoir independently or to a single reservoir (Wurbs, 1996).

2.2.2 Multipurpose Reservoir

The main purpose of a reservoir is to attenuate irregularities of stream flow and control the water release to meet downstream demands by minimizing shortage, especially during drought season. A reservoir that serves for more than one purpose is designated as a multipurpose reservoir (Wurbs, 1996). This type of reservoir is not very simple to operate since different water users may demand a different plan based on their individual interests in its operation. If this is the case, then the water manager should

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take appropriate decisions to achieve optimal release. This should maximize beneficial uses based on the different interests by considering a multi-objective measure associated with the constraints.

Reservoir release decisions associated with multi-purpose demands may include numerous interactions and conflicts or trade-offs. A simple example can be seen in **Figure 2-1**. When the reservoir elevation is low, then the reliability for flood control and damage prevention increases. However, when the pool of storage is increasing, it provides more benefit for power generation than for preventing flood damages (Albertson, 2000).

For instance, in order to meet demands such as water supply for irrigation, municipal use, and industry, the water release can predominantly be utilized to generate hydroelectric power turbines first before discharging to meet the downstream demands. However, conflicts arise when the water supply demands have higher priority than power generation. In the case, for example, of two reservoirs in series, when the operator of a downstream reservoir asks for more release from upstream reservoirs (single purpose-hydropower), the operator of the upstream reservoir may prefer to keep storing water in order to provide more benefits of power generation. This case would be a more complex situation when the owner of each individual reservoir is a different institutions, and especially when each owner has a different interest in obtaining more profits, as in the Citarum Reservoir System series (Sutaryan, 1997).

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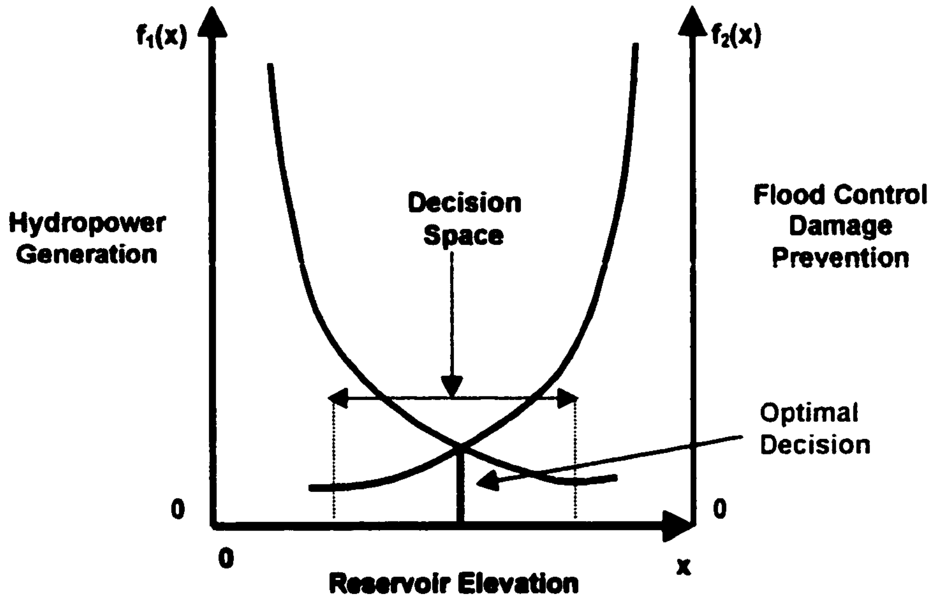

Figure 2-1. Flood Control-Damage Prevention and Hydropower Generation associated with Reservoir Elevation in the Decision Space (Adopted Haimes, 1977)

2.3. Water Balance Model

The most important equation to describe a reservoir is the water balance equation. The water balance of a reservoir in terms of instantaneous rates is (Bedient, 1992):

$$I - O = \frac{\Delta S}{\Delta t} \qquad \textbf{2-1}$$

In which:

I = Inflow rate at instant time (t)

O = Outflow rate at instant time (t)

$\Delta S/\Delta t$ = The change in storage volume (S) with respect to time (t)

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In modeling reservoir operation, **Equation 2-1** for each time interval can be extended as:

$$S_{t+\Delta t} = S_t + \text{Total Inflows} - \text{Total Outflows} \qquad \textbf{2-2}$$

In which the storage terms S_t and $S_{t+\Delta t}$ are volumes at the beginning (initial condition) and end of the time. Ideally, total inflows include precipitation falling on the reservoir surface, stream, sub-surface, and return flow coming into the reservoir. Meanwhile, total outflows deals with withdrawals and downstream releases (from outlet facilities), water spills (over spill way at full reservoir), seepage (through the dam or into the stream) and evaporation on reservoir surface (Wurbs, 1996).

2.4. Reservoir Losses

Rainfall and precipitation that represent gain and loss are usually combined as net rate. Evaporation can be determined as a function of storage (Wurbs, 1996) as:

$$E_t = A_{ave} e_t \qquad \textbf{2-3}$$

In which:

E_t = Net evaporation during period t

A_{ave} = Average of water surface area

e_t = Net evaporation rate

t = Time period

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In a reservoir, the average water surface area (A_{ave}) during the time period can be estimated as follows (Wurbs, 1996):

$$A_{ave} = \frac{1}{2}\left[A_t + A_{t+\Delta t}\right] \qquad \textbf{2-4}$$

in which:

A_{ave} = Average of water surface area

A_t = Water surface area at the beginning of time interval Δt

$A_{t+\Delta t}$ = Water surface area at the end of time interval Δt

2.5. Power Equation

For hydroelectric power generation, the power equation for generating energy can be given as (National Rural Electric Cooperative Association, 1980):

$$P = \rho g Q H_{ave} \eta \qquad \textbf{2-5}$$

in which:

P = Power

ρ = Water density

g = Acceleration due to gravitation

Q = Discharge through turbine

η = Efficiency of turbine

By introducing the analogy of **Equation 2-4**, average head can be presented as:

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$$H_{ave} = \frac{1}{2}\left[H_t + H_{t+\Delta t}\right] \qquad \textbf{2-6}$$

in which:

H_{ave} = Effective head

H_t = Head at the beginning of time interval Δt

$H_{t+\Delta t}$ = Head at the end of time interval Δt

2.6. Incoming Stream Inflow Estimation into a Reservoir

Estimation of a stream inflow into a reservoir can be evaluated by using statistical methods such as arithmetic procedure and frequency analysis. These two methods have been compared in Citarum Cascade Reservoir in Indonesia. The methods are applied in order to determine the amount and distribution of stream inflow discharge entering into the reservoirs for dry, normal, and wet year operation (Petrus, 1997).

2.6.1 Arithmetic Method

Petrus (1997) presents the following results of the arithmetic method application to the example of the Citarum River Basin (CRB) area. In the arithmetic method computation, the distribution of the CRB and its tributaries follow the normal distribution. Based on previous research on the CRB, the corridor range for dry, normal, and wet year operation can be given as in **Figure 2-2** based on the specific operation:

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Dry Year Operation:

$$\text{Between } Q_{s(ave)} - 0.2533\sigma \text{ and } Q_{s(ave)} - 1.2816\sigma \qquad \text{2-7}$$

Normal Year Operation:

$$Q_{s(ave)} \pm 0.2533\sigma \qquad \text{2-8}$$

Wet Year Operation:

$$\text{Between } Q_{s(ave)} + 0.2533\sigma \text{ and } Q_{s(ave)} + 1.2816\sigma \qquad \text{2-9}$$

in which:

$Q_{s(ave)}$ = Average of stream discharge

m = Rank of the data sort from the highest to the lowest or vice versa

n = Number of data

σ = Deviation

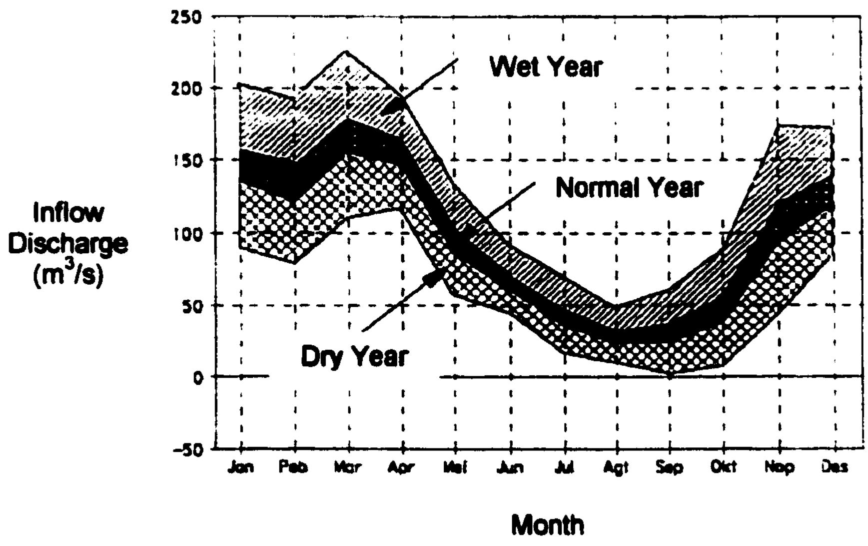

Figure 2-2. Corridor Range of Dry, Normal, Wet Yearly Operation (From Petrus, 1997)

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2.6.2 Frequency Analysis

Distribution of stream inflow discharge by using frequency analysis usually gives a better result if the provided data is recorded for a long duration. This condition may be achieved because each occurrence of data always considers the probability of occurrence. For high flow design (flood flow design), the data is sorted from the highest flow to the lowest flow data. On the other hand, for low flow design discharge, all data is sorted from lowest flow to highest flow data. The probability of occurrence is presented in **Figure 2-3** and **Figure 2-4** (Petrus, 1997):

$$P_o(\%) = \frac{m}{n} x100 \qquad \textbf{2-10}$$

In which:

P_o = Probability of occurrence

m = Rank of the data sort from the highest to the lowest or vice versa

n = Number of data

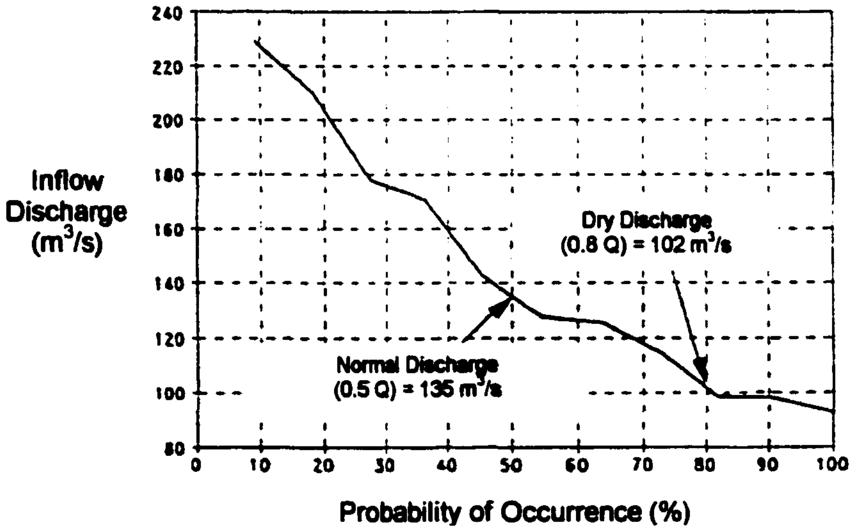

Figure 2-3. Stream Inflow Entering Saguling Reservoir, Indonesia (Dry and Normal Year of Operation) in January (from Petrus, 1997)

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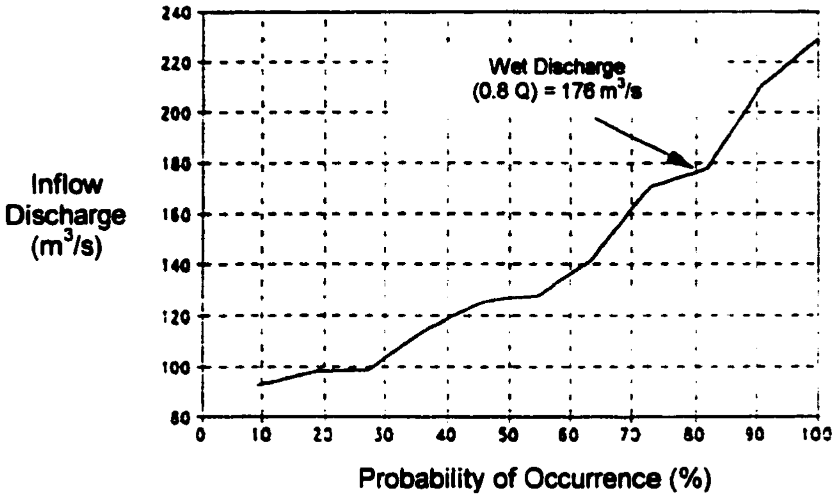

Figure 2-4. Stream Inflow Entering Saguling Reservoir, Indonesia (Wet Year of Operation) in January (from Petrus, 1997)

2.7. Optimization Technique

Modeling of reservoir operation is undertaken in order to find the optimal strategy in releasing water within compromised conflicts of interests. It is necessary to have a systematic process to approach an ideal system modeled in the form of mathematical or optimization algorithmic formulations. Many optimization algorithms have been developed in the past few years (Bazaraa et al., 1990); however, basically, all neglect non-optimal strategy (policy) and concentrate only on better alternatives and optimal policy.

Optimization can be applied in many ways such as complex analytical and numerical methods within simple arithmetic and simple logic. Analytical method is a traditional method using calculus (Haimes, 1977). Optimization techniques such as numerical algorithm methods that analyze part or all of the decision variables

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simultaneously have been used in large scale hydro systems, and include Linear Programming (LP), Dynamic Programming (DP), Optimal Control Theory (OCT), and Non-Linear Programming (NLP).

2.7.1 Linear Programming

Linear programming (LP) is the most widely used in hydro system models and other engineering lines of work, and it is one of the most successful mathematical programming techniques. Numerous other reservoir operation models have been developed with LP in view of the existence of standard programming packages which allow large problems to be solved at tolerable cost and time. According to Hillier and Lieberman [1990], LP is ranked as one of the most valuable scientific advances of the mid-twentieth century. Although LP is capable of coping with a large number of variables and constraints of functions, the groundwork of the LP concept requires that objectives and constraints be linear functions. Non-linear functions can be linearized but it is necessary to consider the nature of the non-linearity associated with the modeled system (Hiew, 1987).

A fundamental solution of the LP model using the simplex algorithm is described in detail in many textbooks such as Wagner [1975], Bazaraa et al. [1990], Mays and Tung [1992], Nash [1996] and many others. Hiew [1987] mentions that Dantzig in 1950 initiated the use of the simplex algorithm in order to solve LP problems. The optimal solution, due to the computational efficiency of simplex algorithm and its variants, lies at the points of intersection among active constraints. The feasible solution moves from one corner point to another in increasing the objective value to search for the optimal

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solution. In addition, LP can be applied to deterministic and stochastic problems in water resources (Yeh, 1985). The applications of LP in hydro systems are described below to illustrate the extensive uses of LP model formulation and its development.

In 1962, Dorfman introduced the application of a linear programming model with three versions, related to average seasonal flows, critical period flows, and treating flows stochastically to represent inflows. Each version dealt with increasing complexity such as maximizing an economic objective function by evaluating the values of decision variables of reservoir storage capacities and release targets.

An LP model for analyzing multiple reservoirs for operation of flood control systems was developed by Windsor [1973]. The LP model developed was associated with channel and reservoir routing. It was proposed to minimize the total damage cost for storm design at appropriate locations by determining release schedules.

In 1982, Palmer et al. introduced the application of the LP model for a single and multiple reservoir system in order to evaluate firm yields in the Potomatic River Basin. Analyses of trade-off were made in order to determine the effect of constraints of instream flow qualification on scheme yields.

In 1988, Palmer and Holmes also developed an LP model associated with a decision support system (DSS) of the Seattle Water Department which incorporated an expert system for drought management. The DSS model dealt with determination of optimal operating policies and system yield by optimizing objectives of minimizing the economic deficiency due to a designated target and maximizing the yield.

In 1990, Randall, Houck, and Wright established an LP model to investigate and analyze drought management due to the operation strategy for an existing metropolitan

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water supply system. The system included several reservoirs, distribution amenities, treatment plans, and groundwater. Trade-off curves were also established in the model study for four objectives that consist of:

1. Maximizing net revenues between costs of electrical pumping and profits of selling water.
2. Maximizing reliability due to the minimization of consumption-demand ratios.
3. Maximizing reservoir storage at the closing stages of the optimization perspective.
4. Maximizing the minimum flow in the river.

In 1995, Diba et al. used LP for a planned operation for large-scale water distribution. The model was designed in order to help operators to find whether the existing model of operation could be improved. A training tool was also established in order to help the operators to learn how to handle competing objectives.

A combination of simulation and LP was developed by Martin [1995] in order to analyze the management operations of six reservoir systems managed by the Lower Colorado River Authority in Texas. An LP model was developed to maximize power generation at four dams with no breaching constraints such as the requirements for sustaining particular storage levels at every reservoir.

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2.7.2 Successive Linear Programming

Since most hydro system problems deal with necessarily nonlinear structure, such as energy generation in which non-separable function of head and turbine discharge is not a linear case, standard LP cannot be applied immediately. Therefore, in order to use standard LP in this situation, many approaches have been developed to manipulate the problem formulations. The piecewise linearization approach converts the original nonlinear function to a series of linear functions associated with the definition of additional variables (Loucks et al., 1981). Another approach is the so-called Successive Linear Programming (SLP), commonly known for solving non-linear problems. SLP is more generalized due to handling a higher degree of non-linearities in which it does not involve the initiation of the supplementary variables (Hiew, 1987).

Palicios-Gomez [1982] demonstrated that when the objective is a differentiable continuous function, an iterative LP algorithm that produces a feasible result at every iteration would converge to a local optimum as the stage size is decreased.

Reznicek and Simonovic [1990] introduced a development of SLP for analyzing power generation operations in Manitoba, Canada. Manitoba Hydro operating multiple reservoir system was the case study for testing the model. A release policy was created for maximizing system revenue and minimizing cost in order to meet energy demands specified by a given curve of load duration for a given set of stream inflows.

Lobbrecht [1997] applied an SLP optimization model for dynamic water-system control associated with design and operation of regional water-resources systems. The developed model was a generally applicable methodology to achieve a well-balanced design and control of regional water systems for both urban and rural areas. The model

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considered the dynamics of the intrinsic processes in the water system and the various requirements of the different interests varying in time.

2.7.3 Dynamic Programming

Dynamic Programming (DP) is an optimization technique using Bellman's Principle of optimality in which a problem is decomposed into stages, with decision required at each stage. This was invented by Bellman [1957]. By definition (Bellman, 1962), DP is a well-known procedure recognized as the optimization theory of multistage decision processes. This optimization procedure allows that the objective or constraint functions may be highly non-linear. The DP model is an optimization technique that can be applied to hydro system problems associated with sequential decision policy.

Buras [1966] described the use of DP in hydro system development. In addition, Yeh [1985] described DP extensions and variations that could be used in developing hydro system models such as reservoir operation and analysis. The success of the model is that the non-linear function and stochastic features can be incorporated in DP formulation (Labadie, 1998).

DP was applied for optimizing water releases in order to maximize revenues from the sale of power and water. The model was implemented for a multi-purpose reservoir and a single reservoir (Hall et al., 1968). In 1977, Collins established a DP model and implemented it on four reservoir systems operated by the city of Dallas in order to meet water supply demand and minimize the cost of withdrawal and release schedule. Trezos and Yeh [1987] implemented a DP technique in order to enhance operations of multiple hydropower project systems.

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2.7.4 Combination Dynamic Programming and Linear Programming

Yeh [1981] described a real time optimization methodology using a combination of applications of DP and LP in order to determine release schedules of multiple reservoirs for hydropower. The case study associated with the application of the DP and LP model was the operation of hydroelectric power generation in the California Central Valley Project.

2.7.5 Non-Linear Programming

The non-linear programming (NLP) technique may be applied to a large variety of problems. Problems that are not LP problems, then, are NLP problems. This technique is regarded as the most generalized mathematical programming technique. Hiew [1987] described how NLP can deal with functions of non-separable objectives and non-linear constraints. However, NLP solutions may also produce a number of local optima and this may encourage confusion of iterative search procedures. Therefore, this situation may generate sub-optimal results.

Lobbrecht [1997] explained the three major divisions of NLP solution methods based on certain assumptions of the objective and constraint functions in which each division requires the objective and constraint functions that must be continuous. Firstly, the NLP model applies objective and constraint functions in order to ascertain the search direction. The second division applies first-order partial derivatives of the constraint and objective functions. The third division, in addition, applies second-order partial

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derivatives for both objective and constraint functions. For the second and third divisions, it is necessary that the first and second-order partial derivatives must be continuous. In addition to all divisions, all functions of objectives and constraints should be continuous functions.

Mays [1989] described three examples of simulation models combined with NLP problems in which a reduced NLP problem is solved associated with a simulation model. This combination method is capable of avoiding the accumulation of imprecision in the NLP problem.

2.7.6 Considerations of Optimization Techniques

In this section, existing optimization techniques will be analyzed and reviewed based on previous recommendations or studies. The analyses deal with optimization model techniques in the solving-formulation when applied to solve hydro system problems. The advantages and disadvantages are described for each optimization technique discussed.

2.7.6.1 Advantages

LP solvers are readily available and are classified as relatively fast solvers compared to other implementations of mathematical programming. LP can solve larger hydro system problems in which it deals with much larger numbers of subsystems and lengths of the control horizon. In addition, LP can be used for deterministic or stochastic problems (Lobbrecht, 1997). According to Wurbs [1996], LP is used widely in numerous applications to hydro system problems. LP, in most applications, has advantages since it

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is a well-defined, readily available algorithm, and easy to understand. The LP model has been developed in generalized computer codes and it includes a very efficient algorithm application to particular formulations. Reservoir operations can be realistically formulated by a set of linear objective and constraint functions.

The application of SLP may be used for further research in special points of interest, such as whether the method developed may be used accurately for generating hydropower and the process associated with optimal reservoir releases in large river basins, since the SLP method has the greatest potential for water system control in regional hydro systems and can be used for deterministic and stochastic problems. In successive iterations, the SLP method becomes very robust if the solution established (at every prior iteration) can be employed as an initial point for the next iteration. This condition is called a warm start and when applied by a solver it normally decreases the running time for the problem solving significantly (Lobbrecht, 1997). For large-scale hydropower, Hiew [1987] showed that SLP is generalized, robust, and reliable in performance due to its computation effectiveness. In addition, SLP is one of the methods that have the best prospective application in optimization studies of large-scale hydropower systems.

DP has some advantages over LP in that DP is capable of formulating problems for nonlinear and non-convex functions for both objective and constraint functions. Therefore, the complex situations typical of hydro system problems may be better dealt with by DP compared to LP (Lobbrecht, 1997). According to Wurbs [1996], DP is used specifically for reservoir system analysis models in which this model may readily reflect the properties of discontinuous problems in addition to non-linearity and non-convexity.

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The DP model solves formulated problems by optimizing a multiple-stage decision process and it can also be used for deterministic and stochastic problems.

In NLP modeling, the exact relationships as used in simulation models can be incorporated very well without further simplification. The solution, achieved by NLP for non-linear characteristics due to the nature of hydro system, provides a more accurate optimal solution compared to LP and DP techniques. Solver availability exists for specific divisions of NLP (Lobbrecht, 1997).

2.7.6.2 Disadvantages

Lobbrecht [1997] indicates that the objective function in LP is limited in terms of a convex piece-wise linear function of the state and decision variables. In addition, according to Wurbs [1996], a linearization technique needs to be applied in order to deal with non-linear problems such as evaporation and hydropower computations. In addition, the forms of strict linearity create a restriction in the applicability of the LP formulation for nonlinear problems.

It is possibly for highly nonlinear function to be linearized in SLP model. However, for non-linear problems, reasonably accurate values should be known beforehand in order to make the iteration converge. Many calculations of the same time step may be necessary (Lobbrecht, 1997).

The most important problem of DP is dealing with the curse of dimensionality. For large problems, the number of alternative solutions is exponential in the number of state variables. DP may be more difficult to understand in terms of modeling and implementation. In addition, the lack of a standard mathematical formulation of the DP

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problem may not encourage general DP solver development. This model is useful to solve only small problems since the computation of the DP solution is very slow, due to the determination at each stage of the optimal strategy for all possible system states (Lobbrecht, 1997). According to Wurbs [1996], DP is not a precise algorithm like LP but it is rather a general approach in solving optimization problems.

Yeh [1985] and Hiew, [1987] indicate that NLP has the disadvantages of mathematical complexity (considerably more difficult than LP), slow convergence, large computer memory and computation time requirements. In addition, Yeh [1985] stated that the process of optimization is slow due to the order of dimensionality, which is large compared to LP. This indicates that much research using NLP needs to be simplified too much if linear methods are to be used, and NLP modeling may generate very complex optimization problems. It is therefore no surprise that NLP is infrequently used in hydro system studies. In addition, there is also the difficulty in NLP associated with computation due to the fact that the optimum solution may lie anywhere within the feasible solution space defined by the constraints set. The NLP model needs an initial feasible point in the solution that must be found in most algorithms in the NLP solver, mainly for complex problems with limited variables, prior to the real problem-solving beginning (Lobbrecht, 1997).

2.7.7 Software Development and Application

Several models incorporating an optimization technique have been developed to encourage easier application in formulation and problem solving in the field of hydro

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systems. Several of these models will be described to indicate their development and application.

2.7.7.1 Software Application of Linear Programming Codes

One of the LP solvers used in the software application, incorporated with a spreadsheet, is Microsoft Excel. The LP problem can be simplify formulated by using the Excel spreadsheet and then the solver can be applied by identifying the problem formulation. In addition, if the constraints of the problem consist of a large number of functions, the limited solver application may need additional software called premium solver to handle a large number of constraints. This case study was carried out in the series of the Citarum Reservoir system in 1995 by Jatiluhur Authority Agency for reservoir operation planning with regard to optimal release for meeting hydropower and water supply demand downstream (Petrus, 1998).

In 1995, Martin used an LP software package called MILP88 marketed by Eastern Software Products of Alexandria, Virginia. The MILP88 was applied to simulate daily operation of a multiple purpose reservoir of the Lower River Authority in Texas, during the winter period, associated with the hydroelectric generation capacity established with the LP model. This software was incorporated with LOTUS 123 to simulate the performance and results produced by MILP88 software.

2.7.7.2 Software Application of Successive Linear Programming Codes

The Texas Water Development Board developed the Monitor-1 model for analyzing complex surface water storage and conveyance systems. The model was

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developed to operate water supply, hydropower, and low flow augmentation. The SLP algorithm was applied to handle nonlinear functions incorporated with hydropower and other features of the formulation (Martin, 1987).

2.7.7.3 Software Application of Dynamic Programming Codes

Labadie [1990] developed generalized codes for DP and it called the microcomputer CSUDP package (developed at Colorado State University, CSU). This is the one of the few available general-purpose DP computer programs. The basic DP computational algorithms are coded in FORTRAN subroutines reflecting the Objective, State, and Constraint functions. In 1998, Labadie enhanced the CSUDP computational algorithm in a new program that is coded in C^{++} language.

2.7.7.4 Software Application of Non-Linier Programming Codes

An NLP solver is also built into the Microsoft Excel Software. The formulation that can be developed is not very different from the LP formulation. In this research, the NLP solver incorporated with Excel Software was used for solving due to the complexity of reservoir sediment-control operation planning and its ability to automatically handle the non-linearity problems.

2.8. Reservoir Sedimentation

Storage capacity of a reservoir decreases eventually as a result of sedimentation accumulation. The rate of sediment accumulation for every reservoir is different based

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on upstream stream inflow and sediment materials from watershed flowing into the reservoirs, and the features of the reservoir itself. Sediment transport increases greatly throughout flood periods, in which it varies considerably, especially given the random nature of floods (Wurbs, 1996). Lopez [1978] and Wu et al. [1996] indicate that sediment deposits in the reservoir rely on natural phenomena, including both sediment and reservoir characteristics, such seasonal discrepancy between flood and drought periods, magnitude and gradation of the sediment, specific gravity of the sediment, sediment inflow discharge, dimension and shape of the reservoir, physical controls and operation cycle of the reservoir.

Sediment accumulation deposits take place all through reservoirs in every selected pool. Since stream flow rate decreases in the entrance of a reservoir, the coarse materials are deposited in the backwater and at the upper reach of the reservoir. The bed load advances in moving waves such as in **Figure 2-5**. The fine particles move further into the reservoir to a much greater distance before depositing (Simons and Sentürk, 1992). Sediment surveys of reservoirs with echo sounding equipment can be carried out periodically to establish recent bed topography and consequential storage volume (Wurbs, 1996). The whole process of sediment deposition is illustrated by **Figure 2-6**.

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Figure 2-5. Motion of Coarse Material Waves illustrated by 1, 2, and 3 along the Longitudinal Profile (From Simons and Sentürk, 1992)

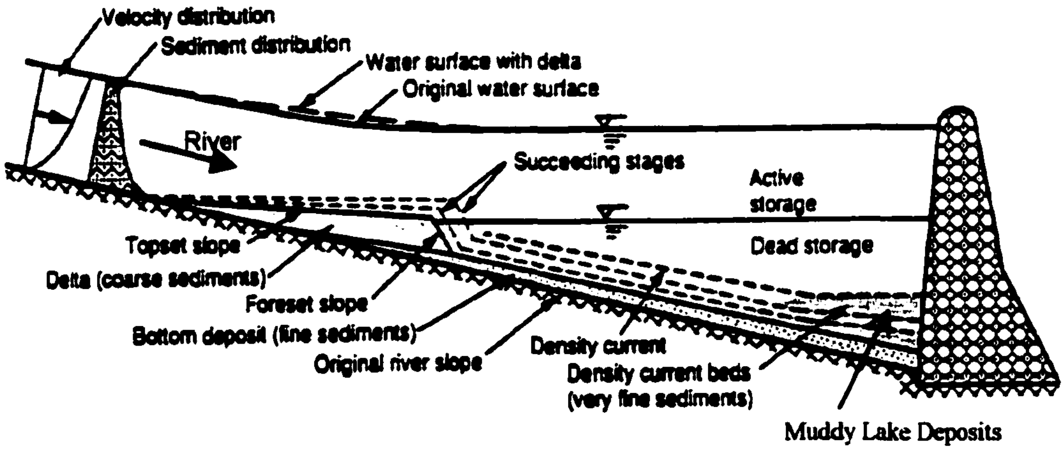

Figure 2-6. Deposited Forming Deltas in a Reservoir (from Frenette and Julien, 1995)

Sediment accumulation and deposit in the reservoir are notable concerns, since this situation influences the storage capacity and several management activities. The sediment deposition takes place all through a reservoir, but mainly in the entrance where stream flow velocities are decreased by the puddle (Wurbs, 1996). The influences of sediment depositions during the lifetime of the reservoir that ought to be identified in project planning and operation of the reservoir include flood prevention, hydropower generation, and irrigation. (Wu et al., 1996).

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Because of the high cost of accomplishing the sub-surface surveys, several reservoirs have been used for decades without sediment inspection ever having been achieved. Consequently, reservoir storage capacity approximations are fairly indeterminate. However, the majority of sizeable reservoirs are built with sediment reserve storage. This is designed to accommodate sediment accumulation and deposition anticipated during a particular design life, in which is normally from 50 to 100 years. After accumulated sediment reaches the elevation of the intake floor, a reservoir may not be functional (Wurbs, 1996).

2.8.1 Erosion and Sedimentation Processes

Erosion and sedimentation are natural phenomena in balancing the element forces and soil surface in watershed and stream. McCuen [1989], and Morris and Fan [1998] described the processes of erosion and sedimentation associated with the principal factors which affect the processes. The process by which soils and minerals are removed from the soil surface and transported to low level regions is so called erosion.

Once the soil elements have been made movable, the most eroded soil is typically moved at lower slopes by surface runoff (Meyer, 1971). The processes, by which eroded particles deposit at lowland regions or downstream, specified by balancing forces between the forces of gravitation and transportation or movement (motion), are identified as sedimentation.

McCuen [1989] described a classification of erosion based on the place of occurrence such as watershed erosion and channel erosion. Erosion in the watershed region of the surrounding channel is recognized as splash erosion, sheet erosion, rill

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erosion and gully erosion. Raindrops encourage splash erosion by striking the surface of the soil especially on bare soil. The striking force of raindrops encourages the soil aggregates to break up and separate the particles (fine soil particles and organic matter) from heavier soil particles. Sheet erosion is encouraged by shallow sheet run-off over the land surface. This run-off also transports the detached soil particles and minerals from the splash erosion. The shallow sheet surface run-off produces the form of waterways to move the loose particles to the lowland region. Rill erosion occurs when the greater surface runoff follows the waterways, forming concentrated flows on the land surface. The energy of concentrated flows increases the detaching of soil particles and cutting of small channels called rills that are able to transport the soil particles. Gully erosion also occurs in the watershed, and is indicated by increasingly deeper and wider rills. This type of erosion in conjunction with greater run-off flow rate is able to carry a much larger amount of sediments than rills. Channel erosion occurs when the vegetation in the riverbank is showing disturbances, and the flow rate in a stream is also increasing beyond the critical point to initiate the movement of the bed sediment particles. These disturbances are the beginning of channel erosion, caused by the unbalancing of the geomorphic equilibrium of a natural stream. Sheng [1975] mentioned that besides those factors, other aspects include wind erosion and mass movement such as soil layer falls, slides, earth flows, creep, and subsidence. Rainfall is the most important aspect of the water erosion process in the watershed area. The intensity of the rainfall is very significant due to the soil surface erosion since the raindrop impact is greater and there is more excess runoff during intense storms.

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Ideally, the sediment problem would not exist if the sediment were transported by flow rate in a stream which goes directly to the sea without any hindrances. However, when barriers exist during the movement of the sediment downstream, such as dams, it is necessary to minimize the unbalancing by encouraging the sediments to move out through the dams. Brune (1953) indicates that more than 90% of the sediment loads associated with stream flow or surface run-off flow are trapped in most reservoir storage of modern design.

In eroded areas, a high sedimentation rate entering the reservoir may not be prevented. However, it can still be delayed. The sediment accumulates in the reservoir and results in a silted reservoir after a certain period of its operation. In the reservoir system, sediment transport is a result of erosion processes occurring in the upstream catchment area, stream, and shoreline around the reservoir. Incoming sediment causes a continual decrease in storage capacity and reduces the beneficial uses and the lifetime expectancy of reservoir operation. Appropriate reservoir locations are limited, and the possibility of collapse due to the failure of the reservoir to meet the design objectives may be associated with unnecessary and unimpeded sedimentation which critically damages the reservoir (Wurbs, 1996).

Natural watershed, stream erosion and sediment deposition courses are considerably changed not only by construction of reservoir developments, but also by reservoir operation to meet the downstream demands. In the case of reservoir operation, the problem would depend, in a long-term operation, on the stream flow and incoming sediment traits of the parent stream, and variation or increase of the demand pattern in the

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long run. In addition, the rate and significance of pool level fluctuations would intimately affect shoreline and bank erosion (Wurbs, 1996).

Many investigations and studies have been carried out in recent years. Studies such as Sheng [1966], Graf [1979], Hudson [1971], Shen [1979], Yalin [1972], Vanoni [1975], Simons and Sentürk [1992], and Food and Agricultural Organization [1977] give an idea of the magnitude of the material available in the areas of erosion and sedimentation at different levels of treatment.

2.8.2 Characteristics of Sediment Load

Simons and Sentürk [1992] and Julien [1995] described a classification of total sediment in three essential parts. This classification is represented in **Figure 2-7**. Large reservoir projects commonly trap and effectively hold the loads of suspended sediments and bed material sediments within the reservoir entrance.

The identification of a reservoir that is clear of sediment loads can be considered by introducing the concept of sediment concentration. There are three classifications for reservoir loading by the sediment associated with the incoming stream flow. The classification can be described in **Table 2-1** such as a clear reservoir, medium clear reservoir, and heavily sediment-laden reservoir (Zhide, 1996).

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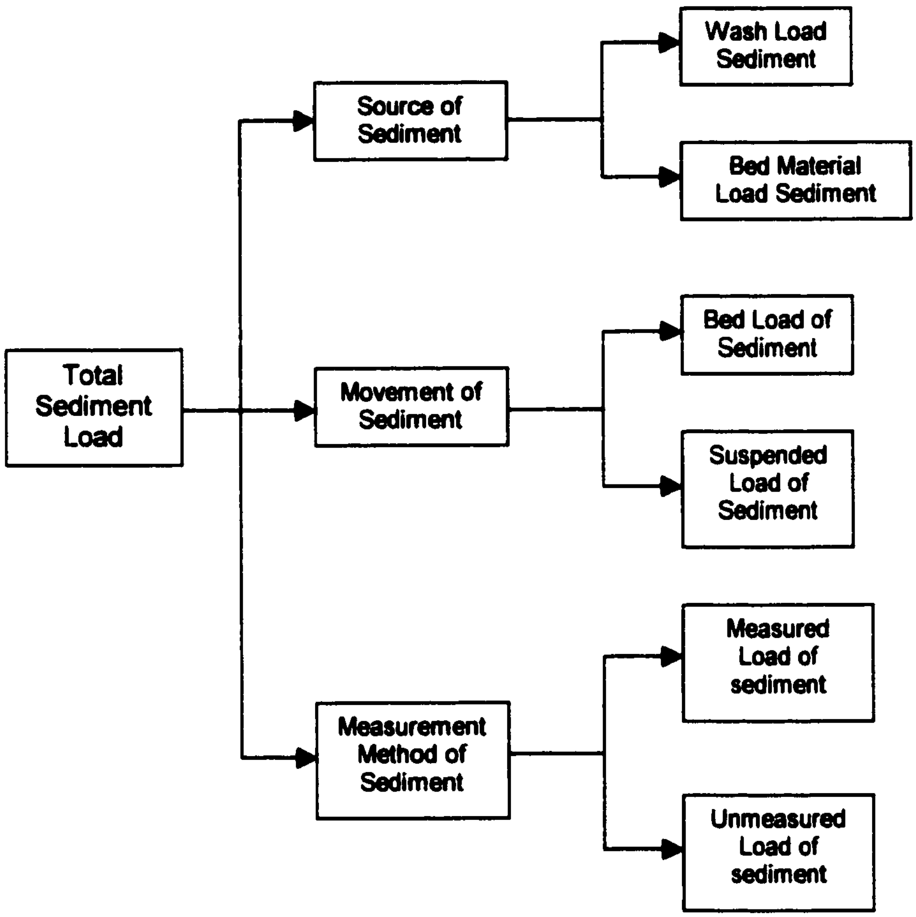

Figure 2-7. Classification of Sediment Transport in Streams (adopted from Julien, 1995)

Table 2-1. Classification of Reservoir (Zhide, 1996).

No.	Type of Classification	Concentration (kg/m^3)
1	Clear Reservoir	Less than 1
2	Medium Clear Reservoir	Between 1 and 10
3	Heavily Sediment-Laden Reservoir	More than 10

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2.8.3 Incoming Sediment into Reservoir

The rate of sediment inflow in the reservoir results from the complex interrelationships of climate drainage, basin, fluvial system and human activities (Simons and Sentürk, 1992). Sedimentation in the reservoir is determined by a combination of the ability of a reservoir to trap the incoming sediment load and the volume of sediment supplied to a reservoir (Frenette and Julien, 1996). Examples to indicate the inflow of sediment load related to the discharge and to the sediment-rating curve are shown in **Figure 2-8** and **Figure2-9**, respectively.

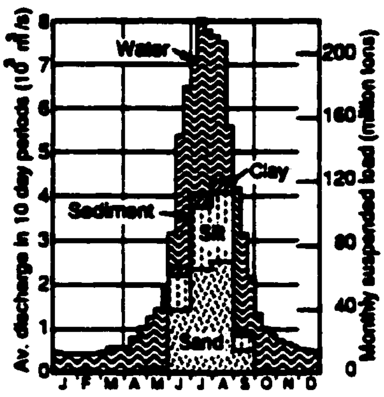

Figure 2-8. Flow Discharge and Sediment Load Upstream: Tarbela Dam in Indus River (From Julien, 1995)

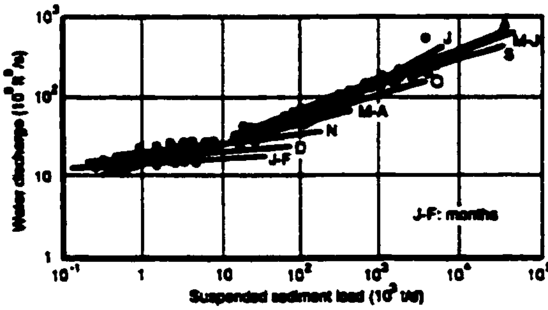

Figure 2-9. Sediment-rating Curve in Indus River (From Julien, 1995)

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Sediment inflow may be considered by measuring the suspended sediment at the upstream of the reservoir. Usually, these measurements represent the inflow discharge associated with sediment discharge expressed as a hydrograph (**Figure 2-8**). Presently, no convenient piece of equipment obtainable precisely for field measurement of bed load materials is in operation. Bed load may be estimated, and is usually in the 5% to 25 % range (Linsley and Franzini, 1979). Garcia [1995] suggested that it is normally between 10% and 25% of the measured suspended load.

The general relation between suspended-sediment transport Q_{si} and stream flow Q_{wi} may be expressed mathematically by a general equation (Linsley and Franzini, 1979) as follows:

$$Q_{si} = a[Q_{wi}]^b \qquad \textbf{2-11}$$

In which:

Q_{si} = Rate of sediment inflow into reservoir

Q_{wi} = Discharge of water inflow into reservoir

a = The intercept when Q_{wi} is unity

b = Varies between 2 and 3

The above equation can be used for predicting sediment discharge for specified estimated water inflow discharge entering reservoir. Parameters *a* and *b* would be evaluated by using recorded data of measured stream and sediment inflow.

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2.8.4 Deposition Pattern of Sedimentation

Pattern and quantity of sediment deposition are crucial issues when accumulated sediments fill the dead storage of the reservoir. Although the sediment goes into provided dead storage, it will impact long-term reservoir operation. Frenette and Julien [1996] gave an example of the deposition pattern of sedimentation in Peligre Reservoir. In this example, the deposition of sedimentation was dominated by clay (about 85%) in the downstream reservoir (just before the dam). The composition of the sediment deposition was 25% clay, 60 % silt, and 15% fine sand. An illustration of the pattern of sediment deposition is presented in **Figure 2-10**.

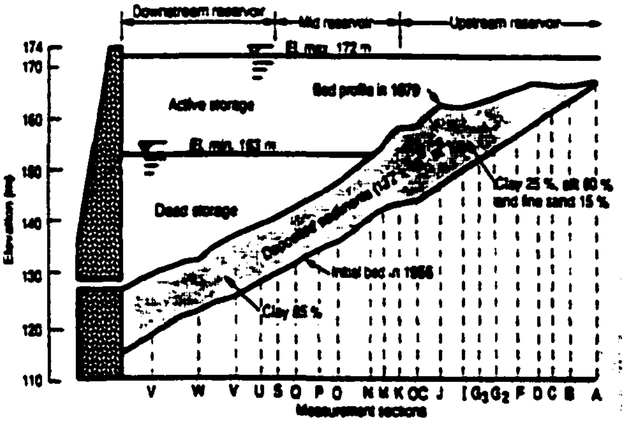

Figure 2-10. Deposition Pattern of Peligre Reservoir (from Frenette and Julien, 1996)

The longitudinal pattern of sediment deposition can be divided into four types as presented in **Figure 2-11**. Those are delta deposits, wedge-shape deposits, tapering deposits, and uniform deposits. <u>Delta deposits</u> hold the coarsest portion of materials of sediment load which are immediately deposited at the upper reach of the entrance zone. The materials may consist completely of coarse sediments that have diameters greater

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than 0.062 mm, or a large portion of finer sediments such as silt. Wedge-shape deposits are thickest at the dam and become thinner along the upstream reach. This pattern is characteristically produced by the movement or flowing motion of fine sediment reaching the dam by turbidity currents. Wedge-shaped deposits are established in small reservoirs associated with a large amount of fine sediment inflow. In addition, such deposits occur in large reservoirs when they are operated at low pool elevation especially during flood events. The operation causes the majority of sediment loads to be transported into the surrounding area of the dam. Tapering deposits occur when deposits turn out to be gradually thinner changing in the direction of the dam. This is a general pattern in long reservoirs typically held at a high pool elevation, and exhibits the gradual deposition of fine sediments from the water traveling in the direction of the dam. Uniform deposits are uncommon. Nevertheless, this pattern of deposits can be found in the field especially related to narrow reservoirs operated by applying numerous water level fluctuations with a small load of fine sediments. This situation may practically generate uniform depth of deposition (Morris and Fan, 1998).

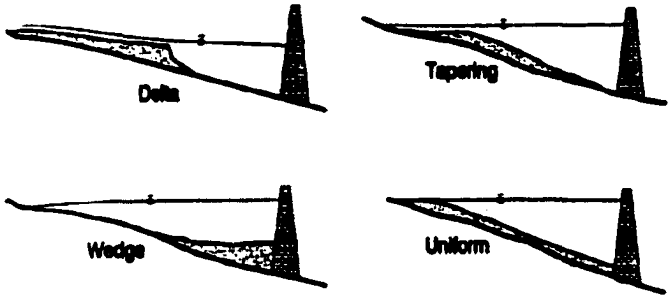

Figure 2-11. Typical Sediment Deposition Patterns in Longitudinal Scheme (from Morris and Fan, 1998)

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2.8.5 Selected Reservoir Sedimentation Problems in the Global Picture

The rivers that have some of the highest discharges have been identified by Walling [1984] as located in large islands of the Western Pacific Region such as Indonesia, Japan, Taiwan, the Philippines, and New Zealand. The main purpose of the reservoirs developed in those regions is mostly for hydropower generation. The characteristics of the region are volcanic soil, steep slopes, small rivers, and heavy rainfall (Chaturvedi, 1996).

In order to reduce sediment deposition in reservoir, hydraulic flushing techniques have been put into practice in Taiwan and were extremely effective for releasing sediment from the reservoir (Hwang and Lai, 1996).

Sanmenxia reservoir, is located in the lower part of the middle Yellow River, in China, had a problem in that its objective could not be attained. The reservoir had the function of storing and operating water during the non-flood period. The height of the dam was 106 m and it had been built for storing water and holding sediment. Total capacity of the storage was 52,300 MCM. The mean annual stream discharge and sediment inflow amounted to 42,800 MCM and 1.6 Billion tons, respectively. The impacts due to excessive erosion and sedimentation required renovation by extending the sluicing dimensions in order to acquire a balancing condition of erosion and sediment transportation passing through the outlet system of the dam (Chaturvedi, 1996).

In Yugoslavia, the Iron Gates or *Gjerdap* reservoir, built for navigation and hydropower, had a problem with sedimentation which impacted hydropower generation. Other impacts affected operation of drainage systems and utilization of groundwater resources in riparian zones. The characteristics of this reservoir were a drainage area of

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577,000 km^2, storage capacity of 3,500 MCM, inflow sediment of 325 million tons, and annual stream flow of 170,000 MCM (Chaturvedi, 1996).

The three Gorges Reservoir in China controls all the upper reaches of the Yangtze River, the largest river in China in terms of the discharge and drainage area, and the third largest in the world in terms of the sediment yield and discharge. This is an enormous hydraulic complex under construction which shows several prominent features (Han and He, 1996). The catchment area is one million km^2, the average annual discharge is about 390,000 MCM and annual suspended sediment load 500 Million tons (Cheng and Wang, 1996). This dam is 185 m high, 175 m for normal pool elevation, maximum storage capacity is around 36,800 MCM, and dead storage is around 14,800 MCM. This reservoir serves also for hydropower generation with an installed capacity of the turbine of 17,680 MW (Chaturvedi, 1996). Han and He (1996) characterize the impact of the erosion and sedimentation problem associated with Three Gorges Reservoir as follows:

a. Severe problem of decreased storage capacity.
b. Scouring and sedimentation due to fluctuating backwater region on the navigable channel.
c. Long term scouring and deformation of the river downstream of the dam.
d. Sediment problem at the dam region and entering the power generation facilities.
e. Impact of backwater increasing by sedimentation on inundation.

This extensive study provides a principle of sediment control and long-term operation of the reservoir with stable storage has been evolved.

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Reseires reservoir, in Sudan, is located in the upper reaches of the Blue Nile in which it is the dominant contributor of an average annual stream flow of 52,000 MCM. This reservoir has a capacity of 15.3 MCM and was built in order to serve irrigation. The annual runoff and estimated annual sediment can be estimated as 50,000 MCM and 133 million tones in 1959, respectively. The dam is operated in order to pass the annual flood volume and to sluice the accompanying sediment volume. However, this operation could not prevent sediment deposition above the power plants. The consequence of this problem was to shutdown of the power plant and a need for re-design for sediment removal (Pemberton, 1996).

2.9. Sediment Control Strategy

To control sediment entering reservoir in order to minimize deposition, three main strategies can be used. The strategies are as follows (Tomasi, 1996):

1. Decreasing the sediment entering into the reservoir
2. Precluding sediment deposition in the reservoir
3. Eliminating previously deposited sediment from the reservoir

The first category deals with conservation in the upstream watershed, construction of check dams or *sabo* dams, and construction of diversion channels. On the other hand, the second and third categories may be incorporated with reservoir operation procedure and a mechanical approach. These last two categories involve sluicing operations, venting of density current operations, flushing operations, and mechanical excavation. Excess water is needed for reservoir operation approaches (Tomasi, 1996).

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2.9.1 Upstream Control (Watershed Control Approach)

This can be implemented by minimizing sediment loads entering reservoirs. The efforts include non-structural approaches such as soil and water conservation, vegetation screens, and urban land controls, and structural approaches such as upstream trapping of sediment by building debris dams or check dams or *sabo* dams (Basson and Rooseboom, 1996). Soil conservation implementation largely reduces the erosion rate from the land surface and riverbank cuttings. By intensive measures, some reservoirs control a drainage of only 1 square mile or 2 square miles, and the sediment yield can be reduced by 95 percent. Other reservoirs control 100 square miles; the reduction in these cases can be as much as 80 percent. The different patterns or groupings of vegetation have a significant effect in protecting soil from direct rainfall impact, enhancing infiltration and decreasing surface runoff (Chen, 1978).

Reduced sedimentation loads can be accomplished by constructing engineering works such as check dams. A check dam is designed to handle traveling sediment moving downstream especially when entering into a reservoir. This structural approach has been introduced when the rate of erosion and sedimentation are predicted to put at risk the lifetime of the reservoir (Hadihardaja, 1994). The application of check dams and reforestation in a watershed is illustrated in **Figure 2-12**.

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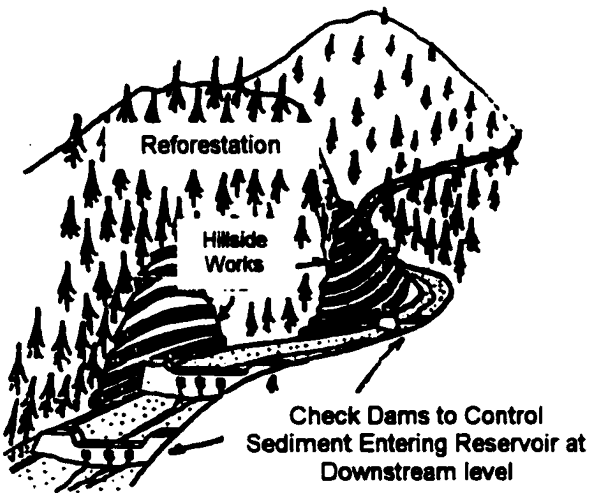

Figure 2-12. Illustration of Reforestation and Several Check Dams Implementation in Watershed to Control Moving Sediment Loads (adopted from Soekardi, 1994)

2.9.2 Reservoir Operation Regulation and Control

U.S. Army Corps of Engineers [1987] suggested that safety measures can appreciably minimize problems of erosion and sediment deposits in a reservoir through operation control as follows:

1. Reduce the rate of reservoir storage elevation draw down.
2. Prevent sudden releases and avoid fluctuations of downstream water level.
3. Maintain reservoir storage elevation as low as possible (during high sediment inflow) to move the sediment toward the dam face.
4. Regularly increase storage at a sufficiently high level to overflow existing deposited sediment.
5. Arrange regular releases through outlet system to prevent sediment deposition in the vicinity of the dam intake and the downstream channel.

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This approach can be established by reservoir operation in order to minimize deposition of sediment. In the following section, reservoir operation techniques for releasing sediment will be discussed. These techniques control sediment accumulation by applying sluicing, venting density current, and flushing operations.

2.9.2.1 Sluicing Operation

A sluicing operation is implemented by passing sediment-laden floodwaters through the downstream reservoir by means of drawing the water level down. This operation is a method of sediment control in order to prevent sediment from depositing in the reservoir. This technique is applied by releasing the sediment-laden flow through the dam before the particles of sediment may remain in the bottom of the reservoir. Sluicing is carried out by operating bottom outlets of the dam so as to increase flow velocities in the reservoir to maintain the particles of the sediment in suspension. This technique is used when there is large excess run-off and a large discharge capacity such as during the flood season. However, for the non-flood season, clear water is stored in the reservoir (Tomasi, 1996). According to Singh [1996], the sluicing operation is extremely effective and appropriate for narrow gorge-type reservoirs. This is classified as a hydraulic method for sediment removal. An operational series involving a sluicing operation is introduced by Morris and Fan [1998] based on flood draw-down by hydrograph prediction. The routing procedure is introduced for small reservoirs without removing them from reservoir service and is illustrated in **Figure 2-13**.

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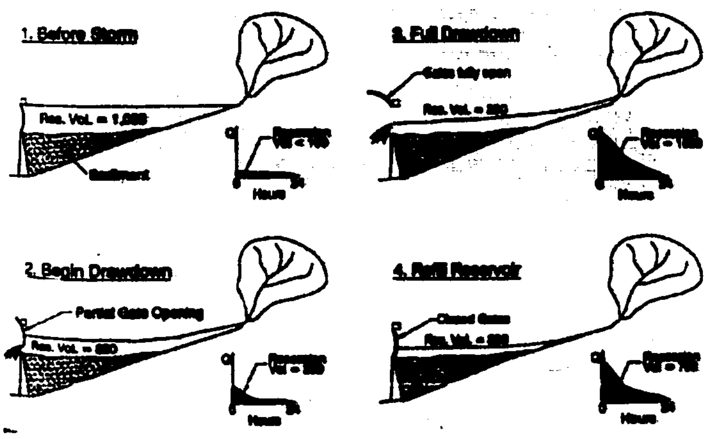

Figure 2-13. Operational Series of Passing Suspended Sediment for Small Reservoir (from Morris and Fan, 1998)

2.9.2.2 Venting Density Current Operation

Generally, floods bring intense sediment loads that are denser than clear water when inflowing to the reservoir. The sediment loads have a tendency to move downstream as submerged flow under the water surface to reach the face of the dam (Tomasi, 1996). Venting of density currents is carried out through bottom outlet operation when sediment-laden density currents develop (Fan, 1985). Operating bottom outlets may enable discharging the density currents to the downstream of the dam. In addition, venting of density current does not necessitate drawing the pool level down and may be implemented without impacting power generation or other beneficial uses (Basson and Rooseboom, 1996). An illustration of venting density current is presented in **Figure 2-14.**

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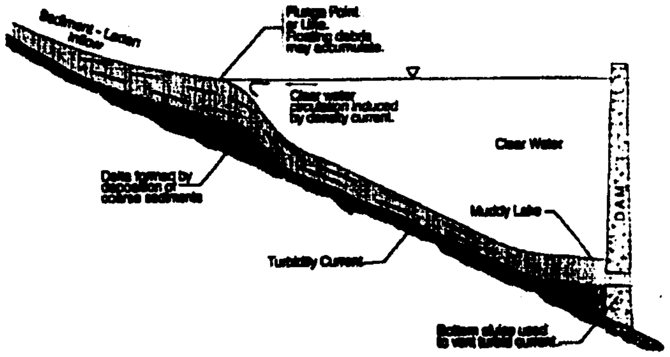

Figure 2-14. Illustration of Venting Turbidity Current at Low Level Outlet in Reservoir (from Morris and Fan, 1998)

2.9.2.3 Flushing Operation

A flushing operation is a method of sediment control intended to remove already deposited sediment from the reservoir. This technique is implemented by increasing flow velocities in the opening outlets, and, therefore, the velocities in the reservoir become higher and sufficient to transport the deposited sediment through the bottom outlets (Tomasi, 1996). Flushing technique may be carried out with or without pool elevation draw-down (Scheuerlein, 1993). Effective flushing may be applied when the reservoir is drawn down until the flow over the deposited sediment reaches free flow condition (White and Bettes, 1984). This is implemented in order to effect re-suspension of previously deposited sediment. Usually, during flood season, flood flushing is appropriate. This is a method used in order to regulate outflow through the outlet to release as much sediment as possible, to minimize sediment deposition and to restore storage capacity of the reservoir for long term beneficial uses. The objective of the flushing operation is to minimize the backwater effect and the hydraulic detention time and to minimize the rate of deposition under specific conditions as well. "The higher the

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backwater effect, the longer the hydraulic detention time, and the greater the deposition, then the higher the trap efficiency" (Fan and Fan, 1996).

Singh [1996] mentioned that flushing is normally used when additional methods such as sluicing and density current venting may not attain a balance between sediment deposition and erosion. In order to have more recovery of reservoir capacity, emptying of the reservoir in a flushing operation is initiated just before a flood. The floodwaters apply their most forceful erosive pressure to remove consolidated sediments. However, it is essential to consider that flushing operation may be constrained during high flood seasons due to the impact of considerable sediment deposition downstream of the dam. Moris and Fan [1998], Tomasi [1996], and Singh [1996] indicate that flushing operation would be very effective if the conditions are characterized such as:

1. Lower height on the sluice
2. Greater flushing discharge
3. Wider sluice
4. Deeper location of the sluice
5. Longer period of flood hydrograph
6. Steeper bed slope

The classification of flushing methods, according to Fan [1985], consists of:

1. Empty or free-flow flushing, by emptying the reservoir of the flushing outlet with river-rine flow through the impoundment (during flood season [more effective] or non-flood season).

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2. Pressure flushing, by requiring a lower draw-down operation (less effective and not common use).

The limitations of flushing, according to Morris and Fan [1998]:

1. It is necessary to draw down or empty the reservoir storage. Small reservoirs without carryover storage may be removed from service during the flushing period.
2. A considerably larger amount of concentrated sediment is released from the reservoir than in a natural fluvial system.

Morris and Fan [1998] indicate that the most effective flushing operation in order to preserve reservoir storage is achieved if the outlet systems are located in the vicinity of the original streambed and the reservoir is completely emptied. A flushing period during a non-seasonal flood gives the greatest amount of sediment release. Planning and implementation of flushing must normally to consider questions such as:

1. What volume of storage can be recovered
2. How much water will be released
3. What the downstream concentration will be
4. How large the bottom outlets should be
5. What the recommended schedule is

Operational series of pressure flushing with partial draw-down is illustrated in **Figure 2-15.**

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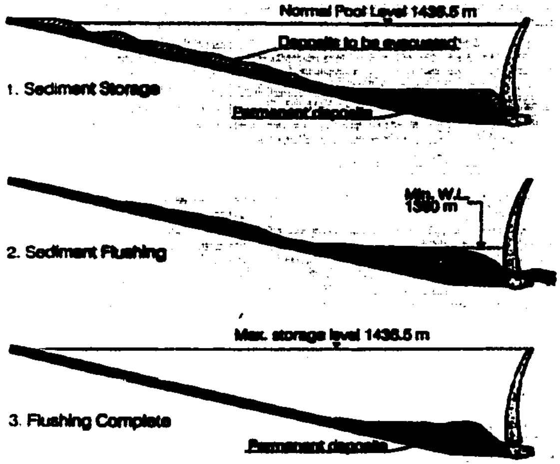

Figure 2-15. Operational Series of Pressure Flushing (after Ullmann, 1970)

2.9.3 Dredging by Mechanical and Hydraulic Approaches

The techniques of dredging applied for removing sediment deposits may use a mechanical excavation and hydro aspirator for hydraulic suction dredging and siphon dredging (Tomasi, 1996). The mechanical approach utilizes buckets to excavate and move up sediment with insignificant water entrapment to the surface. However, the hydraulic approach excavates sediment which is blended with a significant quantity of water and moved from the point of removal to the designated replacement such as sediment-water slurry (Morris and Fan, 1998). Basson [1996] indicates that the dredging approach should only be implemented as a last resort due to operation cost and problems with sediment disposal, and the fact that it does not deal with storage recovery. An illustration of hydraulic and mechanical approaches for dredging sediment is shown in **Figure 2-16 and Figure 2-17.**

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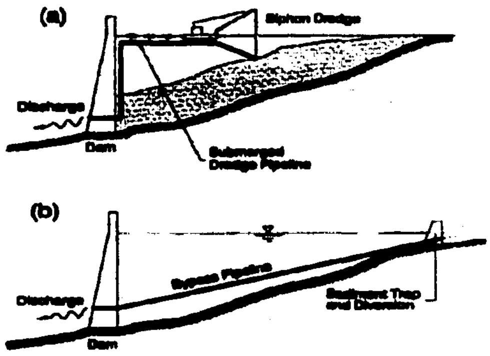

Figure 2-16. (a) Mobile Siphon Dredge and (b) Fixed Sediment Bypass Pipeline (From Morris and Fan, 1998)

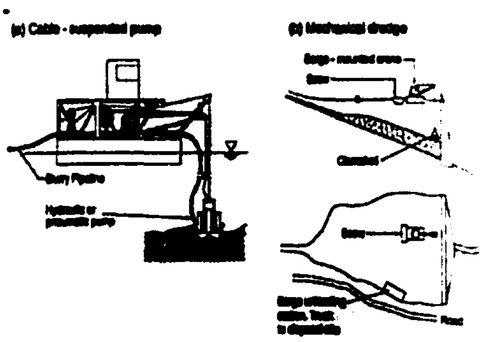

Figure 2-17. (a) Cable Suspended Dredge Pump and (b) Clamshell Mechanical Dredge (From Morris and Fan, 1998)

2.9.4 Planning and Implementation

In general, the approach to minimizing the sediment loads entering reservoir associated with hydraulic methods is difficult to implement. It is necessary to establish strong social and political institutions to enable long-term successes to be achieved (Wolman et al, 1989). When reservoirs are in series, it is necessary for sediment control associated with sluicing, venting of density currents, and flushing operation to be managed mutually.

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Sluicing operation has been implemented successfully for reservoir sedimentation control in the Old Aswan Dam on the river Nile in Egypt and the Roseires Dam on the Blue Nile River in Sudan (Mahmood, 1987).

For venting of density currents, Xiuzhen [1990] suggests the installation of a sampling pipe in the dam to monitor the sediment concentration. This sediment monitoring would be helpful for making the best decision associated with opening of the outlets. Fan [1985] notes that the efficiency with which this technique may be implemented depends on:

1. Capacity and elevation of the outlets system
2. Water level and discharge during the venting operation
3. Timing between opening and closing the bottom outlets

The technique of flushing has been used in sediment management at three of the Rioni hydropower reservoirs in Soviet Georgia. The initial flushing should be in a downstream reservoir in order to scour out a main channel to transport the sediments through the impoundment. If initiation of flushing were from an upstream reservoir, that would spread the release sediment out and cause it to settle on the flood plain deposits in the downstream reservoirs (Kereselidze et al., 1985).

The efficiency of the flushing operation is based on several factors as follows (Delft Hydraulics, 1992):

1. The reservoir's topographic appearance.
2. The gradation and quantity of the initial deposited sediment in the reservoir.
3. The incoming stream flow characteristics.

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4. The reservoir dimension and shape.
5. The outlets capacity and placement.
6. The rate of recurrence and time of pool level drawing down.
7. The flushing period and frequency.
8. The time preference for emptying reservoir.

2.9.5 Erosion of Sediment Deposition Released from Reservoir

Retrogressive erosion is the primary method for the establishment of flushing channels due to sediment deposition in reservoir. The retrogressive erosion is caused by the alteration in hydraulic energy which results from the discontinuous longitudinal profile. This erosion process does not depend on any specified grain size distribution in the accumulated sediment, even though the patterns of the erosion are affected by the characteristics of the sediment deposition. This type of erosion can occur in fine grained and cohesive sediments. However, it may occur in non-cohesive or unconsolidated cohesive sediment deposition, for which the pattern of the erosion process is presented in **Figure 2-18** and **Figure 2-20**. For non-cohesive and unconsolidated material, the erosion pattern is indicated by the face of the eroded area which tends to be close to vertical as in **Figure 2-19** (Morris and Fan, 1998). Retrogressive erosion can occur in coarse sediments on a river delta as well (Randle and Lyons, 1995). **Figure 2-18** and **Figure 2-19** present the laboratory observation. However, **Figure 2-20** presents an observation in the field, a flushing operation of Sanmenxia Reservoir.

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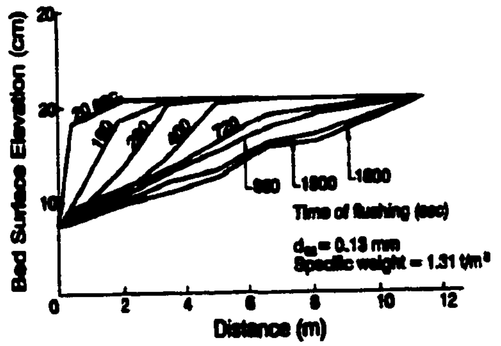

Figure 2-18. Longitudinal Profile in Unconsolidated Sediments during Retrogressive Erosion in Laboratory Experiments (from Morris and Fan, 1998)

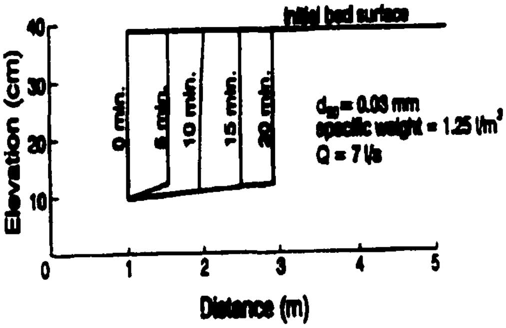

Figure 2-19. Longitudinal Profile in Consolidated Sediments during Retrogressive Erosion in Laboratory Experiments (from Morris and Fan, 1998)

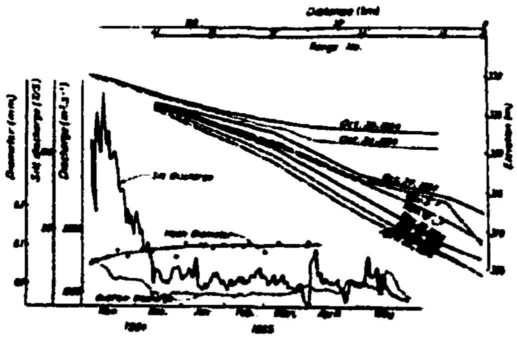

Figure 2-20. Series of Reservoir Water-Level Profiles based on Retrogressive Erosion during Flushing in Sanmenxia Reservoir (Fan, 1985, from Morris and Fan, 1998)

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2.10. Relations and Efficiency of Releasing Sediment from Reservoir

Efficiency in releasing sediment from the reservoir is very important as an indicator of how much sediment can be washed away from the reservoir. However, limitation of the sediment amount to be washed out should be carefully considered appropriately due to downstream aggradation and degradation problems. Morris and Fan [1998] indicate that release efficiency may be higher or less than 100%. This is related to the incoming sediment into the reservoir and the scouring of previously deposited sediment in the reservoir during sluicing or flushing, for example.

2.10.1 Relations between Expended Water and Sediment Outflow

Chongshan [1996] developed an experimental study to measure the relation between quantities of scoured sediment and expended water. "The larger the differences between floodplain and main channel, the higher the flow potential and sediment carrying capacity." In addition, "the longer the exposed time, the more serious the consolidation of deposition, the higher the cohesive force between sediment particles, and the more difficult the sediment scouring."

Relation between expended water and sediment outflow has been studied in China during flushing operations in several reservoirs. There are many equations developed for sediment release associated with the expended water within semi-empirical formula. Several of these equations are discussed in the following section.

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2.10.1.1 Relation of Sediment Rate as Function of Bed Slope and Expended Water Discharge

Fan and Jiang, [1980] developed an empirical equation for Sanmenxia Reservoir during its erosion between 1963 and 1964. The field data during flushing operation includes fine sand sediment material with the diameter between 0.06-0.09 mm. The equation used in the study can be presented as follows:

$$Q_{so} = \left(3.5x10^{-3}\right)Q_{wo}^{1.2}\left(S_{ws}x10^{4}\right)^{1.8} \qquad \textbf{2-12}$$

In which:

Q_{so} = Sediment outflow rate (t/s)

Q_{wo} = Water outflow discharge (m^3/s)

S_{ws} = Water surface slope

2.10.1.2 Relation of Sediment Rate as Function of Bed Slope, Expended Water Discharge, Channel Width, and Soil Erodibility

Other empirical relations to describe the rate of sediment release have also been developed. One equation is based on field data during periods of empty flushing and retrogressive erosion in Chinese reservoirs including Sanmenxia Reservoir (Xia, 1983) as follows:

$$Q_{so} = \frac{E_r Q_{wo}^{1.6} S_{bs}^{1.2}}{B^{0.6}} \qquad \textbf{2-13}$$

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In which:

Q_{so} = Sediment outflow rate (0.0006 t/s – 777 t/s)

E_r = Erodibility coefficient

Q_{wo} = Water outflow discharge (0.1 m^3/s – 5730 m^3/s)

S_{bs} = Bed slope (0.00006 – 0.016)

B = Width of the channel (m)

The value of the erodibility coefficient (E) is presented in **Table 2-2**. In addition, for many reservoirs in China, the sediment release rate during retrogressive erosion is presented in **Figure 2-21**. Curve III was extended by Lai and Shen (1996) based on laboratory flume experiments. Altunin [1964] developed the relationship of the stream channel parameters of water discharge in the stream (Q_s, in m^3/s) and bed slope (S_{bs}) in order to estimate the value of width of the channel (B), as follows:

$$B = \frac{1.5 Q_s^{0.5}}{S_{bs}^{0.2}} \qquad \text{2-14}$$

Table 2-2. Value of Erodibility Coefficient (Morris and Fan, 1998)

No.	Sediment	E-Value
1	D_{50} < 0.1 mm	650
2	D_{50} > 0.1 mm	300
3	Consolidated Clay	180

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The higher the erodibility coefficient established, the easier the sediment material is removed from the deposition. A high value of the erodibility coefficient is related to easily eroded sediment material. On the other hand, a low value of the erodibility coefficient indicates typical sediment such as coarse or consolidated material.

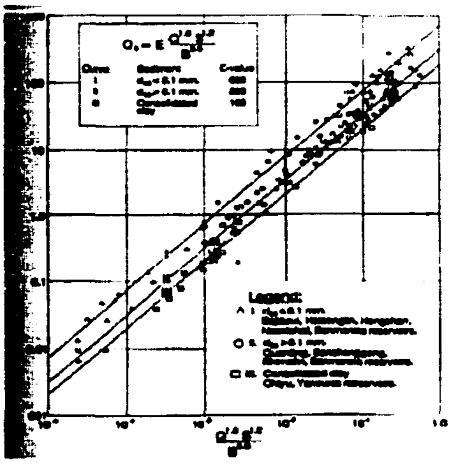

Figure 2-21. Sediment Release Rate during Retrogressive Erosion in Several Reservoirs in China (Xia, 1983, adopted from Morris and Fan, 1998)

2.10.1.3 Relation of Sediment Rate as Function of Bed Slope, Expended Water Discharge, Water Density, and Water Inflow Discharge

The developed equation for computation of sediment discharge from reservoir has been given as (Guozhen, Zhengben and Guoshi, 1987):

$$Q_{so} = \frac{5.24\rho_{wi}^{\ 0.868} Q_{wo}^{\ 2} S_{bs}}{Q_{wi}^{\ 0.868}} \quad \text{2-15}$$

In which:

Q_{so} = Sediment outflow rate (t/s)

ρ_{wi} = Water inflow density (kg/m^3)

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Q_{wo} = Water outflow discharge (m^3/s)

S_{bs} = Bed slope

Q_{wi} = Water inflow discharge (m^3/s)

2.10.1.4 Relation of Sediment Rate as Function of Bed Slope, Expended Water Discharge, Elevation Depth, and Median Diameter of Bed Sediment Material

The empirical formula developed for functions such as elevation height and median diameter of bed sediment load can be presented for Samenxia Reservoir as (Xia and Zhang, 1980):

$$Q_{so} = k\left(\gamma_{mix} Q_{wo} J_{bs}^{1.5}\left\{\frac{H}{D_{50}}\right\}^{0.5}\right)^{1.3} \qquad 2\text{-}16$$

In which:

Q_{so} = Sediment outflow rate (t/s)

k = Constant of 1.6×10^{-6}

γ_{mix} = Mixed water and sediment specific weight (t/m^3)

Q_{wo} = Water outflow discharge (m^3/s)

S_{bs} = Bed slope

H = Head of reservoir elevation (m)

D_{50} = Median diameter of bed load sediment (mm)

J_{bs} = $S_{bs} \times 10^4$

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2.10.1.5 Relation of Sediment Rate as Functions of Bed Slope, Expended Water Discharge, Water Inflow Discharge, and Sediment Concentration

The empirical formula developed as function such as concentration of sediment inflow and stream inflow discharge can be presented for Sanmenxia Reservoir as (Xia and Zhang, 1980):

$$Q_{so} = eQ_{wo}^{2}S_{bs}^{2}\left(\left\{\frac{C_{si}}{Q_{wi}}\right\}+f\right)^{1.75} \quad \text{2-17}$$

In which:

Q_{so} = Sediment outflow rate (t/s)

e = Coefficient of 1.06×10^5

f = Constant of 0.02

Q_{wo} = Water outflow discharge (m^3/s)

S_{bs} = Bed slope

C_{si} = Sediment inflow concentration (kg/m^3)

Q_{wi} = Water inflow discharge (m^3/s)

2.10.2 Trap Efficiency

The closer the river reaches to a reservoir entrance, the more the flow depth increases, and the lower the velocity and the friction slope. The water surface profile under this condition is typically presented as a gradually varied flow (GVF) profile described as a backwater curve in which the flow is sub-critical. The decreasing velocity along the reservoir does encourage a large amount of sediments and most bed load is deposited as delta. If this material cannot be removed, then it will be trapped in the

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reservoir for the life of the reservoir. If the total sediment load trapped in the reservoir cannot be removed, then the trap efficiency is said to be 100% (Julien, 1995).

2.10.3 Release Efficiency

The sediment release efficiency of a reservoir is the mass ratio of the total sediment released from the reservoir to the total amount of sediment inflow over time duration. In other words, sediment release efficiency can be defined as the ratio of sediment release to sediment inflow. The value of release efficiency may vary extensively during draw-down routing (Morris and Fan, 1998). Therefore, release efficiency can be expressed as follows:

$$Release\ Efficiency = 1 - Trap\ Efficiency \qquad \textbf{2-18}$$

2.11. Statistic Indicators and Visual Graphic Fitness Plot

The Statistic indicators used in the study are related to Coefficient of Correlation (C_V) and Discrepancy Ratio (R_D). The statistic indicators are applied to evaluate the relation between the stream flow discharges associated with the sediment rate based on the measured data. In order to approximate the relationship and to reach an ideal condition for computation model and measurement model, a visual graphic fitness plot is developed to enhance the relation.

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2.11.1 Coefficient of Correlation (C_C)

Comparisons between the measured data in the field and computation using the C_C have been done, such as in Kodoatie [2000], and Hydrau-Tech, Inc. [1998]. If the computation and measured data are equal, or in other words, close to the ideal condition, then, the value of C_C would be equal to 1. The C_C is presented as follows:

$$C_c = \frac{\sum_{n=1}^{N}(X_n - X_{ave})(Y_n - Y_{ave})}{\sqrt{\sum_{n=1}^{N}(X_n - X_{ave})^2 \sum_{n=1}^{N}(Y_n - Y_{ave})^2}} \qquad 2\text{-}19$$

in which:

X_n = Computed sedimentation

Y_n = Measured sedimentation

X_{ave} = Average of computed sedimentation

Y_{ave} = Average of measured sedimentation

n = Data set or point number = 1, 2, 3, ..., N

N = Total number of data sets

2.11.2 Discrepancy Ratio (R_D)

The statistic indicator known as the Discrepancy Ratio (R_D) is also used to compare the measured data in the field and the computation method. The method has also been used such studies such as Kodoatie [2000], Wu [1999], and Hydrau-Tech, Inc. [1998]. The $R_{D(AVE)}$ and R_D would have a value of 1 (one) if the measured data and

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computation model are equal or in an ideal condition. The $R_{D(AVE)}$ and R_D are presented, respectively, as follows:

$$R_{D(AVE)} = \frac{1}{N}\sum_{n=1}^{N} R_{Dn} \qquad \text{2-20}$$

$$R_{Dn} = \frac{X_n}{Y_n} \qquad \text{2-21}$$

in which:

$R_{D(AVE)}$ = Average of Discrepancy Ratio

R_D = Discrepancy Ratio

X_n = Computed sedimentation

Y_n = Measured sedimentation

n = Data set or point number = 1, 2, 3, ..., N

N = Total number of data sets

2.11.3 Visual Graphic Fitness Plot

Associated with the other two statistic indicators, the visual graphical fitness plot can also be used to see how far the measured data and computation model approximate the ideal condition which has slope equal to 1. Kodoatie [2000] used this plot to support the model of fitness plot of measured sediment in an alluvial river.

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2.12. Environmental Impact of Reservoir Sedimentation and Releasing the Sediment

Building a dam produces a reservoir to guide entrapment of the incoming sediment load. Since the construction alters a water body from free flow along the stream, the sediment materials are seized in the reservoir. Consequently, there is less supply of sediment load in the downstream region. This condition will produce degradation of the river streambed. However, in reservoir storage, incessant reservoir sedimentation that causes recycling of nutrients, gradual reduction in depth, expansion of the hypolimnion zone, and subsequent reduction of the epilimnion zone, results in a decrease of the overall water quality in terms of dissolved oxygen (DO) levels. In addition, sediment loads bring pollutants and nutrients that can cause serious water quality problems especially for fisheries and recreation (Singh, 1996). The thermal stratification zone of a reservoir shown in **Figure 2-22.**

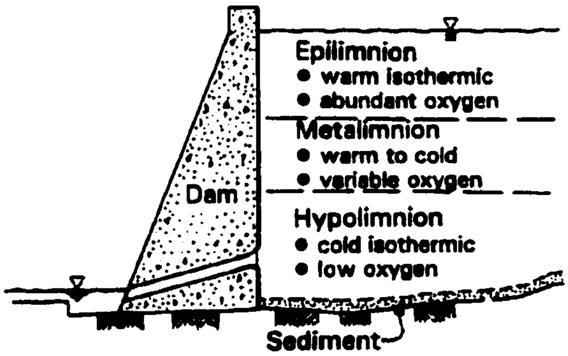

Figure 2-22. Thermal Stratification Zone of Typical Reservoir (from Wurbs, 1996)

Deposited sediments profoundly influence DO concentration in a reservoir. Sediment oxygen demand is produced by biological respiration of living organisms in the

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sediment and by oxidation of reduced substances in the sediment, such as divalent iron, manganese, and sulfides (Wang, 1979). During periods of thermal stratification, sediment oxygen demand significantly influences the quality of water in the hypolimnion zone. The zone enlarges along with augmented SOD concentrations, decreasing the space availability for fish. The increased eutrophication and algal bloom growth further as add to SOD as dead algae progressively sink into the reservoir bottom (Singh, 1996). The statement of Bruk [1985] regarding the releasing of sediment downstream of the dam is cited below:

> "The release of turbulent, sediment-free flows which have an unsatisfied potential for carrying sediment encourages entrainment of suitably sized particles from the riverbed if they are available. Since most readily eroded particles are from the riverbed first, it becomes depleted in fine particles but relatively enriched in coarse material. The resultant stable bed is coarser and has become armored."

2.13. Summary

The optimization techniques have been summarized in this section with regard to the selection of a method that can be applied appropriately to develop the model. In addition, the optimization technique that is used for the model has been selected. The impacts due to dam construction and reservoir operation along with sediment control have been summarized with important features related to the advantages for design work. For the modeling approach, the equation and formula used for the model have been established, including the application of an empirical equation between sediment rate and expended water.

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2.13.1 Concluding Remarks of Optimization Techniques

The general analyses of mathematical modeling are summarized in **Table 2.3.** The analyses include the size of the formulation which can be applied for solving problems, the accuracy of the result which can be achieved with each technique, complexity in developing the model, and solver availability to build, run, and solve the optimization algorithm.

Table 2-3. General Analysis of Optimization Technique (from Lobbrecht, 1997)

Optimization Technique	Solvable Problem Size	Model Accuracy	Model Complexity	Solver Availability	Global Optimum	Solution Speed
Linear Programming	Large	Low to Moderate	Moderate	Yes	Yes	Fast
Successive Linear Programming	Large	Moderate to High	Moderate	Yes	Yes for each Iteration	Moderate to fast
Dynamic Programming	Very Small	High	High to Very High	No	If functions are convex	Very Slow
Non Linear Programming	Moderate	High	High to Very high	Yes	If functions are convex	Slow

2.13.2 Selected Optimization Technique

NLP is an optimization technique that can be used for modeling an operating reservoir system. Although in most cases, the application of LP or DP for solving such problems is usual used, it is important to consider that NLP is more precisely defined and make it easier to build the model for non-linearity when the solver package is available. This advantage could make it easier for a reservoir operator to understand how to

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implement the programming after being trained. In addition, the strict non-linear form of NLP may not be a notable obstacle.

Software development of a solver package associated with NLP is incredibly advantageous if it is possible to develop a simple user interface and easy operation for the reservoir operator. NLP built into the spreadsheet software package incorporated with a solver provides remarkable advantages. The graphic user interface, storing database and management, and simple user interface operation would be very useful in developing interactive DSS. Although NLP techniques have been applied relatively little, compared to LP and DP, to problems of optimizing reservoir operations, the considerable enhancement in computer technology in current years has reduced computational hindrances, which could result in greater utilization of NLP techniques in the near future (Wurbs, 1996). However, in this study the use of an NLP package is a challenge due to the strict non-linear function in the reservoir sediment-control operation model formulation.

The general NLP formulation based on the mathematical objective function associated with the constraints can be non-linear and written as follows (Stark and Nicholls, 1972):

Objective Function:

$$\text{Max or Min}: z = f(x_1, x_2, x_3, \ldots, x_n) \qquad \textbf{2-22}$$

Constraint Functions:

$$g_i(x_1, x_2, x_3, \ldots, x_n) \leq 0 \qquad \textbf{2-23}$$

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or,

$$g_i(x_1, x_2, x_3, ..., x_n) \geq 0 \quad \textbf{2-24}$$

$$x_j \geq 0 \quad \textbf{2-25}$$

For i = 1, ..., m and j = 1, ..., n.

2.13.3 Reservoir Sedimentation Impact

Erosion and sedimentation play an important role related to the life expectancy of the reservoir itself, and have other impacts due to the behavior of the sediment inflow traveling along the reservoir and flushing out from the reservoir to the downstream of the dam. Based on experience of the selected impact of the erosion and sedimentation in the reservoir, it is necessary to balance the inflow and outflow of the sediment into and from reservoirs with a stable storage operation. Excess discharge of sluicing, venting of density currents and flushing of sediment operations from reservoirs need to be carefully done due to the downstream deformation and environmental impacts. Since the construction of the dam for the reservoir is changing the behavior of a natural stream flow and sediment transport, in order to achieve the best outcome, it is necessary to operate the reservoir based on the state of equilibrium of the natural flow as much as possible.

Sedimentation may also influence system yield by reducing conservation pool volume, requiring that reservoir operation be altered due to sediment management, and controlling sediment from the watershed that affects water yield (Morris and Fan, 1998). In view of the seriousness of this second sediment impact, this research offers a valuable response, enabling management or control of sediment by adjusting the reservoir

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operation incorporated and minimizing deposition. The consequences of dam construction are presented in **Table 2-4**.

Table 2-4. Sediment-Related Consequences (adopted Hotckiss and Bollman, 1996)

No.	Primary Impact	Secondary Impact	Tertiary Impact
1	Upstream Deposition	- Tributary aggradation - Increased groundwater level - Decreased navigational clearance - Increased flood frequency - Deposition at diversions - Altered geomorphology - Uncontrolled wetland creation	- Increased Soil moisture in root zone - Flooded homes
2	Downstream Scour	- Armoring of bed band instability - Tributary degradations - Undercut diversions - Increased bridge scour - Lower groundwater levels - Decreased turbidity - Geomorphic changes	- Changes in habitat - Loss of riparian vegetation - Agricultural impacts - Aquatic habitat changes
3	Reservoir Deposition	- Reduction in all benefits - Reduced useful life - Degraded water quality	- Decreased dissolved oxygen - Interstitial deposition - Contaminant concentration

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2.13.4 Approach of Sediment Control Techniques Associated with Reservoir Operation

According to Morris and Fan [1998], modeling techniques for flushing processes are not well developed and the behavior of flushing coarse sediments in reservoirs has received little attention. Therefore, it is necessary to undertake considerable research in this field.

In this research, sluicing, venting of density currents, and flushing techniques are considered in connection with reservoir operation. The operation model will optimize on the basis of minimizing sediment deposition (maximizing release of sediment) and maximizing beneficial uses especially for hydropower generation.

The advantages and disadvantages of these operations may be summarized as in **Table 2-5** based on the review and study from Tomasi [1996], Fan and Morris [1993], and Delft Hydraulic [1992].

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Table 2-5. The Advantages and Disadvantages of Sediment Control incorporated with Reservoir Operation (adopted from Tomasi [1996], Fan and Morris [1993], and Delft Hydraulic [1992]).

No.	Operation System	Advantages	Disadvantages
1	Sluicing	- Considerably reducing sediment deposits - Fine sediment deposition possible reduced - More effective for higher outlet elevation	- Possible sedimentation at downstream - Requires excess water
2	Venting of Density Currents	- Reduces sediment deposition	- Difficult in operation - Requires excess water - Requires very low bottom outlets
3	Flushing	- New sediment deposition is limited when combined with sluicing - Lower cost compared to dredging	- Increasing sediment loads at downstream - Requires excess water - Requires very low bottom outlets - Sudden release increases downstream aggradation - Sediment with high concentration may affect the downstream - High concentration of sediment-laden increase the abrasion of outlet structures

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CHAPTER III

CASE STUDY OF SEDIMENT CONTROL WITH RESERVOIR OPERATION

3.1. General Description

The case study for the research is associated with the single reservoir of Sanmenxia. It is located on the lower part of the middle reach of the Yellow River, Republic of China. A map of Sanmenxia Dam site with the tributary system is presented in **Figure 3-1**. Sanmenxia Reservoir is a multipurpose reservoir and serves especially for flood control. The reservoir controls a drainage area of 684,000 km^2, which is 92% of the whole Yellow River catchment area. The mean annual runoff is about 42,300 MCM, and the maximum peak discharge was verified in Sanmenxia was 22,000 m^3/s and 36,000 m^3/s in 1933 and 1843, respectively (Yuqian and Qishun, 1987).

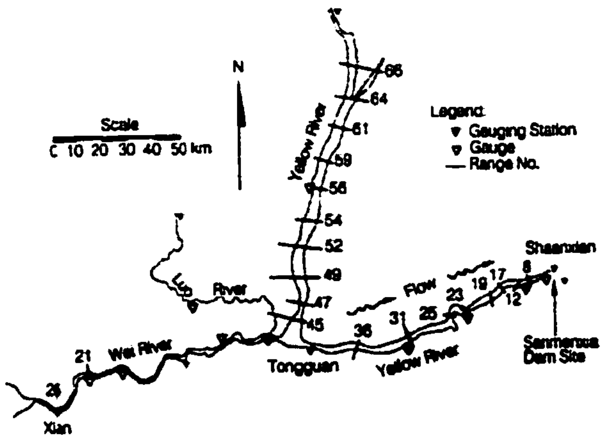

Figure 3-1. Map of Sanmenxia Reservoir (from Morris and Fan, 1998)

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The Yellow River is a typical river basin within a vast loess plateau with an area of 580,000 km^2, of which 430,000 m^2 experiences crucial soil erosion. The median diameter of the suspended sediment is around 0.03 mm. The maximum sediment concentration identified was 911 kg/m^3 in September of 1977 (Wu, 1997). The annual mean sediment load at Sanmenxia amounts to 1600 million tons to be handled, 86% of which comes during the flood season from July to October. Therefore, among the reservoirs in China, Sanmenxia is the most typical reservoir with serious sedimentation (Zhenhuan and Qishun, 1980).

The construction of the dam was initiated in 1957 and the major structures completed in September 1960. The main structure consists of a gravity dam, outlet structures and a power plant. The gravity dam is a concrete dam the height of which is 96 m and length 908 m. The outlet structures consist of 12 deep sluices at an elevation of 300 m and two spillways at an elevation of 338 m. The original design called for a normal high water level at elevation 360 m, a total storage capacity of 64,700 MCM, and installed capacity of 1,160 MW for the hydropower plant. The project evacuated 870,000 people and the reservoir inundated an area of 3,500 km^2 (Yuqian and Qishun, 1987).

After being put into operation, the reservoir became severely silted and the backwater deposits extended rapidly towards the upper stream. Due to the sedimentation problem and in order to develop more benefits, the decision was made to reconstruct the outlet structures to increase the capacity for sluicing sediment and releasing flood water (Yuqian and Qishun, 1987).

The variation of temperature, evaporation and precipitation is presented in **Figure 3-2** and **Figure 3-3**, adopted from studies on the Yellow River Project in June 1947.

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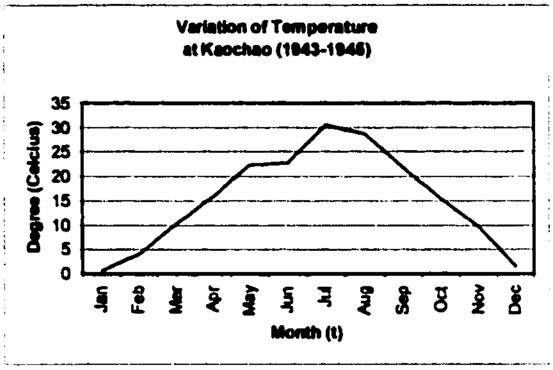

Figure 3-2. Variation of Temperature (sources: Shenyi eds., 1947)

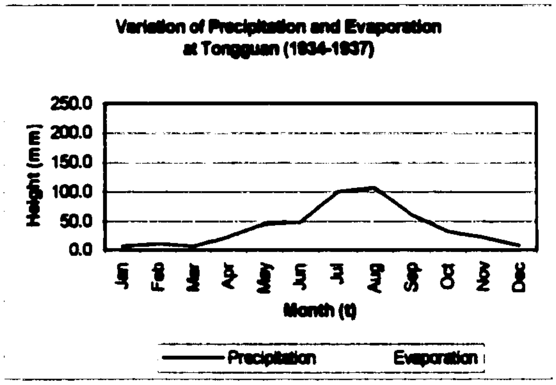

Figure 3-3. Variation of Precipitation and Evaporation (sources: Shenyi eds., 1947)

The typical monthly stream and sediment inflow discharge is shown in the **Figure 3-4** below.

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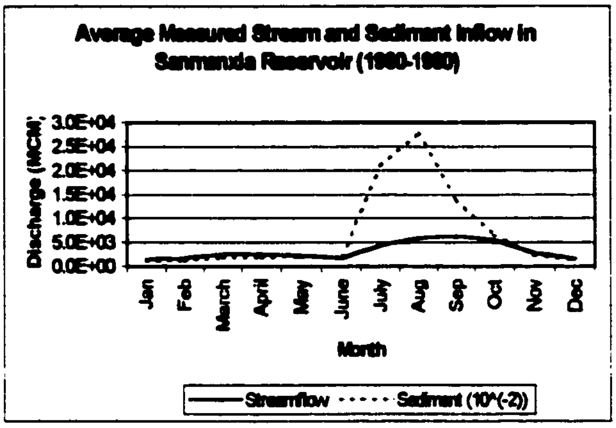

Figure 3-4. Typical Relationship of Sediment Discharge and Inflow Discharge (data provided by Wu, 2000)

3.2. Reconstruction of the Sanmenxia Reservoir

The reconstruction of the reservoir was carried out in two stages. In the first stage, two tunnels were built in order to increase capacity for sluicing sediment and releasing flood. The discharge capacity of the outlet was increased from 3,080 m^3/s to 6,100 m^3/s at stage level of 315 m. This stage was completed in August 1968. The second stage was established by reopening the previous 8 bottom outlets of the diversion channel for sluicing sediment and lowering intake elevation of penstocks for generating power from 300 to 187 m. The installed capacity of the five turbines was 250 MW. The second stage was commenced in December 1969, and the eight bottom outlets were opened one after another until October 1971. The power generation was started for the first time at the end of 1973, and the rest of the turbines were put into operation by the end of 1978. After reconstruction, the total releasing capacity of all the outlets increased to 10,000 m^3/s. The mode of operation was changed from "storing water and retaining sediment" to "storing clear water and releasing the muddy" (Publication Center Yellow

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River Conservancy Commission, 1991). **Figure 3-5** and **Figure 3-6** represents the general plan after reconstruction.

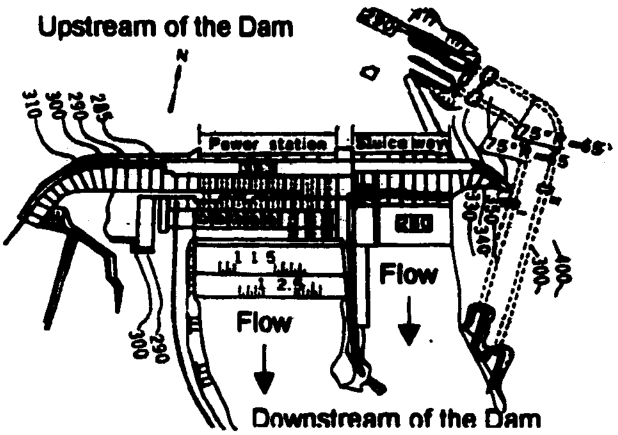

Figure 3-5. Plan View of the Samenxia Dam (from Yuqian and Qishun, 1987)

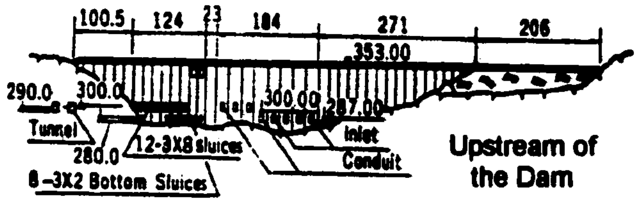

Figure 3-6. The Sanmenxia Dam after Reconstruction (from Yuqian and Qishun, 1987)

3.3. Regulation of Sediment in the Reservoir

Sedimentation in a reservoir depends on the conditions of the incoming water and sediment, the discharge capacity, the operational mode, and the topography of the reservoir. Sanmenxia Reservoir has adopted three different modes of operation (Wu, 1997). Different periods of operating the reservoir by storing clear water and discharging

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muddy water can be divided into different periods of operation through pondage in non-flood described in the section below (Guozhen et al., 1987).

During the flood season, the operating level of the reservoir is controlled at 300 – 305 m, depending on the requirements for flood protection and sluicing of sediment, and also power generation with run-of-the river flows. If necessary, the level may be lowered further below 300 m and, in doing so, the datum behind the dam is lowered in order to be able to (Guozhen et al., 1987):

1. Regulate the slope of water surface.
2. Maintain an adequate discharge capacity compatible with the need for regulation of oncoming stream flow and sediment during floods.
3. Give full play to the role of scouring the sediment lodged in the non-flood season.
4. Restore usable capacity of the reservoir.
5. Gain benefits from flood protection, ice flood protection, irrigation and power generation.

A schematic diagram of typical reservoir operation at Sanmenxia Reservoir is presented in **Figure 3-7**.

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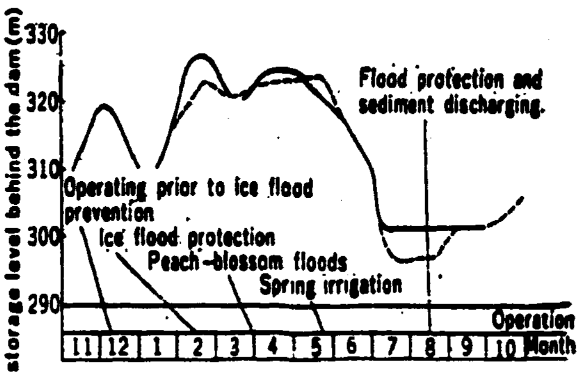

Figure 3-7. Schematic Diagram of Sanmenxia Reservoir Operation (From Guozhen *et all.*, 1987)

The typical operation based on **Figure 3-7** is described in the following section.

3.3.1 Storing Water Prior to Ice-Run

This is effected in November through December with storage level at 317-321 m, the corresponding storage being 700 – 800 MCM. The water stored is used to increase discharge immediately before the freeze-up stage during the formation of ice cover, thus increasing the conveyance capacity under the ice cover.

3.3.2 Storing Water During Ice-Run

This is generally done from mid-January to the end of February or early in March, the maximum storage level reaching 326 m for ice-run prevention. When the outflow is limited to 200 – 250 m^3/s to ensure security against ice flood on the lower course. Subsequent to ice flood, the storage level is lowered to 320 m to prepare for

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impoundment of spring floods, called "peach-blossom" floods, and to make use of them to effect scouring at Tongguan.

3.3.3 Impoundment of Peach-blossom Floods and Spring Irrigation

Peach-blossom floods usually take place in the period from the end of March to the beginning of April. Peaks of discharge usually produce around 2,000 – 3,500 m^3/s and result in reservoir impoundment involving a total of 1,400 - 1,800 MCM of water. Subsequent levels will be sustainedly kept at 323 – 324 m, until spring irrigation in May necessitates replenishment of water downstream at the expense of the storage in the reservoir. In mid or late June, the reservoir is almost emptied before the flood season.

3.4. Summary

The reconstruction of Sanmenxia Reservoir and the change of operation mode were made in order to utilize a valuable experience for solving sediment problems of large-sized reservoirs built on sediment-laden rivers. As indicated by Wu [1997], it is necessary to regulate the water and the sediment through reservoir operation to retain a certain amount of usable capacity for long-term use. The deposition is closely related to the inflow conditions, including both the water and sediment inflows. The regulation of sediment in a reservoir requires adequate outlet discharge capacity at different elevations. In addition, the capacity should be built at least the same as the bankfull discharge of the natural river course.

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CHAPTER IV
MODEL FOR RESERVOIR SEDIMENT-CONTROL OPERATION

4.1. Introduction

The developed model introduces the adjustment and modification concept of reservoir operation for sediment control purposes. The modeling concept will be discussed with schematic diagrams to illustrate the whole concept for developing the optimal decision policy. In the following section, development of the mass balance equation will be discussed and each component or variable associated with the mass balance equation will be identified completely in detail. The components mainly include incoming sediment model development with statistic indicator examination, net evaporation application, and previous sediment outflow model.

4.2. Modeling Concept and Design

The development of the model conceptually involves adjusting the mass balance equation by adding a sediment inflow model and sediment outflow model to the ordinary reservoir operation model. Hydrological and characteristic data of the reservoir associated with the sediment models are introduced to develop the mass balance equation. Constraints limit the model of reservoir operation to produce the optimal decision rule. The design concept of the model is introduced in **Figure 4-1**.

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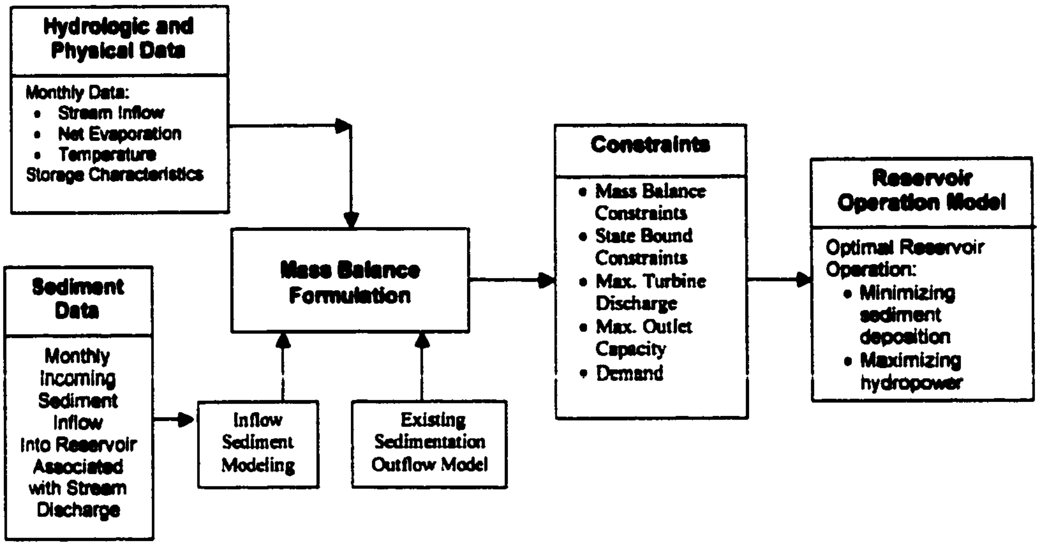

Figure 4-1. Conceptual and Research Design for Modeling of Sustainable Reservoir Sediment-Control Operation

4.3. Adjustment of Mass Balance Formulation

The difference between the common mass balance equation for reservoir operation without applying sediment control, and the developed mass balance for controlling sediment deposition, is achieved by introducing the developed sediment inflow and the existing sediment outflow model.

$$R_t = I_t - E_t - S_t + S_{t-1} - V_{si_t} + V_{so_t} \qquad \text{4-1}$$

In which:

R_t = Total water release during period t

I_t = Stream inflow into reservoir during period t

E_t = Net evaporation during period t

S_t = Total storage (water and sediment) content at the end of period t

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S_{t-1} = Total storage (water and sediment) content at the beginning of period t

$V_{si\,t}$ = Water equivalent volume of sediment inflow into reservoir during period t

$V_{so\,t}$ = Water equivalent volume of sediment outflow from reservoir during period t

In implementing the mass balance equation, the variables in the equation must have the same unit, such as in MCM (million cubic meter). In addition, the sediment terms V_{si} and V_{so} are the non-linear functions.

Total water release R_t consists of power demand release and sediment outflow release. In which t is related to a monthly time step.

$$R_t = R_{td\,t} + R_{so\,t} \qquad \textbf{4-2}$$

In which:

$R_{td\,t}$ = Water release for power generation and water supply during period t

$R_{so\,t}$ = Water release for sediment removal from reservoir during period t

4.4. Sedimentation Model

The inflow sediment reduces the storage capacity of the reservoir. On the other hand, the sediment outflow through flushing operation would be effectively regaining the storage capacity. A reservoir operation model associated with a sediment control strategy

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should consider sediment inflow and sediment outflow. Sediment inflow is modeled based on the relation to stream inflow discharge. However, sediment outflow discharge relations (during release of sediment from reservoir) have been established for several reservoirs in China, and will be implemented to develop the reservoir sediment-control modeling.

4.4.1 Sediment Inflow Entering Reservoir

The sediment inflow quantity is calculated by considering water inflow discharge associated with three types of operation: dry, wet, and normal year operation. In order to obtain each operation, frequency analysis is used for developing the discharge pattern in a year for dry, normal, and wet discharge operation.

The general relation between suspended-sediment transport Q_{si} and stream flow Q_{wi} can be recalled from **Equation 2-7** and modified as follows:

$$V_{si} = a[V_{wi}]^b \qquad \text{4-3}$$

In which:

V_{si} = Volume of sediment inflow into reservoir

V_{wi} = Volume of water inflow into reservoir

a = Coefficient

b = Exponent

In this study, the **Equation 4-3** will be modified to fit between the measurement and calculation of sediment inflow. Actually, there are three equations used to compute

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the relation of sediment rate with stream inflow discharge. The three equations are proposed for different applications such as during non-flood periods, pre-flood and post-flood periods, and flood periods. The **Equation 4-3** is associated with non-flood periods. The other two equations associated with stream inflow discharge are used for pre-flood periods and post-flood periods, and flood periods. For pre-flood and post-flood periods, additional term is introduced associated with exponent c as presented in **Equation 4-4**. During flood periods, the modified equation is also established as shown in **Equation 4-5** by introducing exponents c and d as additional parameters. The equations that are introduced under this condition can be presented, respectively, as:

$$V_{st} = a[V_{wt}]^b + [V_{wt}]^c \qquad \text{4-4}$$

$$V_{st} = a[V_{wt}]^b + \left([V_{wt}]^c\right)^d \qquad \text{4-5}$$

Further modification, for three equations used for predicting sediment rate for specified estimated flood, pre-flood and post-flood, and non-flood discharge, will be presented more detail in Chapter 5. Parameters a, b, c and d would be evaluated by using Non-Linear Programming (NLP) associated with statistics indicators such as Coefficient of Correlation (C_V) and Discrepancy Ratio (R_D). In order to compare the computation result and measured data in the field, a visual comparison for calculation and measurement is introduced to verify the developed equation model.

The formulation model of NLP can be presented in terms of objective and constraint functions as follows:

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Objective Function:

$$\text{Optimize}\quad z=\frac{1}{T}\sum_{t=1}^{T}\left\{\sum_{u=1}^{U}\left(ABS\left[V_{si(measurement)}-V_{si(computation)}\right]_{u}\right)\right\}_{t}=0 \qquad 4\text{-}6$$

Constraint Functions:

$$\frac{1}{T}\sum_{t=1}^{T}\left\{\frac{1}{U}\sum_{u=1}^{U}(R_D)_u\right\}_t=1 \qquad 4\text{-}7$$

$$\frac{1}{T}\sum_{t=1}^{T}\left\{\frac{1}{U}\sum_{u=1}^{U}(C_V)_u\right\}_t=1 \qquad 4\text{-}8$$

In which:

u = 1, 2, 3, ..., U = 30 associated with the total year of measurement

t = 1, 2, 3, ..., T = 12 associated with the month in a year

R_D = Discrepancy Ratio

C_V = Coefficient of Correlation

Parameters a, b, c, and d will be evaluated simultaneously and are defined as the decision parameters in the model. After parameters a, b, c, and d are found, the visual assessment is established in order to compare the developed model and the measurement data obtained in the field.

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4.4.2 Expended Water Discharge and Scoured Sediment Relationship

Five empirical equations of the expended water discharge and the scoured sediment outflow have been studied in China for Sanmenxia Reservoir. These are described in Chapter 2 as **Equation 2-8, Equation 2-9, Equation 2-11, Equation 2-13,** and **Equation 2-14.** All of the equations can be rewritten as follows:

$$Q_{so} = \left(3.5x10^{-3}\right)Q_{wo}^{\ 1.2}\left(S_{ws}x10^{4}\right)^{1.8} \qquad \textbf{4-9}$$

$$Q_{so} = \frac{E_r Q_{wo}^{\ 1.6} S_{bs}^{\ 1.2}}{B^{0.6}} \qquad \textbf{4-10}$$

$$Q_{so} = \frac{5.24\rho_{wi}^{\ 0.868} Q_{wo}^{\ 2} S_{bs}}{Q_{wi}^{\ 0.868}} \qquad \textbf{4-11}$$

$$Q_{so} = k\left(\gamma_{mix} Q_{wo} J_{bs}^{1.5}\left\{\frac{H}{D_{50}}\right\}^{0.5}\right)^{1.3} \qquad \textbf{4-12}$$

$$Q_{so} = eQ_{wo}^{2} S_{bs}^{2}\left(\left\{\frac{C_{si}}{Q_{wi}}\right\} + f\right)^{1.75} \qquad \textbf{4-13}$$

In which:

ρ_{wi} = Water inflow density (kg/m^3)

e = Coefficient of $1.06x10^5$

f = Constant of 0.02

B = Width of the channel (m)

C_{si} = Sediment concentration (kg/m^3)

D_{50} = Median diameter of bed load sediment (mm)

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E_r = Erodibility coefficient

H = Head of reservoir elevation (m)

k = Constant of 1.6×10^{-6}

Q_{so} = Sediment outflow rate (t/s)

Q_{wi} = Water inflow rate (m^3/s)

Q_{wo} = Water outflow discharge (m^3/s)

γ_{mix} = Mixed water and sediment specific weight (t/m^3)

S_{bs} = Bed slope

S_{ws} = Water surface slope

J_{bs} = $S_{bs} \times 10^4$

The five equations above have different dependent variables in each function that provide a challenge to compare every equation due to the reservoir operation model development. Each rule curve will be developed and compared based on all provided sediment outflow equations.

The erodibility coefficient (E_r) is taken within different values based on assumptions and considerations related to the level of reservoir storage. The lower the reservoir storage level, the higher the E_r value used in **Equation 4-10**, since the lower the level of reservoir storage, the higher the sediment deposit material detached from the deposition. The relation between E_r and storage level can be assumed to be non-linear function and is presented in **Figure 4-2**. The change in E_r value is drastically greater in the lower range of storage level. On the other hand, only a slight difference in E_r value is

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given in the higher range of storage level. This relation was developed based on the range of E_r values of Sanmenxia Reservoir data.

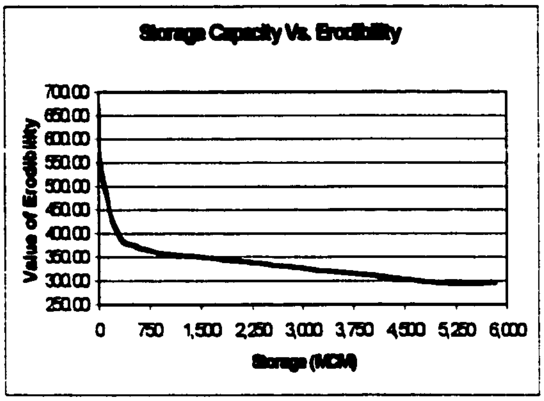

Figure 4-2. The Relationship of Storage Level and Erodibility Coefficient based on Assumption

4.5. Adjustment of Reservoir Operation with Sediment Control

In order to combine the reservoir operation model and sedimentation release model, it is necessary to consider the stages of methodology to formulate the model and solve it by providing any assumptions and limitations of the model. In the development of the reservoir operation model with sediment control, the strategy for formulating the model is based on the consideration of the mass balance equation.

The strategy to develop the model includes the decision to apply the optimization technique associated with each objective function and each constraint function. The selection of the NLP procedure and the improvement of computer capabilities associated with the user interface, database, and formulation with run-time, will affect the development of the model and its success. Currently, computer resources including large

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memory capabilities and adequate speed would avoid obstacles in handling model formulation with the NLP technique.

After the optimization model applied is built, the total release for meeting downstream demand can be obtained. However, the strategy to release the water from the reservoir for two main purposes, such as hydropower associated with water supply at downstream area and sediment release, should be established. The procedure for deciding the water release strategy would be associated with the modification of the NLP technique and multi-objective measure by applying an iterative procedure. This modification of the NLP model would provide the optimal water release strategy for each purpose.

4.5.1 Optimization Model

The enhancement of the optimization model due to the reservoir sediment-control operation model would be established in this study by formulating each objective function and each constraint function. The objectives considered in the research can be presented as:

1. Maximize hydropower
2. Maximize water supply such as irrigation, etc.
3. Minimize sediment deposition or maximize sediment outflow discharge

A trade-off emerges between maximizing hydropower and sediment outflow discharge. On the other hand, other demands can be met from turbine release such as water supply.

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The constraints associated with this problem are the mass balance equation, which includes water inflow, water release, demands, sediments inflow-outflow, and limitation due to the reservoir characteristics and hydrologic conditions, maximum capacity for turbine and outlet system.

4.5.2 Optimization Technique Formulation

The problem is formulated by applying NLP with iterative fashion. The maximization problem of release (R_t) constitutes the objective function in order to ensure that the inflow and water storage meet the demand without shortage. When a shortage in meeting the demands exists, the model should provide as much as possible to distribute the shortage uniformly in terms of the percentage of release and demand discharge.

The general NLP equation can be expressed in the following terms:

Objective function:

$$\max \sum_{t=1}^{T} R_t \qquad \text{4-14}$$

Subject to:

$$R_t = I_t - E_t - S_t + S_{t-1} - V_{sit} + V_{sot} \qquad \text{4-15}$$

$$R_t, S_t \geq 0 \qquad \text{4-16}$$

$$R_t - D_t \geq 0 \qquad \text{4-17}$$

$$Q_{wo(max)t} - Q_{wot} \geq 0 \qquad \text{4-18}$$

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$$R_t \leq O_{\max\,(\text{sediment})} + O_{\max\,(\text{turbine})} \qquad 4\text{-}19$$

In which:

R_t = Total water release during period t

I_t = Stream inflow into reservoir during period t

E_t = Net evaporation during period t

S_t = Total storage (water and sediment) content at the end of period t

S_{t-1} = Total storage (water and sediment) content at the beginning of period t

$V_{si\,t}$ = Water equivalent volume of sediment inflow into reservoir during period t

$V_{so\,t}$ = Water equivalent volume of sediment outflow from reservoir during period t

$Q_{wo(max)\,t}$ = Maximum water outflow discharge for releasing sediment during period t

$Q_{wo\,t}$ = Water outflow discharge for releasing sediment during period t

t = 1, 2, 3, ..., T = 12 associated with the month in a year

O_{max} = Maximum outflow capacity associated with turbine or sediment outlet

Note that V_{si} and V_{so} are the non-linear functions. The terms in the mass balance equation should have the same units. The S_t variable is the decision variable. The volume of sediment outflow (V_{so}) is obtained from sediment outflow rate (Q_{so}) divided by the density of the silt.

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$Q_{wo(max)}$ is obtained by applying $Q_{so(max)}$ and solves for Q_{wo} as $Q_{wo(max)}$ based on **Equations 4-9** through **Equation 4-13**. However, $Q_{so(max)}$ is determined by subtracting cumulative sediment outflow rate at period *t-1* from cumulative sediment inflow rate at period *t*. Q_{wo} is related to the dynamic value of release index and sediment outflow release described more detail in the section of dynamic release determination.

Total release R_t consists of turbine or power demand release (R_{td_t}) and sediment outflow release (R_{so_t}) as presented in **Equation 4-20**. A multi-objective measure is applied in order to determine R_{td_t} and R_{so_t}.

$$R_{td_t} + R_{so_t} \leq R_t \qquad \textbf{4-20}$$

4.5.2.1 Maximizing Objective Function

Maximizing objective function is intended to provide more release for maximizing hydropower and sediment release discharge. The pool elevation is expected to be as low as possible, achieving a lower rule-curve operation in which this is the lower limit for operation to reach a free flow condition. However, this still meets the demands during the non-flood period such as periods during which the stream inflow discharge is less than the total demand.

4.5.2.2 Multi-objective Measures

There would be a trade off between maximization of hydropower and minimization of sediment deposition in the reservoir. A multi-objective measure is introduced in order to find the optimal decision policy of releasing water for hydropower

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(associated with downstream demand) or sediment discharge with the same priority or different priority. In order to obtain optimal decision policy for specified preference in releasing water, the method that may be used in the developed model can be established by modifying **Equation 4-20** as follows:

$$\alpha_{\text{turbine}} R_t + (1 - \alpha_{\text{turbine}}) \beta_{\text{sediment}\,t} R_t \le R_t \qquad \textbf{4-21}$$

$$\alpha_{\text{turbine}} R_t = R_{td\,t} \qquad \textbf{4-22}$$

$$(1 - \alpha_{\text{turbine}}) \beta_{\text{sediment}\,t} R_t = R_{so\,t} \qquad \textbf{4-23}$$

Parameter α and β represent the static and dynamic values of release index, respectively. In addition, they also reflect the percentage of release adjustment to lead the amount of water provided for turbine (power generation) and sluicing or flushing, respectively.

In the case of determining a priority between power generation and sediment release, then, it is necessary to develop an additional equation based on annual release or energy production associated with the annual target for both sediment release and energy production. The equations relating the operation achievement and the target can be presented as follows:

$$\text{Energy Demand Ratio (\%)} = \frac{\text{Annual Energy Provided}}{\text{Annual Energy Target}} \qquad \textbf{4-24}$$

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$$\text{Firm Energy Ratio (\%)} = \frac{\text{Annual Firm Energy Provided}}{\text{Annual Firm Energy Target}} \qquad \textbf{4-25}$$

$$\text{Sediment Demand Ratio (\%)} = \frac{\text{Annual Sediment Release}}{\text{Annual Released Sediment Target}} \qquad \textbf{4-26}$$

Two scenarios will be developed based on energy demand ratio (EDR) versus sediment demand ratio (SDR), and firm energy ratio (FER) versus sediment demand ratio (SDR). If the EDR or FER versus SDR have the value of 1.0, then the target for energy accessibility and sediment release is completely achieved with respect to the objective target. However, if EDR or FER versus SDR have the same value but less than 1.0, then both purposes having the same priority within the full target cannot be accomplished. The higher the value of the ratio, the higher the priority provided for that purpose being accomplished.

4.5.2.3 Decision Achievement with Static and Dynamic Values of Release Index

The NLP equation for maximizing problem with static value of release index can be expressed in the following terms:

<u>Objective function:</u>

$$\max \sum_{t=1}^{T} R_t \qquad \textbf{4-27}$$

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<u>Subject to:</u>

$$R_t = I_t - E_t - S_t + S_{t-1} - V_{sit} + V_{sot} \qquad \textbf{4-28}$$

$$\alpha_{\text{turbine}} R_t + (1-\alpha_{\text{turbine}})\beta_{\text{sediment}\,t} R_t \le R_t \qquad \textbf{4-29}$$

$$R_t, S_t \ge 0 \qquad \textbf{4-30}$$

$$R_t - D_t \ge 0 \qquad \textbf{4-31}$$

$$Q_{wo(\max),t} - Q_{wot} \ge 0 \qquad \textbf{4-32}$$

$$\alpha_{\text{turbine}} R_t = R_{td\,t} \le O_{\max\,(\text{turbine})} \qquad \textbf{4-33}$$

$$(1-\alpha_{\text{turbine}})\beta_{\text{sediment}\,t} R_t = R_{sot} \le O_{\max\,(\text{sediment})} \qquad \textbf{4-34}$$

In which:

R_t = Total water release during period t

$R_{td\,t}$ = Total water release for turbine and demand during period t

$R_{so\,t}$ = Total water release for sediment outflow during period t

I_t = Stream inflow into reservoir during period t

E_t = Net evaporation during period t

S_t = Total storage (water and sediment) content at the end of period t

S_{t-1} = Total storage (water and sediment) content at the beginning of period t

$V_{si\,t}$ = Water equivalent volume of sediment inflow into reservoir during period t

$V_{so\,t}$ = Water equivalent volume of sediment outflow from reservoir during period t

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$Q_{wo(max)\,t}$ = Maximum water outflow discharge for releasing sediment during period t

$Q_{wo\,t}$ = Water outflow discharge for releasing sediment during period t

$\alpha_{turbine}$ = Static value of release index

$\beta_{sediment\,t}$ = Dynamic value of release index during period t

t = Monthly time reference = 1, 2, 3, ..., T = 12

O_{max} = Maximum outflow capacity associated with maximum turbine or sediment outlet

S_t is the decision variable and given as the initial value before running the model. In addition, $\alpha_{turbine}$ and $\beta_{sediment\,t}$ are given for the initial value to run the model. $\alpha_{turbine}$ is very important in order to search the appropriate or desired priority for both energy production and sediment release. However, $\beta_{sediment\,t}$ will be determined by the following developed model (in the next section) to provide accurate decision release due to the sediment outflow.

4.5.2.4 Determination of Dynamic Value of Release Index

The general NLP equation for determining dynamic value of release index can be expressed in the following terms:

<u>Objective function:</u>

$$\text{Optimize} \quad z = \sum_{t=1}^{T}\left(ABS\left[Q_{wo(max)} - Q_{wo}\right]_t\right) = 0 \qquad \text{4-35}$$

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Subject to:

$$Q_{wo(\max)_t} - Q_{wo_t} \geq 0 \quad \textbf{4-36}$$

$$0 \leq \beta_{sediment_t} \leq 1 \quad \textbf{4-37}$$

In which:

$Q_{wo(max)_t}$ = Maximum water outflow discharge for releasing sediment during period t

Q_{wo_t} = Water outflow discharge for releasing sediment during period t

$\beta_{sediment_t}$ = Dynamic value of release index during period t

Q_{wo} can be obtained from R_{so} by changing the unit from the unit of volume (MCM) to the unit of discharge (m^3/s). As presented in **Equation 4-34**, $\beta_{sediment_t}$ is introduced to produce R_{so_t}.

4.6. Solving Method Procedure

The solving method procedure is presented as a research design in **Figure 4-3**. This schematic procedure shows how the solution with optimal decision is achieved by considering the priority preference of the two main objective targets. The NLP with iterative fashion is introduced to search for the optimal decision until the specified preference is accomplished.

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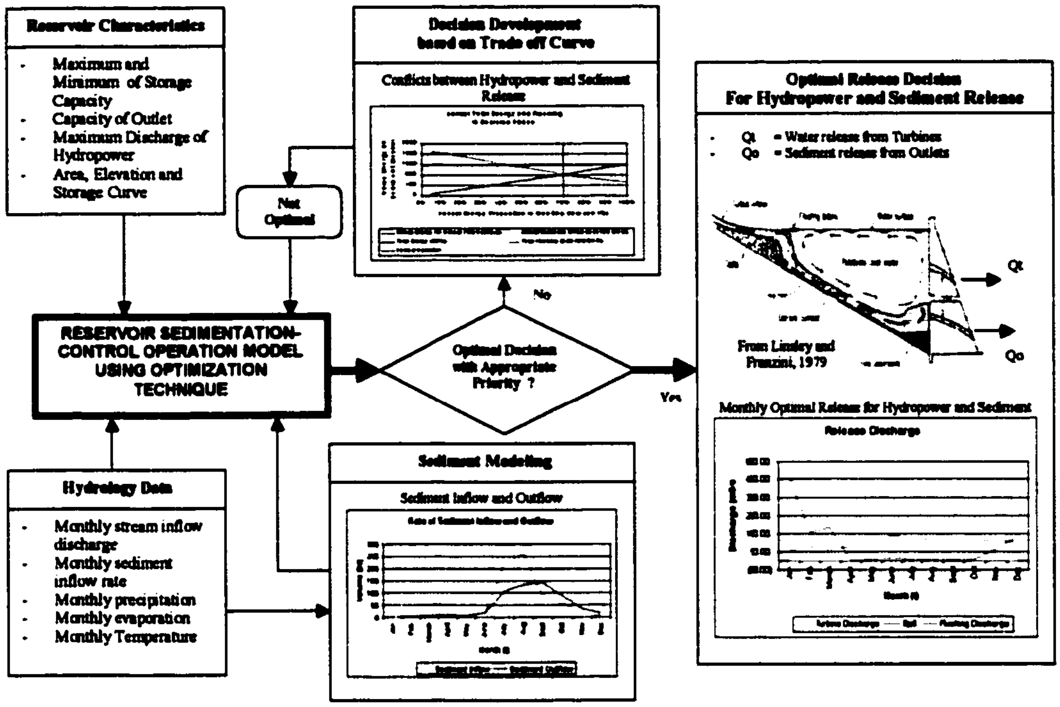

Figure 4-3. Solving Procedure for Sustainable Reservoir Sediment-Control Operation Model

4.7. Decision Support System Modeling Application

The development of the Graphic User Interface (GUI) is described briefly. The interface is important in order to understand the model and to make it easier for an operator to run the program and see the result immediately with a comfortable visual performance. The GUI is helpful in developing the Decision Support System (DSS) and its ability to interact with the operator.

A macro application using the Visual Basic programming built into the Excel package is developed. This macro application is introduced in the DSS in order to accelerate the process of iteration of the NLP application (provided in the Solver package

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in the Excel Software). The GUI is developed to provide visual results after the execution of the sedimentation inflow model and optimization model has been done. It may be noted that the capabilities of the standard Solver software, due to a number of constraints, are limited. In order to enhance the standard Solver, it is necessary to install additional software called Premium Solver, if it is necessary.

In this study, the DSS is developed in order to easily use and access the running of this model. As in many publications, the DSS consists of a user interface (computer hardware), a model sub-system provided by developing software, and a data base sub-system to record the results and any necessary data for running the model application. In this case, the model and data base subsystem will be developed and restored in the same Excel Software in order to make adjustment, saving, retrieval or replacement easier.

4.8. Summary

The development of the model for reservoir sediment-control operation planning can be accomplished by involving the sediment inflow model and the application of the existing released sediment outflow model. These two models are linked to the mass balance equation of the reservoir optimization model. The multi-objective measure is developed in the model to provide the optimal decision of water release with specified preference, especially in maximizing hydropower and minimizing sediment deposition in reservoir.

In the sediment inflow model, there would be selection of the appropriate sediment inflow equation in finding the best value parameters of a, b, c, and d based on two statistic indicators and visual graphic assessment. The appropriate sediment inflow

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model would be used in the mass balance equation in the optimization model. The five existing sediment outflow equations associated with the expended water release from the outlet system would be applied and compared in the application of the reservoir sediment-control model.

In the NLP formulation, there are introduced two types of release index such as static and dynamic values used for determining the amount of water should be released through the turbine and sediment outlet system. Static value of release index is given as initial value before running the model and provided as a trial value input in the next execution until the priority for both energy production and sediment outflow arrive at a desired value. Therefore, by changing the static value of the release index, the optimal condition should be found with the desired weight or priority between maximizing energy and minimizing sediment deposition.

The dynamic values of release index are given in monthly value that might have the same or different value for every month. Like monthly storage (S_t) values in the reservoir, the dynamic values are given before running the model as initial values. Then, they are determined precisely by using sub model to achieve appropriate water release through sediment outlet system based on the desired priority. However, monthly storage (S_t) values are determined based on the main developed model.

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CHAPTER V
APPLICATION OF MODEL FOR SUSTAINABLE RESERVOIR SEDIMENT-CONTROL OPERATION

5.1. Introduction

The developed model is established based on the development of the mathematical model described in the previous section. Chapter III noted that the case study deals with the single multi-purpose reservoir named Sanmenxia Reservoir. The research model of the reservoir operation is established by developing the early stage of the model which serves mainly for hydropower and sediment control reservoir operation.

5.2. Stream Inflow for the Year of Operation

The pattern of yearly operation consists of three types: dry year, normal year, and wet year operation. The determination of the three patterns of operation is established by using frequency analysis. This is presented in **Figure 5-1**.

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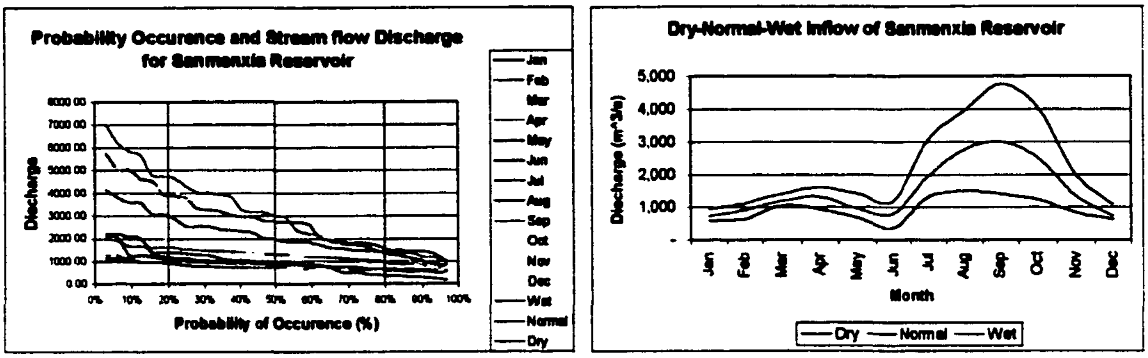

(a) (b)

Figure 5-1. (a) Evaluation of Dry, Normal, and Wet Year Operation Based on the Frequency Analysis, (b) Stream Inflow Pattern for Dry, Normal, and Wet Year Operation

5.3. Sediment Inflow for the Year of Operation

For sediment inflow, the same considerations arise as with the dry, normal, wet year operation of the stream inflow pattern. In other words, the pattern of the sediment inflow would be based on the stream inflow pattern for dry, normal, or wet year operation. Three categorized sediment inflow models are developed in this study. The first uses the basic **Equation 4-3**, modifying **Equation 4-3**, and then modifying **Equation 4-3** with the adjustment of the parameters. The classification of flood period month is shown in **Table 5-1**. The classification consists of non-flood periods, pre-flood and post-flood periods, and flood periods. The non-flood period includes the months of January, February, March, April, May, October, November, and December. The months of June and September are designated as pre-flood and post-flood periods. July and August are the crucial months of the flood period.

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Table 5-1. Monthly Classification of Flood Period

No.	Month	Classification of Flood or Non Flood Period
1	January	Non-Flood Season
2	February	Non-Flood Season
3	March	Non-Flood Season
4	April	Non-Flood Season
5	May	Non-Flood Season
6	June	Pre-Flood Season
7	July	Flood Season
8	August	Flood Season
9	September	Post-Flood Season
10	October	Non-Flood Season
11	November	Non-Flood Season
12	December	Non-Flood Season

5.3.1 Using Basic Equation

The sedimentation model for sediment entering the reservoir in non-flood period, pre-flood and post-flood periods, and flood period uses the common basic equation for all periods and can be expressed as:

$$V_{si} = 8.77x10^{-6}\left[V_{wi}\right]^{.763} \qquad \textbf{5-1}$$

In which:

V_{si} = Volume of sediment inflow into reservoir

V_{wi} = Volume of water inflow into reservoir

The plots of the measured data from field and the computation model based on **Equation 5-1** are shown in **Figure 5-2**.

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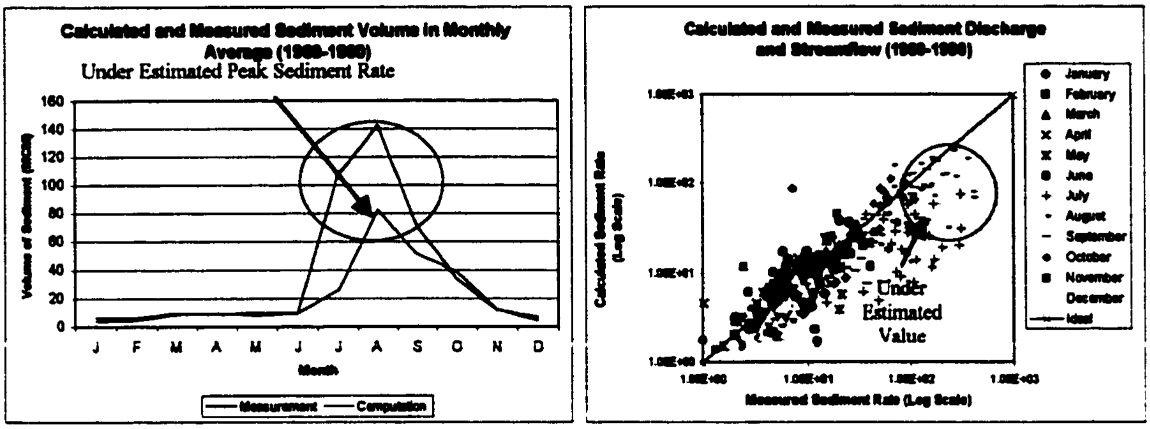

(a) (b)

Figure 5-2. Visual Comparison (a) Measured and Calculated Model, and (b) Comparison of Sediment Inflow Model Based on Basic Equation Application

Based on the statistical analysis, the Coefficient of Correlation and Ratio of Discrepancy incorporated with **Figure 5-2** are presented in **Table 5-2.**

Table 5-2. Correlation Coefficient and Discrepancy Ratio Evaluation in Using Basic Equation

No.	Month	C_C	Measured and Computation Difference (MCM)	R_D
1	January	0.72	68.82	0.70
2	February	0.63	59.59	0.78
3	March	0.67	69.55	1.06
4	April	0.79	65.73	1.20
5	May	0.82	117.15	0.89
6	June	0.57	162.28	1.28
7	July	0.31	2,560.36	0.36
8	August	0.45	2,339.20	0.77
9	September	0.82	766.74	0.70
10	October	0.74	417.31	1.39
11	November	0.76	120.94	1.08
12	December	0.68	80.06	1.79
	Average	0.66	568.98	1.00

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5.3.2 Using Modified Basic Equation

The sedimentation model for non-flood period sediment entering the reservoir can be expressed as:

$$V_{si} = 2.0x10^{-6}[V_{wi}]^{1.8998} \quad \textbf{5-2}$$

During the periods of pre-flood and post-flood, the equation of sediment inflow rate entering the reservoir would be as follows:

$$V_{si} = 2.0x10^{-6}[V_{wi}]^{1.8998} + [V_{wi}]^{0.1971} \quad \textbf{5-3}$$

During the period of flood, the equation of sediment inflow rate entering the reservoir would be:

$$V_{si} = 2.0x10^{-6}[V_{wi}]^{1.8998} + [V_{wi}]^{0.5053} \quad \textbf{5-4}$$

In which:

V_{si} = Volume of sediment inflow into reservoir

V_{wi} = Volume of water inflow into reservoir

The plots of the sediment rate and comparison of measured data and computation by the model using the developed equations are presented in **Figure 5-3**.

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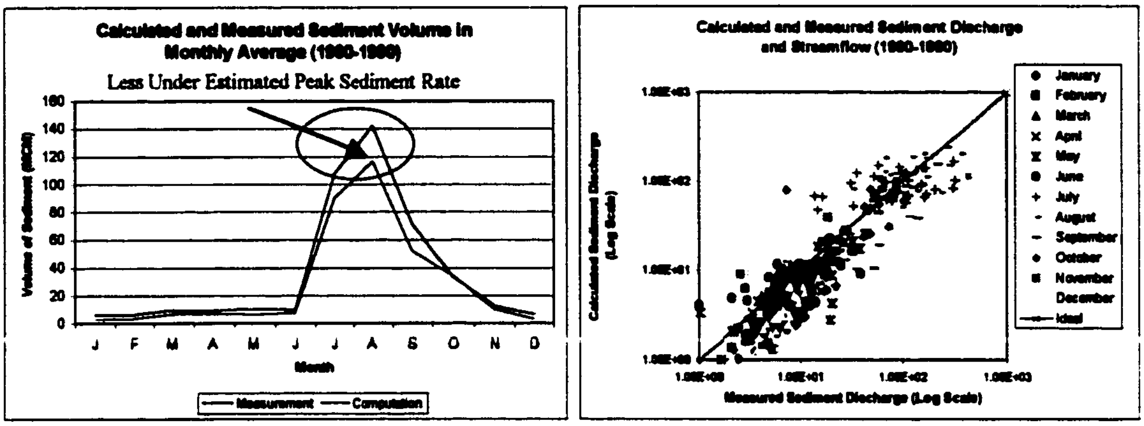

(a) (b)

Figure 5-3. Visual Comparison (a) Measured and Computation Model, and (b) Comparison of Sediment Inflow Model Based on Modified Equation Application

Based on the statistical analysis, the Coefficient of Correlation and Ratio of Discrepancy incorporated with **Figure 5-3** are presented in **Table 5-3.**

Table 5-3. Coefficient of Correlation and Discrepancy Ratio Evaluation in Using Modified Basic Equation

No.	Month	C_C	Measured and Computation Difference (MCM)	R_D
1	January	0.72	100.30	0.50
2	February	0.60	87.25	0.58
3	March	0.66	96.54	0.80
4	April	0.79	75.33	0.92
5	May	0.81	144.59	0.67
6	June	0.57	129.69	1.77
7	July	0.32	1,728.94	1.41
8	August	0.46	2,001.89	1.29
9	September	0.81	748.91	0.74
10	October	0.73	388.65	1.20
11	November	0.75	139.51	0.84
12	December	0.68	109.51	1.28
	Average	0.66	479.26	1.00

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5.3.3 Using Modified Basic Equation with Parameter Adjustment

The modification of the sedimentation model with adjustment of parameters for non-flood period sediment entering the reservoir can be expressed as:

$$V_{si} = 2.95x10^{-6}\left[V_{wi}\right]^{.90} \qquad \textbf{5-5}$$

During the period of pre-flood and post-flood, the equation for sediment inflow rate entering the reservoir would be:

$$V_{si} = 2.95x10^{-6}\left[V_{wi}\right]^{.90} + \left[V_{wi}\right]^{0.21} \qquad \textbf{5-6}$$

During the period of flood, the equation of sediment inflow rate entering the reservoir would be as follows:

$$V_{si} = 2.95x10^{-6}\left[V_{wi}\right]^{.90} + \left[V_{wi}\right]^{0.525} \qquad \textbf{5-7}$$

In which:

V_{si} = Volume of sediment inflow into reservoir

V_{wi} = Volume of water inflow into reservoir

The plots of the sediment rate and comparison of measured data and computation by the model incorporating the developed equations is presented in **Figure 5-4**.

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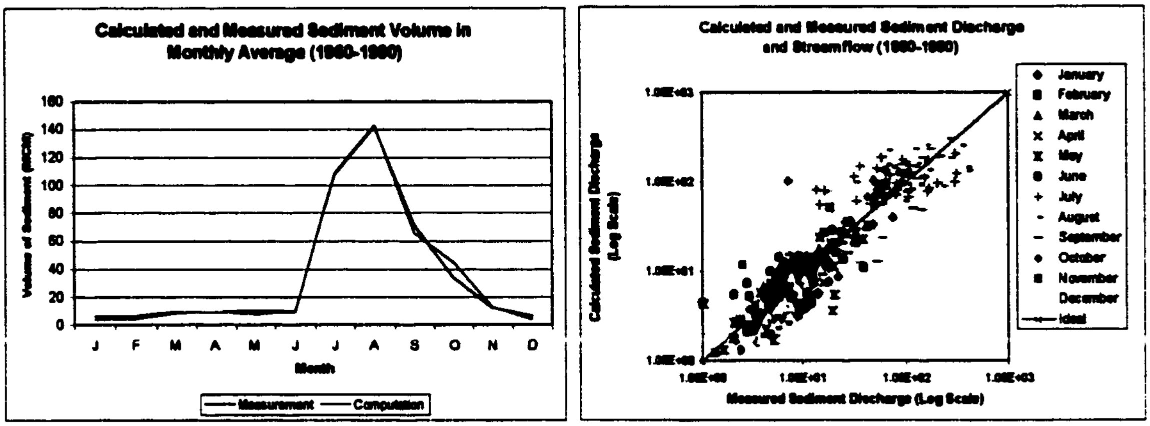

(a) (b)

Figure 5-4. Visual Comparison (a) Measured and Computation Model, and (b) Comparison of Sediment Inflow Model Based on Modified Equation within Parameter Adjustment

Based on the statistical analysis, the Coefficient of Correlation and Ratio of Discrepancy incorporated with **Figure 5-4** are presented in **Table 5-4.**

Table 5-4. Coefficient of Correlation and Discrepancy Ratio Evaluation in Using Modified Basic Equation

No.	Month	C_C	Measured and Computation Difference (MCM)	R_D
1	January	0.72	76.56	0.65
2	February	0.62	65.17	0.73
3	March	0.66	71.95	1.04
4	April	0.79	67.17	1.18
5	May	0.82	116.03	0.86
6	June	0.57	140.21	2.02
7	July	0.32	1,831.09	1.69
8	August	0.46	2,117.60	1.56
9	September	0.81	731.49	0.94
10	October	0.73	544.15	1.55
11	November	0.75	133.37	1.09
12	December	0.68	85.36	1.65
	Average	0.66	498.35	1.25

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5.3.4 Selected Equation for Sediment Inflow Model

Based on the statistical analyses including the Correlation Coefficient, Discrepancy Ratio, and visual fitness plot assessment, the modification of sedimentation model with adjustment of parameters has been selected in this study. During non-flood periods such as from January to May and October to December, the rate of sediment inflow associated with stream inflow entering the reservoir can be rewritten as:

$$V_{si} = 2.95x10^{-6}\left[V_{wi}\right]^{1.90} \qquad \textbf{5-8}$$

During the periods of pre-flood and post-flood, both June and September, the rate of sediment inflow entering the reservoir would be as follows:

$$V_{si} = 2.95x10^{-6}\left[V_{wi}\right]^{1.90} + \left[V_{wi}\right]^{0.21} \qquad \textbf{5-9}$$

During the period of flood, both July and August, the sediment inflow rate entering the reservoir would be:

$$V_{si} = 2.95x10^{-6}\left[V_{wi}\right]^{1.90} + \left[V_{wi}\right]^{0.525} \qquad \textbf{5-10}$$

In which:

V_{si} = Volume of sediment inflow into reservoir

V_{wi} = Volume of water inflow into reservoir

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5.4. Selected Equations and Definition of Expended Water Discharge Associated with Sediment Outflow Rate

The model is developed and assessed based on five different sediment outflow rate equations associated with expended water outflow through the outlet system of the reservoir. The five equations for sediment outflow rate associated with the expended water outflow discharge are rewritten again and defined from A to E as:

Equation A:

$$Q_{so} = \left(3.5x10^{-3}\right)Q_{wo}^{\ 1.2}\left(S_{ws}x10^{4}\right)^{1.8} \quad \textbf{5-11}$$

Equation B:

$$Q_{so} = \frac{E_r Q_{wo}^{\ 1.6} S_{bs}^{\ 1.2}}{B^{0.6}} \quad \textbf{5-12}$$

Equation C:

$$Q_{so} = \frac{5.24\rho_{wi}^{\ 0.868} Q_{wo}^{\ 2} S_{bs}}{Q_{wi}^{\ 0.868}} \quad \textbf{5-13}$$

Equation D:

$$Q_{so} = k\left(\gamma_{mix} Q_{wo} J_{bs}^{1.5}\left\{\frac{H}{D_{50}}\right\}^{0.5}\right)^{1.3} \quad \textbf{5-14}$$

Equation E:

$$Q_{so} = eQ_{wo}^{2} S_{bs}^{2}\left(\left\{\frac{C_{si}}{Q_{wi}}\right\} + f\right)^{1.75} \quad \textbf{5-15}$$

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In which:

ρ_{wi}	= Water inflow density (kg/m^3)
e	= Coefficient of 1.06×10^5
f	= Constant of 0.02
B	= Width of the channel (m)
C_{si}	= Sediment concentration (kg/m^3)
D_{50}	= Median diameter of bed load sediment (mm)
E_r	= Erodibility coefficient
H	= Head of reservoir elevation (m)
k	= Constant of 1.6×10^{-6}
Q_{so}	= Sediment outflow rate (t/s)
Q_{wi}	= Water inflow discharge (m^3/s)
Q_{wo}	= Water outflow discharge (m^3/s)
γ_{mix}	= Mixed water and sediment specific weight (t/m^3)
S_{bs}	= Bed slope
S_{ws}	= Water surface slope
J_{bs}	= $S_{bs} \times 10^4$

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5.5. Basic Considerations and Assumptions of the Developed Model

The reservoir related to the case study is categorized as relatively flat and long reservoir. This situation reflects that a slightly changing of the elevation will affect sensitively to the storage capacity of the reservoir. The minimum capacity of the reservoir is around 2.58 MCM and the maximum capacity of the storage is around 5,823 MCM. The typical sediment consists of silt as a turbidity current entering the reservoir. Silt density used in the model is around 2.724 t/m^3 with respect to Sanmenxia Reservoir built in the sediment-laden Yellow River.

The initial condition of the storage volume is 1,000 MCM. By the end of the year of operation, the reservoir storage pool is to be set that the capacity will be more than or equal to the initial storage volume. The demand pattern is assumed as indicated in the results of operation planning in the following sub-section.

The installed capacity used in the model is around 1100 MW approximates the original design for five existing turbines. However, in the long run operation the new design of installed capacity of the turbines (250 MW) will be compared to the original design due to the accumulation effect of sediment deposition.

5.6. Optimal Decision Policy of Reservoir Sediment-Control Operation Model based on Annual Energy Target

The developed model is established under three conditions: dry, normal, and wet year operation. In this section, the static value of release index is introduced in order to obtain the desired priority for both maximizing hydropower and minimizing sediment deposition under the five different sediment outflow rate equations. The optimal decision

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is found by searching for the same priority or weight of the two objectives such as the total annual energy provided and sediment release based on the total annual energy target and sediment release target. The static value release index is given as initial trial value and changed to search appropriate weights for both objectives. The value of release index would be the same for all months of the year of operation planning.

The operation follows the stream inflow for dry, normal and wet year patterns as in **Figure 5-1 (b)**, in which each pattern is used to estimate the dry, normal and wet year pattern of the sediment inflow, respectively.

5.6.1 Dry Year Operation Results

The optimal decision policy for all five equations is presented in **Figure 5-5**. The decision policy is based on the optimal value of release index and priority for both maximizing energy and minimizing sediment deposition. In addition, both of these two objectives, maximizing energy and minimizing sediment deposition, have the same priority in this case.

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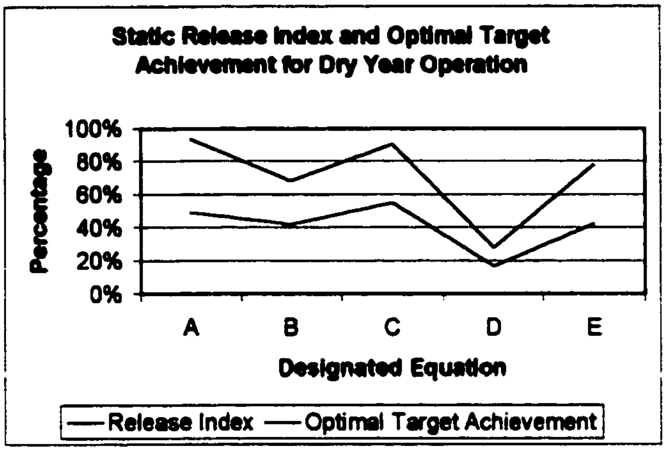

Figure 5-5. Static Value of Release Index and Optimal Weight Comparison for Five Different Equations A, B, C, D, and E during Dry Year Operation

The operation planning will be presented in the following section based on monthly operation. The planning of operations presented related to dry year operation applications is consists of (a) storage curve, (b) elevation curve, (c) inflow, release and demand curve, (d) power and energy output, (e) rate of sediment inflow and outflow, (f) change of storage capacity, (g) shortage or surplus of the demand, and (h) release decision. These figures are presented with respect to the five different equations of sediment outflow indicated by Equation A, B, C, D, and E.

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5.6.1.1 Results Based on Sediment Release as Function of Bed Slope and Expended Water Discharge

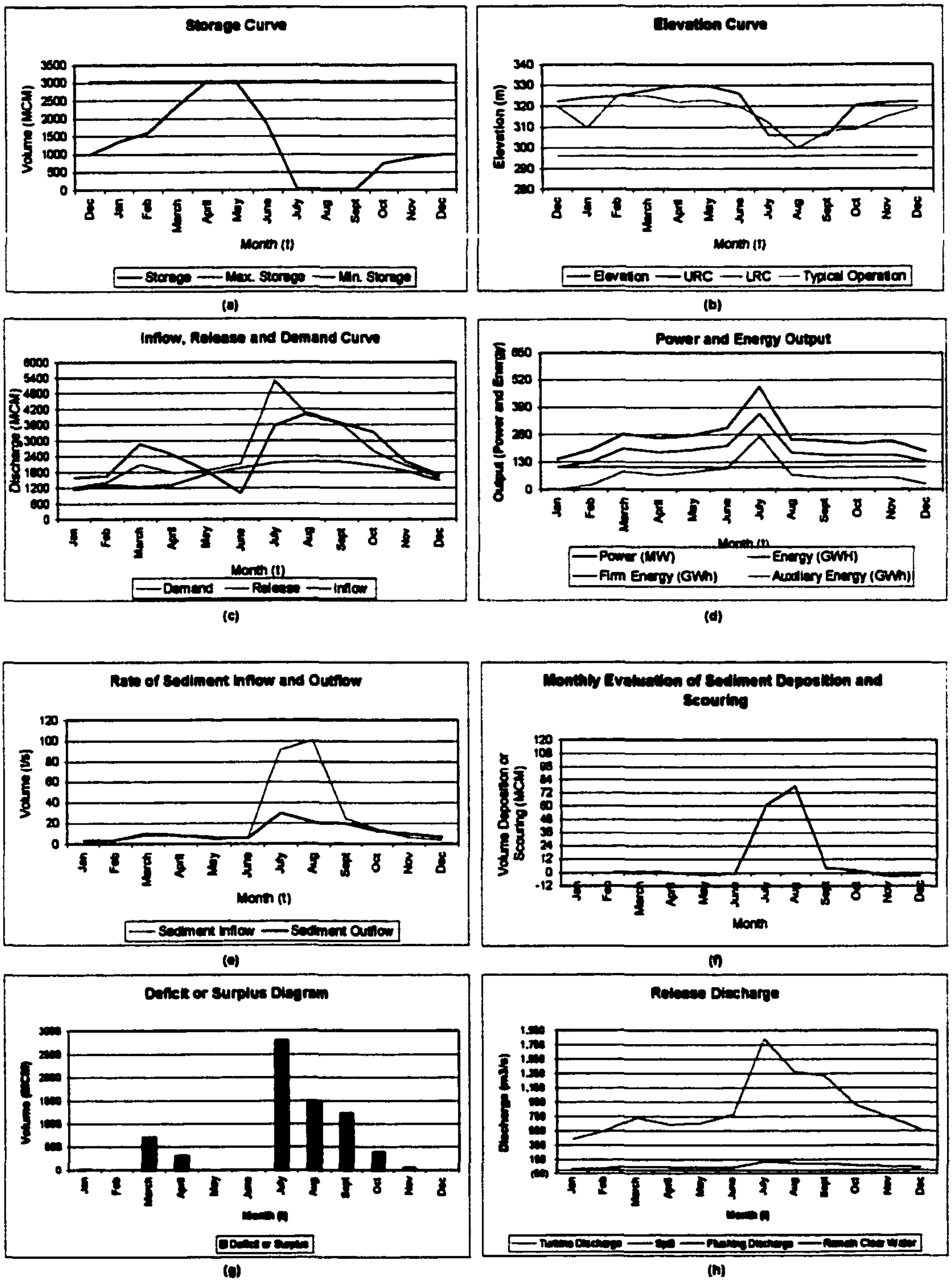

Figure 5-6. Results of Optimal Operation based on Equation A during Dry Year Operation based on Total Annual Energy Target

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5.6.1.2 Results Based on Sediment Release as Function of Bed Slope, Expended Water Discharge, Channel Width and Soil Erodibility

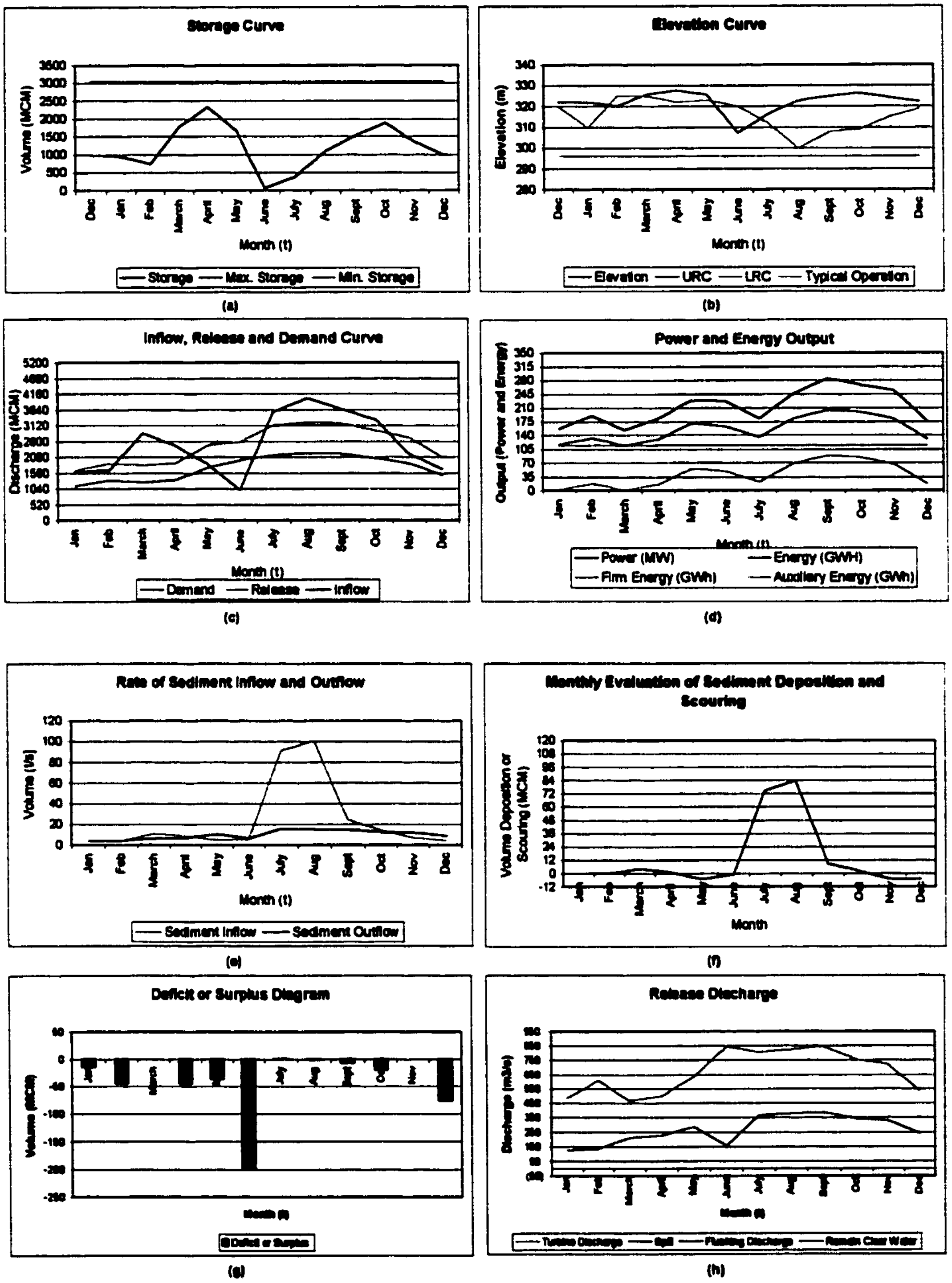

Figure 5-7. Results of Optimal Operation based on Equation B during Dry Year Operation based on Total Annual Energy Target

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5.6.1.3 Results Based on Sediment Release as Function of Bed Slope, Expended Water Discharge, Water Density and Water Inflow Discharge

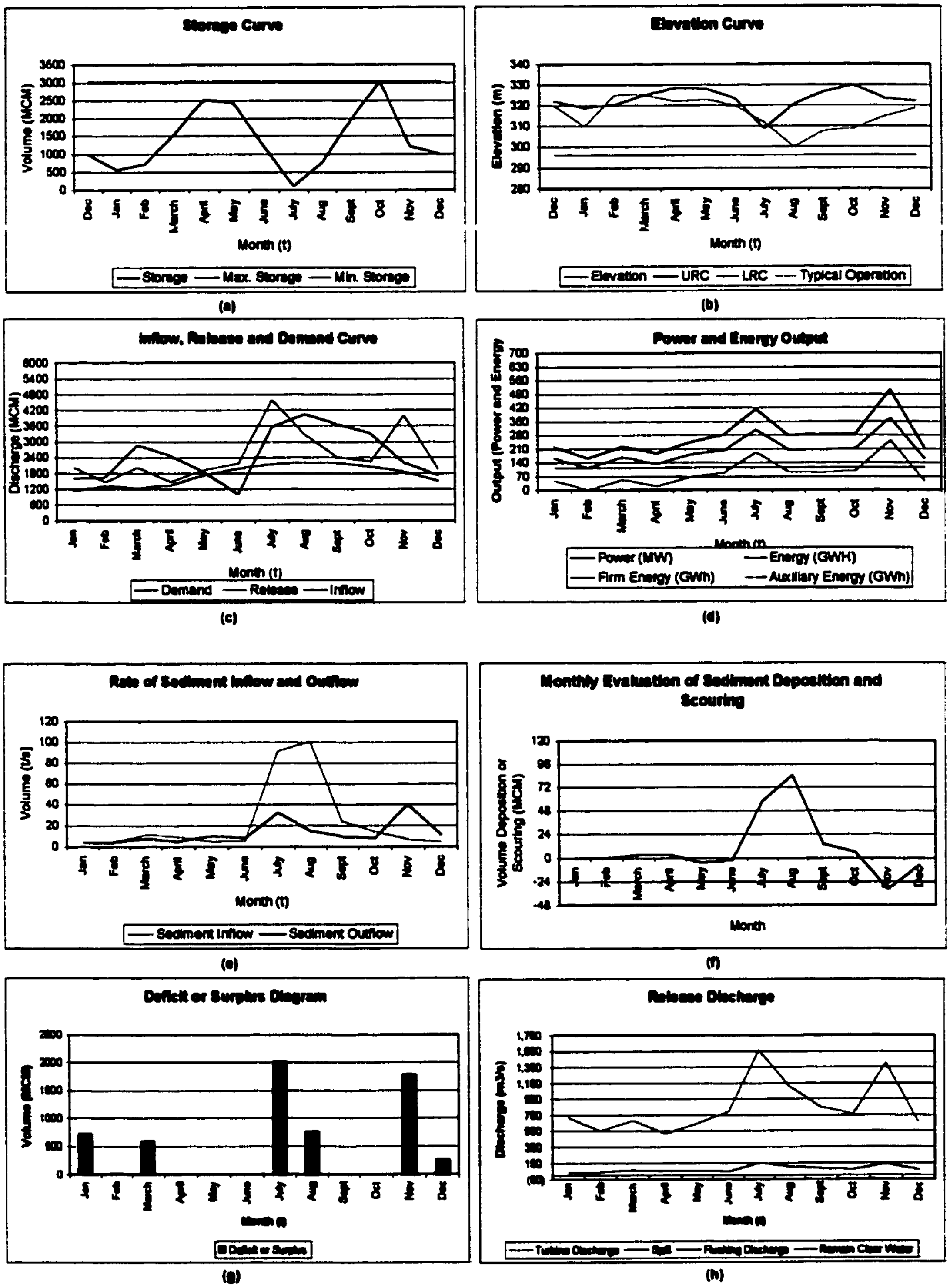

Figure 5-8. Results of Optimal Operation based on Equation C during Dry Year Operation based on Total Annual Energy Target

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5.6.1.4 Results Based on Sediment Release as Function of Bed Slope, Expended Water Discharge, Elevation Depth and Median Diameter of Sediment

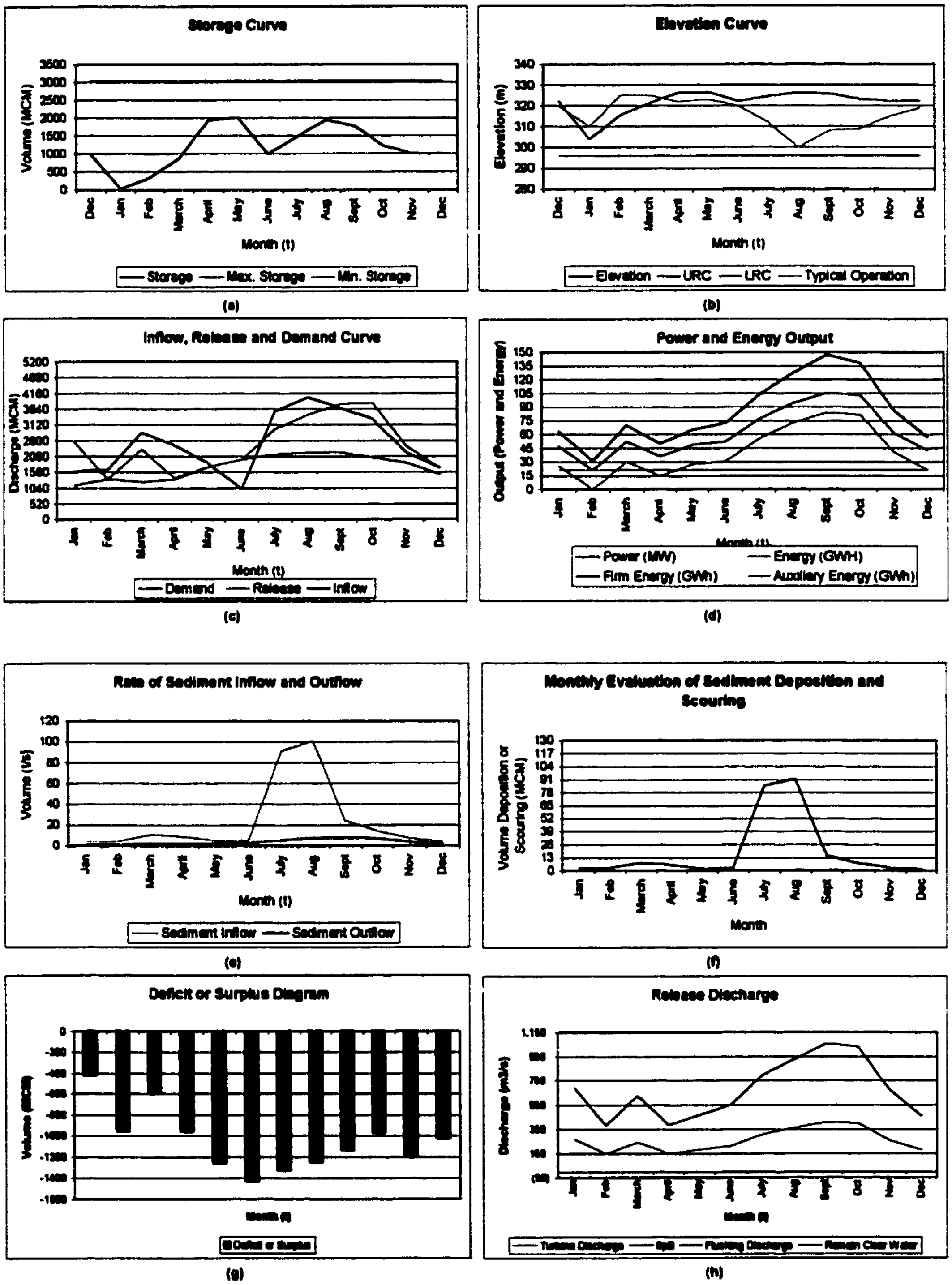

Figure 5-9. Results of Optimal Operation based on Equation D during Dry Year Operation based on Total Annual Energy Target

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5.6.1.5 Results Based on Sediment Release as Function of Bed Slope, Expended Water Discharge, Water Inflow Discharge and Sediment Inflow Concentration

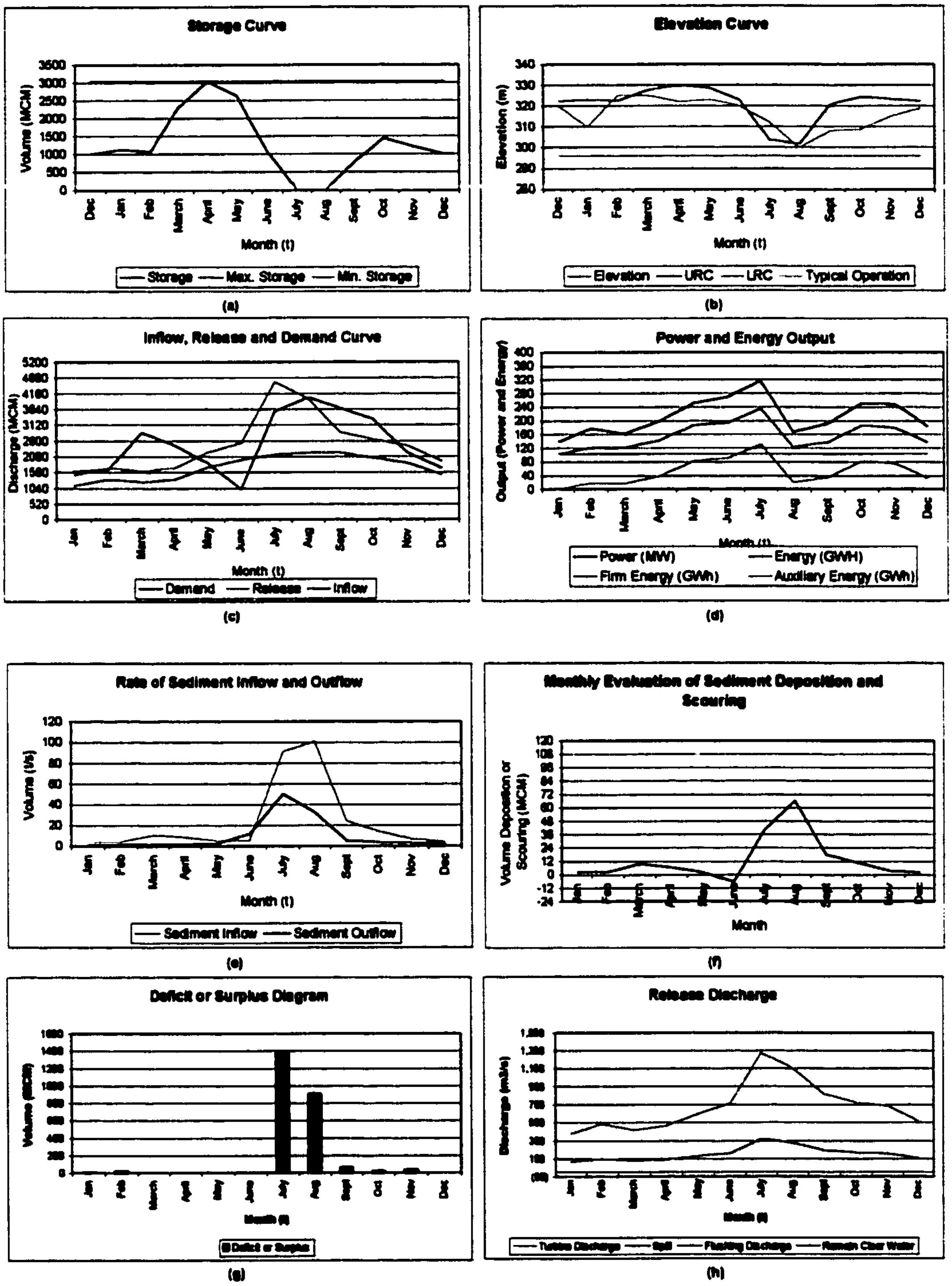

Figure 5-10. Results of Optimal Operation based on Equation E during Dry Year Operation based on Total Annual Energy Target

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5.6.2 Normal Year Operation

The optimal decision policy for maximizing hydropower and minimizing sediment deposition based on all five equations is indicated by optimal target achievement curve and presented in **Figure 5-11**. In this case, both of the two objectives, maximizing energy and minimizing sediment deposition, also have the same priority.

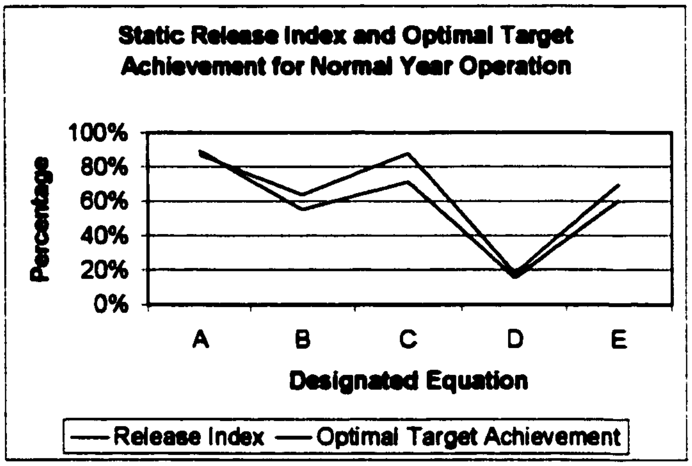

Figure 5-11. Static Value of Release Index Comparison for Five Different Equations A, B, C, D, and E during Normal Year of Operation

The operation planning is presented in the following section as results based on the five different equations of sediment outflow associated with the expended water discharge. The planning of operations deals with normal year operation applications and presents (a) storage curve, (b) elevation curve, (c) inflow, release and demand curve, (d) power and energy output, (e) rate of sediment inflow and outflow, (f) change of storage capacity, (g) shortage or surplus of the demand, and (h) release decision.

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5.6.2.1 Results Based on Sediment Release as Function of Bed Slope and Expended Water Discharge

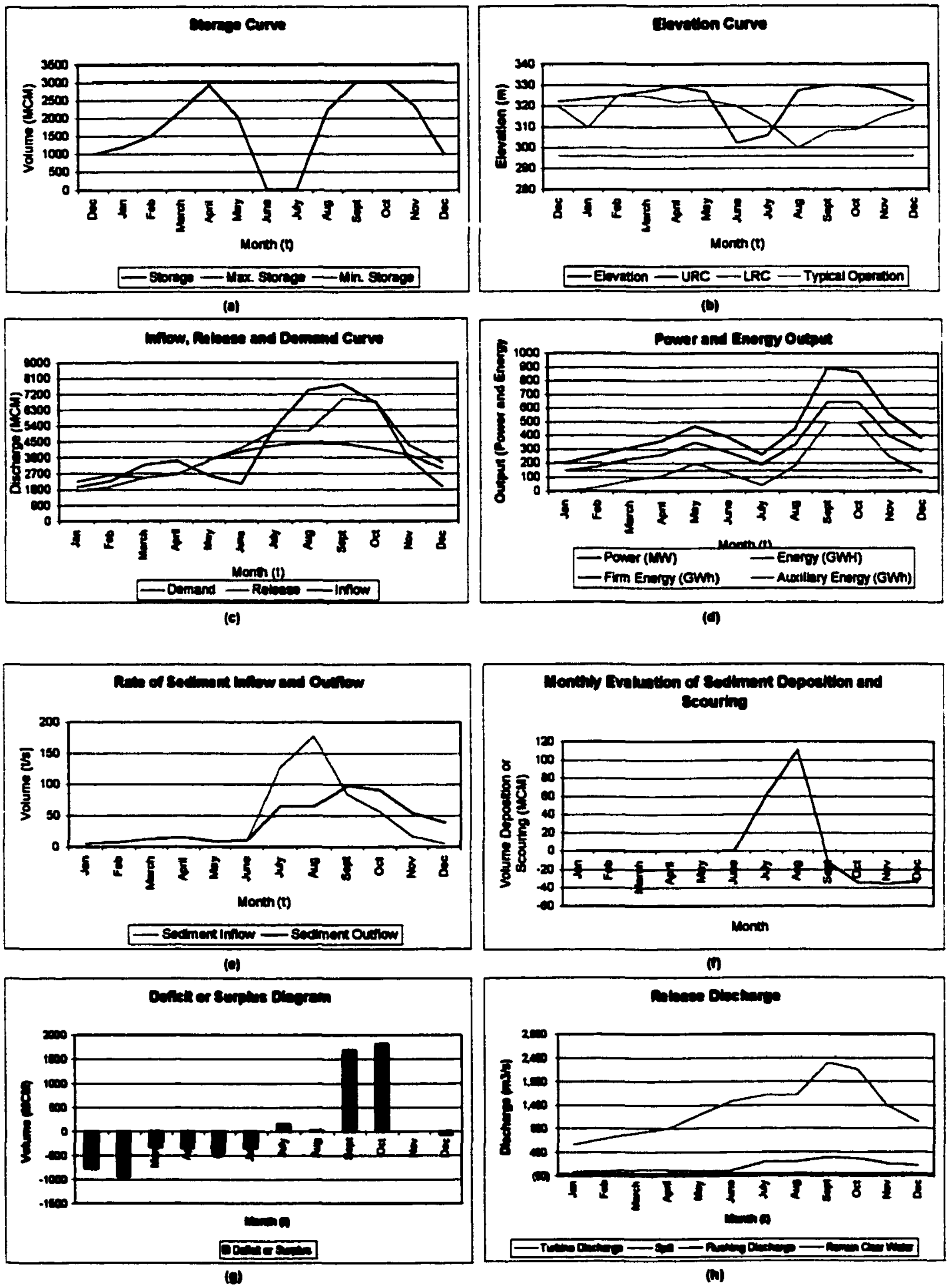

Figure 5-12. Results of Optimal Operation based on Equation A during Normal Year Operation based on Total Annual Energy Target

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5.6.2.2 Results Based on Sediment Release as Function of Bed Slope, Expended Water Discharge, Channel Width and Soil Erodibility

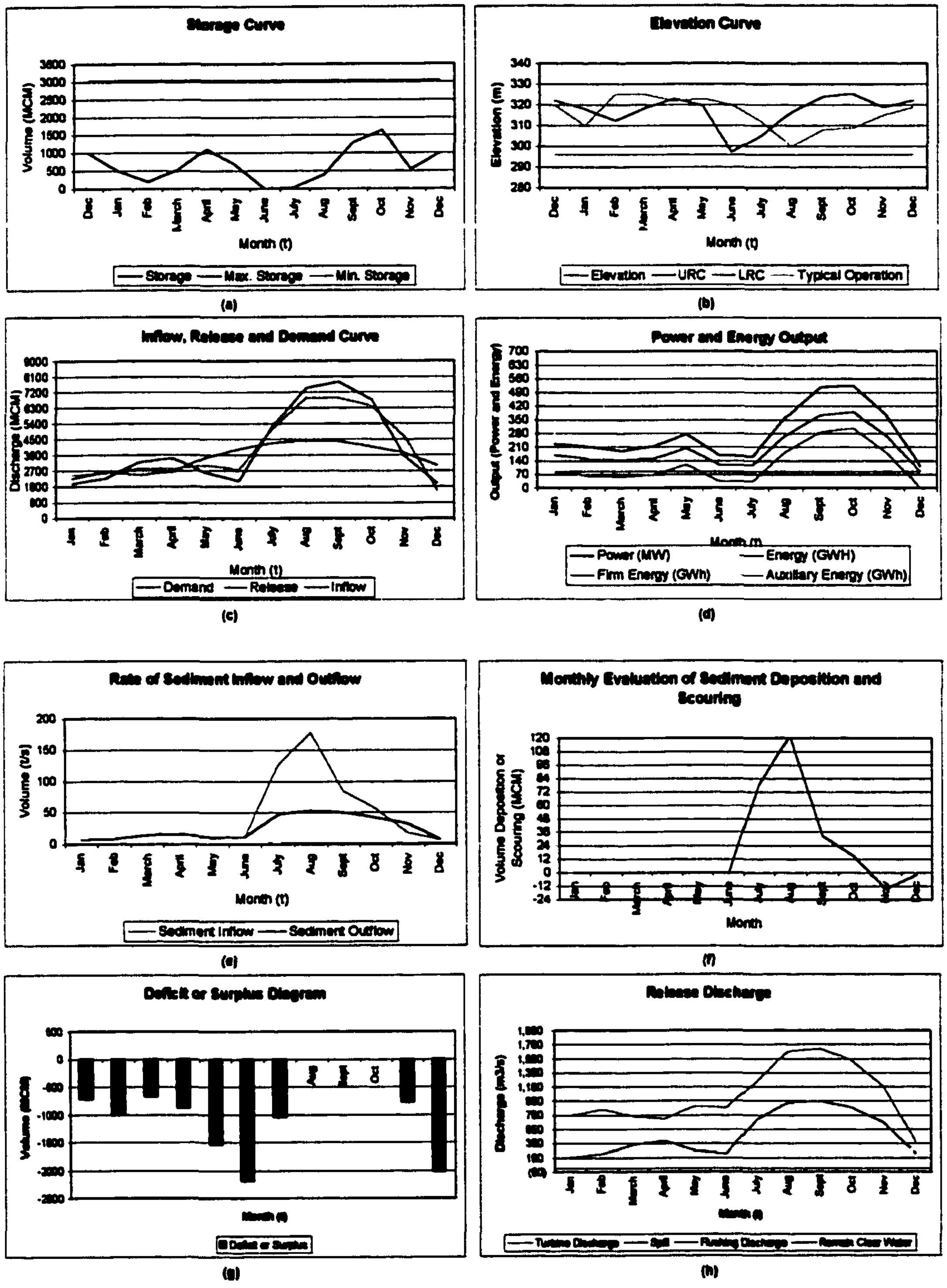

Figure 5-13. Results of Optimal Operation based on Equation B during Normal Year Operation based on Total Annual Energy Target

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5.6.2.3 Results Based on Sediment Release as Function of Bed Slope, Expended Water Discharge, Water Density and Water Inflow Discharge

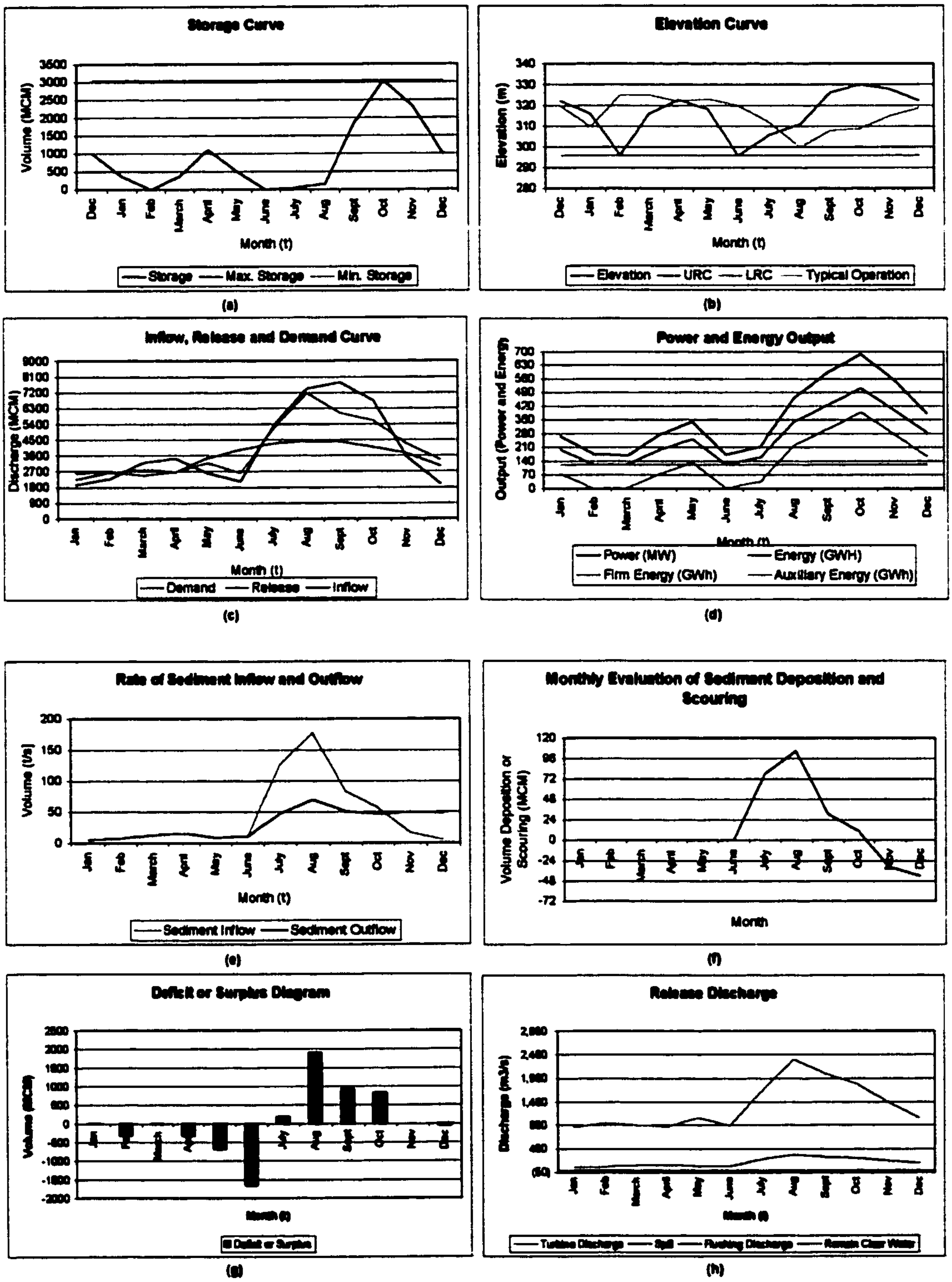

Figure 5-14. Results of Optimal Operation based on Equation C during Normal Year Operation based on Total Annual Energy Target

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5.6.2.4 Results Based on Sediment Release as Function of Bed Slope, Expended Water Discharge, Elevation Depth and Median Diameter of Sediment

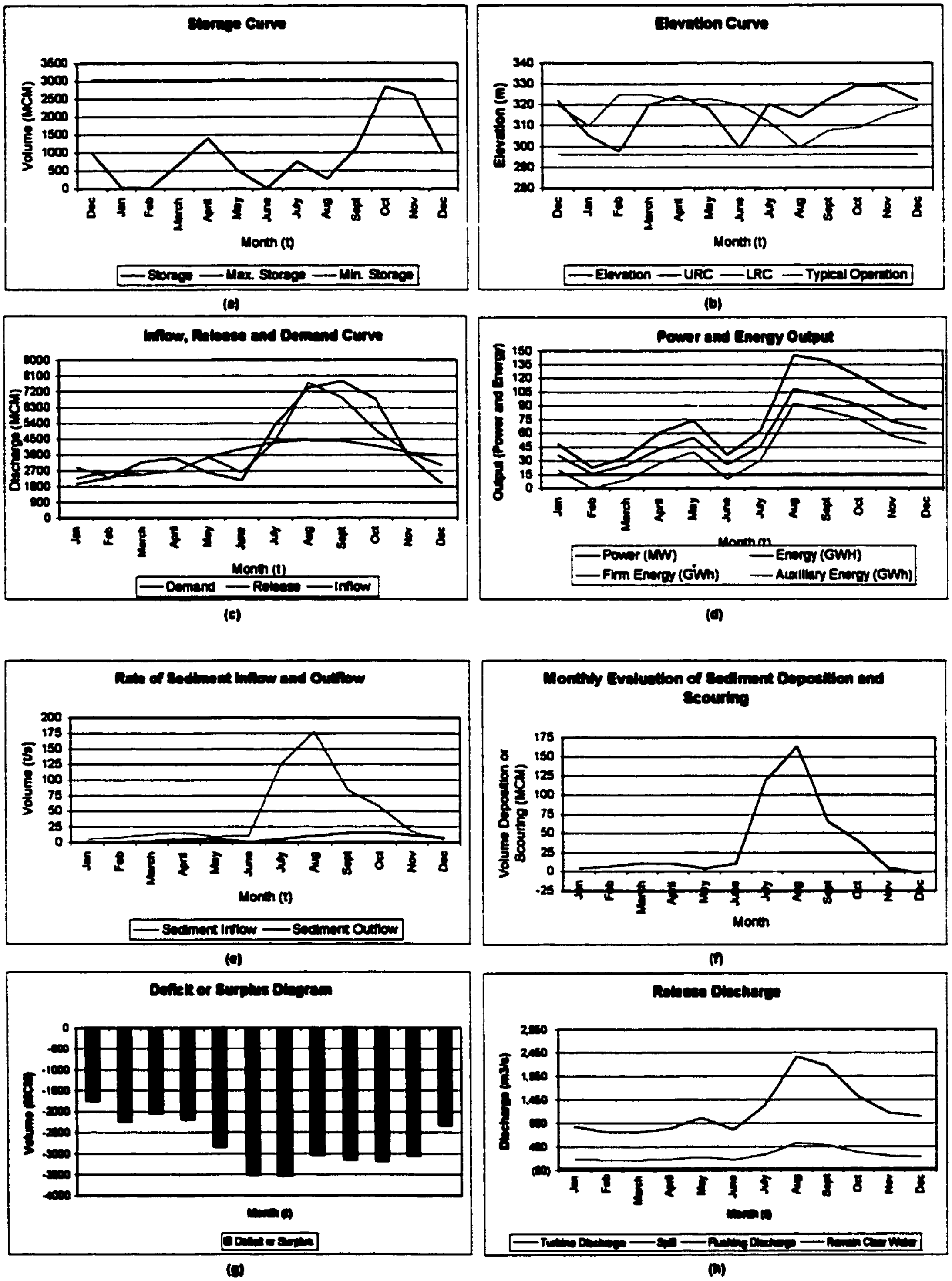

Figure 5-15. Results of Optimal Operation based on Equation D during Normal Year Operation based on Total Annual Energy Target

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5.6.2.5 Results Based on Sediment Release as Function of Bed Slope, Expended Water Discharge, Water Inflow Discharge and Sediment Inflow Concentration

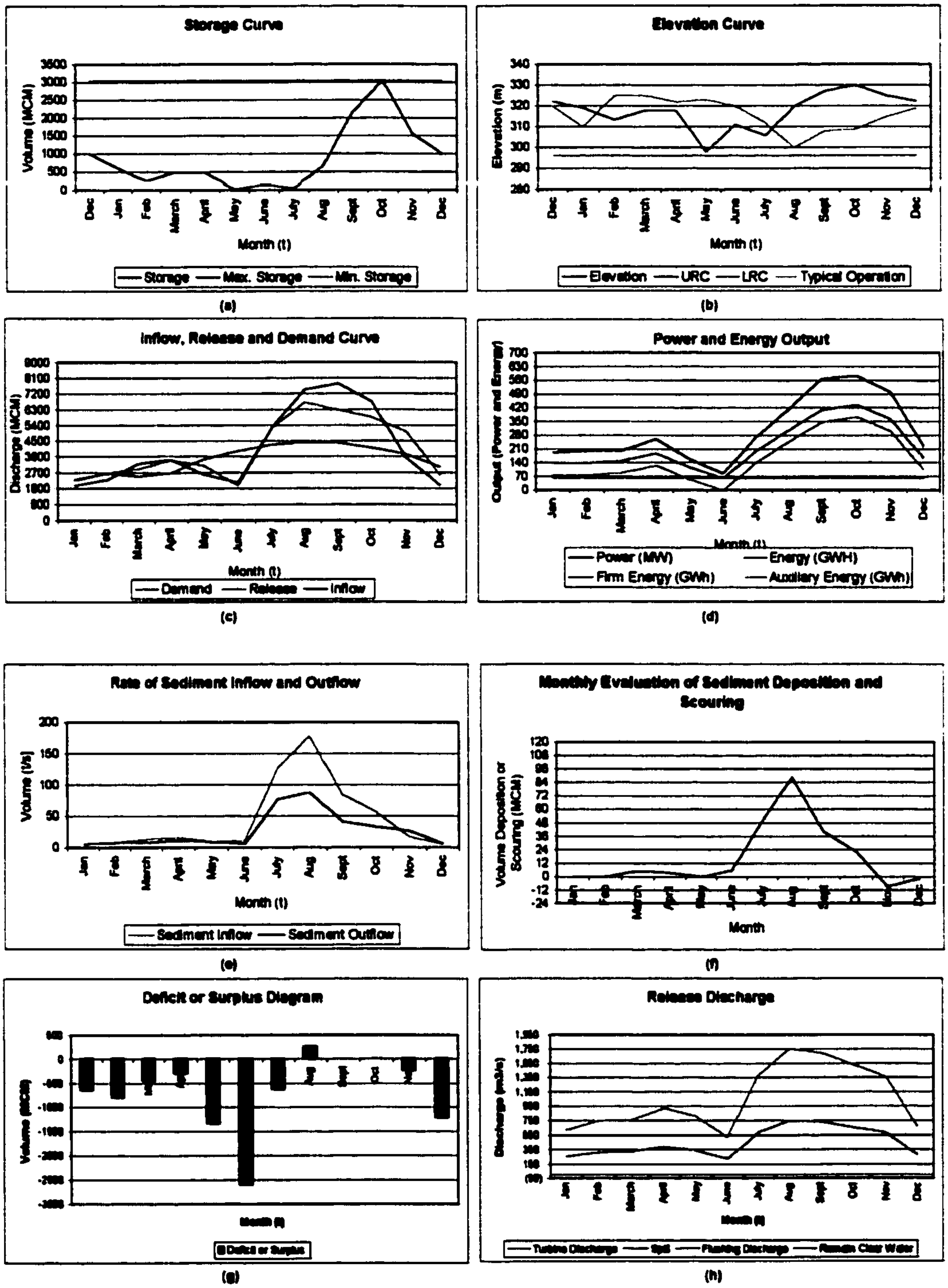

Figure 5-16. Results of Optimal Operation based on Equation E during Normal Year Operation based on Total Annual Energy Target

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5.6.3 Wet Year Operation

The optimal decision policy for all five equations is shown in **Figure 5-17**. The decision policy is based on the optimal value, such as release index and priority for both maximizing energy and minimizing sediment deposition. In this case, the optimal priority for both of the two objectives, maximizing energy and minimizing sediment deposition, has the same weight.

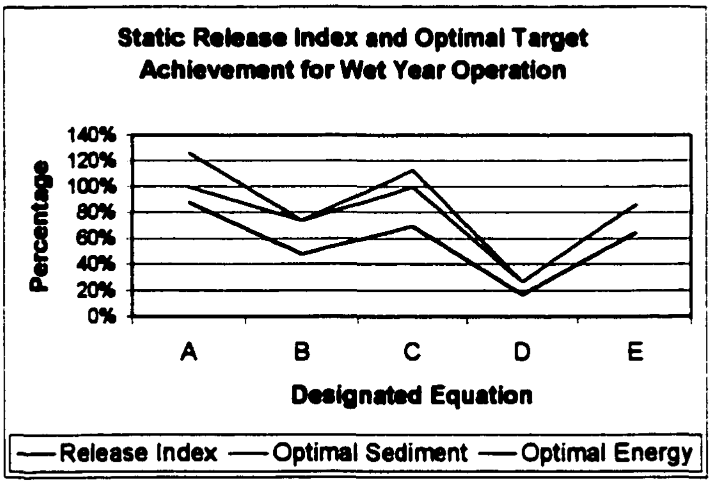

Figure 5-17. Static Value of Release Index Comparison for Five Different Equations A, B, C, D, and E during Wet Year of Operation

The optimal operation planning is shown in the following section as results based on the five different equations of sediment outflow associated with the expended water discharge. The planning of operations includes wet year operation applications, and presents (a) storage curve, (b) elevation curve, (c) inflow, release and demand curve, (d) power and energy output, (e) rate of sediment inflow and outflow, (f) change of storage capacity, (g) shortage or surplus of the demand, and (h) release decision. Those figures are presented for monthly operation.

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5.6.3.1 Results Based on Sediment Release as Function of Bed Slope and Expended Water Discharge

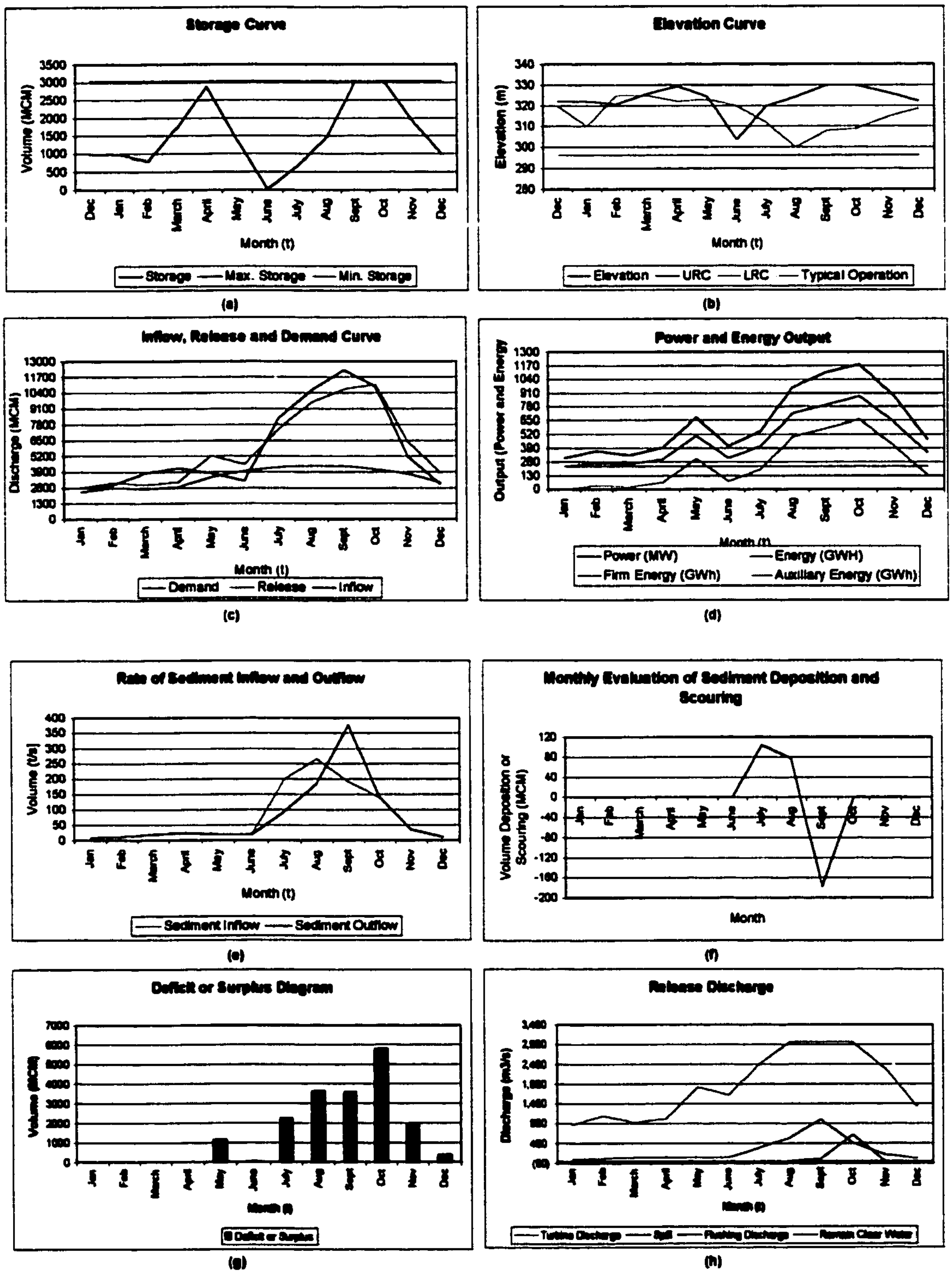

Figure 5-18. Results of Optimal Operation based on Equation A during Wet Year Operation based on Total Annual Energy Target

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5.6.3.2 Results Based on Sediment Release as Function of Bed Slope, Expended Water Discharge, Channel Width and Soil Erodibility

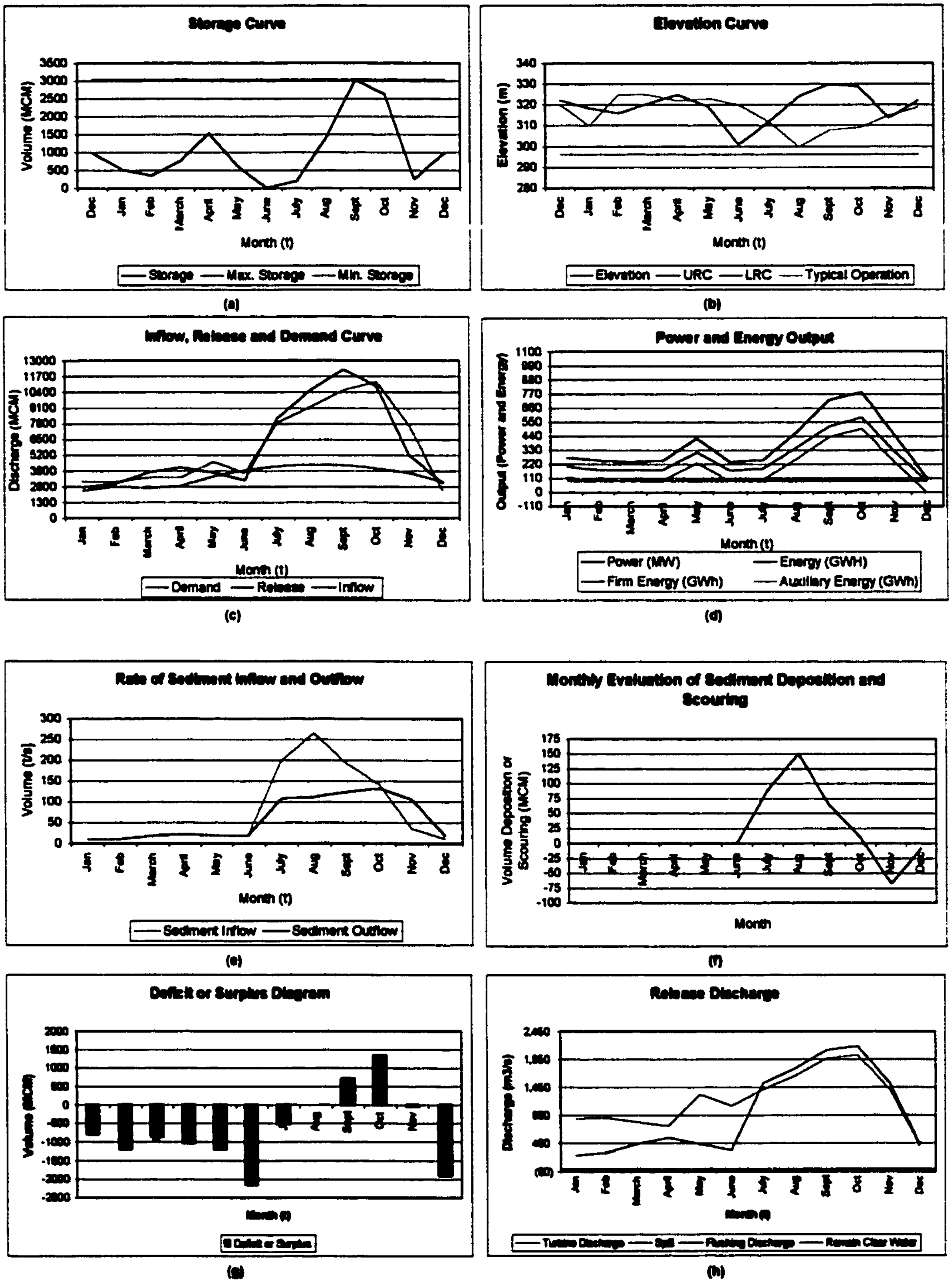

Figure 5-19. Results of Optimal Operation based on Equation B during Wet Year Operation based on Total Annual Energy Target

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5.6.3.3 Results Based on Sediment Release as Function of Bed Slope, Expended Water Discharge, Water Density and Water Inflow Discharge

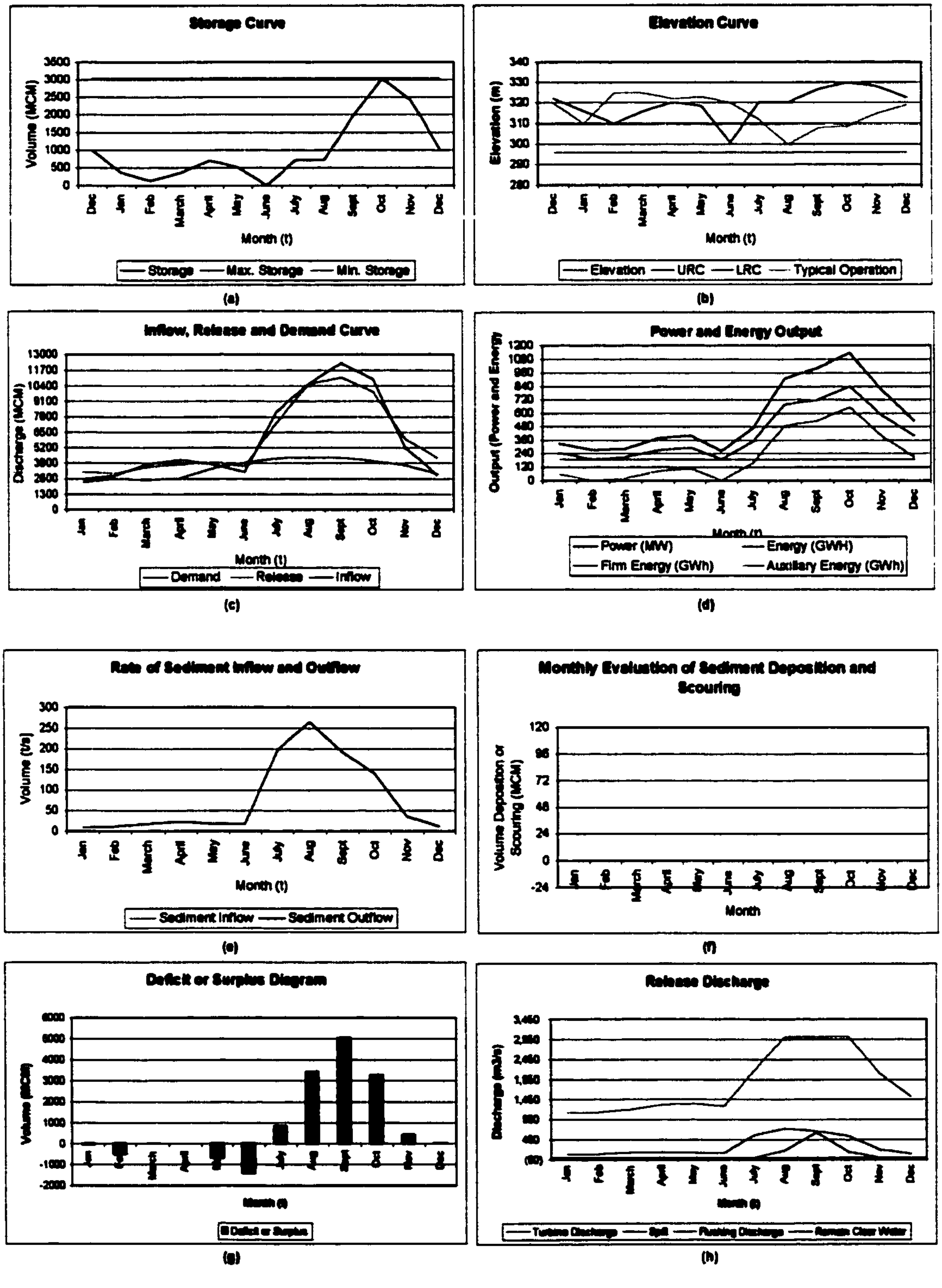

Figure 5-20. Results of Optimal Operation based on Equation C during Wet Year Operation based on Total Annual Energy Target

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5.6.3.4 Results Based on Sediment Release as Function of Bed Slope, Expended Water Discharge, Elevation Depth and Median Diameter of Sediment

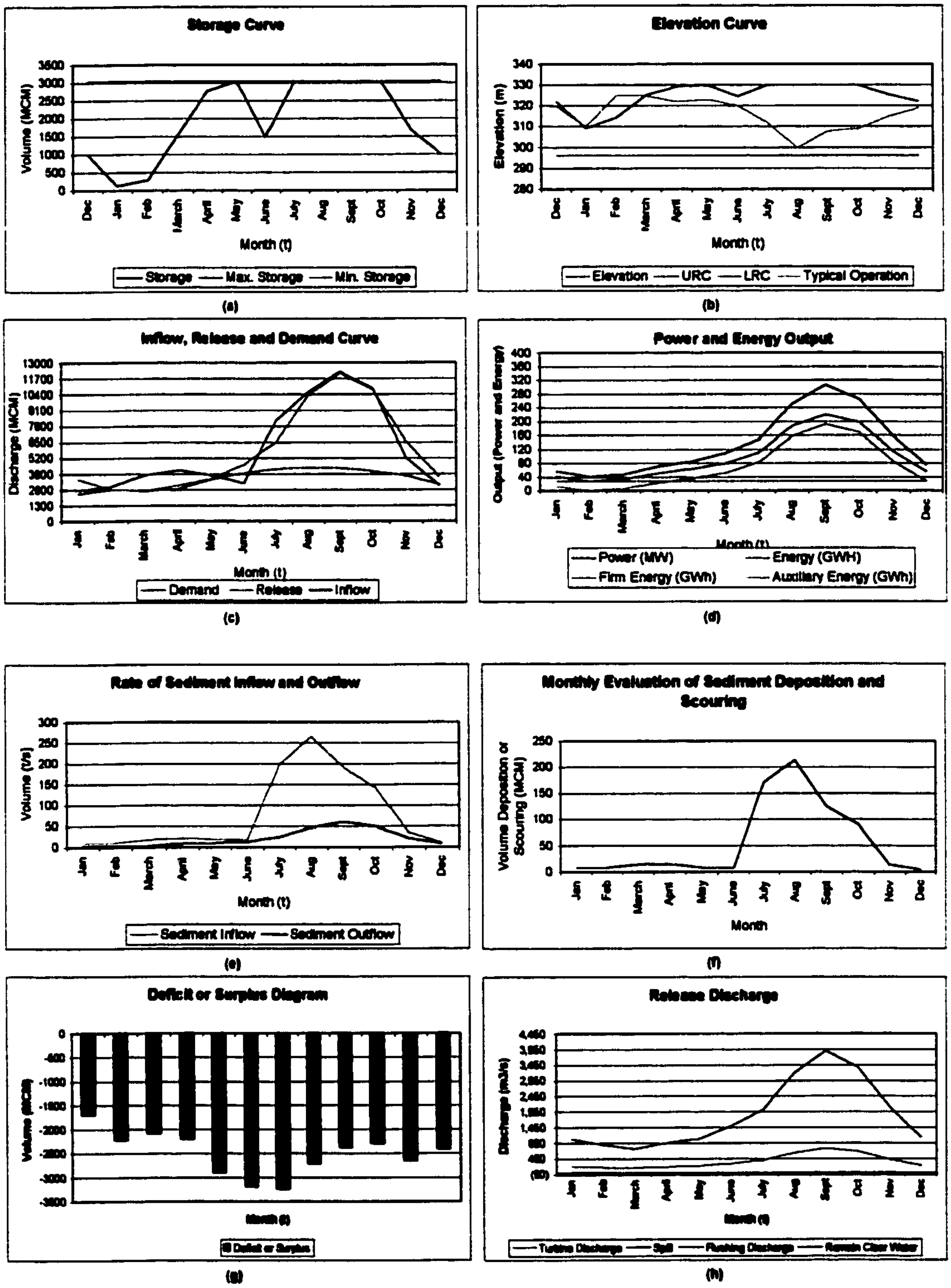

Figure 5-21. Results of Optimal Operation based on Equation D during Wet Year Operation based on Total Annual Energy Target

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5.6.3.5 Results Based on Sediment Release as Function of Bed Slope, Expended Water Discharge, Water Inflow Discharge and Sediment Inflow Concentration

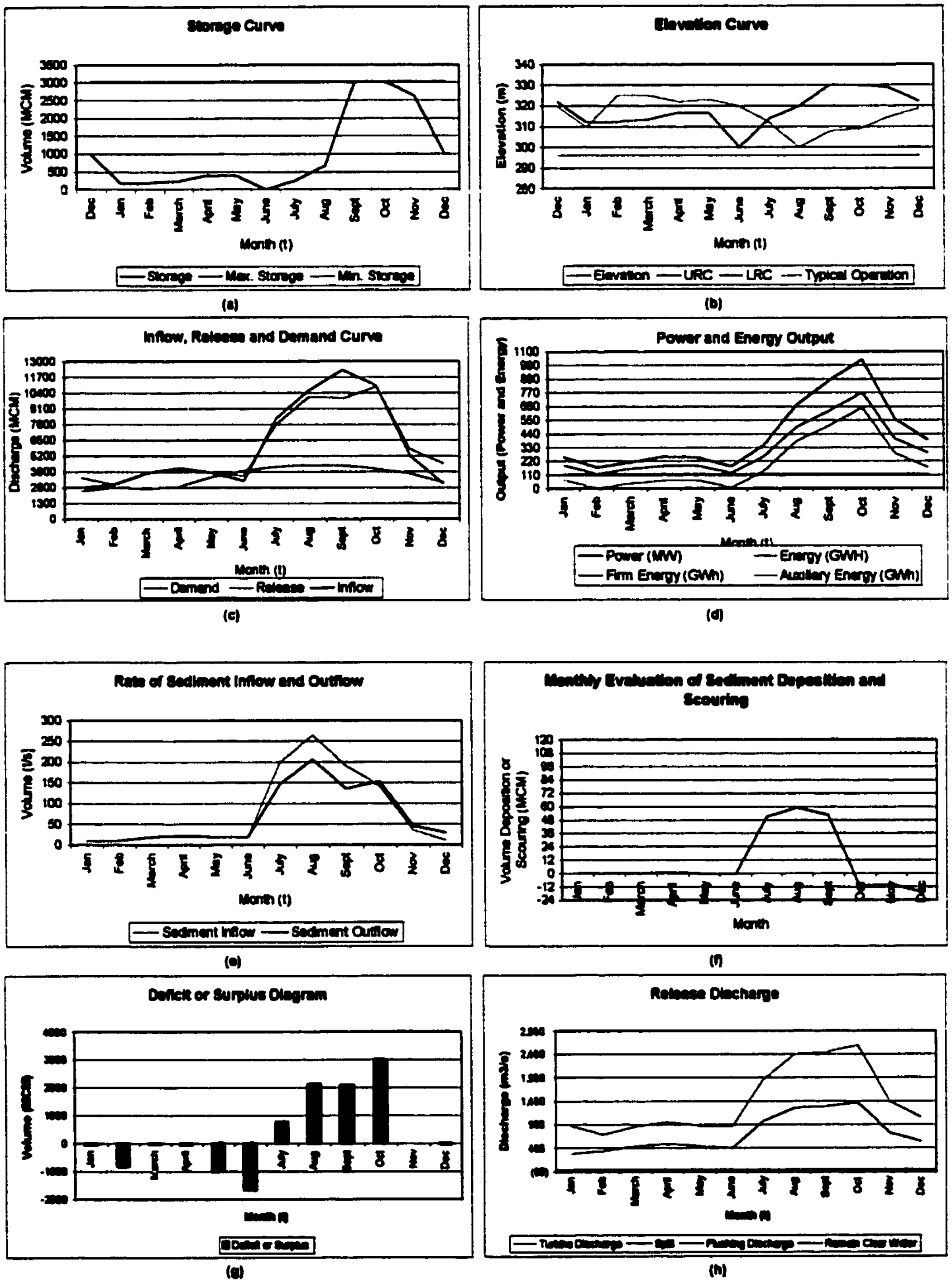

Figure 5-22. Results of Optimal Operation based on Equation E during Wet Year Operation based on Total Annual Energy Target

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5.7. Optimal Decision Policy of Reservoir Sediment-Control Operation Model based on Annual Firm Energy Target

Under the same assumptions, the optimal decision policy of reservoir sediment-control operation model based on annual firm energy target is presented. The results include dry, normal, and wet year operation. In this case, the firm energy is assumed to be constant. Then, the total annual value of firm energy is used for the target in the developed model excluding the sediment release operation.

As in the previous execution, the static value is given as initial trial-value and changed to search the desired priority based on both objectives. On the other hand, in this case, the optimal decision policy is found by searching the same priority or weight for both the annual firm energy provided and sediment release based on the total annual firm energy target and sediment release target. The value of static release index would be the same for all months of the year of operation planning.

5.7.1 Dry Year Operation Results

The optimal decision policy for all five equations is presented in **Figure 5-23**. The decision policy is based on the optimal value of static release index, and the same priority for both maximizing annual firm energy and minimizing sediment deposition.

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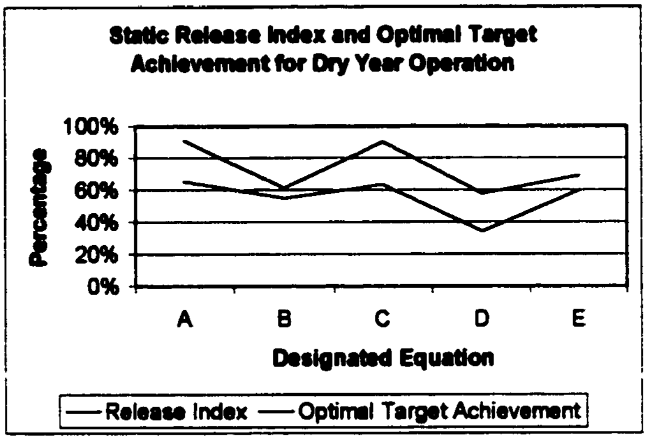

Figure 5-23. Static Value of Release Index and Optimal Weight Comparison for Five Different Equations A, B, C, D, and E during Dry Year Operation

The operation planning is presented in the following section based on monthly operations. The planning of operations presented related to dry year operation applications and consists of (a) storage curve, (b) elevation curve, (c) rate of sediment inflow and outflow, and (d) power and energy output.

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5.7.1.1 Results Based on Sediment Release as Function of Bed Slope and Expended Water Discharge

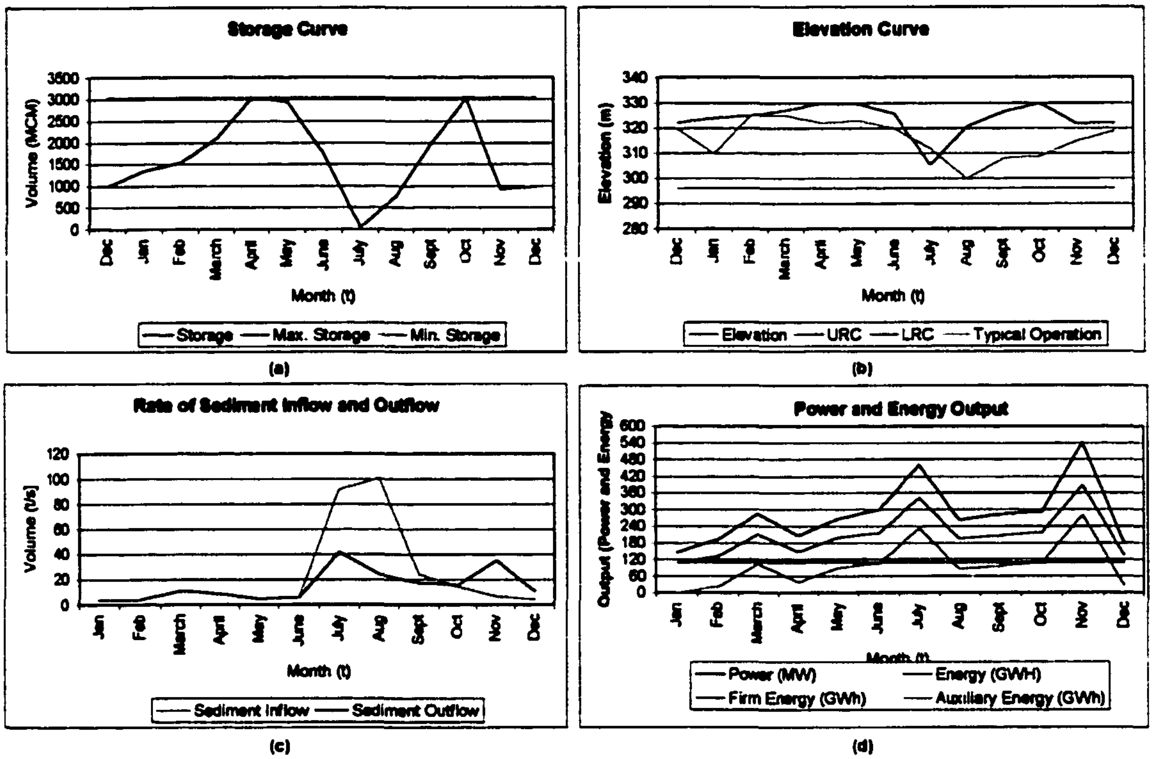

Figure 5-24. Results of Optimal Operation based on Equation A during Dry Year Operation based on Annual Firm Energy Target

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5.7.1.2 Results Based on Sediment Release as Function of Bed Slope, Expended Water Discharge, Channel Width and Soil Erodibility

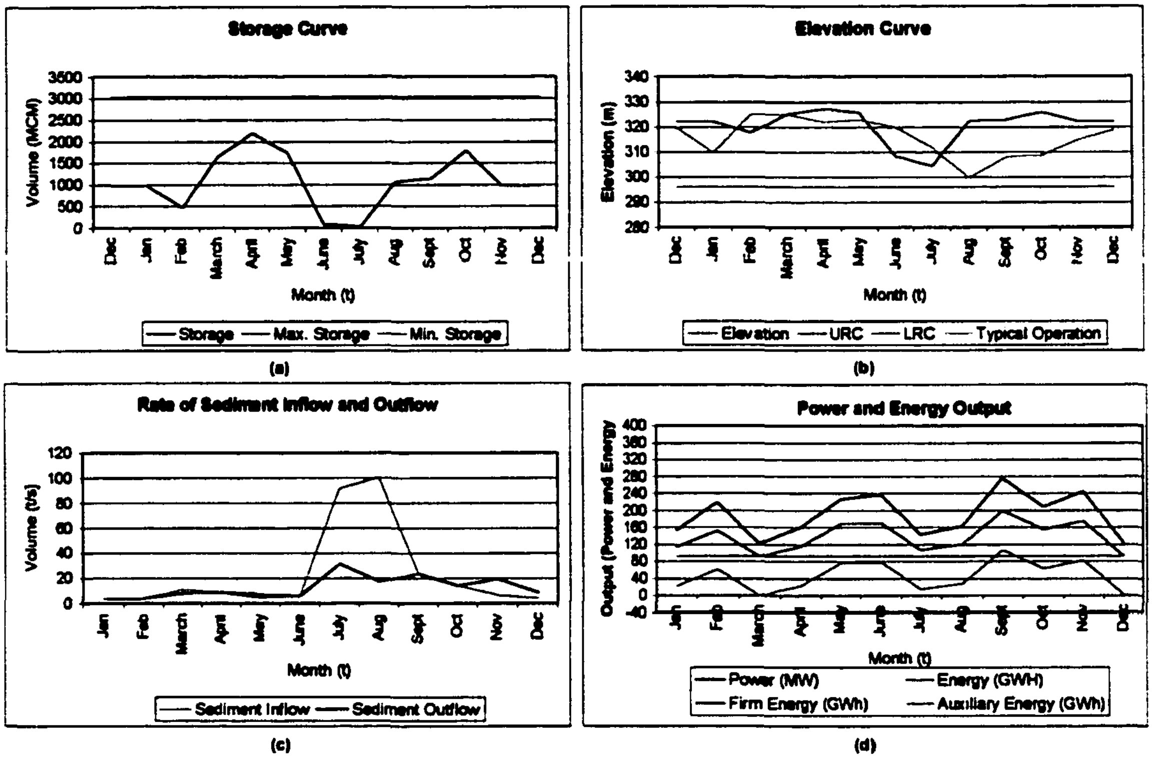

Figure 5-25. Results of Optimal Operation based on Equation B during Dry Year Operation based on Annual Firm Energy Target

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5.7.1.3 Results Based on Sediment Release as Function of Bed Slope, Expended Water Discharge, Water Density and Water Inflow Discharge

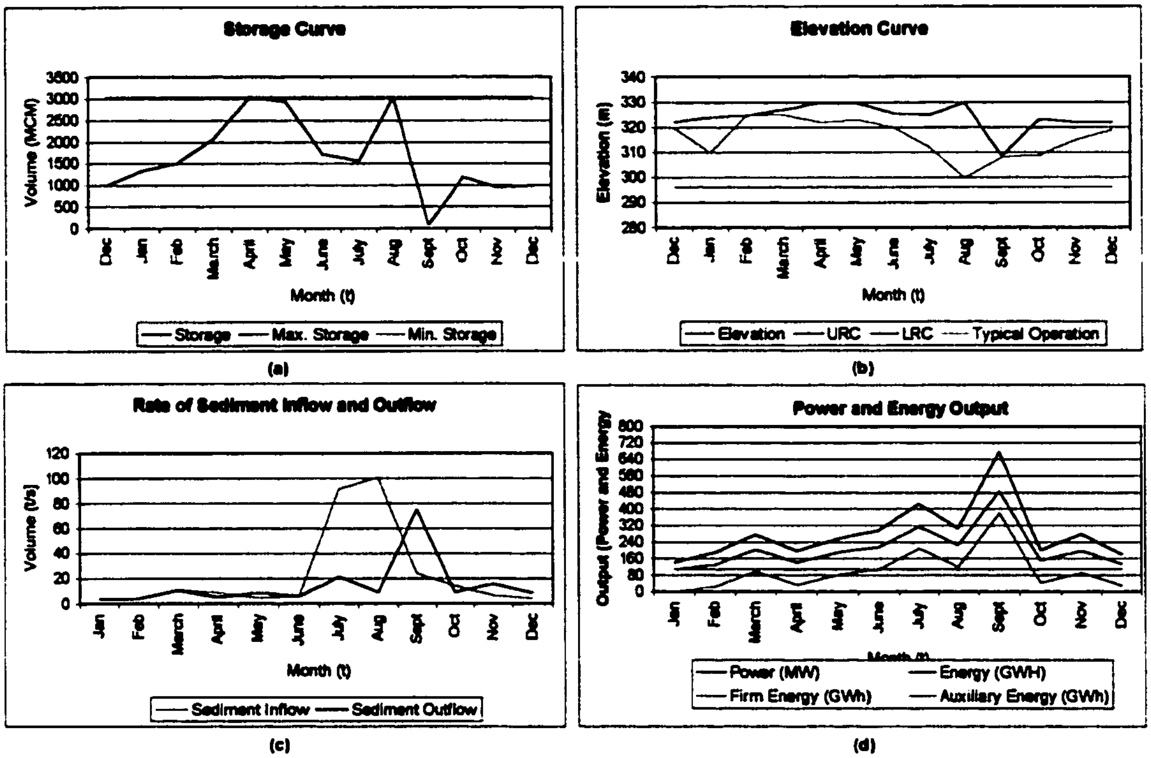

Figure 5-26. Results of Optimal Operation based on Equation C during Dry Year Operation based on Annual Firm Energy Target

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5.7.1.4 Results Based on Sediment Release as Function of Bed Slope, Expended Water Discharge, Elevation Depth and Median Diameter of Sediment

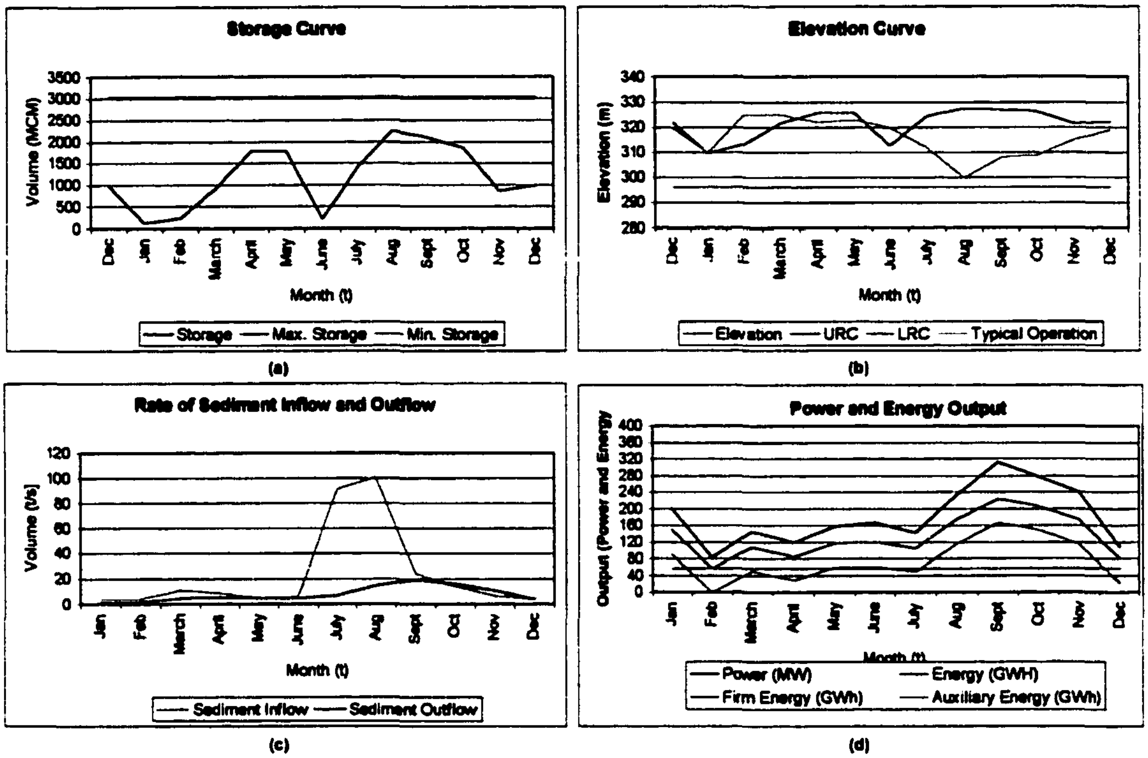

Figure 5-27. Results of Optimal Operation based on Equation D during Dry Year Operation based on Annual Firm Energy Target

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5.7.1.5 Results Based on Sediment Release as Function of Bed Slope, Expended Water Discharge, Water Inflow Discharge and Sediment Inflow Concentration

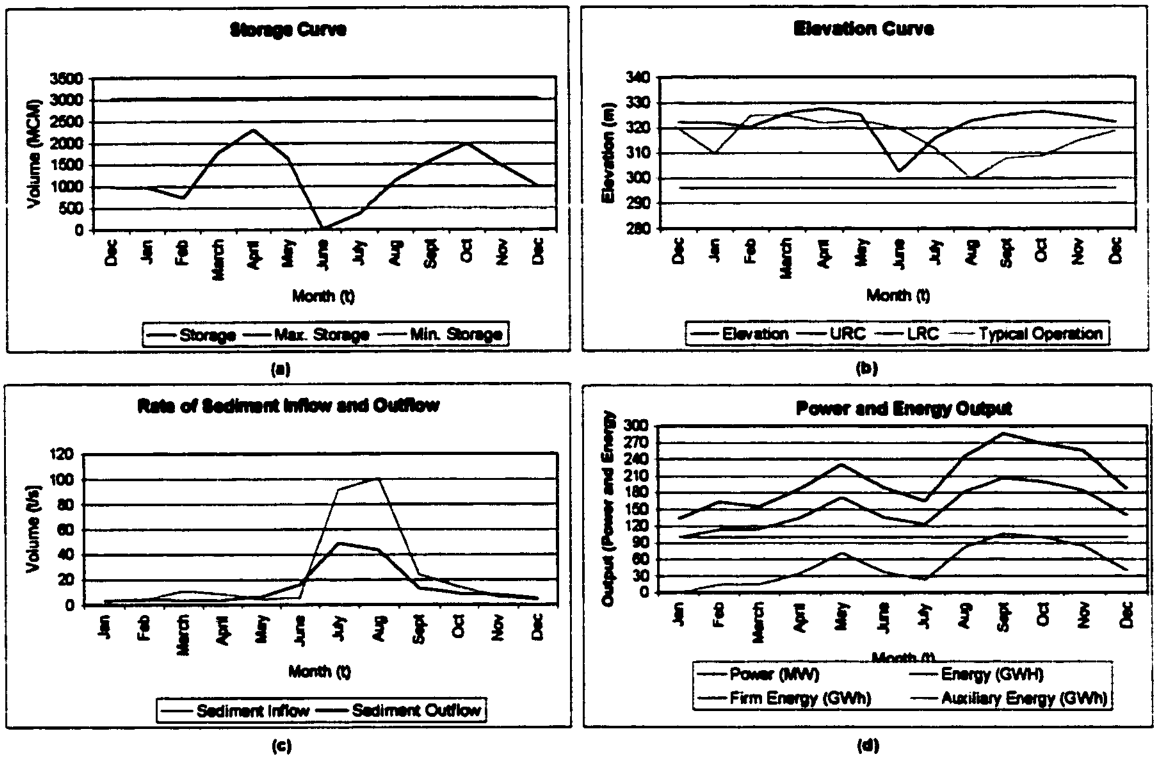

Figure 5-28. Results of Optimal Operation based on Equation E during Dry Year Operation based on Annual Firm Energy Target

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5.7.2 Normal Year Operation

The optimal decision policy, for maximizing hydropower and minimizing sediment deposition based on all five equations, is indicated by optimal target achievement curve and presented in **Figure 5-29**. In this case, both of the two objectives, maximizing annual firm energy and minimizing sediment deposition, also have the same weight or priority in the model.

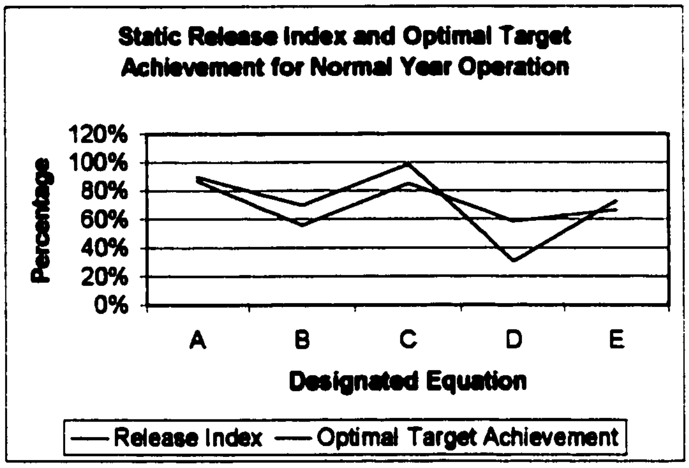

Figure 5-29. Static Value of Release Index Comparison for Five Different Equations A, B, C, D, and E during Normal Year of Operation

As in the previous section, the planning of operations includes normal year operation applications and presents (a) storage curve, (b) elevation curve, (c) rate of sediment inflow and outflow, and (d) power and energy output.

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5.7.2.1 Results Based on Sediment Release as Function of Bed Slope and Expended Water Discharge

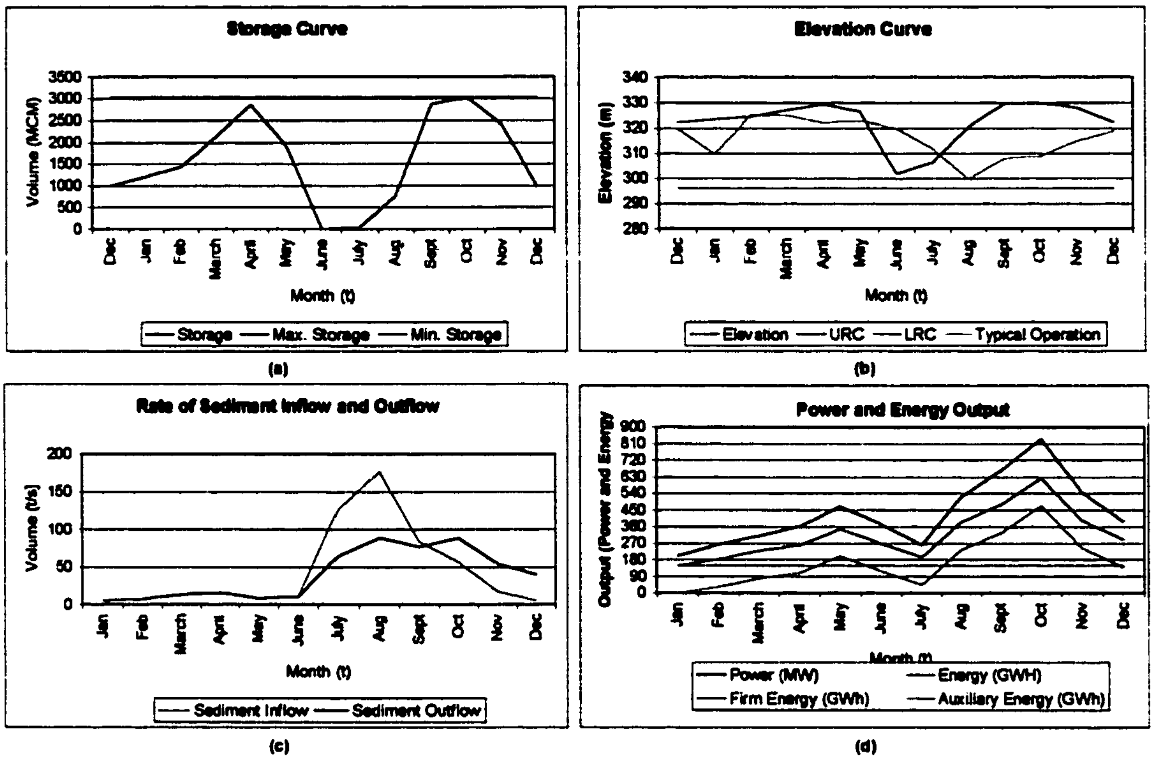

Figure 5-30. Results of Optimal Operation based on Equation A during Normal Year Operation based on Annual Firm Energy Target

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5.7.2.2 Results Based on Sediment Release as Function of Bed Slope, Expended Water Discharge, Channel Width and Soil Erodibility

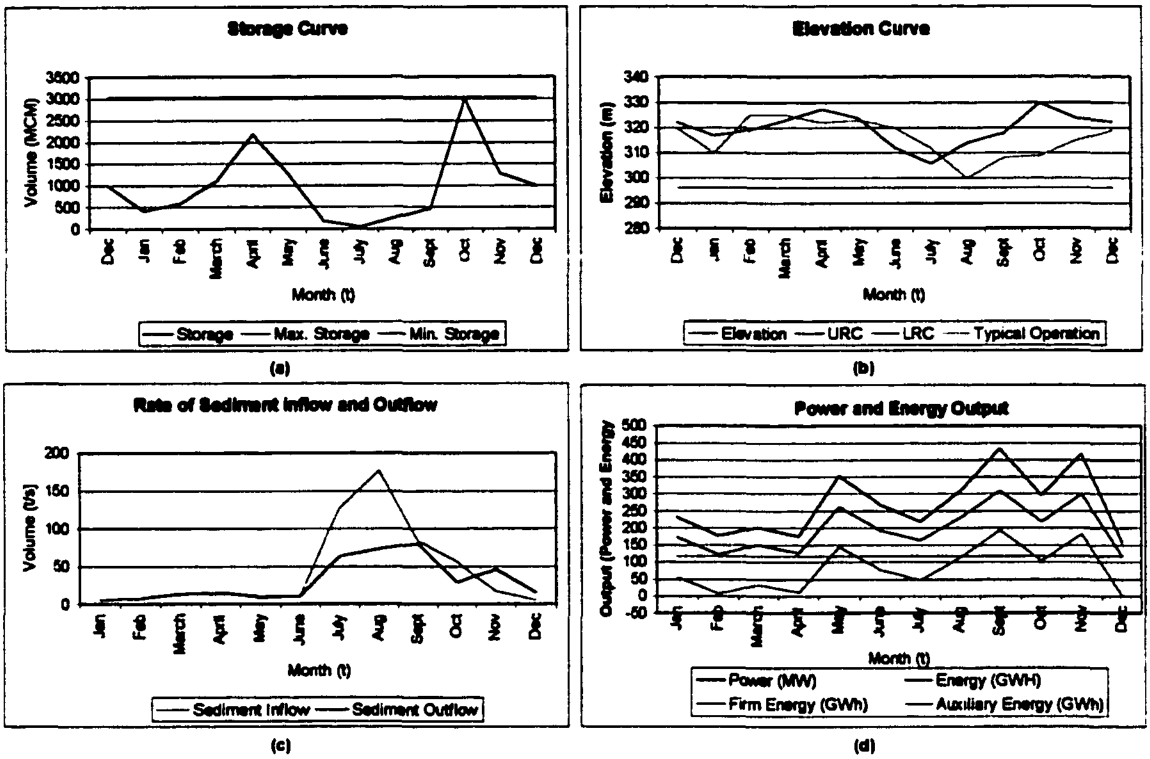

Figure 5-31. Results of Optimal Operation based on Equation B during Normal Year Operation based on Annual Firm Energy Target

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5.7.2.3 Results Based on Sediment Release as Function of Bed Slope, Expended Water Discharge, Water Density and Water Inflow Discharge

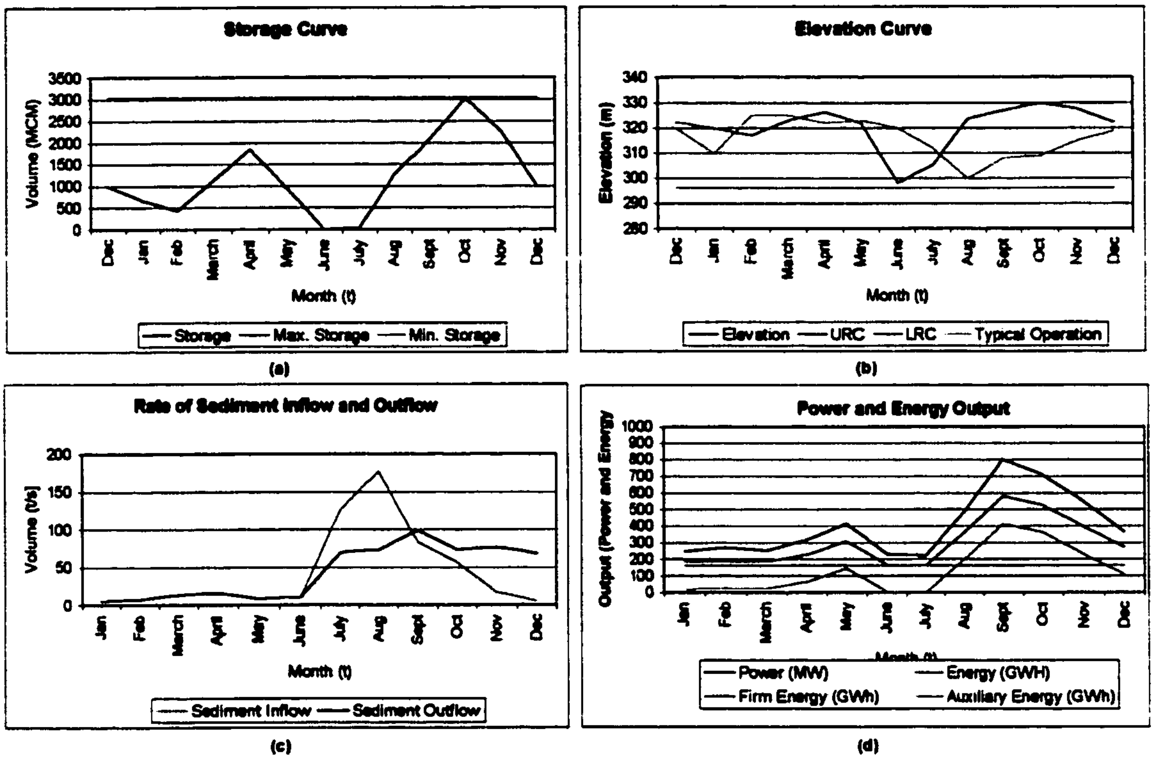

Figure 5-32. Results of Optimal Operation based on Equation C during Normal Year Operation based on Annual Firm Energy Target

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5.7.2.4 Results Based on Sediment Release as Function of Bed Slope, Expended Water Discharge, Elevation Depth and Median Diameter of Sediment

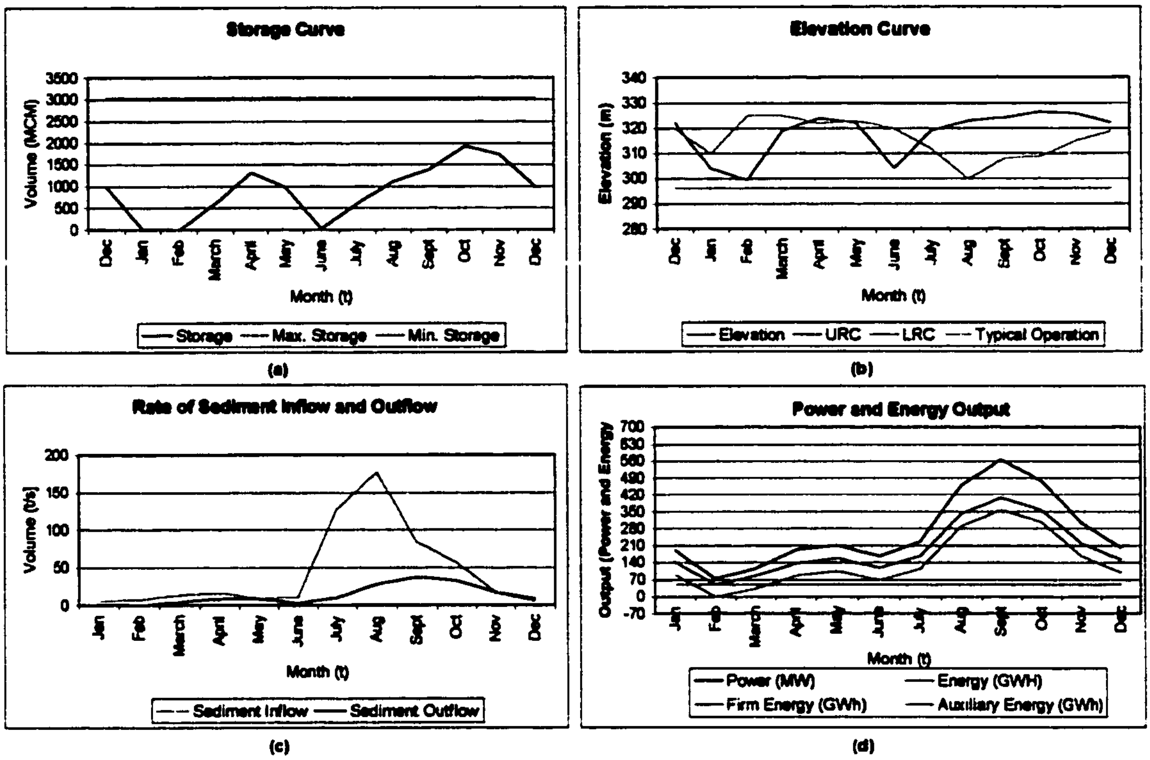

Figure 5-33. Results of Optimal Operation based on Equation D during Normal Year Operation based on Annual Firm Energy Target

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5.7.2.5 Results Based on Sediment Release as Function of Bed Slope, Expended Water Discharge, Water Inflow Discharge and Sediment Inflow Concentration

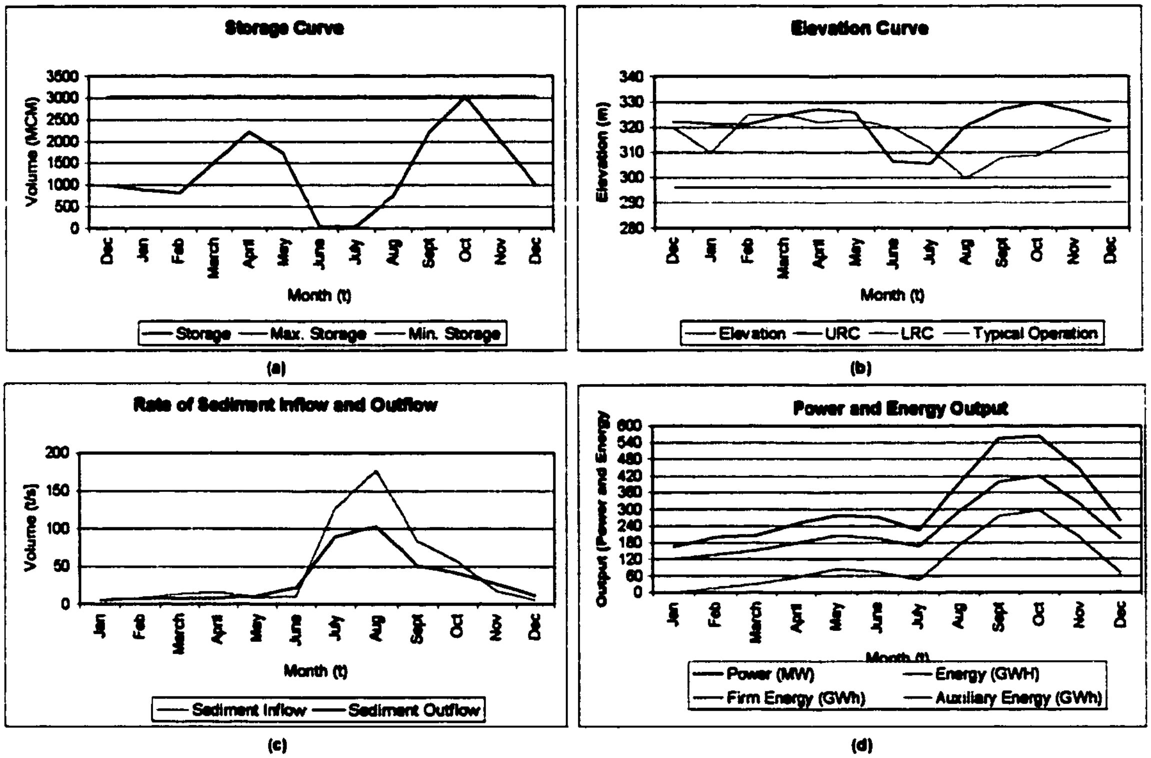

Figure 5-34. Results of Optimal Operation based on Equation E during Normal Year Operation based on Annual Firm Energy Target

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5.7.3 Wet Year Operation

The optimal decision policy for wet year operation is also presented in **Figure 5-35**. The decision policy is based on the optimal value of release index, and priority for both maximizing energy and minimizing sediment deposition. In addition, both of the two objectives, maximizing annual firm energy and minimizing sediment deposition, also have the same priority in the model and apply five different equations of sediment outflow relation. Equation A, B, D, and E have the same priority, however, Equation C provides different priority for hydropower generation and sediment release based on the designated target.

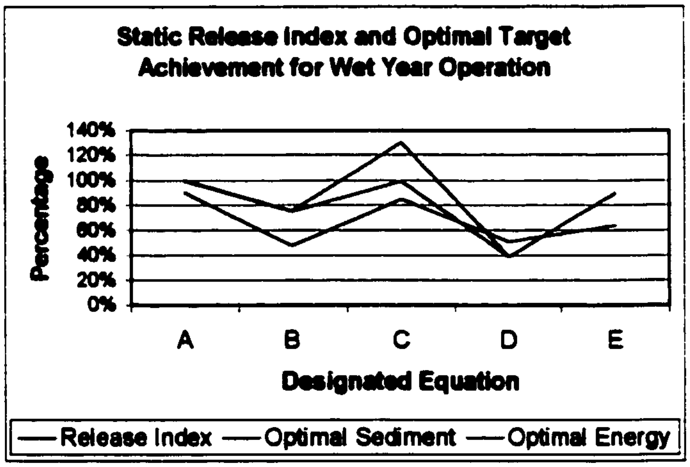

Figure 5-35. Static Value of Release Index Comparison for Five Different Equations A, B, C, D, and E during Wet Year of Operation

As in the previous section, the planning of operations deals with wet year operation applications and presents (a) storage curve, (b) elevation curve, (c) rate of sediment inflow and outflow, and (d) power and energy output.

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5.7.3.1 Results Based on Sediment Release as Function of Bed Slope and Expended Water Discharge

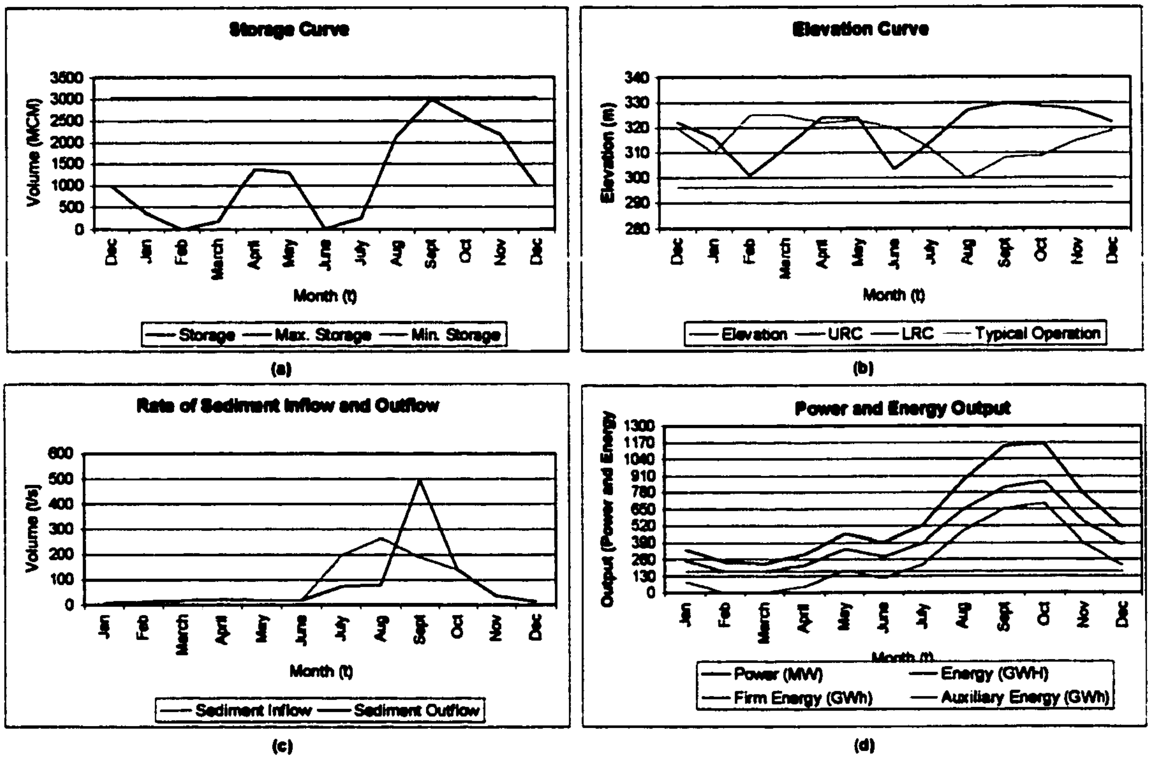

Figure 5-36. Results of Optimal Operation based on Equation A during Wet Year Operation based on Annual Firm Energy Target

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5.7.3.2 Results Based on Sediment Release as Function of Bed Slope, Expended Water Discharge, Channel Width and Soil Erodibility

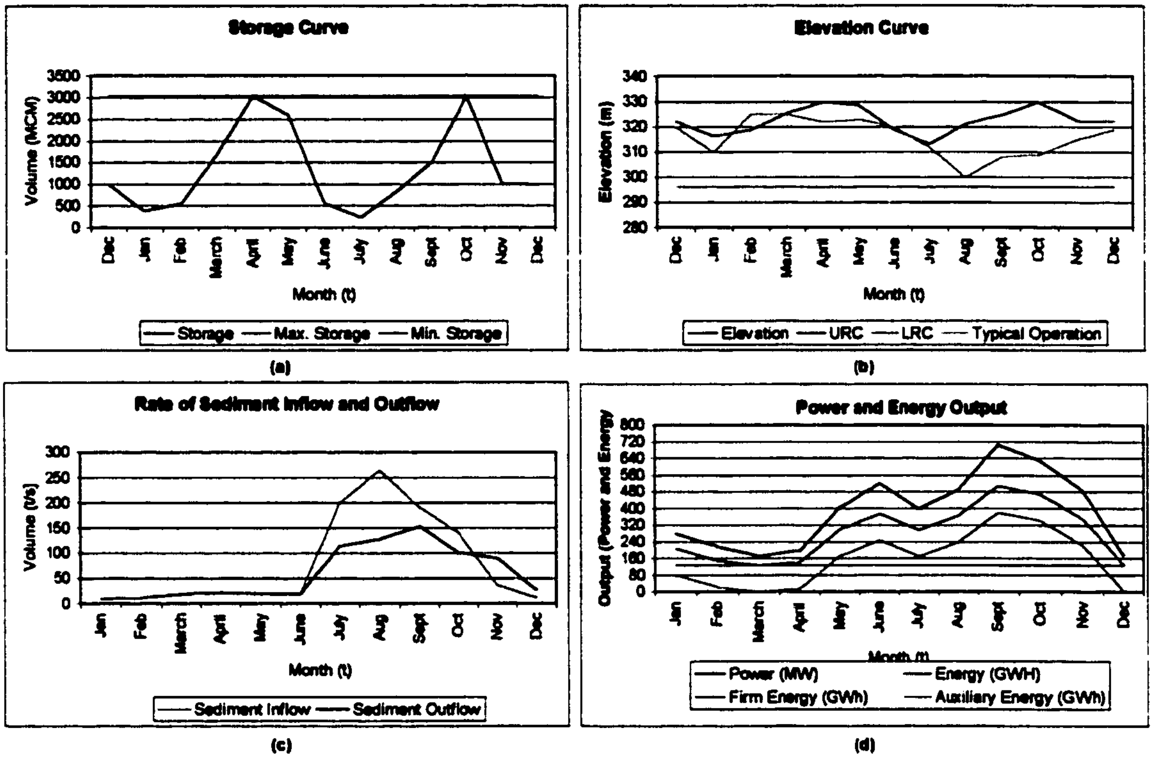

Figure 5-37. Results of Optimal Operation based on Equation B during Wet Year Operation based on Annual Firm Energy Target

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5.7.3.3 Results Based on Sediment Release as Function of Bed Slope, Expended Water Discharge, Water Density and Water Inflow Discharge

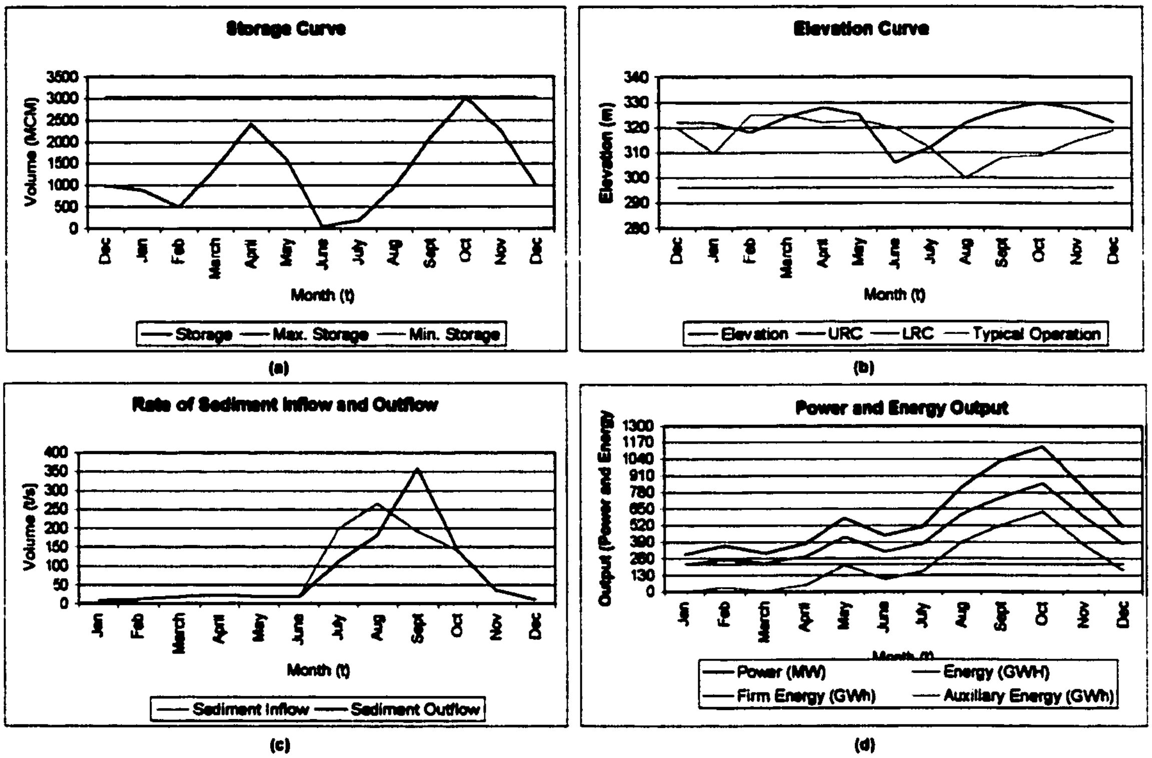

Figure 5-38. Results of Optimal Operation based on Equation C during Wet Year Operation based on Annual Firm Energy Target

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5.7.3.4 Results Based on Sediment Release as Function of Bed Slope, Expended Water Discharge, Elevation Depth and Median Diameter of Sediment

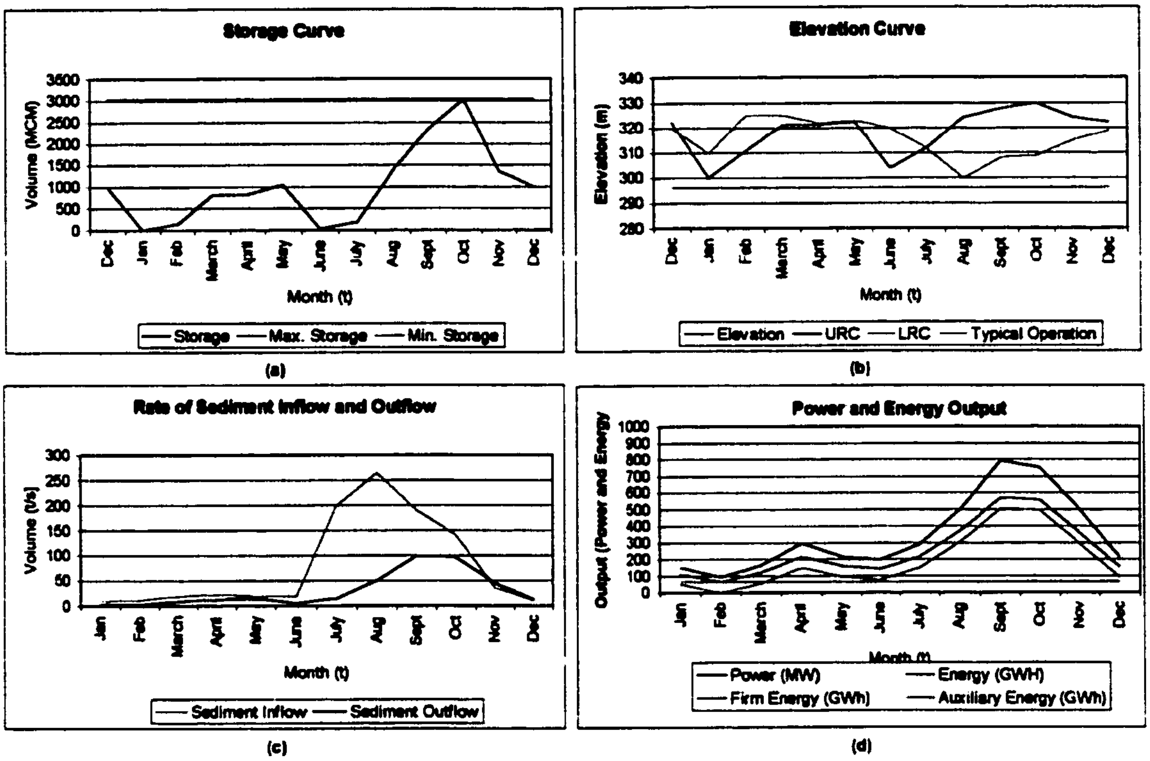

Figure 5-39. Results of Optimal Operation based on Equation D during Wet Year Operation based on Annual Firm Energy Target

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5.7.3.5 Results Based on Sediment Release as Function of Bed Slope, Expended Water Discharge, Water Inflow Discharge and Sediment Inflow Concentration

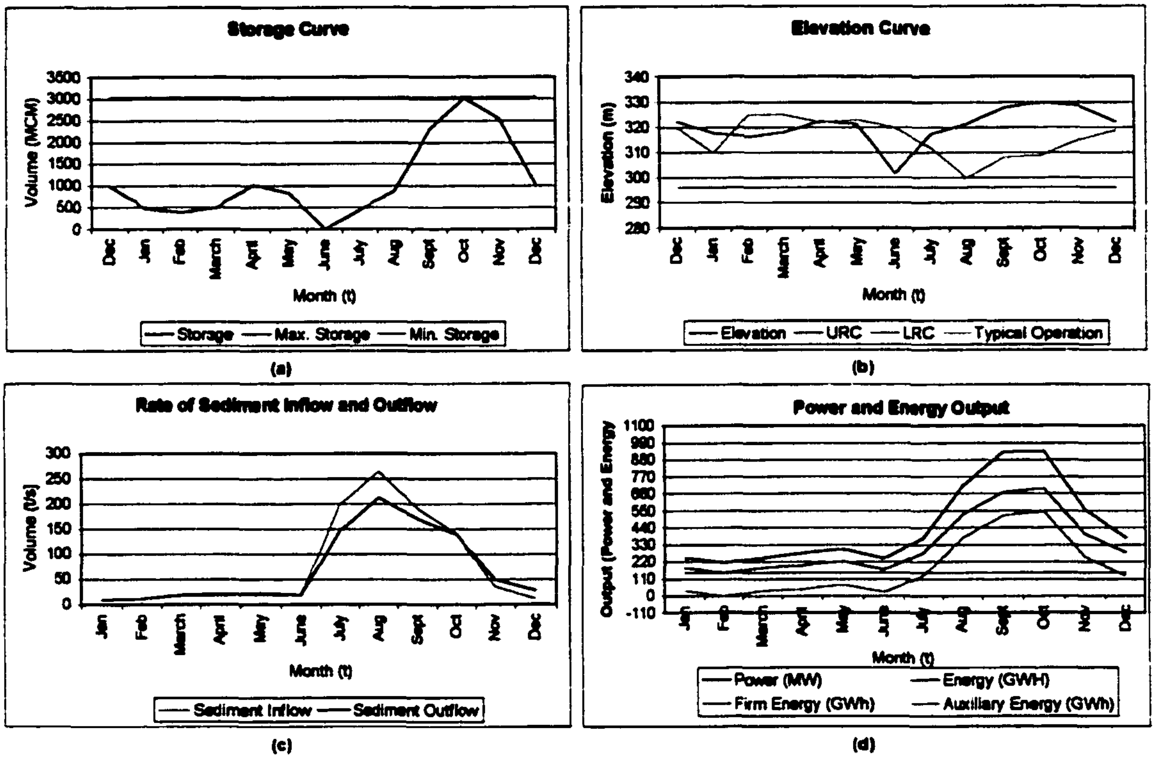

Figure 5-40. Results of Optimal Operation based on Equation E during Wet Year Operation based on Annual Firm Energy Target

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5.8. Establishment of Trade-off Curves

The desired priority of maximizing hydropower and minimizing sediment deposition depends upon the trial value of initial static release index. In the following section, the typical selected optimal decision curves of operation planning are presented. The figures are based on the results related to Equation B and D. Those two equations are selected since they have dependent variable follows the reservoir operation such as the depth of the reservoir.

The intersection point indicates the optimal value for both maximizing energy and minimizing sediment deposition in which it has certain value of static release index. The intersection point also reflects the same priority or weight of reservoir operation based on the objective measure of maximizing hydropower and minimizing sediment deposition in the reservoir. Due to the sediment release operation achievement, the optimal intersection point also reflects the release efficiency of flushing sediment from reservoir.

The conditions such as dry and wet year operation are selected and evaluated related to both annual energy production target and annual firm energy generation target. Since for one or the other typical equations of sediment outflow have crucial sediment deposition during dry or wet year operation. The relation between the energy generation and sediment release achievement is also presented in the figures of the following section.

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5.8.1 Results of Trade-off Curves during Dry Year Operation

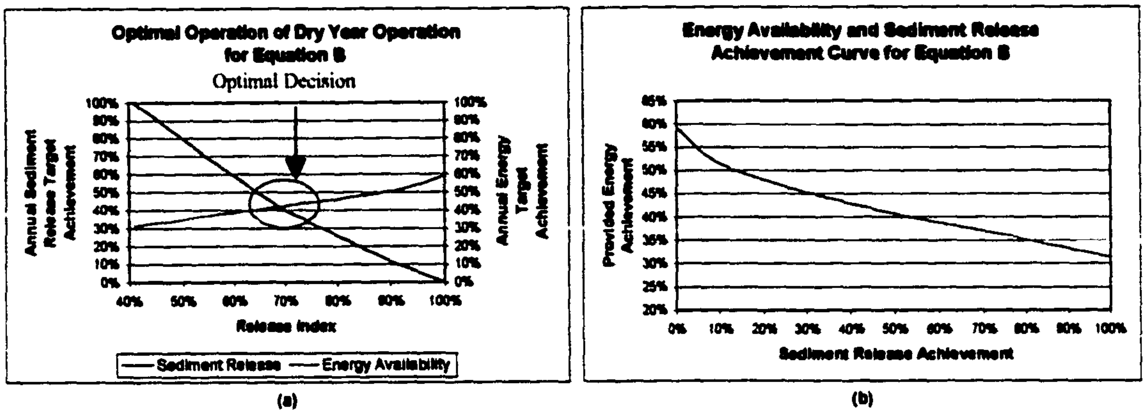

Figure 5-41. Optimal Value at Different Levels of (a) Static Release Index and (b) Energy Generation and Sediment Release Achievement, for Equation B during Dry Year Operation

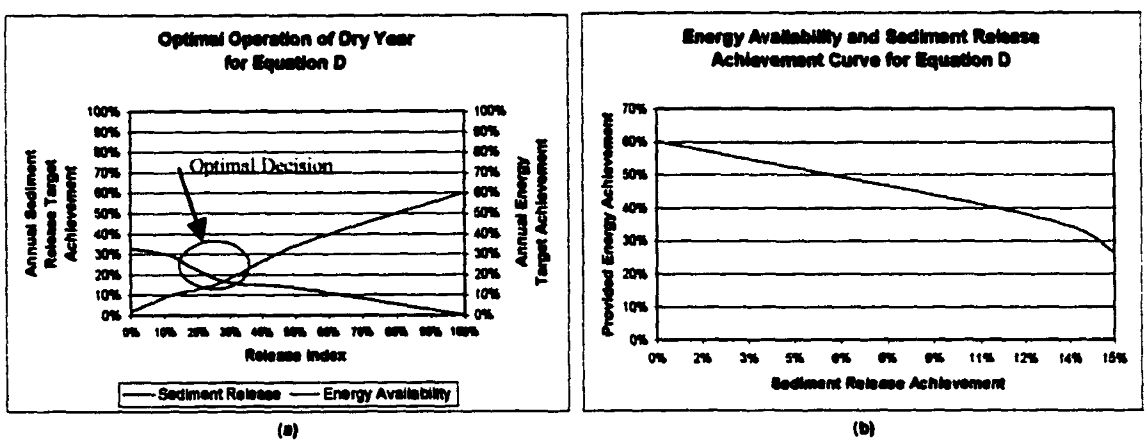

Figure 5-42. Optimal Value at Different Levels of (a) Release Index and (b) Energy Generation and Sediment Release Achievement, for Equation D during Dry Year Operation

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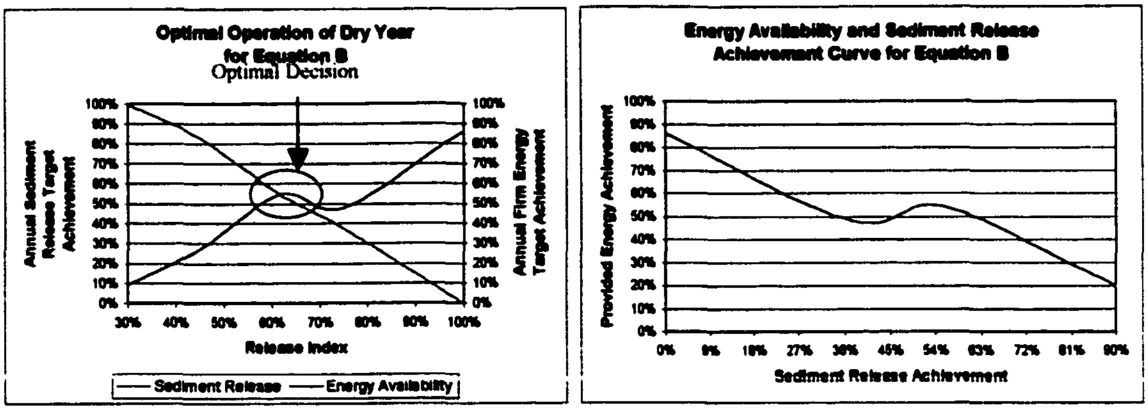
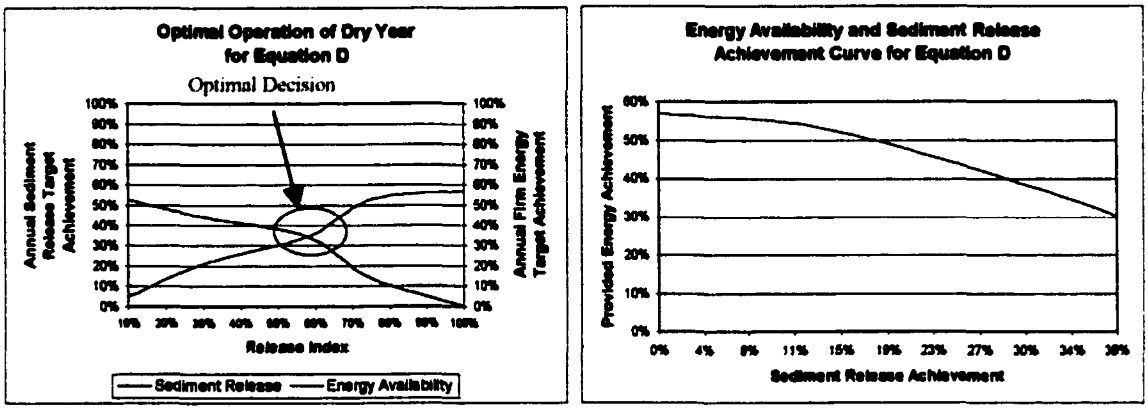


(a) (b)

Figure 5-43. Optimal Value at Different Levels of (a) Release Index and (b) Firm Energy Generation and Sediment Release Achievement, for Equation B during Dry Year Operation



(a) (b)

Figure 5-44. Optimal Value at Different Levels of (a) Release Index and (b) Firm Energy Generation and Sediment Release Achievement, for Equation D during Dry Year Operation

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5.8.2 Results of Trade-off during Wet Year Operation

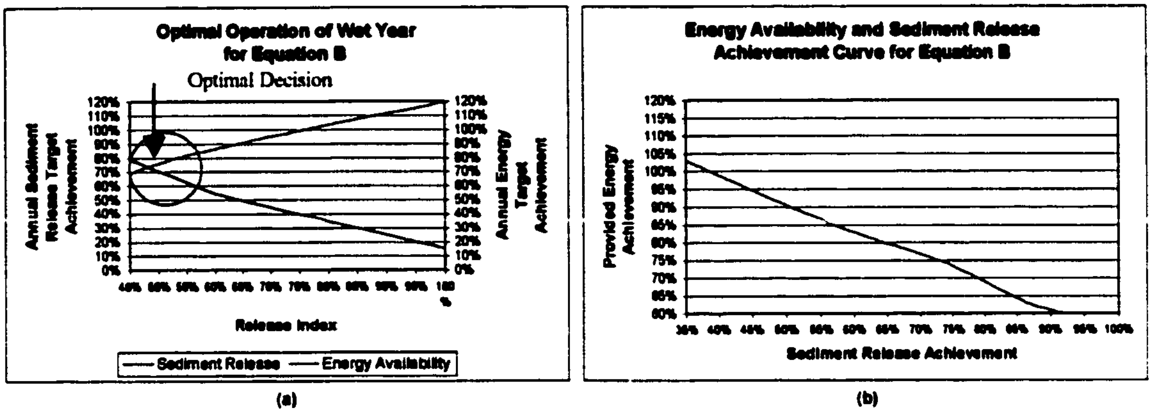

Figure 5-45. Optimal Value at Different Levels of (a) Release Index and (b) Energy Generation and Sediment Release Achievement, for Equation B during Wet Year Operation

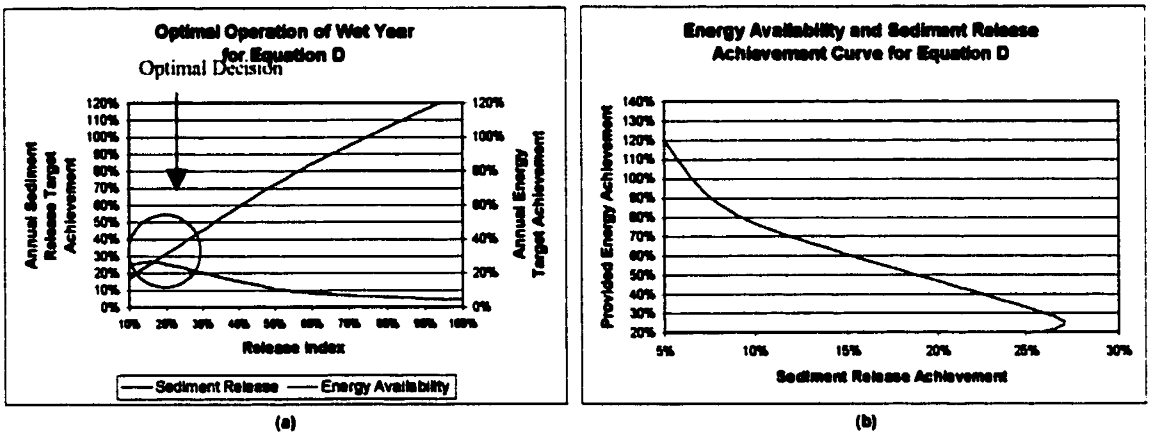

Figure 5-46. Optimal Value at Different Levels of (a) Release Index and (b) Energy Generation and Sediment Release Achievement, for Equation D during Wet Year Operation

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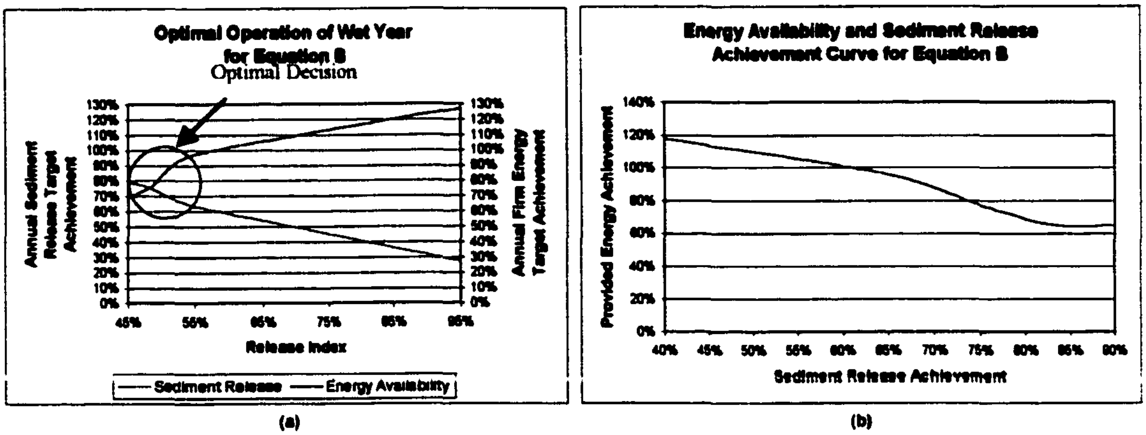

Figure 5-47. Optimal Value at Different Levels of (a) Release Index and (b) Firm Energy Generation and Sediment Release Achievement, for Equation B during Wet Year Operation

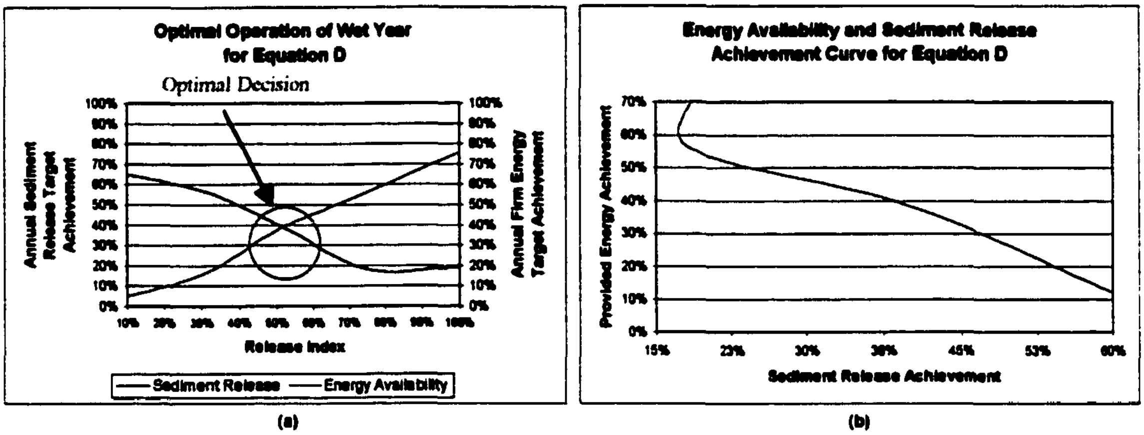

Figure 5-48. Optimal Value at Different Levels of (a) Release Index and (b) Firm Energy Generation and Sediment Release Achievement, for Equation D during Wet Year Operation

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5.9. Summary

The application of the developed model has provided the mathematical results presented in the figures above. The sediment inflow model was developed to estimate how much sediment would enter the reservoir associated with stream inflow discharge. The pattern of monthly sediment discharge, peak of sediment volume during flood season and total annual volume should be estimated appropriately to provide calculation more accurately.

Five different equations of sediment outflow associated with the expended water discharge through the outlet system were established in the model and provide different decision policies. The characteristic of the five equations related to the dependent variables, such as expended water discharge, sediment inflow rate, elevation depth, sediment inflow concentration, etc., affect the running time of the model execution.

The initial static value of release index was applied in the model for all conditions such as dry, normal, and wet year operations to evaluate the different optimal decision policies of the developed model associated with the five sediment-outflow equations to meet the objectives. In addition, the dynamic value of release index was applied and might have different values for every month.

The release index, energy availability for both total energy production and firm energy, and sediment release achievement curves were developed as trade-off curves to present the point of optimality established in the model results. These curves were developed based on dry and wet year operation associated with the static value of release index.

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CHAPTER VI
ANALYSIS AND DISCUSION

6.1. Introduction

This section provides analysis and discussion of the results of the developed model for reservoir sediment-control operation. Analysis and discussion deal with the comparison of operation planning for dry, normal, and wet years. During wet year operation, there is a possibility that the optimal priority achieved by maximizing energy and minimizing sediment deposition has different weights for given static value of release index, since after the sediment outflow meets the target of 100%, the excess water can be used for hydropower if it is less than the maximum discharge allowed for the turbines.

In addition, further discussion is provided to illustrate different values for both static and dynamic indeces in the developed model. These release index values represent the optimal release decision based on operation planning. Some remarks on the results also establish in order to evaluate the impacts due to operation planning related to the reservoir environment.

Long-term operation is also evaluated based on dry year operation with selected Equation B which depends on the depth of reservoir elevation associated with the erodibility coefficient.

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6.2. Results of the Research Study

The comments of this research overview related to this study can be listed as follows:

1. The model for maximizing hydropower and minimizing sediment deposition can be developed for reservoir operation planning when the stream inflow discharge may be available to generate power and to release sediment from the reservoir. Even if there is sufficient stream inflow discharge, the demand for energy and sediment release might not be met. This condition depends on the sediment outflow equation linked to the developed model, since there would be a conflict in reservoir operation to meet both the energy target and sediment release demand from the reservoir with limited stream inflow discharge.
2. Since the results present the fluctuation of reservoir operation (rule curve), it might be difficult to maintain the draw-down pool elevation at a relatively constant or gradual level as far as possible when emptying or lowering storage level for the release of sediment. This condition may result in a sudden draw-down of the reservoir, which encourages bank erosion along the shoreline of the reservoir.
3. An inflow sediment model should be carefully developed, especially related to peak sediment inflow rate, annual volume, and the monthly pattern associated with the coefficient and exponent parameter adjustment. An extended period of measurement of sediment inflow would be helpful for establishing the sediment inflow model more accurately.

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6.2.1 Sediment Inflow Model Considerations

It is necessary to consider three important concerns for developing the sediment inflow model. Firstly, the peak sediment rate, especially at the peak flood of the stream inflow discharge, is significantly related to the underestimated value of the peak rate of the sediment inflow. Secondly, the monthly pattern of the sediment inflow rate should approach the value measured in the field. Finally, the total annual volume of the incoming sediment of the model should be equivalent to the measurement.

The sediment inflow rate model is not necessarily the same for every year. The model might be modified to determine the best parameters of a, b, c, and d in order to approximate the measurement of the sediment inflow rate. Extended periodic measurement of the sediment inflow rate associated with the stream inflow discharge should be recorded from time to time in order to confirm and enhance the accuracy of the model as long as the reservoir is operated. In any modification of the model, the two statistical indicators, coefficient of correlation and ratio of discrepancy, are very important in conjunction with the visual graphic assessment. **Figure 5-2**, **Figure 5-3**, and **Figure 5-4** show the appropriate process for sediment inflow model development.

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6.2.2 Dry, Normal, and Wet Year Operation Results and Remarks

A comparison of the results is presented in the following tables. **Table 6-1** through **Table 6-6** deals with the dry, normal, and wet year operation based on the total annual energy target and firm energy, respectively. The accumulated sediment at the end of the year is mostly higher for the total annual energy target than for total annual firm energy as the target. However, the optimal priority that can be achieved is higher for total annual firm energy than for total annual energy as the target.

The pattern of the operation rule has a typical curve if the rule curve pattern resulting from the model is almost identical to the existing rule curve. The steepness or gradualness of movement is related to the rule curve slope shown in the reservoir operation planning strategy. The time of execution to determine optimal priority is affected by the sediment outflow equation. A sediment outflow equation which has a dependent variable related to the reservoir state variable, for instance elevation depth, will need more execution time to obtain a convergence value.

In running the model, the optimal solution may arrive at a local optimum instead of a global optimal solution. Therefore, it is necessary to continue running the model until the convergence value is obtained and remains the same value although the program is continuously executed over an extended period.

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Table 6-1. Dry Year Operation Remarks based on Annual Energy Target

Equation	Accumulated Sediment (MCM)	Fluctuation of Operation Rule	Optimal Value	Convergence
A	139.73	Typical	49.52%	Fast
B	159.64	Typical	42.33%	Moderate
C	124.18	Typical	55.14%	Fast
D	230.18	Relatively Constant	16.85%	Moderate
E	159.26	Typical	42.47%	Fast

Table 6-2. Dry Year Operation Remarks based on Annual Firm Energy Target

Equation	Accumulated Sediment (MCM)	Fluctuation of Operation Rule	Optimal Value	Convergence
A	95.96	Typical and steep	65.34%	Fast
B	124.78	Typical and gradual	54.92%	Moderate
C	100.66	Relatively constant and steep	63.64%	Fast
D	181.57	Typical and gradual	34.41%	Moderate
E	111.63	Typical and steep	59.68%	Fast

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Table 6-3. Normal Year Operation Remarks based on Annual Energy Target

Equation	Accumulated Sediment (MCM)	Fluctuation of Operation Rule	Optimal Value	Convergence
A	54.91	Typical and steep	89.53%	Fast
B	233.32	Typical and steep	55.50%	Moderate to slow
C	150.39	Typical and steep	71.32%	Fast
D	442.81	Typical and steep with fluctuation	15.55%	Moderate to slow
E	206.72	Typical and steep with fluctuation	60.58%	Fast

Table 6-4. Normal Year Operation Remarks based on Annual Firm Energy Target

Equation	Accumulated Sediment (MCM)	Fluctuation of Operation Rule	Optimal Value	Convergence
A	54.26	Typical and steep	89.65%	Fast
B	157.78	Typical and gradual	69.91%	Moderate to slow
C	7.52	Typical and steep	98.53%	Fast
D	364.32	Typical and steep with fluctuation	30.60%	Moderate to slow
E	142.03	Typical and steep	72.91%	Fast

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Table 6-5. Wet Year Operation Remarks based on Annual Energy Target

Equation	Accumulated Sediment (MCM)	Fluctuation of Operation Rule	Optimal Value	Convergence
A	0.00	Typical and Steep	100.00% (S) 126.76% (H)	Fast
B	241.36	Typical and Steep	74.13%	Moderate to slow
C	0.00	Typical and steep	100.00% (S) 113.00% (H)	Fast
D	682.20	Relatively Constant	26.88%	Moderate to slow
E	125.86	Typical and steep	86.51%	Fast

Note: S = sediment, H = Hydropower

Table 6-6. Wet Year Operation Remarks based on Annual Firm Energy Target

Equation	Accumulated Sediment (MCM)	Fluctuation Operation Rule	Optimal Value	Convergence
A	0.00	Typical and steep with fluctuation	100.00% (S) 100.32% (H)	Fast
B	228.40	Typical and gradual	75.91%	Moderate to slow
C	0.00	Typical and steep	100.00% (S) 130.93% (H)	Fast
D	565.97	Typical and steep with fluctuation	39.27%	Moderate to slow
E	93.88	Typical and steep	89.94%	Fast

Note: S = sediment, H = Hydropower

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In **Table 6-5** and **Table 6-6**, the optimal values in Equation A and C, respectively, are achieved at different priorities. This indicates that the excess water after meeting the sediment release target can be used for hydropower as long as the excess water discharge is less than the maximum allowable discharge for the turbines. Therefore, the energy provided will be greater than the demand target.

Based on the results, the larger amount water (during wet season) does not specifically indicate sufficient excess water for releasing sediment from the reservoir. This is indicated as for Equation B and D. The more stream inflow is entering the reservoir, the more sediment is entering the reservoir as well. This may impact to more sediment deposition in the reservoir itself as presented in the tables for the accumulated sediment column.

6.2.3 Illustration of Static and Dynamic Value of Release Index Results

The values of the static and dynamic release index are presented in **Figure 6-1 (a)** and **Figure 6-1 (b)** for every designated sediment outflow equation. The static values are constant for the whole month of operation in a year. However, the dynamic values show some variations, especially before flood season (the month of July) and during dry year operation. The dynamic values are mostly less than 1.0. However, after flood season, the dynamic values are relatively constant. In this period, the dynamic values are equal to 1.0.

A reasonable explanation is that the dynamic release index controls the unnecessary allocation of water for releasing sediment from the reservoir. If the incoming sediment load is small, it is not necessary to release much sediment from the

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reservoir. An advantage of this is prevention of degradation in the bottom of the reservoir region. After flood season, the dynamic values are equal to 1.0 and provide sufficient water allocated for sediment release which can be used for discharging the sediment from the reservoir. The release decisions related to allocated water for turbine and sediment release are shown in **Figure 6-1 (c)** and **Figure 6-1 (d)**. The percentage presentation reflects the allocated water for the specific purpose divided by total release water availability.

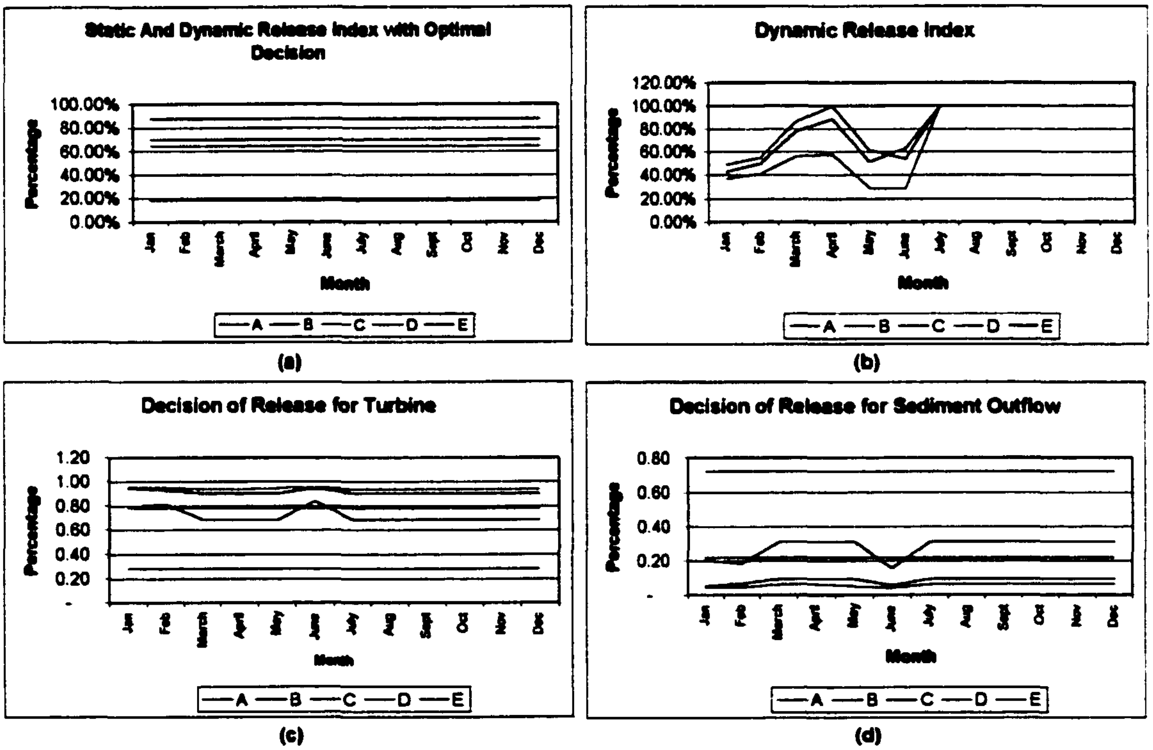

Figure 6-1. Static and Dynamic Value of Release Index, and Decision Release for Turbine and Sediment Outflow during Dry Year Operation based on Annual Energy Target

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6.2.4 Deposition of Sediment during Dry, Normal, and Wet Year Operation

Logically, during wet season, more water can be used for releasing sediment while meeting the energy demand. This condition is indicated in the results, in which the amount of sediment deposition provided by most of the equations, such as Equation A, C, and E, is less during the wet year operation. However, Equation B and D gives more sediment accumulation during wet year operation. An illustration of this condition is presented in **Figure 6-2** and **Figure 6-3**. Based on a study of reservoir sedimentation in China, Fontane [2000] states that during the wet season the accumulation of sediment is relatively large compared to the dry season after a flushing operation.

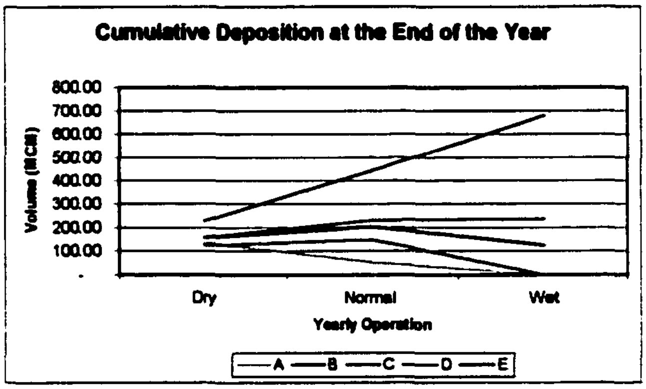

Figure 6-2. Cumulative Deposition for Five Different Equations During Dry, Normal, and Wet Year Operation based on Total Annual Energy Target

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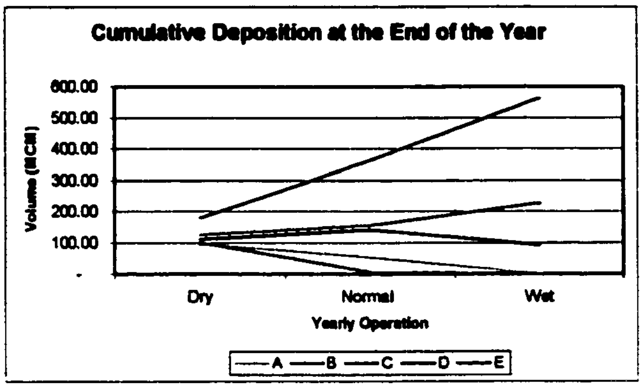

Figure 6-3. Cumulative Deposition for Five Different Equations During Dry, Normal, and Wet Year Operation based on Total Annual Firm Energy Target

6.2.5 Long-term Operation

Long-term operation is established to evaluate sediment deposition accumulation after a few years. **Figure 6-4** shows long-term operation for the original design and the new design after reconstruction, which have the same capacity for the sediment outlet system and installed capacities of 1,100 MW and 250 MW, respectively.

The operation planning based on the original design indicates that after 5 years the accumulated sediment is around 500 MCM. This amount of the sediment is one tenth (10%) of the total capacity of the reservoir (5,823 MCM). Even though in the new design installed capacity of the turbine is reduced to 250 MW, sediment deposition can still be reduced to one third of the amount generated by the original design in five years.

The values of the decision of release vary before the month of July in the first year of operation for both original and new design for hydropower generation. However, the values of the decision of release are constant after the month of July in the second to fifth year of operation.

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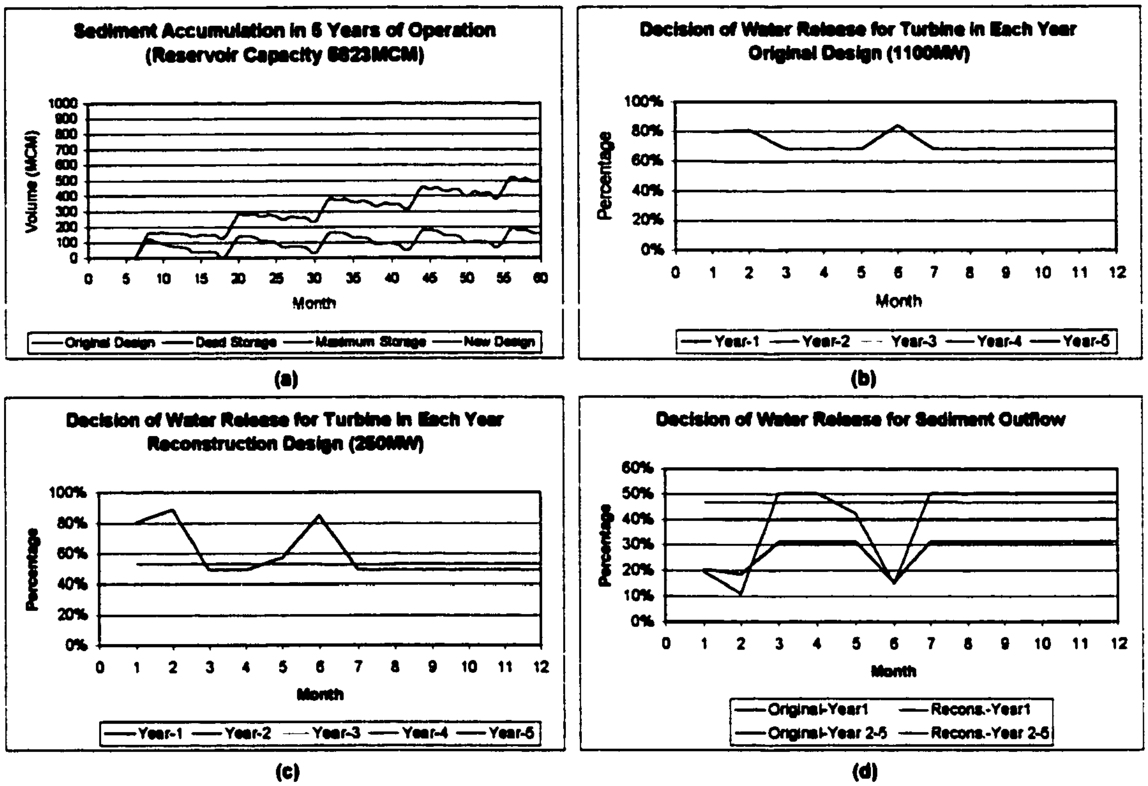

Figure 6-4. Long Term Operation based on Original Design and New Design after Reconstruction

6.3. Operational Planning Impact

The fluctuation of the storage level could potentially encourage bank erosion along the shoreline of the reservoir. Based on the operational planning from the model, the fluctuation of the storage level is strictly affected by the sediment outflow equation associated with the dependent variables.

The period after the flood season, from September to December, is an especially difficult period due to the higher sediment deposition at the downstream region of the dam. This would encourage sediment accumulation and is potentially an aggradation

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problem of the channel bottom. If the flow at downstream cannot carry the accumulated sediment released from the outlet system, then a mechanical action to dredge the deposited sediment should be undertaken as appropriate.

During a period of sediment release, it is necessary to consider the permissible rate of sediment discharge through the outlet systems with respect to the size of the sediment material. This is important in order to prevent abrasion along the inner side of the wall along the outlet system.

6.4. Advantages of the Developed Model

The NLP model with iterative fashion was introduced to search for the optimal decision for reservoir operation with sedimentation control. The solver availability and advanced computer capabilities used for the NLP formulation are very powerful and easy to understand. The solving procedure for the nonlinear problem with formulation of the circle calculation for both evaporation and sediment outflow rate (in the mass balance equation) was applied by introducing the convergence value as the indicator. This iteration procedure was applied in order to achieve greater accuracy in the results. The NLP solver may be widely applied in water system applications in the near future, given the success of this research associated with this non-linear problem.

6.5. Disadvantages

The considerable trial-and-error input is time-consuming during the running of the model since the trial input of the release index value and circle calculation for both

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evaporation and sediment outflow rate need to be converged. A simplification of the circle calculation for evaporation might be carried out if the evaporation could be ignored at the accuracy level by considering the pattern of evaporation in the model as a fixed value. However, in the case of the circle calculation of the sediment outflow rate, the calculation must be carried out since the accuracy of the results is very important.

6.5.1 Improvements

Reservoir operation development can be linked to the sediment control operation. This is especially important for reservoirs located in sediment-laden rivers. This management operation would provide for further design improvement for new reservoirs built in sediment-laden rivers with respect to the outlet system for releasing sediment. Outlet system location and position level are very important to achieve a better reservoir sediment-control operation.

6.6. Impact of the Research Study

In summary, the research will aid in the development of an easily applicable reservoir operation model and its application for sediment control in order to minimize sediment deposition and maximize hydropower generation. Possible general outcomes and contributions of the research include:

a. In general, a reservoir operation model incorporated with sediment release can be developed in order to reduce sedimentation deposition in the reservoir.

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b. A foundation is established for improved management of sustainable reservoir operation through use of the model to extend the life expectancy of the reservoir as far as possible.

c. From the hydraulic point of view, this encourages the development of a more general formula accurately related to sediment discharge scour associated with the operation pattern.

d. This research encourages consideration of how to continuously record sediment inflow and sediment scour rate during the release of sediment from the reservoir to improve the developed model and its responsiveness and to ensure adequate performance in the near future.

e. The downstream situation should be considered in relation to the reduction of sediment accumulation. The sediment discharge may affect water or environment quality if the downstream flow cannot transport this sediment to the sea.

6.7. Construction Design and Impacts on Management Operation

This research shows the importance of construction design and how it might impact management problems. Reconstruction needs to be carried out since the reservoir cannot be operated due to the accumulated sediment loads which cannot be released from the reservoir. This is because of the underestimation of the quantity of the incoming sediment and the lack of sufficient outlet systems to carry and release the sediment from the reservoir. While a sustainable reservoir sediment-control model can be developed, appropriate outlet systems should be considered in order to release the sediment

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inexpensively from the reservoir instead of using mechanical dredging activity. In addition, it is necessary to consider how to remove the accumulated sediment at the downstream of the dam if the flow is not sufficient to carry the sediment loads to the sea. If mechanical activity must be undertaken, then, the cost should not be prohibitively high.

6.8. Remarks and Constraints on the Research Study

The research, which needs to be carried out for further improvement, includes recording the rate of sediment release from the reservoir associated with the expended water discharge through the outlet systems during its operation. These records are very important for the accuracy and responsiveness of the model design in the future. The appropriate variables affected by the sediment outflow rate equation might be determined more accurately and precisely. Continuous records for stream inflow and outflow, and for sediment inflow and outflow associated with expended water are of considerable importance for monitoring and evaluating the model's responsiveness and accuracy.

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CHAPTER VII
CONCLUSIONS

7.1. General

The general conclusion is that this research study was carried out and implemented with success related to the developed model for controlling sediment deposition by releasing the sediment through operation planning. Planning of operation strategy for actual reservoir operations is very important especially for those built in sediment-laden rivers. The sustainable reservoir operation model was developed in order to maximize hydropower, minimize sediment deposition through sluicing or flushing operations, and extend the lifetime of the reservoir by decreasing trap efficiency.

7.2. Sediment Control by Reservoir Operation

In order to control sediment deposition, reservoir operation is one possible approach. It is more effective if the reservoir system has the following characteristics:

1. Run-off river system operation.
2. Sediment outlet systems such as for flushing, venting of density current, and sluicing operation are available.
3. Measurements of sediment and water inflow and outflow rates are continuously gauged upstream of the reservoir and downstream of the dam. These measurements should be made in order support and enhance the accuracy and responsiveness of the model.

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4. The relation of sediment outflow to expended water discharge from the outlet system should be developed appropriately with respect to the pattern and peak of sediment inflow rate.
5. Sufficient excess water is very important in order to release sediment and to meet downstream demands.

7.3. Model Application

Non-linear programming (NLP) is an appropriate mathematical technique to solve and search for the optimal decision in the planning strategy for a reservoir sediment-control operation system. NLP is a powerful tool built in Excel Software and capable of high-speed running of the model in searching the optimal solution. However, it is necessary to run the model until the global optimum solution is achieved.

The best policy for the multi-objective problem was developed based on the maximization of total annual energy production and firm energy targets. This provided different operations for reservoir sediment control associated with the sediment outflow rate equations linked to the mass balance equation in the model.

7.4. Appropriate Reservoir Design for Better Management

Appropriate reservoir design associated with facilities such as outlet systems can be carried out in order to achieve better management. Lifetime expectancy can be extended considerably to achieve more beneficial operation, while meeting downstream demands, by releasing the sediment from the reservoir. The outlet systems will be

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critically important to reservoir sediment-control operations in the near future. The optimal outlet system location, position and level for handling the sediment load for various river characteristics are very important areas of research for the future.

7.5. Contributions and Implications

The research describes the development of an easily applicable reservoir sediment-control operation model which can be applied to minimize sediment deposition while meeting downstream demands, especially for hydropower and water supply.

The research also contributes an insight into the mechanisms of sustainable reservoir sediment-control operation that may influence appropriate innovative design of the outlet systems when the sediment load is somewhat high. Other contributions of the research include:

1. The foundation of improved management systems by implementing the sustainable reservoir sediment-control operation model to minimize sediment deposition in the reservoir. This activity reduces trap efficiency and consequently extends the life expectancy of the reservoir.
2. The establishment of continuous gauging systems for inflow and outflow for the sediment rate associated with the expended water discharge at the same time and the same location at upstream of the reservoir and downstream of the dam.
3. The relation of the expended water with the sediment outflow rate should be a focus of further research. For instance, it might be a function of water inflow and outflow discharge, storage, release efficiency, and sediment concentration

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inflow. This is important in order to determine the significant dependent variables which affect the sediment outflow rate during sluicing or flushing operations. Since the operation depends on dependent variables of the sediment outflow equation.

4. This research encourages the consideration of the importance of continuous recording activities for sediment inflow and sediment scour discharge during release of the sediment from the reservoir in order to improve the model and its responsiveness for more adequate performance in the future.

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CHAPTER VIII
RECOMMENDATIONS

8.1. General

This section provides suggestions related to the scientific and practical enhancement of the sustainable reservoir sediment-control operation model. The research also identifies the knowledge base that should be considered for advanced development associated with the establishment of a system model to approximate actual condition.

8.2. Scientific Recommendations

The scientific recommendations deal with the theoretical science that should be developed for the next research study. This provides a better scientific background to approach real situations and to make the model system more practicable (although this may be somewhat difficult).

8.2.1 Lay-out of the Sediment Outlet System

Lay-out of the reservoir is very important with respect to the placement of the outlet systems. For reservoirs such as runoff river systems, it is easier to conduct the sediment loads to the downstream outlets. However, for irregularly shaped of reservoirs,

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great care is necessary in placing the outlet systems where they can be reached by moving sediment load flow along the reservoir.

The replacement of the outlet systems for irregularly shaped reservoirs may possibly be assisted by a simulation model of the dispersion of the flow in the reservoir in order to determine the optimal location. The optimal location would be decided based on the location that provided the strongest or highest velocity, since this can more easily to scour and carry the sediment to downstream outlets.

This research encourages the development of a two and/or three-dimensional model to establish the dispersion and distribution of current flows and their magnitude and direction in the reservoir. This model would be useful to determine the strategic locations for the replacements of the outlet systems to wash out the sediment material.

8.2.2 Model of Between the Rate of Sediment Inflow and Outflow associated with Water Inflow and Expended Water Discharge through Outlet Systems

Two main suggestions to enhance the model system are given as follows:

1. The predicted sediment loads incorporated in the stream inflow entering into the reservoir should be modeled appropriately.
2. The relation between the expended water and the sediment scour outflow rate released through the outlet system should be evaluated continuously.

These two models should be enhanced from time to time with the support of continual and periodical measurement to estimate the parameters of the sediment inflow and the sediment outflow model. The parameters may change frequently since natural

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conditions are usually unpredictable. The parameters can be optimized in a simple way by using NLP. The result of the optimal parameters provides the best mathematical equation that can be applied for the model for the specified period of measurements and operations. For the next planning, these parameters should be determined all over again for a better approximation in estimating total sediment loads for both the sediment inflow and the sediment scour outflow rate.

8.3. Practical Recommendations

Ideally, in order to develop the operation model, the case study should have all measurement data for sediment inflow and outflow rate, besides hydrological and reservoir characteristic data. This is especially important for developing and evaluating a specific formula relating to the sediment inflow and outflow rates and the expended water discharge.

From the mathematical modeling point of view, especially for the optimization method, there are no constraints considered at this time. The availability of the software package Microsoft Excel with the Non-Linear Programming Solver tool can be used to solve the problem.

8.3.1 Other Reservoir Operation Considerations based on Engineering Economics Concepts

A cost/ benefit analysis can be used to identify the best operation strategy, based on engineering economics considerations, associated with the reservoir sediment-control operation activities. It might be a possibility to carry out the reservoir operation based on

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the "reservoir region" category as presented in **Table 8-1**. The benefit is based on selling the energy. On the other hand, some costs are associated with turbine maintenance or replacement and sediment deposition in the reservoir or sediment accumulation downstream of the dam.

Therefore, it is necessary to quantify in terms of money for both benefit and cost analyses. In addition, it is also necessary to provide the relationship of the cost in terms of money associated with the decrease of the storage capacity. An illustration of this consideration is presented in **Figure 8-1**.

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Table 8-1. Cost-Benefit Identification for Reservoir Operation for Sediment Control (Grigg, 2000)

Benefit – Cost	Upstream Watershed	Reservoir Region	Downstream of the Dam
Cost	- Reforestation for Erosion Control	- Turbine Maintenance or Replacement - Sediment Deposition (Loss of Storage Capacity)	- Reduction of River Capacity - Sediment Accumulation - Water Quality Degradation - River Bed Degradation - Loss of Habitat
Benefit	- Less Sediment Load Entering into Reservoir	- Energy Generation	

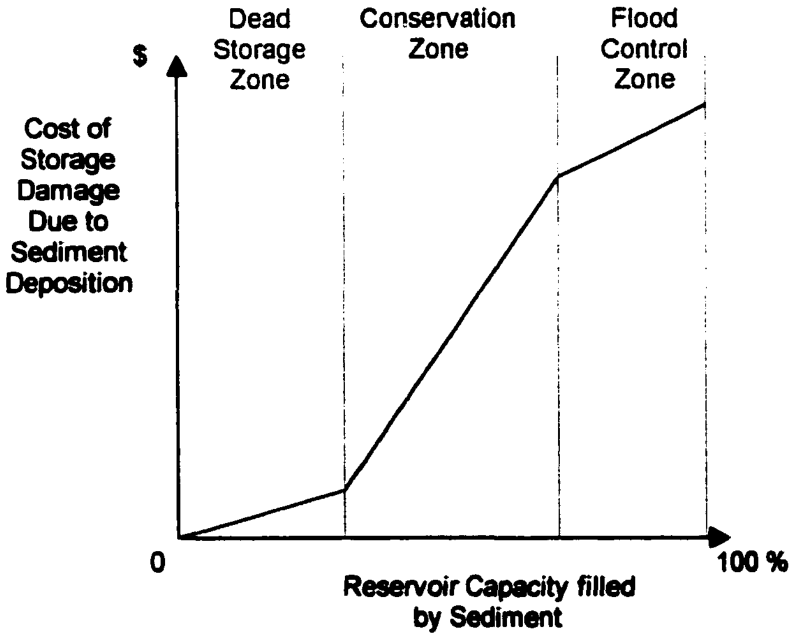

Figure 8-1. Illustration of Schematic Cost Analysis due to Sediment Deposition in a Reservoir (Grigg, 2000)

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In addition, to the cost in **Figure 8-1** must be added the cost of the removal of the accumulated sediment released in downstream region of the dam. The best operation would be based on a benefit-cost analysis in which the B/C ratio should have a value of more than one. The higher the B/C ratio, the better the decision policy that has been made for reservoir sediment-control operation.

8.3.2 Outlet System Design and Construction

As described above, the location of the outlet systems is crucial if the reservoir basin has an irregular shape. The location of the outlet systems should be determined based on facilitation of sediment movement by considering the topographical map and the developed simulation model. The construction cost should be held to the minimum possible and the outlet systems can be built without any significant restrictions such as building longer tunnel systems.

8.3.3 Institutional Responsibilities of Watershed Management

As noted in the literature, sediment problems are effectively handled by managing the watershed upstream of the reservoir appropriately. This needs a more efficient coordination to manage the watershed based on the different interests and purposes. A change of land-use could result in increased or decreased sediment loads at downstream reservoirs. Reforestation is a very important strategy to prevent a large amount of sediment loads (wash loads) going through the river and depositing in the reservoir.

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Therefore, inter-related institutions such as the Ministry of Forest, local government, and reservoir management groups should sit together to discuss policies related to land-use planning integrated with reservoir management operation. If the sediment load can be decreased when entering the reservoir, then the excess water can be used for increasing the downstream benefits.

8.3.4 Monitoring and Evaluation

Monitoring and evaluation are very important with regard to the infrastructure facilities and the accuracy of measurement instruments. The appropriate model will provide accurate results depending on the reliability of the measurement and infrastructure facilities, surveys and recording activities.

A bathimetric survey or underwater mapping is one of the most important surveys for re-evaluating the storage capacity of the reservoir. This can be used to verify the area and storage capacity curves that are used in the mass-balance equation of the reservoir operation model. This survey should be carried out once every 3 to 5 years of operation.

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