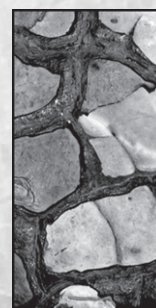
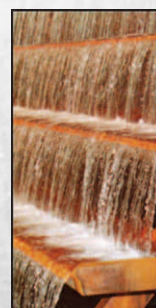
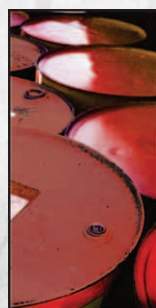


Optimising reservoir operation

A case study of the Hoa Binh reservoir, Vietnam

Long Le Ngo

INSTITUTE OF ENVIRONMENT & RESOURCES



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Ph.D. Thesis
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Institute of Environment & Resources
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Preface

The present thesis “**Optimising reservoir operation – A case study of the Hoa Binh reservoir, Vietnam**” has been submitted as one of the requirements for the Ph.D. Degree. The study has been carried out from September 2003 to August 2006, at the Institute of Environment & Resources, Technical University of Denmark, Kongens Lyngby, Denmark, and at the River and Flood Management Department, DHI Water & Environment, Hørsholm, Denmark, under the supervision of Prof. Dan Rosbjerg and Dr. Henrik Madsen.

The Ph.D. thesis is accompanied by three journal papers:

- (A) **Ngo, L.L.**, Madsen H., Rosbjerg D., Pedersen C.B., 2006, Implementation and comparison of reservoir operation strategies for the Hoa Binh reservoir, Vietnam using the MIKE 11 model. *Water Resources Management*. Submitted.
- (B) **Ngo, L.L.**, Madsen H., Rosbjerg D., 2006, Simulation and optimisation modelling approach for operation of the Hoa Binh reservoir, Vietnam. *Journal of Hydrology*. Submitted.
- (C) **Ngo, L.L.**, Madsen H., Rosbjerg D., 2006, Real-time reservoir operation for flood control and hydropower generation. Case study: The Hoa Binh reservoir, Vietnam. *Advances in Water Resources*. Submitted.

The papers are not included in this www-version but can be obtained from the Library at the Institute of Environment & Resources, Bygningstorvet, Building 115, Technical University of Denmark, DK-2800 Kongens Lyngby (library@er.dtu.dk).

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Finally, grateful acknowledgements are extended to my parents and parents-in-law for their constant encouragement and moral support. A special thank to my wife, Duong Thuy Huong, for her dedication and for taking good care of the family during my study.

Kongens Lyngby, October 2006

Long Le Ngo

Abstract

Application of optimisation techniques to reservoir operation has become a major focus of water resources planning and management. Traditionally, reservoir operation is based on heuristic procedures, embracing rule curves and, to a certain extent, subjective judgements by the operator. Water use involves a large number of stakeholders with different objectives, and optimisation techniques are expected to provide balanced solutions between often conflicting objectives. The thesis proposes an avenue for changing traditional reservoir operation into optimised strategies, taking advantage of the rapid development in computational techniques.

The main contribution of the thesis is the development of a framework in which a simulation model is coupled with a numerical search method for optimising decision variables specifically defined for operation of the reservoir. The MIKE 11 modelling system is adopted for simulating the flow in the river system including the reservoir, and the shuffled complex evolution algorithm as implemented in the AUTOCAL software is selected for optimisation. Hereby it has become possible to estimate the trade-off between the various objectives, also denoted the set of non-dominated or Pareto-optimal solutions.

The framework is tested on the Hoa Binh reservoir in the Red River basin, Vietnam, considering hydropower production and downstream flood control. The results show that optimised rule curves significantly improve the reservoir performance in terms of hydropower production without reducing the downstream safety against flooding. To further improve the operation, real-time optimisation is performed taking real-time and forecast information about reservoir levels, reservoir inflows and water demands into account. The optimisation problem puts focus on the trade-off between short-term hydropower and flood risk objectives and long-term penalties in terms of deviations from the optimized rule curves. The analysis demonstrates that the real-time optimisation procedure improves the performance and enhances the flexibility of the reservoir operation in comparison to a strict application of the optimised regulation.

Dansk resumé

Anvendelse af optimeringsteknik til drift af reservoirer er blevet et væsentligt element i vandressourceplanlægning og -forvaltning. Traditionelt har reservoirer været styret af heuristiske procedurer for udledning af vand, i en vis udstrækning suppleret af subjektive beslutninger. Udnyttelse af reservoirer involverer en lang række interessenter med meget forskellige formål, og optimeringsteknik kan langt bedre lede frem til afbalancerede løsninger af de ofte modstridende interesser. Afhandlingen foreslår en række tiltag, der kan lede fra den traditionelle driftsstrategi til optimale strategier baseret på den nyeste udvikling indenfor computer-baserede beregninger.

Hovedbidraget i afhandlingen er udviklingen af et beregningssystem, hvori en simuleringsmodel er koblet til en model for optimering af nogle udvalgte beslutningsvariable, der i særlig grad har betydning for driften af reservoiret. MIKE 11 modelsystemet er udvalgt til simulering af flodsystemet med reservoiret inkluderet, mens den såkaldte "shuffled complex evolution algorithm", der indgår i softwaresystemet AUTOCAL, er benyttet som optimeringsværktøj. Herved er det blevet muligt at beregne gruppen af ikke-dominerede løsninger, den såkaldte Pareto-front.

Metodikken er afprøvet på Hoa Binh reservoiret beliggende i Den Røde Flods opland i Vietnam under hensyntagen til såvel vandkraftproduktion som beskyttelse af nedstrøms beliggende områder mod oversvømmelse. De opnåede resultater viser, at optimerede driftsstrategier i betydelig grad kan forbedre reservoirdriften i form af større vandkraftproduktion uden at kompromittere sikkerheden mod oversvømmelse. En yderligere forbedring af driften kan opnås ved i realtid at udnytte såvel tilstrømningsprognoser som aktuelle værdier for reservoirvandstand og -indstrømning. Optimeringen balancerer korttidsgevinster relateret til vandkraftproduktion og oversvømmelsesbeskyttelse mod langtidseffekter i form af at "straffe" afvigelse fra de optimerede driftsstrategier. Beregningerne viser, at den mere fleksible realtidsoptimering kan medføre en væsentlig gevinst i sammenligning med en regelbaseret anvendelse af de optimerede strategier.

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Chapter 1

INTRODUCTION

1.1 Background

As a result of tropical monsoon climate with strongly variable flow in time and space, Vietnam has a lot of reservoirs, which play a significant role in the development of the country economy. Most of the reservoirs are multipurpose including flood control, hydropower generation, water supply, navigation, restoration, etc. However, in many cases, the purposes of flood control and hydropower generation are regarded as being most important in the determination of control strategies for reservoirs. In recent years, the problem of ineffective operation of existing reservoirs using outdated technology and highly subjective management practices has been repeatedly indicated by many specialists (e.g. Guariso et al., 1986; Oliveira and Loucks, 1997; Chen, 2003; John, 2004). The situation of too much water in the rainy season and too little water in the dry season causes many difficulties in reservoir operation. Many reservoirs in Vietnam are dry in the dry season, but they are also threatened by dam-break disasters in the flood season. It is necessary to emphasise that the reservoir operation rules should be soundly adapted to global climate change as well as economic activities in the river basin. Due to changes of hydro-meteorological conditions and shifting goals of water requirements from one region to the others, the reservoirs have different operation rules. Therefore, without careful consideration of these conditions the reservoir operation will be inefficient.

Reservoir operation is a complex problem that involves many decision variables, multiple objectives as well as considerable risk and uncertainty (Oliveira and Loucks, 1997). In addition, the conflicting objectives lead to significant challenges for operators when making operational decisions. Traditionally, reservoir operation is based on heuristic procedures, embracing rule curves and subjective judgements by the operator. This provides general operation strategies for reservoir releases according to the current reservoir level, hydrological conditions, water demands and the time of the year. Established rule curves, however, do not allow a fine-tuning (and hence optimisation) of the operations in response to changes in the prevailing conditions. Therefore, it would be valuable to establish an analytic and more systematic approach to reservoir operation, based not only on traditional probabilistic/stochastic analysis, but also on the information and prediction of extreme hydrologic events and advanced computational technology in order to increase the reservoir's efficiency for balancing the demands from the different users.

Applying optimisation techniques for reservoir operation is not a new idea. Various

techniques have been applied in an attempt to improve the efficiency of reservoir(s) operation. These techniques include Linear Programming (LP); Nonlinear Programming (NLP); Dynamic Programming (DP); Stochastic Dynamic Programming (SDP); and Heuristic Programming such as Genetic algorithms, Shuffled Complex Evolution, Fuzzy logic, and Neural Networks etc.

In reservoir operation, LP is well known as the most favoured optimisation technique with many advantages. It is easy to understand and does not require any initial solution. A number of examples of applying LP to reservoir operation are provided by Yeh (1985). Mujumdar and Teegavarapu (1998) developed a deterministic LP model for short-term annual operation of an irrigation reservoir. Duranyildiz et al. (1999) developed a chance-constrained LP model, which takes the random nature of inflows into consideration to optimise the monthly operation of a real reservoir. Unver and Mays (1990) developed a model for real-time flood control operation for a reservoir system and demonstrated that it is possible to link nonlinear optimisation models with unsteady flow routing models to solve large-scale LP problems associated with flood control reservoir operation. In this method the nonlinear optimisation is performed by using the generalized reduced gradient code GRG2. Wang et al. (2004) studied optimisation of short-term hydropower generation and demonstrated that with the development of a direct search procedure, a reformulated problem with only linear constraints of outflow release and storage content can be solved.

Another approach to deal with the reservoir operation problem is the so-called Dynamic programming. In the method, sequential decision problems are divided into a sequence of separate, but interrelated, single-decision sub-problems. In this way, large, complex problems can be solved by combining the solutions of the smaller problems (sub-problems) to obtain the solution of the entire problem (Mays and Tung, 2002). It is well suited to deal with short-term operation (hourly or daily) when the hydrologic inputs and water demands are generally considered deterministic. Mujumdar and Ramesh (1997) developed a short-term reservoir operation model for irrigation. The model consists of two components including an operating policy model and a crop water allocation model that were formulated using deterministic dynamic programming. Teixeira and Marino (2002) also developed a DP model to solve the problem of two reservoirs in parallel supplying water for irrigation districts. In the model, forecasted information including crop evapotranspiration, reservoir evaporation and inflows is updated, which allowed application of the model for real-time reservoir operation and generation of a more precise irrigation schedule.

An extension of dynamic programming is stochastic dynamic programming (SDP). This method takes into account the stochastic nature of the hydrological conditions. Kelman et al. (1990) developed a sampling SDP that captured the complex temporal and spatial structure of the streamflow process. Mujumdar and Vedula (1992) developed a model for optimal reservoir operation for irrigation using SDP. In their study, reservoir storage, inflow and soil moisture in the irrigated area were treated as state variables.

Yang et al. (1995) combined an autoregressive model with DP to produce a SDP model that was investigated to provide steady-state operation rules taking into account the stochasticity of reservoir inflows.

During the last two decades, heuristic algorithms have been developed for solving reservoir optimisation problems. These algorithms use a set of points simultaneously in searching for the global optimum. Oliveira and Loucks (1997) proposed an approach to identifying reservoir operating rules using genetic algorithms (GA) and argued that the approach overcomes some of the difficulties of many techniques based on more traditional mathematical programming models. Chen (2003) successfully applied real-coded GA in combination with a simulation model to optimise 10-day operating rule curves of a major reservoir system in Taiwan. The results showed that the method can be powerfully used to optimise the rule curves, not being limited by the type of the objective function and simulation model used. Moreover, a comparison between binary-coded and real-coded GA was exploited in optimising the reservoir operating rule curves (Chang et al., 2005). The results showed that the new operating rule curves obtained from both methods are better than the current operation rule curves, and the real-coded GA is more efficient than the binary-coded GA.

In order to solve the uncertainty of hydrological information as well as define the objectives and constraints, fuzzy set theory has been successfully used. Dubrovin et al. (2002) applied a fuzzy rule-based control model for multipurpose real-time reservoir operation. A comparison between Total Fuzzy Similarity and a more traditional method (the Sugeno method) was done. The results showed that this model can perform generally well and is easy for the operator to understand due to its structure based on human thinking. Akter and Simonovic (2004) combined fuzzy sets and GA for dealing with the uncertainties in short-term reservoir operation. In the paper, uncertainties involved in the expression of reservoir penalty functions and determining the target release value were considered.

Besides the uncertainty of input data, the complexity of physical and hydrological characteristics of a reservoir system often requires the use of computationally expensive simulation models. Thus, the computational time needed for optimisation may be overwhelming, making the optimisation infeasible, especially for real-time applications. A multilevel optimisation procedure that allows for maximum reduction of the time required to solve optimisation problems has been developed by using surrogate models including Artificial Neural Network (ANN). In the optimisation process the ANN model is trained to replace the simulation model. Thus, the requirement of calculation time is minimised without markedly reducing the accuracy of the solution. Neelakantan and Pundarikanthan (2000) applied this approach to improve the policies for reservoir operation. The results indicate that the solution performs satisfactorily as compared to the conventional simulation-optimisation model. Solomatine and Avila (1996) used ANN to approximate the hydrodynamic part of the MIKE 11 river model in optimising reservoir operation. The ANN was trained based on the water levels given by the MIKE

11 model.

1.2 Objectives of the study

The aim of this project is to develop a framework for adaptive reservoir management, which utilises maximum available information. The project will change traditional reservoir operation by combining real-time data (reservoir levels and inflows) and inflow forecasts with historical data in order to optimise operation strategies, taking advantage of the rapid development in computational techniques.

The developed framework will be tested on the Hoa Binh reservoir in the Red River basin. It has been in operation for 16 years, and in the future it will be operated in combination with other large reservoirs in the basin. The flood control location is the Red River delta incorporating a long river dyke system, the capital Hanoi, and many municipal zones. The Red River delta also plays a key role in rice production and, therefore, in Vietnam's agricultural economy. Specific expected results include:

- Improved multi-purpose reservoir operation rules for the Hoa Binh reservoir, more soundly based on information and prediction of extreme hydrological events as well as achievements of modern computational technology.
- Application of new proposed strategies and technical adaptation options in operation of the Hoa Binh reservoir. The trade-off between conflicting objectives, such as flood control and hydropower generation, will be particularly emphasised in determining the control strategies for the reservoir.
- A framework upon which it is easy to develop new, optimal rule curves for reservoir system operation, when considering series of reservoirs. In the near future, a number of reservoirs will be built in the upstream part of the Red River basin to protect the downstream part from flooding and produce electricity.

1.3 Content and structure of the thesis

This thesis consists of five chapters including the introduction as Chapter 1 (this Chapter). The conclusions obtained from the study and future works are presented in Chapter 5. The other three chapters (Chapter 2 to Chapter 4) can be summarised as follows.

Chapter 2 starts with a general mathematical formulation for optimal reservoir operation including the major objectives, criteria, and constraints. The problem of multi-objective optimisation is reviewed to provide basic concepts for solving a multi-purpose reservoir operation problem. The Chapter also presents the proposed framework that will be used

in this research effort. The framework is based on incorporation of an optimisation technique into a simulation model. The MIKE 11 river network simulation model is selected to set up the strategies for reservoir operation and evaluate the performance of the system with respect to different objectives, and the Shuffled Complex Evolution (SCE), a heuristic global optimisation algorithm, is adopted for optimising operational strategies. Brief descriptions of these models are also presented in the Chapter.

The framework is applied to the Hoa Binh reservoir in the Red River basin, the largest basin in Vietnam. The basin also includes an extensive delta, the Red River delta, with a flat topography. The delta plays a significant role for the socio-economic development of Vietnam and includes the national capital Hanoi. Although it is protected by a dike system, the delta is still threatened by floods during the flood season. In order to introduce the problem that is considered in this study, the flood characteristics and synchronization of floods in the Red River are presented in Chapter 3. The characteristics of the basin, including the river network and rainfall-runoff properties, are summarised. The Hoa Binh reservoir is one of the key constructions to control floods in the Red River basin. Besides, the Hoa Binh power plant is expected to produce on average 7.8 billion kWh per year. The general features as well as issues in operation of the reservoir are also introduced. The regulation for the reservoir operation during the flood season is then described. The main objective of the chapter is to point out the role of the Hoa Binh reservoir in the Red River basin in terms of flood control and hydropower generation.

In Chapter 4, the results of the study are presented via an overview of the three papers. These papers illustrate three levels of improvement in solving the reservoir operation problem. First, the control strategies for the Hoa Binh reservoir operation are set up in the MIKE 11 model. A data set consisting of twenty years of flood season data was used to evaluate the control strategies. The results showed that a complete and automated control system outperforms the actually used control system. Second, a combination of a heuristic global optimisation tool and the simulation model is used to optimise control variables for the reservoir operation. Hereby a further and significant improvement is achieved. The optimisation puts focus on the trade-off between flood control and hydropower generation in the flood season and the reservoir level at the beginning of the dry season. Third, by also including real-time forecast of the inflow during the flood season the control strategies can be relaxed resulting in increasing hydropower production.

Chapter 2

RESERVOIR OPERATION PROBLEM

2.1 General mathematical formulation

Reservoir operation is an important element in water resources planning and management. It consists of several control variables that defines the operation strategies for guiding a sequence of releases to meet a large number of demands from stakeholders with different objectives, such as flood control, hydropower generation and allocation of water to different users. A major difficulty in the operation of reservoirs is the often conflicting and unequal objectives. Therefore, it is necessary to optimise reservoir operation in determining balanced solutions between the conflicting objectives.

Optimisation models are based on clearly defined goals (objective functions), criteria for evaluation of control decisions, and constraints as limitations during optimisation (Djordjevic, 1993). John (2004) states “Objective functions used in reservoir optimisation models should incorporate measures such as efficiency (i.e., maximizing current and future discounted welfare), survivability (i.e. assuring future welfare exceeds minimum subsistence levels), and sustainability (i.e. maximizing cumulative improvement over time)”. The criteria are economic, social and environmental issues. The typical constraints in a reservoir optimisation model, including conservation of mass and other hydrological and hydraulic constraints, minimum and maximum storage and release, hydropower and water requirements as well as hydropower generation limitations, are presented as follows

- Hydraulic constraints are defined by the reservoir continuity equation.

$$S(t+1) = S(t) + I(t) - R(t) \quad \forall t = 1, 2, \dots, T$$

Where $S(t+1)$ is storage at time step $t+1$; $S(t)$ is storage at time step t ; $I(t)$ is the reservoir net inflow at time step t (including reservoir inflow, precipitation and evaporation); $R(t)$ is the reservoir outflow at time step t . T is the total number of time steps in the considered period.

- Constraints on discharge defined by maximum and minimum permissible reservoir releases:

$$R_{\min} \leq R(t) \leq R_{\max} \quad \forall t = 1, 2, \dots, T$$

- Constraints on storages defined by maximum and minimum permissible reservoir storages:

$$S_{\min} \leq S(t) \leq S_{\max} \quad \forall t = 1, 2, \dots, T$$

- Constraints on elevations defined by maximum and minimum permissible water level at specified sites:

$$h_{\min} \leq h(t) \leq h_{\max} \quad \forall t = 1, 2, \dots, T$$

- Constraints on hydropower generations defined by maximum capacity and minimum requirement of hydroelectricity:

$$HP(t)_{\min} \leq HP(t) \leq HP_{\max} \quad \forall t = 1, 2, \dots, T$$

HP(t) is a nonlinear function of S(t) and R(t).

Optimisation problems can, generally, be either single-objective or multi-objective. The main concern of single-objective optimisation is to define the minimum or maximum value of an objective function, depending on the goal. The single-objective is just measuring the goal of operation of a single-purpose reservoir, or it may weight different objectives using a fixed set of weights for operation of a multi-purpose reservoir. It can provide operators with direct decisions for reservoir operation. However, in most cases operation objectives have trade-offs, and hence single-objective optimisation cannot provide a unique optimum solution. In such situations improvement of some objectives cannot be achieved without the sacrifice of others. The goal of the single-objective analysis should be replaced by the concept of “noninferiority” in the multi-objective analysis (Mays and Tung, 2002). An operation decision based on the solution of a multi-objective optimisation problem requires that the operator expresses his/her preference by choosing the most suitable solution in the set of optimal solutions.

Multi-objective optimisation refers to problems with several objectives that are expected to be fulfilled simultaneously. The objectives are, however, often in conflict with each other and measured by different units. In general, a multi-objective reservoir operation problem can be formulated as follows

$$\text{Minimise } F(X) = [F_1(X), F_2(X), \dots, F_N(X)]$$

Subject to

$$q_i(X) \leq 0 \quad i = 1, 2, \dots, m$$

Where $F_j(X)$, $j=1, \dots, N$ are the objective functions.

X is a vector of decision variables.

$q_i(X)$ are constraints that define the feasible solutions.

A number of techniques to solve multiple objective function optimisation problems have been presented in the literature. They can be classified into two main groups: (1) aggregation approaches; (2) Pareto domination approaches. In the first approach, the priorities of the objectives are established, whereas in the second approach, no preference information is considered or is available before the search (Burke and Landa Silva, 2006).

a. *Aggregation approach*

This approach is commonly used when assigning an objective function value to evaluate the dominance of solution sets hence transforming the multi-objective optimisation problem into a single-objective optimisation. Two common methods (i) the constraint approach, and (ii) the weighting approach are presented below.

- *Constraint approach*

The main idea of this method is to choose one objective as the dominating objective and treat the rest of the objectives as constraints. For example, in reservoir operation, the user tries to maximise hydropower generation under the constraints of flood control. The constraints can be specified by the flow rates at downstream target points as well as the water level at the dam site. In this method, the search is moving towards the direction of optimising the chosen objective, while satisfying the rest of the objectives. It can be formulated as follows:

$$\text{Minimise } F_k(X)$$

Subject to

$$F_h(X) \geq L_h \quad \text{for all } h \neq k$$

where L_h is a lower bound on objective h .

The optimal solution can be identified after all the objectives have been considered as the dominating objective regarding the others as constraints.

- *Weighting approach*

This method transforms the various objectives into a single scalar objective function. The obtained optimal solution is based on the weights assigned to the objectives. Mathematically the objective function is given as follows:

$$\text{Minimise } F(X) = \sum_{i=1}^N w_i g_i(F_i(X))$$

where w_i is the weight assigned to the i^{th} objective.

$$0 \leq w_i \leq 1 \text{ and } \sum_{i=1}^N w_i = 1$$

$g_i(\cdot)$, $i=1, \dots, N$ are transformation functions assigned to each objective function.

The priority of each objective functions can be specified by using different weights. However, it should be noted that the priority also depends on the value of each objective. In order to compensate for differences in the magnitudes of the different measures, transformation functions are used. These functions are determined so that each objective function has about the same influence on the aggregated objective function near the optimum. Commonly applied aggregate functions include (i) weighted sum, (ii) distance function, and (iii) utility function (Khu and Madsen, 2005) as follows:

Weighted sum	$g_{ws}(F(X)) = \sum_{i=1}^N \alpha_i F_i(X)$
Distance function	$g_D(F(X)) = \left[\sum_{i=1}^N \alpha_i F_i^k(X) \right]^{1/k}$
Utility function	$g_U(F(X)) = \sum_{i=1}^N \alpha_i U_i(F_i(X))$

where α_i is the associated weight to each function; k is a chosen coefficient (for $k = 2$ the Euclidean distance measured is obtained); and $U(F_i(X))$ is a suitable utility function.

b. Pareto domination approach

This approach is not based on a single comparative value but on whether one solution is dominated by others (Khu and Madsen, 2005). The trade-off among the different objectives is presented by the set of Pareto optimal solutions. For each member in this solution set, an improvement in one objective is paid by a deterioration of the others. By definition, the Pareto set has following properties (e.g., Yapo et al., 1998; Madsen, 2000):

- For each non-member, it is possible to find at least one member of the Pareto set where all its objective functions are smaller.
- It is not possible to find any member of the Pareto set for which all its objective functions are better than those of another member.

The first property indicates that the parameter space can be divided into two parts: “good” solutions and “bad” solutions. The second property says that a member of the Pareto set may be better than the others with respect to some objective functions but not all.

Multi-objective optimisation algorithms have been designed based on the Pareto domination approach (eg. Guariso et al., 1986; Liong, et al., 2004; Khu and Madsen, 2005). The entire Pareto front can also be estimated by using the weighting approach by performing several individual optimisations with different combinations of the weights. An example of a Pareto front of a two-objective problem is illustrated in Figure 2.1. Points on the Pareto front have the characteristic that no other points have both a smaller value of F_1 and a smaller value of F_2 .

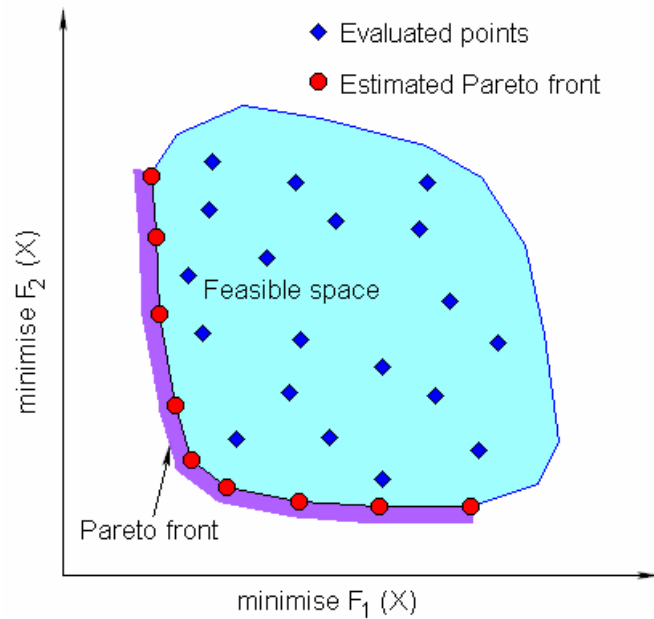


Figure 2.1 Example of a Pareto front for optimisation of a two-objective problem.

2.2 Proposed methodology

2.2.1 Combination of simulation and optimisation models in reservoir operation

Generally, system analysis models used to optimise reservoir operation may be categorized as: simulation models; optimisation models; and combination of simulation and optimisation models. Simulation models are effective tools for studying the operation of complex physical and hydrological characteristics of a reservoir system including the experience and judgment of operators. However, since they are limited to predict the performance of a reservoir for a given operation policy, optimisation models have an advantage in being able to search for the optimum policy from an infinite number of feasible operation policies that are defined through decision variables. In recent years, incorporation of an optimisation technique into a simulation model to execute a certain degree of optimisation has been advocated (Ranjithan, 2005). The framework of the simulation-optimisation process is shown in Figure 2.2. First, different parameter sets defining the control strategies are generated. For each trial parameter set

the simulation model is used to evaluate the performance of the system with respect to different objectives. Then, the parameter set is modified toward optimality by using the optimisation algorithm. The process is continued until one of the termination criteria is satisfied. The common objectives that have been considered are: maximising total energy production; minimising downstream flood risk including flow rate and water level; and maximising minimum downstream discharge for water supply.

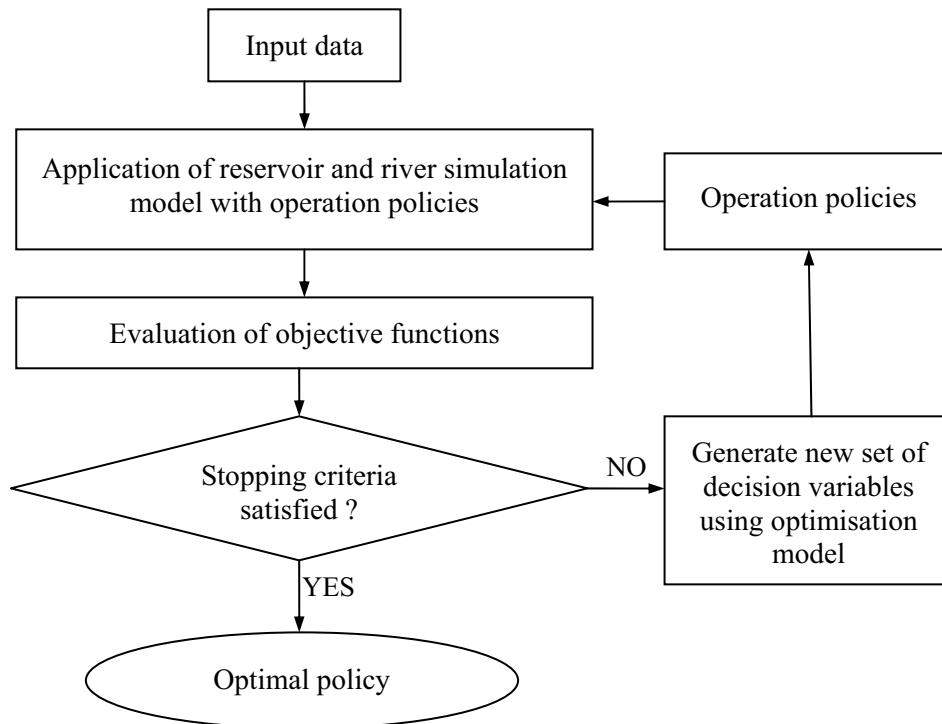


Figure 2.2. General framework of simulation-optimisation modelling approach for reservoir operation.

This study proposes to optimise the control strategies for the Hoa Binh reservoir operation by applying a combination of simulation and optimisation models. The control strategies are set up in the MIKE 11 simulation model (DHI, 2005b) to guide the releases of the reservoir system based on the current reservoir level, hydrological conditions, water demands and the time of the years. The Shuffled Complex Evolution (SCE) algorithm, a heuristic global optimisation tool, is adopted for optimising the reservoir operation. In this study the SCE algorithm as implemented in the AUTOCAL software (DHI, 2005a) is applied.

2.2.2 MIKE 11 - Structure Operation module

MIKE 11, developed by DHI Water & Environment, is a software package for simulation of fully dynamic, one-dimensional flows in estuaries, rivers, irrigation channels and other water bodies (DHI, 2005b). The Hydrodynamic (HD) module is the core component of the model. It consists of an implicit finite-difference 6-point Abbott-

Ionescu scheme for solving the Saint-Venant equations. Applications related to the MIKE 11 HD module include: Flood forecasting and reservoir operation; Simulation of flood control measures; Operation of irrigation and surface drainage systems; Design of channel systems etc. In addition, add-on modules are available for a wide range of applications, including rainfall-runoff, sediment transport, water quality, dam break etc. Structure Operation (SO) is one of the add-on modules. It is used to define operating strategies for structures such as sluice gates, overflow gates, radial gates, pumps, and reservoir releases, which may be included in the river network. With the SO module, reservoirs may be operated by choosing among an arbitrary number of different control strategies, which are presented as a sequence of 'IF – THEN' statements. If all conditions that are specified for a control strategy are satisfied, the control strategy will be executed. By using several control strategies the user can simulate multi-purpose reservoirs taking into account a large number of objectives, including flood protection, energy production and water supply.

A control structure is implemented with control strategies that determine how the structure is operated based on values at a control point such as reservoir stage, downstream water level and time of the year. A control strategy is defined using a list of logical statements according to priorities of different controls. Therefore, the user can define which logical statement that is evaluated first, second, third and so on. A logical statement consists of two parts: (i) The conditions that must be evaluated as TRUE or FALSE; (ii) The target points that are applied to the structure. If all conditions that specify the strategy are met at a control point, the target points of the strategy are executed.

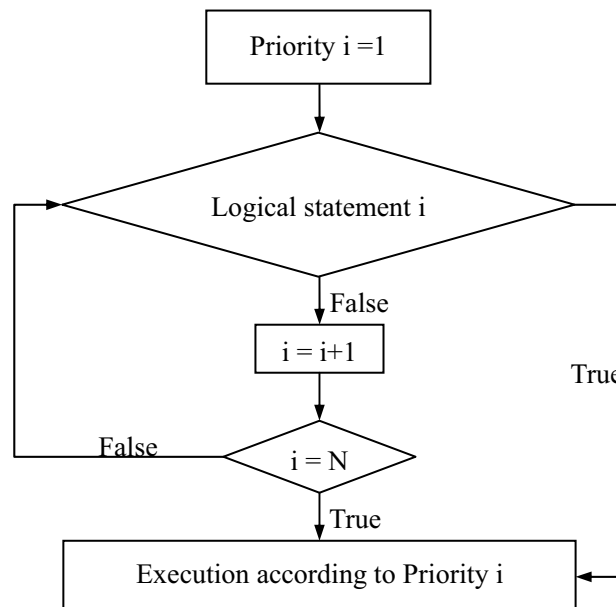


Figure 2.3 Diagram of structure operation. A logical statement can have any number of conditions that all must be evaluated as true for the statement to become true.

Figure 2.3 describes an operational procedure of a control structure at an arbitrary time

step. In the figure, N indicates the lowest priority, which always will be evaluated to true if all other logical statements are false.

2.2.3 Shuffled Complex Evolution Algorithm – AUTOCAL model

Optimisation problems can be solved by using “local” or “global” search methods. The local search methods such as gradient-based methods and direct search methods have been widely applied in water resources management (Yeh, 1985). The advantages of these methods are that they are effective and efficient when applied for optimisation of convex, single extremum functions. However, for more complex functions they may produce a local optimal solution. In fact, there are many functions such as non-convex, non-differentiable and multi extrema functions, which cannot be effectively solved by local methods. It requires more robust optimisation techniques to find the global optimum solution of complex problems. The shuffled complex evolution (SCE) algorithm is one of these techniques.

This algorithm has synthesized the best features from several existing algorithms, including genetic algorithms (GA), and introduced the concept of complex shuffling (Duan, 1994). It conducts an efficient and robust search of the parameter space and has been widely applied in calibrating various conceptual models (e.g. Duan, 1994; Yapo, 1998; Madsen, 2000; Eckhardt, 2001; Brath, 2004). The method combines the strength of the “simplex search” with the “concept of controlled random search”, “competitive evolution” and “complex shuffling” (Duan, 1992). The algorithm is presented in detail by Duan (1994).

A brief description of the algorithm is given in the following:

- (1) *Generate sample*: A sample of points, i.e. parameter sets or sets of decision variables, are randomly generated from the feasible parameter space. For each parameter set the objective function value is calculated. The initial sample has the size $s = pr$ where p is the number of complexes and r is the number of points in each complex.
- (2) *Rank points*: Sort the s points in order of increasing objective function value so that the first point represents the point with the smallest objective function value (best point) and the last point represents the point with the largest objective function value.
- (3) *Partition into complexes*: partition the s points into p complexes, such that the first complex contains every $p(k-1) + 1$ ranked point, the second complex contains every $p(k-1) + 2$ ranked point, and so on, where $k=1,2,\dots,r$.
- (4) *Evolution*: A sub-complex of size q is formed from the complex by randomly choosing q points. A triangular probability distribution is used for assigning the

probability of a point to be included in the sub-complex (larger probability for points with smaller objective function value). The sub-complex is evolved according to the simplex algorithm (Nelder and Mead, 1965). Each complex is evolved β times.

- (5) *Complex shuffling*: Combine the points in the evolved complexes into a single sample of s points and return to step 2.

Steps 2-5 are repeated until one of the criteria for termination is satisfied.

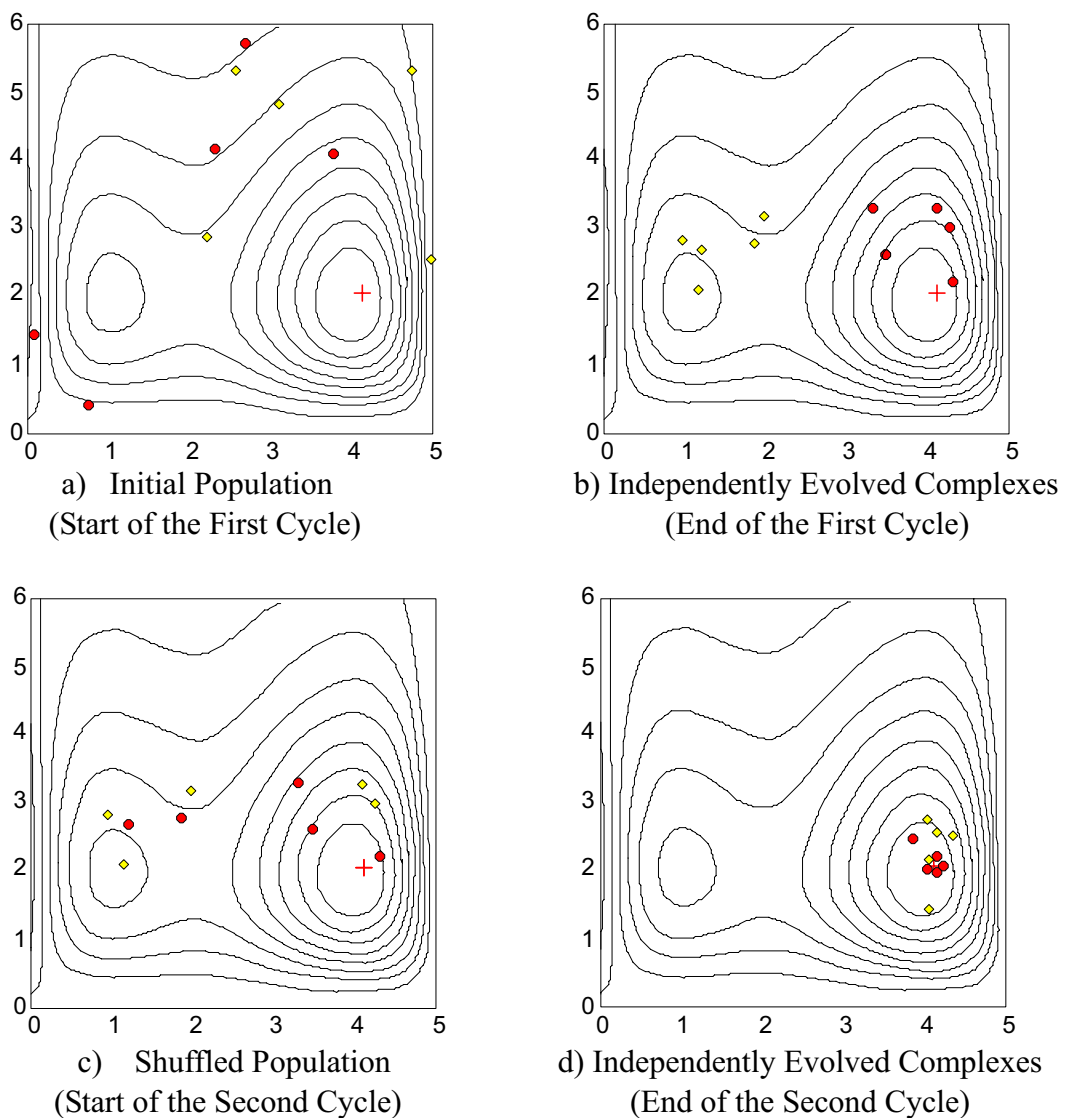


Figure 2.4 Illustration of the SCE algorithm.

(Extracted from Duan et al., 1994)

Cross point indicates the global optimum of the objective function; Diamond and circle points indicate two complexes of the sample population.

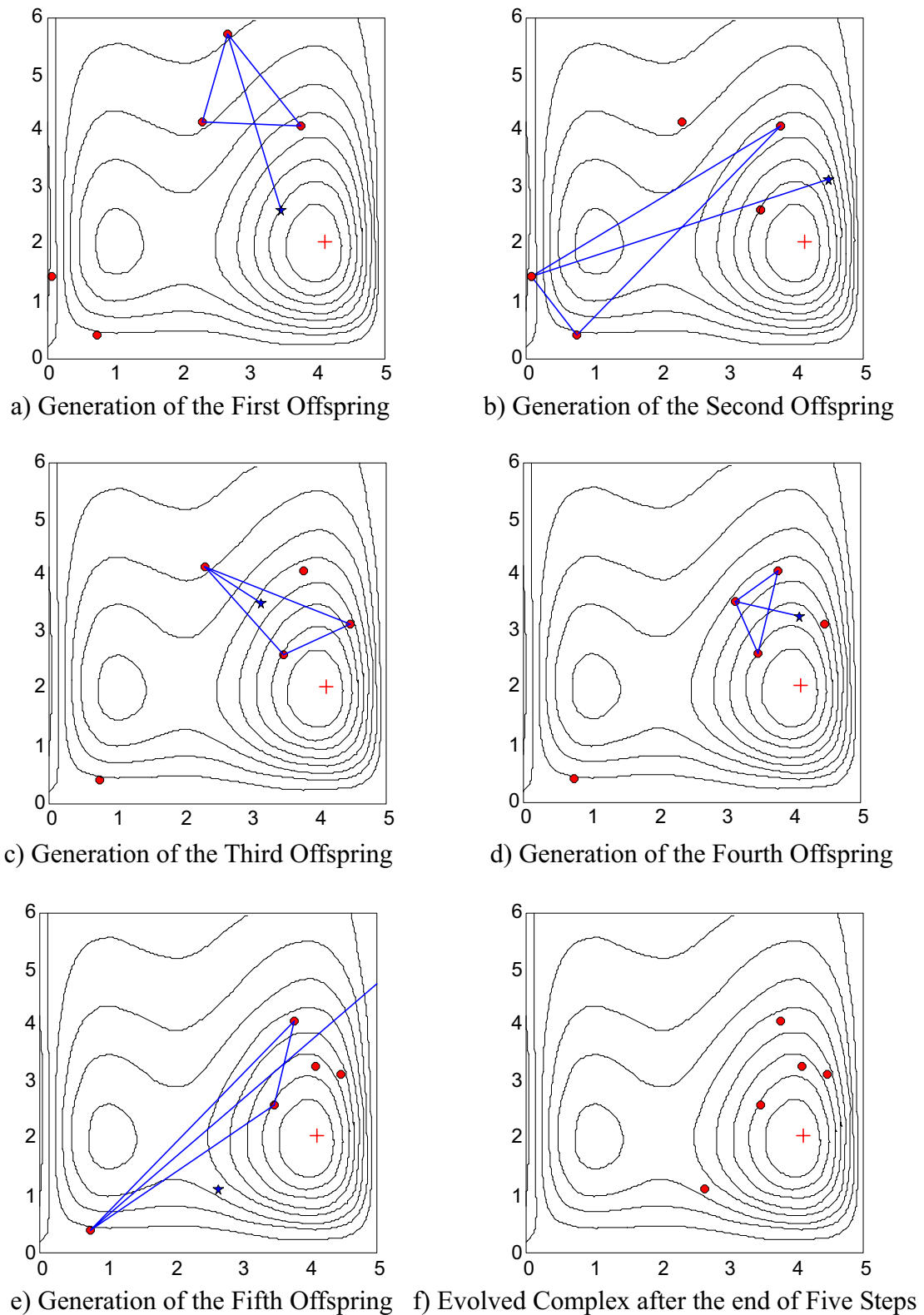


Figure 2.5 Illustration of the evolution steps taken by each complex
 (Extracted from Duan et al., 1994)

Cross point indicates the global optimum of the objective function; Circle points indicate one complex of the sample population.

The SCE method is explained in figure 2.4 by using a two-dimensional example. The function includes one global optimum and one local optimum. In this example the sample population including 10 points is divided into two complexes, each complex contains 5 members. The initial locations of these members are shown in figure 2.4 (a). In the first evolution cycle the two complexes are converging toward two distinct optima, as each complex spend an independent evolution process. The description of the evolution steps taken by each complex is explained in figure 2.5. For more details readers are referred to Duan et al. (1994). The locations of the members at the end of the first evolution cycle are presented in figure 2.4(b). The two evolved complexes are shuffled according to the procedure presented in step 5. The new memberships of the two evolved complexes after shuffling are displayed in figure 2.4 (c) and the locations of the members at the end the second evolution are shown in figure 2.4 (d). It is clear that both complexes are now converging toward the global optimum.

The SCE algorithm contains different algorithmic parameters, which must be chosen carefully. An analysis of these parameters was undertaken by Duan et al. (1994), providing range and recommended values (Table 2.1).

Table 2.1 Algorithmic parameters for the SCE algorithm
(n is the number of decision variables)

Parameter	Description	Range	Recommended value
p	Number of complexes	$p \geq 1$	-
r	Number of points in a complex	$r \geq 2$	$2n + 1$
q	Number of points in a sub-complex	$2 \leq q \leq r$	$n + 1$
β	Number of evolution steps taken by each complex before shuffling	$\beta \geq 1$	$2n + 1$
p_{\min}	Minimum number of complexes required in the population	$1 \leq p_{\min} \leq p$	p

The number of complexes p is the most important algorithm parameter. In general, a larger value of p will give a higher possibility of converging into the global optimum but it requires a larger number of model evaluations, and vice versa. In the application by Madsen (2003) two complexes in SCE provided a reasonable compromise between robustness and computing time.

The SCE algorithm is one of two parameter optimisation methods that is implemented in the AUTOCAL (AUTO CALibration) software. The AUTOCAL is a generic tool for performing parameter optimisation, sensitivity analysis and scenario management, especially customised to the suite of DHI modelling software.

The core of the AUTOCAL tool consists of the following steps:

1. Provide a set of parameter values to the numerical model, which will be used in a

specific model run.

2. Execute the simulation model using the specified set of parameter values.
3. Calculate statistical performance measures of the model output.

In the first step, all files that include parameters to be manipulated in the AUTOCAL run should be specified. When a model parameter file is selected, a corresponding template file is automatically created. This template file is used for placing parameter identification tags at the locations where the values of the model parameters to be manipulated in AUTOCAL are given. The set of parameters ($\Theta = [\theta_1, \theta_2, \dots, \theta_m]$, m is total number of parameters) are restricted to a feasible parameter space using box constraints

$$\theta_{i,\text{lower}} \leq \theta_i \leq \theta_{i,\text{upper}}$$

Moreover, inequality constraints can be applied

$$u(\Theta) \leq v(\Theta)$$

where $u(\cdot)$ and $v(\cdot)$ can be defined using any linear or non-linear function. Finally, equality constraints can be defined in the following explicit form

$$\theta_i = h(\theta_1, \theta_2, \dots, \theta_{i-1}, \theta_{i+1}, \dots, \theta_m)$$

where $h(\cdot)$ defines any linear or non-linear relationship between the i 'th parameter and the remaining $m-1$ parameters.

Whenever AUTOCAL is used for parameter optimisation, the performance of the model simulation given the specified parameter set must be assessed. This is done by calculating statistical performance measures. These measures are typically statistics that compare simulation results with corresponding targets.

AUTOCAL includes three basic comparison statistics

- Average error $AE = \frac{1}{T} \sum_{i=1}^T (x_i - y_i)$

- Root mean square error $RMSE = \sqrt{\frac{1}{T} \sum_{i=1}^T (x_i - y_i)^2}$

- Standard deviation $STD = \sqrt{\frac{1}{T} \sum_{i=1}^T \left((x_i - y_i) - \frac{1}{T} \sum_{j=1}^T (x_j - y_j) \right)^2}$

Besides the basic statistics, AUTOCAL includes two event-based statistics

- Error of maximum value $\text{Err max} = \text{Max}\{x_i\} - \text{Max}\{y_i\}$
- Error of minimum value $\text{Err min} = \text{Min}\{x_i\} - \text{Min}\{y_i\}$

where x_i and y_i , $i = 1, \dots, T$ are the model output and the target values, respectively. The index i represents the time step, and T is the total number of time steps.

For aggregation of the performance statistics given above, three different objective functions are used in AUTOCAL

- Weighted sum $F_{\text{pool},i} = \sum_{j=1}^N w_j F_j$
- Weighted sum of absolute values $F_{\text{pool},i} = \sum_{j=1}^N w_j |F_j|$
- Weighted sum of squares $F_{\text{pool},i} = \sum_{j=1}^N w_j F_j^2$

where F_j is a comparison statistic, w_j are weights assigned to each statistic, and N is the number of statistics that are pooled. In the second aggregation level in AUTOCAL the defined objective functions are aggregated into one measure

$$F_{\text{agg}} = \sum_{i=1}^M w_i g_i(F_{\text{pool},i})$$

where M is the number of objective functions that are aggregated, w_i is the weight and $g_i(\cdot)$ is the transformation functions assigned to each objective function. In AUTOCAL three different transformation options are provided including: (a) No transformation; (b) Transformation to a common distance scale; (c) Transformation to a common probability scale.

The model runs until one of the stopping criteria as presented below is satisfied

- (i) Maximum number of model evaluations.
- (ii) Convergence in objective function space.
- (iii) Convergence in parameter space.

Chapter 3

RED RIVER BASIN - HOA BINH RESERVOIR

3.1 Introduction

The Red River basin, which is the largest river basin in Vietnam, is located in the northern and north-eastern part of the country (Figure 3.1). The total catchment area of the basin is 169,000 km², of which 48% is in China and less than 1% is in Laos. Three major upstream tributaries Da, Thao, and Lo join and form the Red River delta near Hanoi. The river delta has a triangular form with the apex near to Viet Tri, about 150 km from the coast and a 130 km long base at the coastal line with many estuaries. The area of the delta is 16,644 km² and covers 11 provinces. The delta is very flat with elevations between 0.4 m and 12 m above mean sea level and more than half less than 2 m (Binnie et al., 1995). Virtually the whole Red River delta is protected by two systems of dykes, the river dykes and the sea dykes, where the total lengths are 3000 km and 2000 km, respectively.

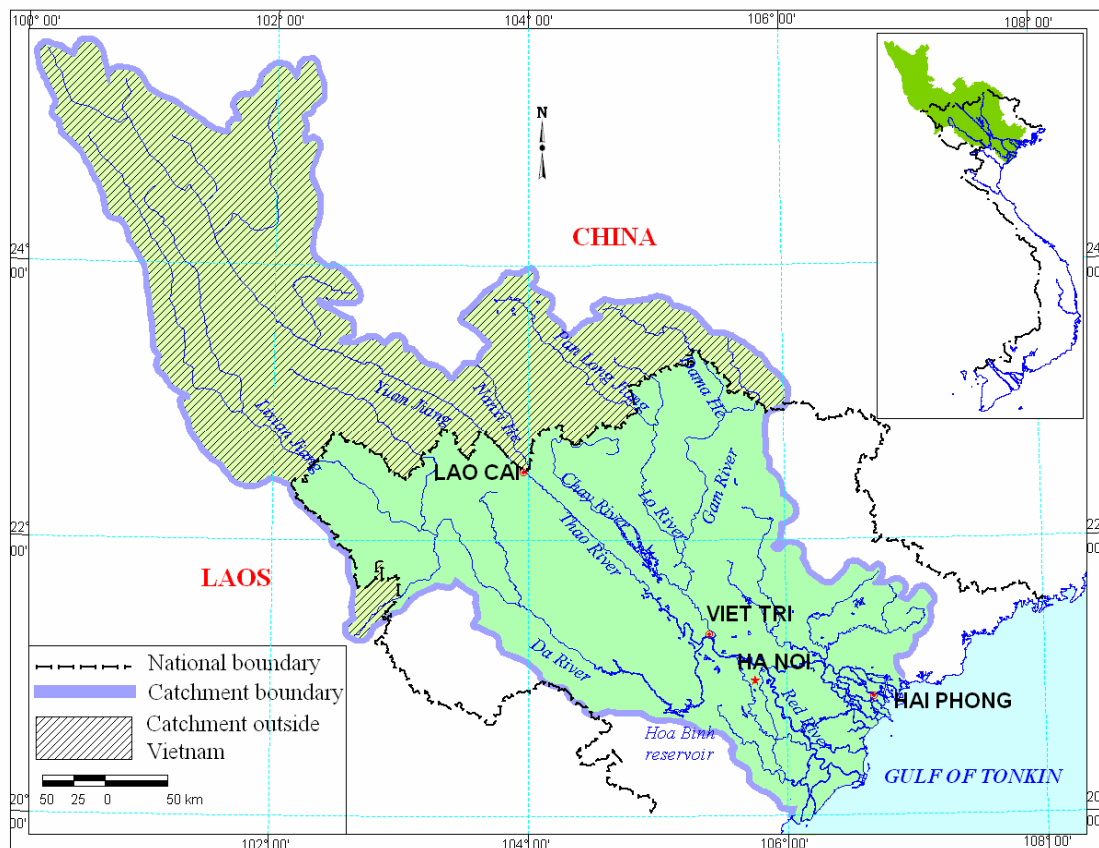


Figure 3.1 Map of the Red River basin

The population in the Red River basin is about 24 million people of which 15 percent live in urban areas (Tinh, 2001). With almost 17 million people living in the delta, the Red River delta is one of the most densely populated rural areas in the World – about more than 1000 persons/km². The delta comprises two big cities of Vietnam: the national capital Hanoi and a big seaport city Hai Phong. It is an important area for the socio-economic development of Vietnam.

3.2 Characteristics of the Red River basin

3.2.1 River network

The Red River rises at 1776 m height in the mountainous region of the Yunnan Province in China and flows through Vietnam to the Gulf of Tonkin (part of the South China Sea) at Ba Lat. The reach of the Red River from Lao Cai to Viet Tri is also called Thao River. The downstream part of the Red River system is mature with a small bed slope. The total length is 1126 km of which 556 km are in Vietnam with a mean value of the bed slope equal to 0.13%. The 220 km from Viet Tri to Ba Lat the mean bed slope is only 0.031%. The Da River flows to Vietnam at Bat Hat in northwest-southeast direction and joins the Red River at Trung Ha. The total length of the Da River is 1010 km of which 570 km are in Vietnam. The river flows in high mountain ranges with narrow valleys and high river slope. Due to many cascades, the river has a high potential for hydropower. The Lo River flows to Vietnam at Thanh Thuy in northwest-southeast direction and joins the Red River at Viet Tri. The total length of the Lo River is 470 km of which 275 km are in Vietnam. The Lo River has three main tributaries: the Gam River, the Chay River and the Pho Day River.

3.2.2 Rainfall and runoff

The climate of the basin is tropical to sub-tropical. It is dominated by the monsoon winds of eastern Asia. The mean annual rainfall of the Red River basin varies from 1200 mm to 5000 mm (Figure 3.2). In the Red River delta, the variation is smaller with an average rainfall between 1700 mm and 1800 mm. It is necessary to point out that the seasonal variation is significant in the Red River basin. Only about 20% of the annual rainfall occurs in the dry season, from November to April. The remainder falls in the rainy season, from May to October. The delta region is affected by typhoons from June to October, especially in July and August with a maximum wind speed recorded to about 180 km/h (Binnie et al., 1995). The amount of precipitation during storms can reach to more than 300 mm/day.

The annual discharge volume of the basin is around 130 billion m³, representing an average discharge of about 3700 m³/s. This corresponds to about 16% of the total runoff for the whole country. The minimum recorded discharge is 370 m³/s, while the maximum is 38000 m³/s (in 1971).

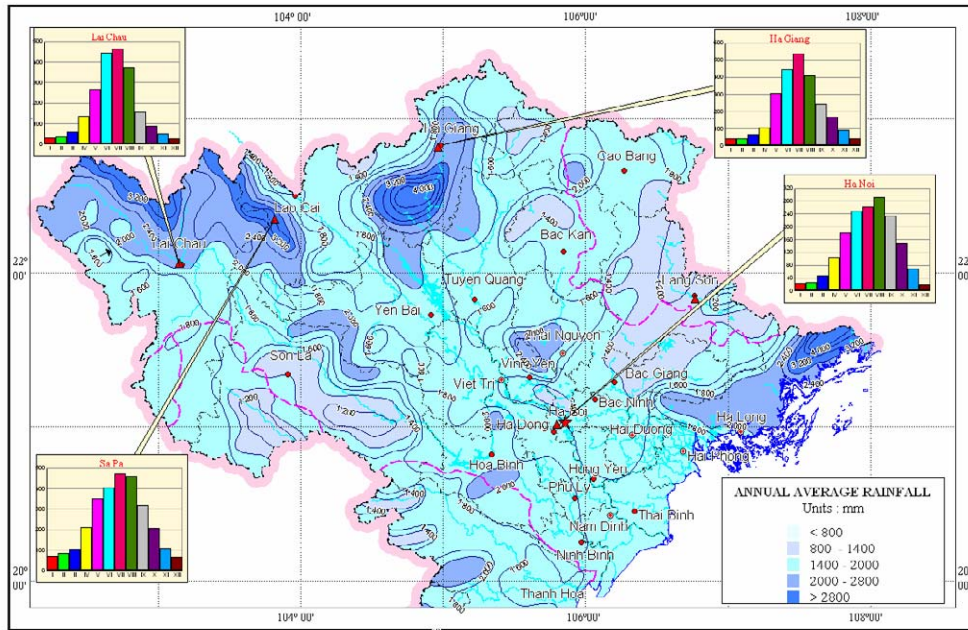


Figure 3.2 Map of annual rainfall in the Red River basin (part of Vietnam)
(Source: Vietnam National Water Resources Council)

3.3 Floods in the Red River basin

3.3.1 General information

The floods, which are formed from the sub-basins of Da, Thao and Lo River, propagate along the channels, join into the Red River at Viet Tri and then move downstream. Before reaching Hanoi, a part of the flood volume is distributed to Thai Binh River by the Duong River. The main location to be protected against flooding is Hanoi. Four levels of official flood alarms are used by the Vietnam Standing Office of the Central Committee for Flood and Storm Control including: Alarm level I (possible flood condition), alarm level II (dangerous flood condition), alarm level III (very dangerous flood condition), and alarm level III+ (emergency flood condition). The water levels corresponding to alarm level I, II, and III at the Hanoi hydrometric station are 9.50 m, 10.50 m and 11.50 m, respectively (Tuan, 2002).

The annual maximum water levels observed at Hanoi are shown in Figure 3.3. From the figure it can be seen that the maximum level (14.05 m) ever recorded occurred in 1971. It is close to the 100-year event (Tinh, 2001) and is 5 - 10 m higher than the altitude of Hanoi city. According to Hoa et al. (1997), without a dike break, the peak water level at Hanoi would have been +14.67 m. Besides, during 49 years (from 1956 – 2004), there were 33 years where the annual maximum water level at Hanoi was above alarm level II, and 15 years where it was above alarm level III. It can be said that flood risk in the basin is serious. It does not only threaten the socio-economic activities of the basin in general but also the safety of the downstream part, especially the Hanoi capital.

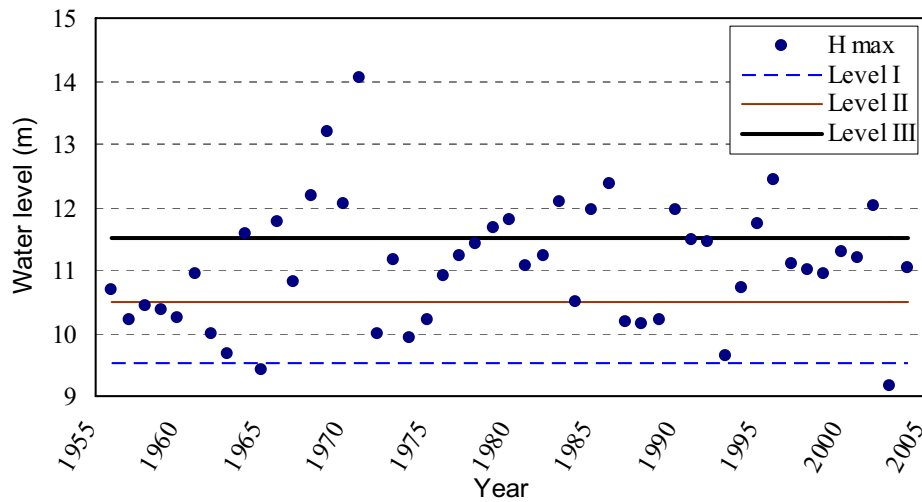


Figure 3.3 Annual maximum water level at Hanoi, the water levels that occurred after 1990 have been obtained with the regulation of the Hoa Binh reservoir.

Because of the rainfall regime and the resulting flow in the basin, the year is divided into a flood season and a dry season. The flood season is defined as continuous months in which the monthly discharge is greater than or equal to the annual discharge with a frequency greater than or equal to 50%. According to this criterion, the flood season in the upstream region of Da River and eastern region of Lo River lasts in 4 months, from June to September, whereas it is 5 months from June to October in the remaining regions of the basin. The flow volume in the flood season corresponds to about 70 % of the total annual flow volume. The maximum of mean monthly discharge usually occurs in August, where the flow volume is about 20 % of the annual flow volume. Extreme floods in all tributaries and in the main-stream of the Red River usually occur in August as well (Tuan, 2002).

3.3.2 Synchronization of floods in the Red River basin

The floods in the basin are the result of floods in the three main tributaries Da, Thao, and Lo River, where the Da River on average contributes 51.2 % of the Red River flow (Tinh, 2001). Analysing the observed data from 1902 to 2005 shows (Phuc, 2005):

- The percentage of floods in all three main tributaries synchronized with a flood in the Red River is 13%.
- The percentage of floods in Da River synchronized with a flood in the Red River is 68%.
- The percentage of floods in Lo River synchronized with a flood in the Red River is 47%.
- The percentage of floods in Thao River synchronized with a flood in the Red River is 44%.

- The percentage of floods in Da River and Lo River synchronized with a flood in the Red River is 34%.
- The percentage of floods in Da River and Thao River synchronizg with a flood in the Red River is 25%.
- The percentage of floods in Lo River and Thao River synchronized with a flood in the Red River is of 23%.

From the analysis it can be said that the flood in the Da River plays an important role in forming floods in the Red River, both with respect to frequency and flow volume.

3.3.3 Flood control in the Red River basin

Mitigation of flood damages is one of the highest priorities for water resources management in the Red River basin, and structural methods have to a large extent been used. As presented in Section 3.1 the Red River delta has been protected by two systems of dykes. Although the dyke systems have been strengthened, the proposal of using a cascaded reservoir system as a mean of flood control is increasingly being considered, especially as it can be combined with harnessing the hydropower potential. In this basin the Hoa Binh dam is the most important installation (Tinh, 2001).

3.4 The Hoa Binh reservoir

3.4.1 General features

Table 3.1 Key features of the Hoa Binh reservoir

- Crest level of the dam	123 m
- Dead storage level	80 m
- Minimum operational level	75 m
- Storage capacity	$9.6 \cdot 10^9 \text{ m}^3$
- Flood control storage	$5.6 \cdot 10^9 \text{ m}^3$
- Installed generating capacity	1,920 MW
- Maximum discharge through turbines	$2,400 \text{ m}^3/\text{s}$
- Number of bottom sluice gates	12
- Number of spillways	6
- Release through bottom sluice gates at level of 120 m	$21,900 \text{ m}^3/\text{s}$
- Spillways release at level of 120 m	$13,500 \text{ m}^3/\text{s}$

The Hoa Binh reservoir, 70 km from Hanoi, is located on the Da River. It was completed in 1989. The reservoir is designed to keep the peak flood level of the most extreme historical flood that occurred in 1971 at Hanoi below 13.3 m. Besides flood control, the reservoir is expected to produce on average 7.8 billion kWh per year corresponding to 40 percent of Vietnam's electricity (Tinh, 2001).

Taking into account flood protection, hydropower generation and other demands, which have been required by the Vietnamese Government, the key features of the Hoa Binh reservoir are presented in Table 3.1.

3.4.2 Issues in operation of the Hoa Binh reservoir

The Hoa Binh reservoir is Vietnam's most ambitious project related to water resources management. However, many issues have appeared since the reservoir started its operation in 1989. The conflict between the two main purposes, flood control and hydropower generation, is a major problem in operation of the reservoir. Besides that, several other factors, including the physical and hydrological conditions, may render the conflict more serious. Four main factors are presented as follows (Hoa et al., 1997).

- The Hoa Binh reservoir is on the Da River, the largest tributary of the Red River, which contributes with more than 50% of the flow as well as flood peaks to the downstream part. Therefore, floods on Da River play the key role in downstream flooding and Hoa Binh reservoir is key measure for controlling flood in the Red River basin.
- The reservoir is regulated by spillways and bottom sluice gates. In operation, each bottom gate has to open or close entirely, without any intermediate adjustment. Therefore, it is impossible to maintain the reservoir level at a desired level. Furthermore, as the discharge through one bottom gate is very large, it can make a significant change of the downstream flood panorama.
- The fraction of active storage is quite big. This storage is required for serving both of the two conflicting purposes: flood control and power generation.
- The requirement of power generation from the Hoa Binh reservoir for Vietnam's socio-economic development is large.

There have been many research efforts devoted to the Hoa Binh reservoir operation. Some of these have concentrated on floods in the Red River: Hoa et al. (1997) focussed on flood forecasting in the upstream basin for reservoir operation; Tuan (2002) applied a 1-D unsteady flow model for simulating flood flow in the Red River basin and used this model for practical studying of flood control in the basin. Other efforts have concentrated on improving the efficiency of the reservoir regulation, including Dao et al. (1988) and Phach et al. (1994). However, the results obtained from these works only satisfy part of the overall requirements for the Hoa Binh reservoir operation, and further studies needs to be conducted.

3.4.3 Reservoir operation policy

The Central Committee for Flood and Storm Control (CCFSC) takes responsibility for operation of the reservoir during the flood season by regulating the outflow as

appropriate. From 15th June to 15th September every year, the Hoa Binh has to be regulated to meet the demands on flood protection for the dam itself and downstream taken the priority order as follows (CCFSC, 2005)

- (I) Strictly ensuring the safety of the head-work.
- (II) Taking part in cutting downstream floods (both regular and design floods).

During periods of flood protection, the Hoa Binh reservoir is still operated in the way of ensuring the headwater level and discharge to keep electric generators working normally without compromising the flood control tasks mentioned above.

The reservoir regulation is composed of guidelines that describe how the reservoir should be operated according to the current reservoir level, hydrological conditions, water demands and the time of the year.

In order to ensure both flood protection and efficient hydropower generation, three regulation periods have been defined:

- | | |
|-----------------------|---------------------------------|
| a. Pre-flood season: | From 15 June to 15 July; |
| b. Main flood season: | From 16 July to 20 August; |
| c. Post-flood season: | From 21 August to 15 September. |

Regulation for flood control

The target water level in the reservoir should be kept below the flood control (normal) level (see Figure 3.4) in order to provide sufficient storage for flood cutting.

In the pre-flood season a target water level of 95 m is defined. In the main flood season the flood control capacity is increased and a target water level of 93 m is defined. In the post-flood season, operation is reviewed in consideration of rainfall forecasts with the goal of ensuring a full reservoir and maximum power generation before the dry season. However, in order to prevent late floods, the maximum water level before 25th August must not exceed +103 m and before 31st August not exceed +108 m. Until the end of September the water level in the Hoa Binh reservoir can be increased but must not exceed +117 m.

Reduction of downstream flood damage is the primary objective of the reservoir. To reduce the risk of flooding, the Hoa Binh reservoir has implemented the following actions:

- (1) Operational procedures for reducing regular floods. If it is predicted that the water level in the Red River at Hanoi exceeds +11.50 m within the next 24 hours, flood-reducing operations will be initiated for the Hoa Binh reservoir. The aim is to keep the water level at Hanoi below +11.50 m, while at the same

time keeping the water level in the reservoir below +100 m (flood control level 1).

(2) Operational procedures for reducing a major downstream flood in the Red River. Given that the water level is +11.50 m at Hanoi, +100.00 m at Hoa Binh reservoir (i.e. the maximum level for regular flood regulation), and the predicted water level in the Red River in the next 24 hours increases rapidly, then the normal operational procedures will be changed to procedures for reducing a major flooding in the downstream part of the Red River. First, if the reservoir level is below +108 m (flood control level 2), the allowed maximum water level at Hanoi should be kept below +12.00 m. In the case where the water level at Hanoi reaches +12.00 m, the reservoir level is +108 m, and the predicted water level in the Red River in the next 24 hours increases rapidly and may exceeds +13.10 m, then the reservoir have to store water to keep the water level at Hanoi below +13.10 m and the reservoir level below +120 m (flood control level 3).

(3) Operational procedures for safe protection of the Hoa Binh reservoir. In the case where the water level at Hanoi reaches +13.10 m, the reservoir level is +120 m, and there is a flooding in Da that is rapidly increasing (which can become harmful for operations of the Hoa Binh reservoir), the procedures are changed to reservoir protection. Based on predicted water levels for the Da and the Red River, a step-by-step opening of bottom and spillway gates is commenced to reach a situation where the release through the reservoir and the turbines is as close as possible to the inflow, but not larger.

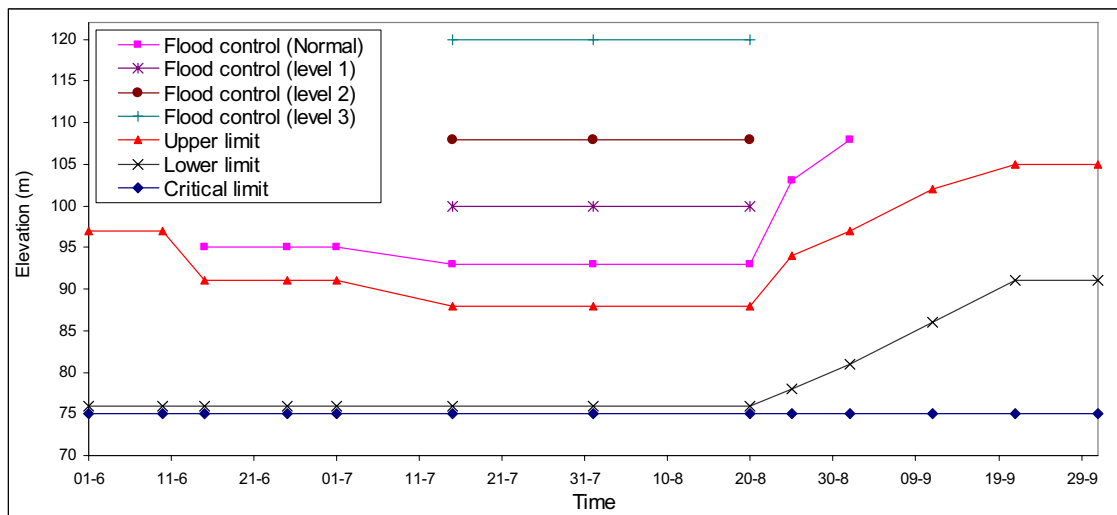


Figure 3.4 Time varying reservoir levels for regulation of the Hoa Binh reservoir

Water releases are usually accomplished by operating the turbines at maximum capacity until the necessary quantity of water has been discharged from the reservoir. At other times, additional water must be released through the bottom gates or spillways to lower the reservoir level more quickly and regain the needed storage capacity for future flood

events. For a detailed description of the regulation, refer to CCFSC (2005).

Regulation for hydropower generation

Because hydropower generation is the second objective of the reservoir in the flood season, the reservoir is operated to get as much hydropower as possible within the constraints of the flood mitigation rules. For this purpose, a regulation for hydropower generation has been developed in this study. The regulation is based on the characteristics of the turbines, the flood control curve as well as the minimum downstream discharge requirement. A 10-day scheme is used to define how much water is supplied in the model for hydropower generation. The regulation consists of three curves (upper, lower, and critical limit) as shown in Figure 3.4. The 10-day reservoir operations for hydropower generation are described as follows (see Figure 3.5):

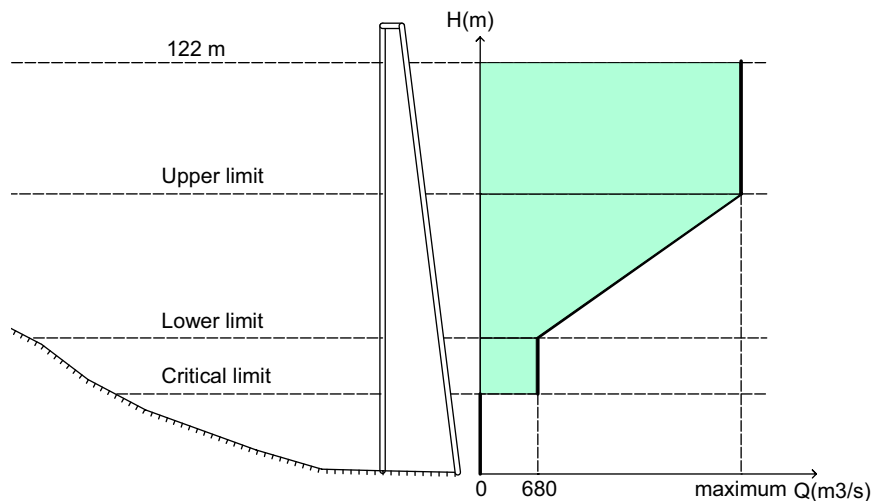


Figure 3.5 Rule curves for discharge through turbines for hydropower generation.

- 1) When the water level is above the upper limit, hydropower generation is operated with maximum discharge through turbines. In the pre-flood and main flood season the maximum discharge through turbines is set to $2400 \text{ m}^3/\text{s}$. In the post-flood season, in order to save water for the following dry season, the maximum discharge through turbines is determined according to the present headwater level for the turbines to work at maximum capacity. This gives a maximum discharge less than $2400 \text{ m}^3/\text{s}$.
- 2) When the water level is between the lower and upper limits, hydropower generation is operated with a discharge through turbines between the minimum downstream discharge requirement ($680 \text{ m}^3/\text{s}$) and the maximum.
- 3) When the water level is between the critical and lower limits, hydropower generation is operated with a discharge through turbines that meets the minimum downstream discharge requirement ($680 \text{ m}^3/\text{s}$).
- 4) When the water level is below the critical limit, hydropower generation is halted.

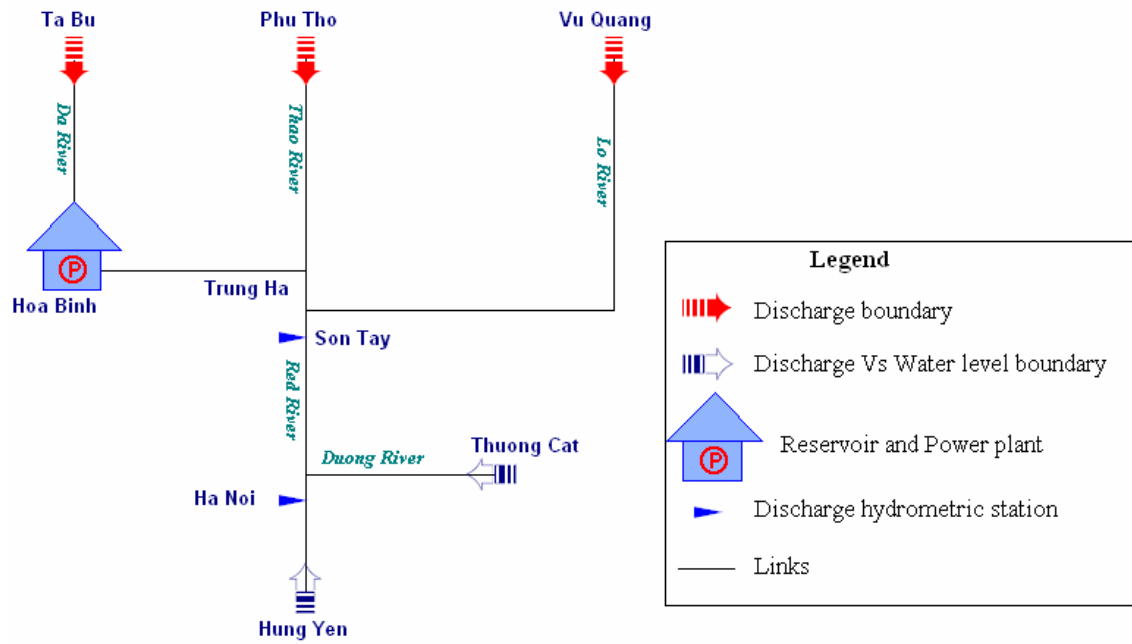


Figure 3.6 Description of the downstream part of the Red River basin system.

In order to evaluate the control strategies, historical data of twenty flood seasons including very large floods and normal flood conditions are selected. The General Department of Hydrometeorological Service (GDHS) is responsible for collection, processing and management of these data. The data include the upstream discharge boundaries at Ta Bu on Da, Phu Tho on Thao, and Vu Quang on Lo River and the downstream rating curve (discharge vs. water level) boundaries at Hung Yen on the Red River and Thuong Cat on Duong River. The data used for model calibration are discharge and water level at Son Tay and Hanoi on the Red River (See Figure 3.6).

Chapter 4

OVERVIEW OF THE PAPERS

4.1 Paper A

In this paper, the operation rules of the Hoa Binh reservoir are analysed by applying the MIKE 11 river modelling tool.

For the purpose of flood control, three key parameters are used: (i) Water level at Hanoi, the most important site for flood control in the Red River basin; (ii) Water level at the Hoa Binh reservoir; and (iii) 24-hour hydrological forecast information of the reservoir inflow as well as the water level at Hanoi. The MIKE 11 model has been used for the river network simulation including the main tributaries: Da, Thao, Lo, and Duong rivers. The Hoa Binh reservoir has been placed in the reservoir branch of the network, and the 6 spillways and 12 bottom gates as well as the turbines have been included as control structures in the model. The discharges through spillways and bottom gates are specified for different water levels.

The control strategies for the reservoir operation in the flood season including flood control and hydropower generation are set up in the MIKE 11 simulation model. The forecasted water level at Hanoi with a lead time of 24 hours is defined as a function of the forecasted discharge at Hanoi through an empirical equation provided by the National Centre for Hydrometeorological Forecasting of Vietnam.

Three alternative cases including: (i) present regulation; (ii) The Hoa Binh reservoir starts its operation for regular flood cutting when the 24 hour forecast of the water level in the Red River at Hanoi exceeds + 10.5 m (+11.5 m in the present regulation); and (iii) The water level in the reservoir in the main flood period is set to + 95 m before storing water for flood cutting (2 m higher than that in the present regulation) are analysed and compared with the actual reservoir operation. The comparison focuses on the maximum water level and the duration of high water levels at Hanoi, and the generated electricity production during the flood season. Twenty historical flood season data are used to evaluate the control strategies.

The different operation rule curves for the Hoa Binh reservoir were implemented in MIKE 11, and the results showed that the model can be used efficiently to regulate the reservoir under different hydrological conditions and can assist in operator decision-making.

In addition, the reservoir operation using the complete control system can lower the maximum water level and shorten the duration of high water level at Hanoi compared to the actual operation. With respect to hydropower generation, releases can be scheduled so that hydropower turbines are operated to maximize their value to the power supply system. The analysis of alternative strategies showed that lowering the target water level at Hanoi for which the reservoir starts its flood control operation can improve both flood control and hydropower generation as compared to the present regulation. Alternatively, by increasing the target water level in the reservoir in the main flood season, hydropower generation can be improved but at the expense of a reduced flood protection.

4.2 Paper B

The approach considered in the paper puts focus on identifying optimum control strategies for the Hoa Binh reservoir operation in terms of flood control and hydropower generation based on coupling the MIKE 11 simulation models with the SCE algorithm.

Generally, hydropower generation conflicts with the flood control function, since the reservoir should reserve storage space for cutting floods at the same time as it should be filled to provide hydraulic head to the turbines. The problem is solved using a two-step optimisation procedure. In the first step, the flood control regulation is optimised considering the objective of minimising the downstream flood peak at Hanoi and maximising the hydropower potential, which is manifested by the reservoir level during the flood season. The control variables to be optimised in this step consist of the reservoir level targets and water level targets at the flood control point at Hanoi, which is used to define the flood control strategies for the reservoir operation. In the second step, the hydropower generation is optimised considering the objective of maximising the hydropower generation during the flood season and maximising the reservoir level at the beginning of the dry season. In this step the variables that define the rule curves for hydropower generation are optimised. For the optimisation, selected data from the historical record and synthetically generated floods are used as input to the MIKE 11 model.

Under the new regulation scheme, optimised by SCE, the trade-off between flood control and hydropower generation was solved. An optimum solution can be found that is better with respect to both flood control and hydropower generation compared to the present regulations. The balanced optimum solution can maintain a higher water level in the reservoir, and at the same time reduce the downstream flood peak as well as the duration of emergency reservoir status. Furthermore, the optimised regulations can enlarge the power generation in the flood season as well as increase the water availability for the following dry season. In comparison with the present regulations, the results show that the increase of the hydropower production in the flood season under the optimised (balanced) solution is on average about 1.8. The reservoir level at the end

of the flood season which could be obtained under the optimised (balanced) solution is on average approximately 3 m higher than that under the present regulations.

In this study, Pareto optimum solutions for reservoir regulations have been achieved. An analysis on the variation of the parameters as well as the efficiency of each solution along the Pareto front has been carried out. Based on these results the operator can express his/her preferences and choose a preferred Pareto optimum solution.

4.3 Paper C

This paper presents a framework for real-time operation of the Hoa Binh reservoir. The combination of the SCE algorithm and the MIKE 11 river network simulation model provides an efficient tool that can be used to determine the optimal release decision variables for reservoir operation based on short-term forecasted information. In the present study, 3-day forecasted information is used to optimise the control variables that define the water release decision for each 6-hour window during the forecast period. The forecast lead time and the time window correspond well with the forecast capacity and the frame for operating the gates and measuring inflow to the Hoa Binh reservoir.

The real-time operation of Hoa Binh reservoir is defined for three situations with different goals corresponding to the given reservoir level, the forecasted inflow and the time of the year.

- (I) Case 1: The Hoa Binh reservoir is operated for only hydropower generation
- (II) Case 2 : The Hoa Binh reservoir is operated for flood control
- (III) Case 3: The Hoa Binh reservoir is operated for its safe protection

In Case 3 the reservoir is operated under the dam protection regulation defined in Paper B. Therefore, only Case 1 and Case 2 experiments are carried out to demonstrate the proposed method. The optimisation problem considers the trade-off between short-term objectives in terms of hydropower production and flood risk reduction in the forecast period and long-term objectives in terms of penalized deviations from the optimised rule curves. The obtained results are evaluated using Pareto optimisation, which provides the basis for choosing preferred solutions that balances short-term and long-term objectives taking other considerations into account. The application of different sets of control variables for each case (Case 1: decision variables of water release through turbines for hydropower generation; Case 2: bottom gate decision variables) can reduce the time required to solve the optimisation problem without reducing the accuracy of the result.

For each forecasted time period, Pareto-optimal operation strategies have been derived by analysis of the variation of the control variables as well as the efficiency of each solution along the Pareto front. The results demonstrate that the real-time optimisation framework improves the performance and enhances the flexibility of reservoir operation

in comparison to a strict application of the rule curves. The operator can express his/her preference to choose the most suitable solution in the set of Pareto-optimal solutions.

Chapter 5

CONCLUSIONS AND FUTURE WORK

5.1 Conclusions

In the thesis, a new method to improve the efficiency of the Hoa Binh reservoir operation in terms of flood control and hydropower generation during the flood season has been developed. The reservoir has been operated under a regulation that guides the release according to the current reservoir level, the water level at a downstream flood control site, and the time of the year.

Reservoir operation is described using the MIKE 11 simulation system for modelling the river flow in the lower part of the Red River system and the reservoir regulation. The main obtained results can be summarised as follows:

A number of logical statements that define the strategies for the reservoir operation are set up in the MIKE 11 simulation model. The results of implementing the reservoir operation under different alternative strategies demonstrate that the model can be used efficiently to regulate the reservoir and can assist in operator decision-making. Two alternative strategies for operation have been compared to the present regulation, and it has been shown that more efficient regulation schemes can be developed.

An optimal reservoir operation is found by combining the MIKE 11 modelling with a heuristic global optimising tool that is used for optimising different control variables. The SCE algorithm is adopted for searching the set of non-dominated or Pareto optimal solutions according to the trade-offs between the objectives. The optimisation is carried out using a two-step optimisation procedure, where in each step the variables defining the strategies for, respectively, flood control and hydropower generation are optimised. The results show that Pareto-optimal solutions can be chosen that are better with respect to both flood control and hydropower generation objectives compared to the present regulation. In addition, the optimised rule curves can increase the water level at the end of the flood season, thereby providing a larger hydropower potential in the following dry season.

To further improve the reservoir operation a real-time optimisation framework has been developed that includes real-time forecast of the inflows during the flood season. In this case, short-term operation for a 3-day forecast period is optimised considering the trade-off between short-term objectives in terms of hydropower production and flood risk reduction and long-term objectives in terms of penalized deviations from the optimised

rule curves. The control variables including the decision releases through turbines and bottom sluice gates are implemented for a 6-hour time step during the forecast period. The real-time framework improves the performance and enhances the flexibility of the reservoir operation in comparison to a strict application of the rule curves, so that flood risk can be reduced and hydropower production can be increased.

5.2 Future work

Mitigation of flood damages is one of the highest priorities for water resources management in the Red River basin. Although the basin is protected by a dyke system and the regulation of the Hoa Binh reservoir, the proposal of using a cascaded reservoir system as a mean of flood control is increasingly being considered, especially as it can be combined with harnessing the hydropower potential. In this case, the problem of multi-objective, multi-reservoir management should be considered for defining optimal reservoir operations.

Besides using powerful modelling and optimisation techniques, the efficiency of the derived reservoir operations also depends on the accuracy or uncertainty of input data. An important aspect that needs to be considered in the future work is how to handle uncertainties and stochasticity in the optimisation process. Uncertainties and stochasticity are normally represented by multiple system states in an ensemble setting, which adds an additional computational challenge to the optimisation problem.

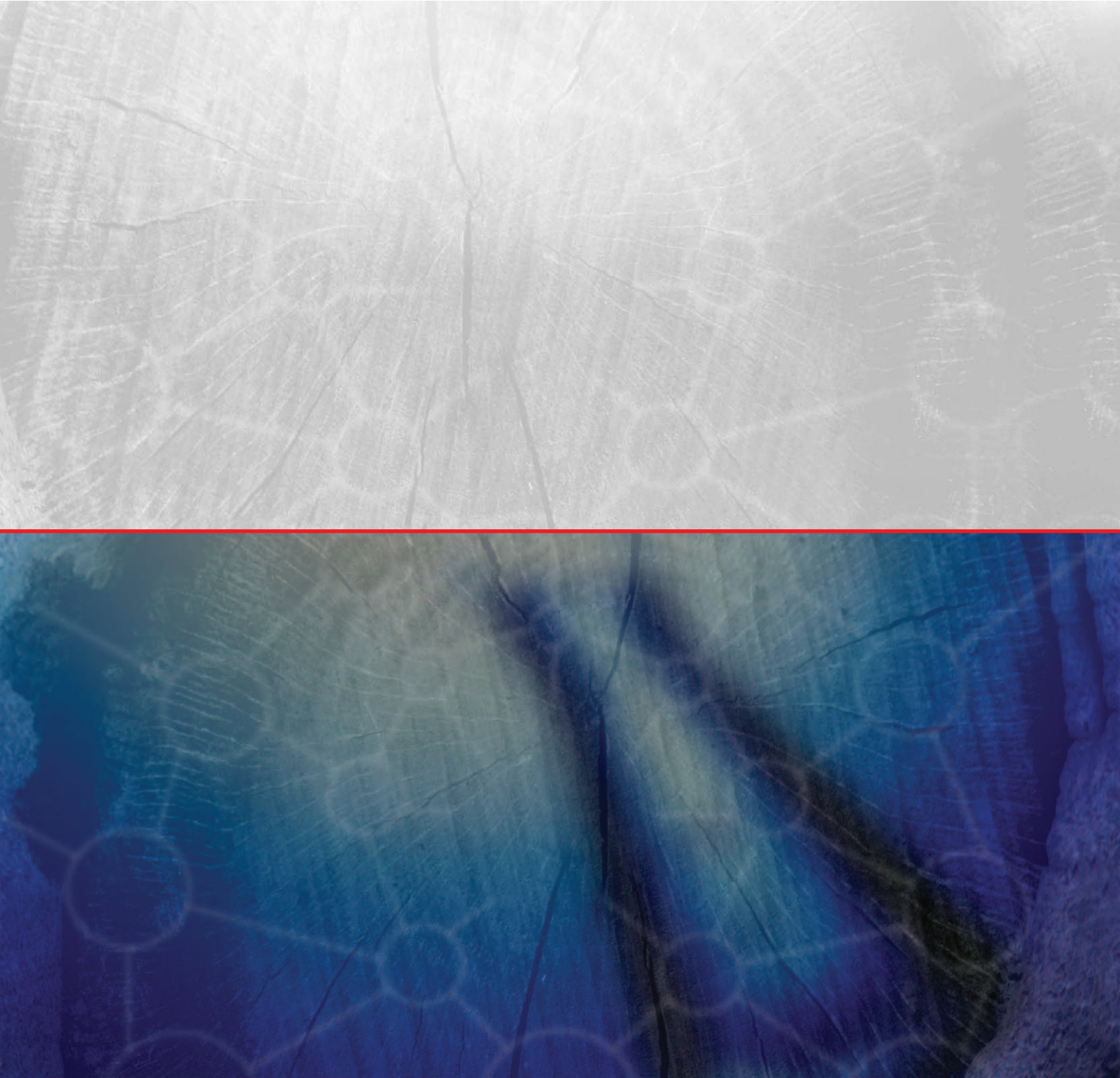
Finally, for optimisation problems that involve expensive simulation models a method that combines the simulation-optimisation approach with surrogate modelling should be applied. Basically, surrogate modelling (also known as meta-modelling) is a concept of approximating an expensive high-fidelity simulation model with an inexpensive surrogate. This procedure minimises the number of times the highest fidelity model is involved without reducing the accuracy of the solution.

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A microscopic image of plant cells, showing a network of cell walls and circular cell structures. A prominent red horizontal line runs across the middle of the image, separating the top and bottom halves.

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