

# Study on optimal operating rule curves including hydropower purpose in parallel multireservoir systems

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## Abstract

For multireservoir systems with hydropower purposes, the best strategy of joint operation is to firstly release water from the reservoir with the higher hydropower efficiency in order to achieve the highest benefits of the whole system. Considering the scarcity of water resources however, the operational practice is to follow a proper set of rule curves so as not only to reduce the water shortage amount and duration for downstream water demand but also to enhance the hydropower efficiency. Therefore, an operational model coupled with simulation and genetic algorithms is presented in this paper to overcome the difficulty with nonlinear and multiple parameters. In this paper, the joint operation of Shihmen and Festui Reservoirs in northern Taiwan was chosen for the case study. The study results indicate that the optimal operating rule curves of the parallel multireservoir system can achieve the highest hydropower benefit and meet the designed firm yield for water supply simultaneously.

*Keywords:* parallel multireservoir systems, soft optimization, rule curve-based reservoir operation, hydropower.

## 1 Introduction

Numerous studies address the problem of defining optimum operation rules for reservoir systems with multiple purposes. (Nalbantis and Koutsoyiannis [11], 1997; Belaineh et al., 1999 [1]; Lund and Guzman, 1999 [9]; Oscar and Eduardo, 2005 [12].) However, considering scarcity of water resources for water supply, the operation practice is to follow a proper set of rule curves so as not only to



reduce the water shortage amount and duration for downstream water demand but also to enhance the hydropower efficiency. As we know, water yield of a multireservoir system can be evaluated by employing a simulation model, which is a representation of physical system under a given set of conditions. Simulation model using historic discharge data of at least 30 years long (USCOE, 1982 [15]) includes a specification of operation rules and mass-balance among all the water components. As reported by Simonovic (1992) [14] and Wurbs (1993) [16], simulation model permits very detailed realistic representation of complex physical characteristics of a reservoir system [13]. The concepts inherent in simulation model are easier to be understood than other approaches, but simulation approach may need more time for users to find system's water yield with hydropower purpose by applying a cut and trial procedure. Because hydropower effectiveness evaluation based on reservoir operating rule curves involving relations among hydropower plant's efficiency, flow rate, reservoir water head and storage is highly nonlinear and complex, and the traditional optimization techniques are difficult to solve such a problem.

Some researchers paid attention to optimization techniques instead of simulation for reservoir operation problems. As stated by Yeh (1982) [17] and Siminovic (1973) [13], optimization is still less adopted in practice due to the gap between research and practice. Hence this paper present a method of determining a general operating policy for multireservoir in parallel system in which the operating policy for reservoir is performed by coupling the Genetic Algorithms (GAs) with simulation modeling to overcome computational intractability of the multireservoir systems.

Joint operating policies realize the benefit derived from joint operation (Lund and Ferreira 1996 [8]; Mohan and Raipure 1992 [10]). However, for the complicated reservoir system including several reservoirs in parallel and/or in series for both joint and side demands, rule curves of individual reservoir are not sufficient. Therefore, this paper elucidates the application of an optimization-simulation approach for implementing joint operating policies for a parallel multiple reservoir system. The optimization-simulation uses the historical inflow. Under such a joint operating policy, the rule curve of individual reservoir specifies the release toward each side demand. With respect to the joint demand, the release from each reservoir is defined as a function of the individual storage, the time of a year and the balanced level indices BLI (Lin and Wang 1996 [7]), and yields the ideal distribution of storage levels among the reservoirs.

This study results indicate that the optimal operating rule curves of the parallel multireservoir system can achieve the highest hydropower benefit and meet the designed firm yield for water supply simultaneously.

## **2 Search process for optimal operating rule curves alternative**

### **2.1 Simulation module with hydropower purpose**

#### **2.1.1 Hydropower and its efficiency**

Reservoir type hydropower involves two parts, i.e., firm power and secondary power. Firm power based on the corresponding energy is the amount of power



that can be generated with little interruption, and the secondary power will be generated in excess of firm power. The maximum power that can be generated by a hydropower plant under the conditions of normal water head and full flow is called the plant capacity. The secondary power value is much lower than the plant capacity value. However, the available reservoir water volume restricts the amount of energy generated by a hydropower plant.

Power available from a river is directly proportional to the flow rate  $Q$  that passes through the turbines and the potential head available to operate the turbines. Hydroelectrical power HP (in terms of horsepower, hp) that can be generated by a turbine is

$$HP = \frac{e_t \gamma Q h_e}{550} \quad (1)$$

In the above equation,  $Q$  is the flow rate in cfs through the turbine,  $\gamma$  is the specific weight of water in  $lb/ft^3$ , and  $h_e$  is the effective potential head available in *feet*, and  $e_t$  is the turbine efficiency of the power generating units. A commonly used metric unit for power is kilowatt (kW). One horsepower is equal to 0.7457 kW. Thus Eqn. (1) can be expressed as Eqn. (2) in metric unit.

$$HP = \frac{e_t \times 1000 \times Q \times h_e}{102} = 9.8 e_t Q h_e (KW) \quad (2)$$

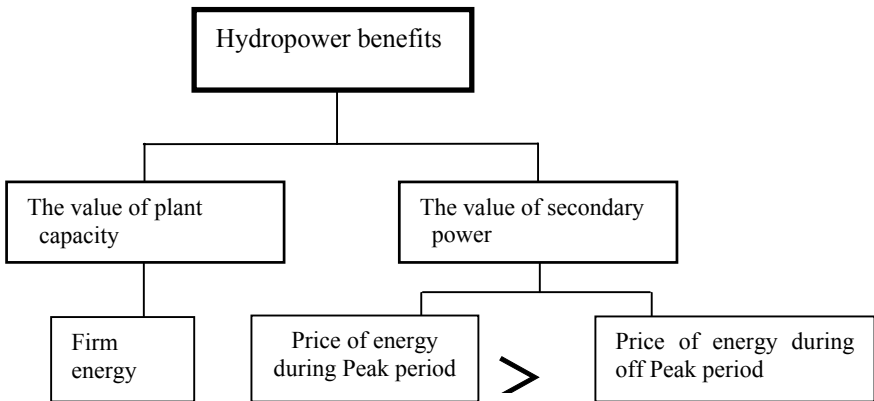


Figure 1: Typically simplified benefit classification.

Since power is the rate of energy, energy produced by a power-generating unit is equal to the power multiplied by the time period of production. The commonly used units for energy are kilowatt-hour (kWh). The term  $e_t$  in eqn. (1) or eqn. (2) is the efficiency of the power generating unit resulting from energy losses through machine operation. Therefore, the overall efficiency of a hydropower plant ( $e_p$ ) can be obtained by multiplying hydraulic efficiency, the ratio of the net head to the gross head, and turbine efficiency ( $e_t$ ).

According to the economic evaluation criteria for hydropower project published by the Taipower (Taiwan Power Company), firm power is typically

thought as that available in 85 percent of time. The typically simplified benefit classification is as shown in fig. 1.

**2.1.2 Water release operating policies**

Solutions for water releases from parallel multireservoirs are derived from governing equations including water mass balance and balanced water level index (BWL) which was originally introduced in the HEC-5 model by the Hydrologic Engineering Centre (HEC) of the U.S. Army Corps of Engineers [4][5], and modified by Lin and Wang (1995) [6]. According to BWLI, water release from reservoirs will maintain equal WLI for all the reservoirs.

Water release from each reservoir can be related to temporal level index, which is calculated from the prevailing reservoir water level (RWL) and rule curves. Integer indices,  $IB_j$  ( $j = 1,5$ ) of 0, 1, 2, 3 and 4 are respectively assigned to elevations of minimum operation level, critical rule curve, lower rule curve, upper rule curve and the maximum RWL of each reservoir, as shown in fig. 2. The volume of each reservoir is divided into four operation zones by these five integer indices. The lower and the upper bounds of level indices are respectively 0 and 4. An index corresponding to a RWL at the end of time period  $t$  is equal to an integer number adding a decimal fraction number denoting the ratio of current reservoir storage volume above the curve to the storage capacity between water levels corresponding to two rule curves:

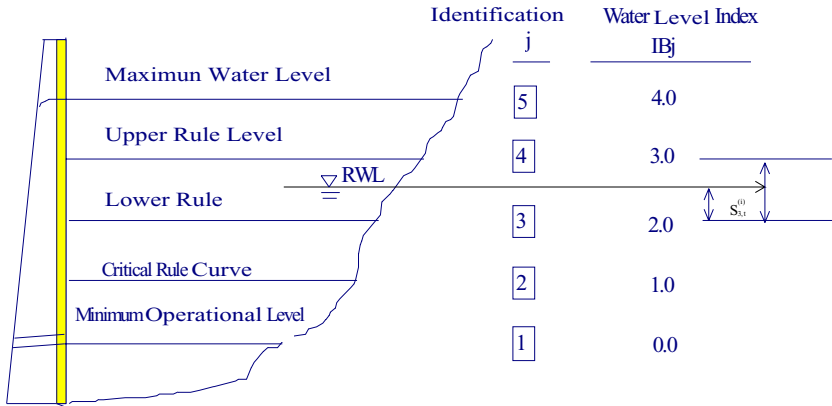


Figure 2: Illustration of water level index for reservoir  $i$ .

Based on the principle of water mass balance in the time interval between time  $t$  and  $t-1$ , temporal reservoir release is a function expressed as follows,

$$O_t^{(1)} = \frac{V_j^{(1)}}{V_j^{(1)} + V_j^{(2)}} \left( A + \frac{V_j^{(2)}}{V_j^{(1)}} B^{(1)} - B^{(2)} \right) \tag{3}$$

$$O_t^{(2)} = \frac{V_j^{(2)}}{V_j^{(1)} + V_j^{(2)}} \left( A - B^{(1)} + \frac{V_j^{(1)}}{V_j^{(2)}} B^{(2)} \right) \quad (4)$$

where

$$A = D_t - U_t^{(1)} - U_t^{(2)} \quad (5)$$

$$B^{(i)} = S_{j,t-1}^{(i)} + Q_t^{(i)} - E_t^{(i)} - R_t^{(i)} \text{ for } i=1,2 \quad (6)$$

In the above equation,  $Q_t$  is reservoir inflow,  $E_t$  reservoir evaporation loss,  $O_t$  reservoir release for project water-demand,  $R_t$  reservoir release for water right uses and minimum instream flow required in the downstream of reservoir  $i$ . uncontrolled streamflow  $U_t$ .

## 2.2 Encapsulating simulation results in a Genetic algorithm

Herein, a search technique, Genetic Algorithms, based on the mechanics of nature selection and natural genetics, which are theoretically and empirically proven to provide robust and efficient search in complex spaces, is employed to find decision variables automatically [3].

GAs (Genetic Algorithms) imitate the way for populations of species genetically evolve to suit their environment over numerous generations. Based on this analogy, a process that involves selection, crossover and mutation can be applied to evolve a population of potential solutions for a scheme design and to analyze problems to yield the improved solutions. These solutions will satisfy the specified constraints, while minimizing or maximizing the objective function. Fig. 3 presents the flowchart.

GAs can improve an initial population of strings that represent a set of randomly generated possible solutions. The repeated application of genetic operators searches efficient solutions to the problem at hand. Solutions with the higher values of the objective function (or fitness function) are retained, while those with objective functions of the lower values are discarded. The advantages of GAs over traditional search methods include their retention of a population of the well-adapted sample points, increasing the probability of reaching the global optimum. Finally, these algorithms apply probability rules that govern the transition from one set of trial solutions to the next, and they have the flexibility of admitting various types of objective functions to meet the requirements of continuity and the existence of derivatives.

### 2.2.1 Objective function

The objective is to determine a set of optimal operation curves for hydropower that is the maximum when both the shortage index and the maximum shortage ratio are the minimum. The objective function is

$$\text{Max } fitness = c1 \cdot \frac{1}{SI} + c2 \cdot P + c3 \cdot (1 - R) \quad (7)$$

where  $c1=1$ ,  $c2=0.001$  and  $c3=1$  are coefficients in the weight relationship, determined by sensitivity analyses.



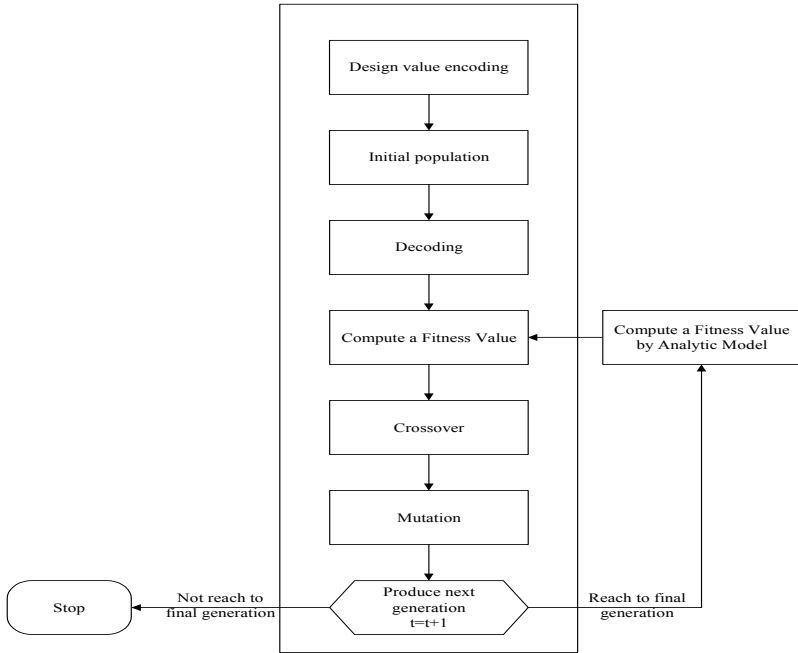


Figure 3: Flow chart of GA-based optimization.

$$SI = \frac{100}{N} \left[ \sum_{i=1}^N \left( \frac{S_i}{D_i} \right)^2 \right] \tag{8}$$

*SI* was introduced by USCOE (1982[4]), where *j* is a subscript that denotes the number of years, ranging from 1 to *N*. Annual water shortage and *S<sub>i</sub>* and *D<sub>i</sub>* represent water-demand quantities, respectively. *P* = hydropower, and *R* = percentage of the maximum water-shortage ratio.

**2.2.2 GA coding**

Herein, six turning points in the operating curves are the decision variables in the model. This fact is emphasized because the coding scheme suffices to describe the hydrological characteristics of Taiwan. The initial population of strings of decision variables in the GA process is generated randomly from values in a continuous range between the selected lower and upper bounds. The ranges for the seeding of the turning points were from the minimum operational level to the maximum water level, as presented in fig. 4.

The application of GAs involves the appropriate choice of the alphabet to represent the decision variables in the problem. An efficient reproduction procedure must also be chosen. Despite the successful application of GAs to various kinds of problems, GAs does not guarantee the identification of the global optimum. The solutions obtained by the GAs must thus be considered to be almost optimal.”



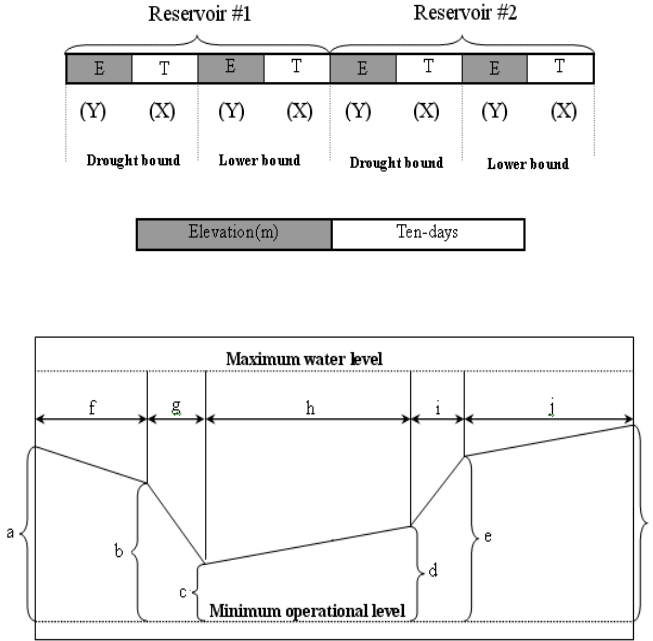


Figure 4: Schematic map of GA coding.

### 3 Application to the Shihmen and Festui Reservoirs joint system

The reservoir system, consisting of Shihmen Reservoir and Feisui Reservoir, in the Tanshui River Basin in the northern Taiwan is employed as a case study. The total drainage area is 2,726 km<sup>2</sup>. The Tanshui River Basin system, as presented in fig. 5, includes two reservoirs that are operated to control floods, generate hydropower, provide recreation function and supply domestic water. The total storage capacity of these two reservoirs is 715 million m<sup>3</sup> approximately. Current regulations provide the rule curves of these two reservoirs, as plotted in fig. 6. The schemes for operating these two reservoirs are determined by the release curve. The total release requirement is based on the release curves, and is allocated between those two reservoirs.

The capacity of power plant for Feisui and Shihmen Reservoir are 70,000 kW and 90,000 kW, respectively. The existing rule curves of Feisui and Shihmen Reservoir are shown as fig. 6.

### 4 Results

In the GA-based optimization model, the 43 years of the recorded streamflow data and the water demand pattern in year 2021 are used as input data set. The

result of the optimization contains all the releases in each period, which is taken as ten days. The objective value is expressed as a function of  $(1000 \cdot 1/SI+1 \cdot Power+1000 \cdot (1-R))$ . The optimal joint rule curves and the calculated results are shown in fig. 7 and Table 1.

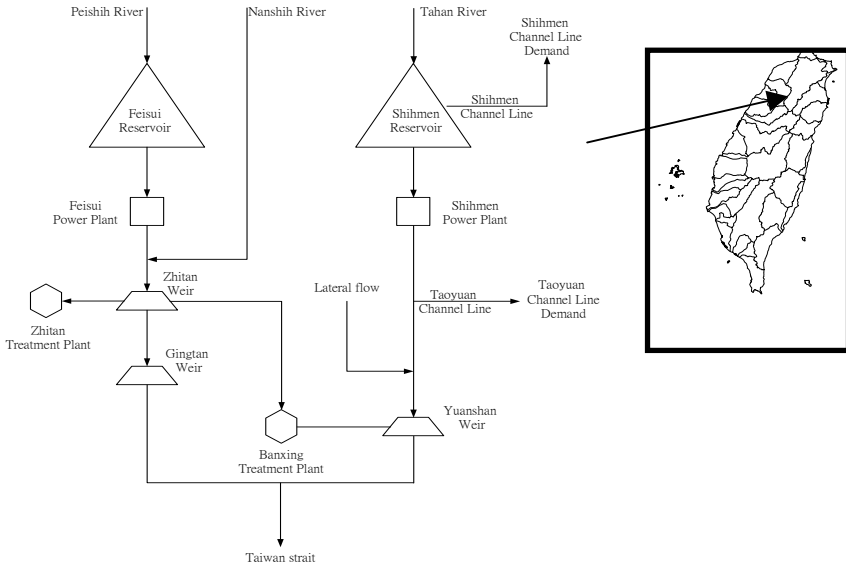


Figure 5: Schematic diagram of Feisui and Shihmen reservoir system.

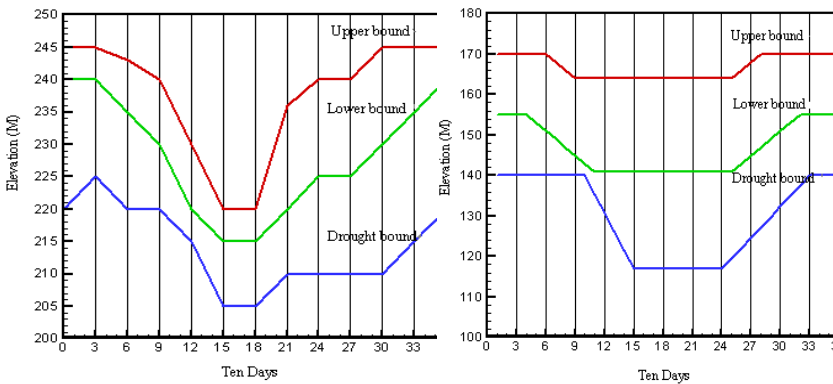


Figure 6: Existing rule curves of Feisui (the right) and Shihmen (the left) reservoir system.





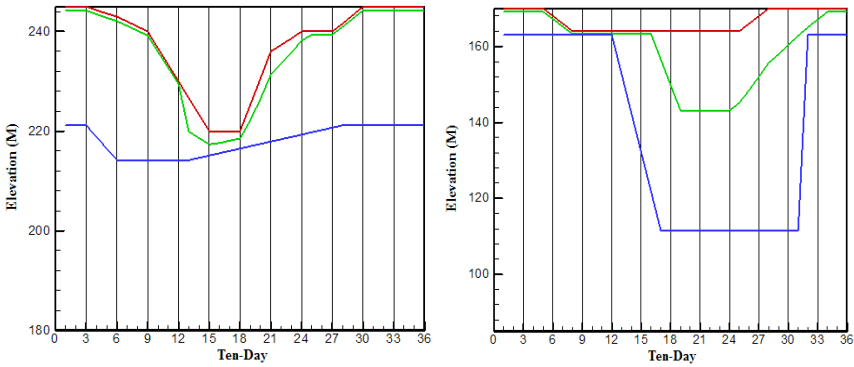


Figure 7: Optimal rule curves of Feisui (the right) and Shihmen (the left) reservoir system.

Table 1: Comparisons of simulation results for the existing rule curves and the optimal rule curves.

Category	43-year recorded flow		Unit
	Optimal	Existing Rule Curves	
Annual demand	35,133	35,133	cmsd
Total deficit	4,454	4,478	cmsd
Water shortage index	1.65	1.75	-
Max. Shortage ratio	90.8	90.8	%
Shihmen electricity	237.9	237.5	10 <sup>6</sup> kw-hr
Feisui electricity generated	241.6	240.8	10 <sup>6</sup> kw-hr
Total electricity generated	479.5	478.3	10 <sup>6</sup> kw-hr
Objective function value	1,177	1,141	-

## 5 Conclusions

1. The study results indicate that the optimal operating rule curves of the parallel multireservoir system can achieve the highest hydropower benefit and meet the designed firm yield for water supply purpose simultaneously.

2. The objective function ( $Fitness = W1 \cdot 1/SI + W2 \cdot Power + W3 \cdot (1-R)$ , where  $W1 = 1000$ ,  $W2 = 1$ ,  $W3 = 1000$ ,  $SI =$  shortage index,  $Power =$  hydropower,  $R =$  percentage maximum water-shortage ratio) yields proper rule curves, which not only reduces the shortage in meeting water demand but also enhance hydropower efficiency.

3. The side demand of Shihmen reservoir is relatively large, and hence prevents Shihmen reservoir from being dominant in the joint operation. The water demand of the system is almost met by the operation of Feitsui reservoir.



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