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Suitable Conditions of Reservoir Simulation for Searching Rule Curves

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Abstract: The objective of this study is to carry out a suitable length of inflow record using in the simulation model. The second objective is to find an effect of initial reservoir capacity of reservoir simulation for searching the optimal rule curves. The reservoir simulation model was connected with genetic algorithms to search the optimal rule curves quickly. The model has been applied to determine the optimal rule curves of the Bhumibol and Sirikit Reservoirs (the Chao Phraya River Basin, Thailand). The optimal rule curves of each condition were used to assess by a Monte Carlo simulation. The results show that the shortest period of dry inflow record using in the simulation model in order to search the optimal rule curves is 10 year. Furthermore, the minimum initial capacity of reservoir for searching optimal rule curves is 10% of full capacity.

Key words: Reservoir operation, monte carlo simulation, optimization model, rule curve

INTRODUCTION

A supply management of water resources management is a reservoir operation. A reservoir simulation model is a modeling technique that is used to analyze the behavior of a system on the computer for operating the reservoir. The rule curves of reservoir are basic monthly guides for long term operation. Normally, rule curves are searched by simulation model and optimization techniques. In the past decade, the rule curves are obtained by using several sets of trial rule curves to test in simulation model (Jain *et al*., 1998). This method is straightforward and applicable for both simple and complex systems. The monthly input data of reservoir simulation are inflows into reservoir, evaporation, rainfall, infiltration, physical characteristic of the reservoir and conditional rule curves etc (Xu and Ito, 1997; Tilmant *et al*., 2002). However, the simulation method does not guarantee to yield the optimal rule curves because of human adjustment.

A Dynamic Programming (DP) is another optimization technique applied to search the non-linear problems of water resource (Bellman, 1959; Yakowitz, 1982; Esogbue, 1989). Unfortunately, the application of DP to multi-reservoir system is limited due to a curse of dimensionality. To overcome this problem Chaleeraktrakoon and Kangrang (2007) applied the DP with a Principle Progressive Optimality (DP-PPO) to determine the optimal rule curves. The input data of this technique are similar to the data using in the simulation method. However, this method required the long period of dry inflow record for searching the optimal curves. Moreover, the starting condition of the search is set at the full capacity only.

Recently, Genetic Algorithms (GAs) embedded the simulation model have proposed to search the rule curves of the reservoir system (Chang *et al*., 2003, 2005; Chen, 2003) The best part of GAs is that they can handle any type of objective function. Furthermore, the model can handle several initial conditions of reservoir simulation such as initial reservoir capacity and the length of inflow record. The popular objective functions of the search are a shortage index, a frequency of water shortage, an average water shortage and a magnitude of water deficit. However, the proper objective function for searching the optimal curves is the minimum of average water shortage (Kangrang and Chaleeraktrakoon, 2007). Also, a smoothing function constraint is required to include into the model for fitting the obtained rule curves.

The simulation models which mentioned above require the same necessary input data including inflows into reservoir, physical characteristic of the reservoir (initial reservoir capacity) and conditional rule curves. Moreover, all models require more long duration of dry historic inflows (Chaleeraktrakoon and Kangrang, 2007; Meigh and Reynard, 2005; Tospornsampan *et al*., 2005). Therefore, this is the limitation search of some area lagging long inflow record. Further, the starting conditions of the simulation models are assumed as the full reservoir capacity only. This assumption is the barrier

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for some area having short period record, because it will not meet the shortage situation that used to be the objective function of the search for irrigated purpose reservoir. Hence, it is difficult to obtain the optimal rule curves from the searches.

This study thus uses the GAs embedded the simulation model to search the optimal rule curves for finding the suitable length of historic inflow record. Furthermore, the effect of initial reservoir capacity is carried out in this study. The searching model is applied to the Bhumibol and Sirikit Reservoirs (the Chao Phraya River Basin, Thailand).

MATERIALS AND METHODS

Study area and data: The GAs embedded the simulation model was applied to search the optimal rule curve of the Bhumibol and Sirikit Reservoirs locating in the watershed area of the Chao Phraya River Basin (Thailand). Figure 1 shows the location of the Chao Phraya River Basin. Two sequences of 45 year (1956-2000) monthly-flow records of stations P.12 and SK covering several dry and flooding years were commonly used for searching the optimal rule curves. The others duration of monthly-inflow data are sub-period of this duration. Figure 2 and 3 show the yearly inflow of the two reservoirs from 1956 to 2000. The summation of yearly inflow was considered to use in the rule curve search. The large duration of dry-year inflow is during 1970-1995 (26 years), the shortest length is 4 years (1985-1988). These duration lengths were used to apply in the search. The other average hydrological data for each month included series of evaporation losses and precipitation of the reservoirs and those of side flows of stations W.4A (River Wang) and Y.5 (River Yom) were used for the search.

Several conditions of the simulation model were set before starting to search the optimal rule curves. This study considered the effect on duration length of inflow records and the effect on the initial capacity of reservoir. The simulation embedded GAs model was applied to search the optimal rule curve of the two reservoirs.

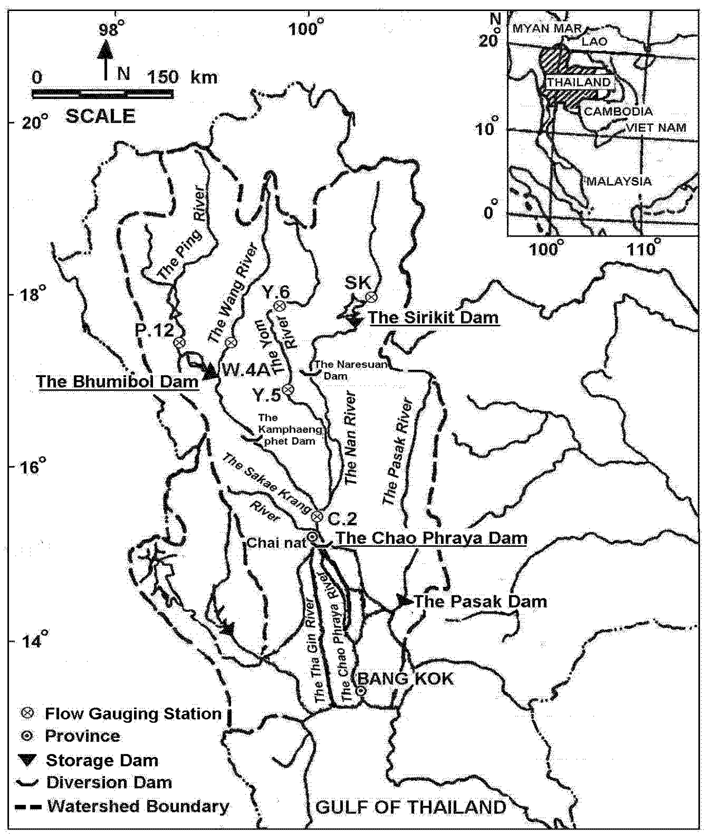

Fig. 1: Location of the Chao Phraya River

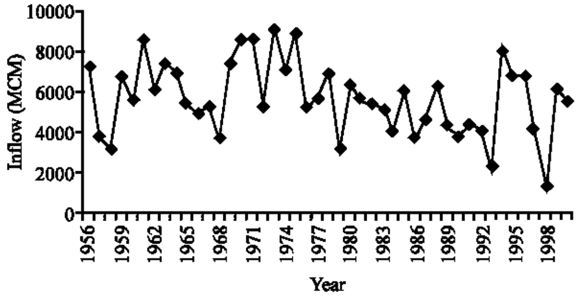

Fig. 2: Yearly inflow of the Bhumibol reservoir

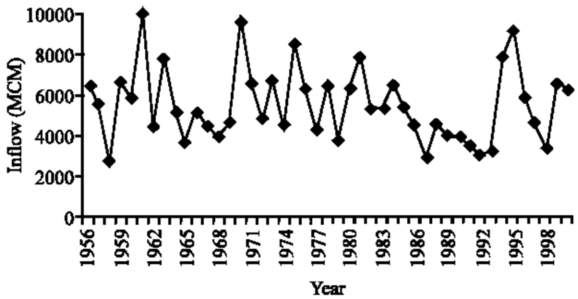

Fig. 3: Yearly inflow of the Sirikit reservoir

The obtained rule curves were then assessed to examine the situations of water shortage and excess release by comparing related characteristics (e.g., frequency, magnitude and duration) of the referred circumstances with those of the optimal curves. The Monte Carlo simulation study against 500 samples of generated monthly flows of stations P.12 and SK (Chaleeraktrakoon, 1999) was used to compute the interval (mean±standard deviation) of the referred statistics for the assessment. There are two main conditions that were considered in this study. Firstly, several durations of dry inflow were used to find the suitable length of historicinflow data. Secondly, several initial reservoir capacities of starting run were adjusted to find the minimum initial capacity of the reservoir. In the following, the obtained assessment results of the considered water-deficit and excess-release properties for all cases are presented.

Genetic algorithms embedded simulation model: The simulation model of this study had been constructed based on the concept of HEC-3 (US, HEC-3, 1974) and it can be used to simulate the reservoir operation. The reservoir operating policies are based on the rule curves of individual reservoirs and the principles of water balance concept. The reservoir system is operated along the standard operating policy expressed in Eq. 1 as:

$$R_{\upsilon,\tau} = \begin{cases} D_\tau + W_{\upsilon,\tau} - y_\tau, \text{ for } W_{\upsilon,\tau} \geq y_\tau + D_\tau \\ D_\tau, \text{ for } x_\tau \leq W_{\upsilon,\tau} < y_\tau + D_\tau \\ D_\tau + W_{\upsilon,\tau} - x_\tau, \text{ for } x_\tau - D_\tau \leq W_{\upsilon,\tau} < x_\tau \\ 0, \text{ otherwise.} \end{cases} \quad (1)$$

in which $R_{v,\tau}$ is the release discharges form the reservoir during year v and period τ (τ = 1 to 12 representing month, January to December). D_τ is the water requirement of month τ, x_τ is lower rule curve of month τ, $W_{v,\tau}$ is upper rule curve of month τ and $W_{v,\tau}$ is the available water calculated using simple water balance described in Eq. 2 as:

$$W_{\upsilon,\tau+1} = S_{\upsilon,\tau} + Q_{\upsilon,\tau} - R_{\upsilon,\tau} - E_\tau - DS \quad (2)$$

Where:

$S_{\upsilon,\tau}$	=	Stored water at the end of month
τ, $Q_{\upsilon,\tau}$	=	Monthly reservoir inflow
E_τ	=	Average value of evaporation loss
DS	=	Minimum reservoir storage capacity (the capacity of dead storage).

In the first equation, if available water is in a range of the upper and lover rule level, then demands are satisfied in full. If available water over tops the upper rule level, then the water is spilled from the reservoir in downstream river in order to maintain water level at upper rule level and if available water is below the lower rule level, reduce supply is made. The policy usually reserves the available water $W_{v,\tau}$ for reducing the risk of water shortage in future, when $0 \leq W_{v,\tau} < x_\tau$-D.

The results of simulation run are the situations of water shortage and excess release water (e.g., the number of failure year, the number of excess release water and the average annual shortage), they will be recorded for using in GAs technique.

The model of GAs technique was developed to connect with the simulation model. This GAs model requires encoding schemes that transform the decision variables (rule curves) into chromosome. Then, the genetic operations (reproduction, crossover and mutation) are performed. This study used population size = 80, crossover probability = 0.85, mutation probability = 0.01 (Jain *et al*., 1998).

The objective function of searching the optimal rule curve is the minimum of average water shortage (Aver-MCM/year) (Kangrang and Chaleeraktrakoon, 2007) obtaining from the simulation model which described as follows:

$$Aver = \frac{1}{n}\sum_{\upsilon=1}^{n} Sh_{\upsilon} \quad (3)$$

Where:

n = Total number of considered year

Sh_{υ} = Water deficit during year υ

RESULTS AND DISCUSSION

Suitable duration length of inflow record: Table 1 and 2, respectively show the assessment intervals of water shortage and excess release characteristics for all duration lengths of inflow records (initial reservoir capacity is full). They indicate that the rule curves of using long durations included 45, 26, 21, 17, 14 and 10 year give the magnitude of water deficit are not different significantly and their situations less than the situation using the 4 year duration. In addition, the rule curves of using 7 year inflow record are explicit higher than the curves of using 10 year inflow records. Hence, it indicates that the shortest duration length of dry inflow record is 10 year inflow. Moreover, the magnitudes of excess release of using the 7 and 4 year inflow record are higher than using the other periods. Therefore, the searching model using at least 10 year duration of inflow records can be used to run in the simulation model embedded GAs technique.

From above tables, it can conclude that the shortest duration of dry-year inflow records is 10 years. However, the suggested duration of inflow records is smaller than 30 years using in the literature (Tatano *et al*., 1992; Tospornsampan *et al*., 2005).

Initial reservoir capacity effects: Figure 4 and 5 show the patterns of the rule curves between the two reservoirs

Table 1: Frequency, magnitude and successive period of water shortage for all conditions of dry-year inflow records

Duration lengths of inflow records (Years)		Frequency (times/year)	Magnitude (MCM/year) Average	Magnitude (MCM/year) Maximum	Duration (year) Average	Duration (year) Maximum
4	μ	0.157	34	495	2.2	3.4
	σ	0.084	28	379	1.0	1.7
7	μ	0.191	35	431	2.1	3.6
	σ	0.089	23	257	0.9	1.8
10	μ	0.118	22	313	2.0	2.8
	σ	0.072	18	210	1.0	1.6
14	μ	0.124	23	329	2.0	2.9
	σ	0.072	18	205	0.9	1.6
17	μ	0.137	24	323	2.0	3.1
	σ	0.076	18	206	1.0	1.7
21	μ	0.137	24	323	2.0	3.1
	σ	0.076	18	206	1.0	1.7
26	μ	0.137	24	323	2.0	3.1
	σ	0.076	18	206	1.0	1.7
45	μ	0.113	19	289	1.9	2.7
	σ	0.070	16	219	0.9	1.6

μ = Mean, σ = Standard deviation

Table 2: Frequency, magnitude and successive period of excess release for all conditions of dry-year inflow records

Duration lengths of inflow records (Years)		Frequency (times/year)	Magnitude (MCM/year) Average	Magnitude (MCM/year) Maximum	Duration (year) Average	Duration (year) Maximum
4	μ	0.833	1179	4537	7.9	16.5
	σ	0.073	196	1842	4.2	6.6
7	μ	0.819	1172	4524	7.0	15.1
	σ	0.074	197	1831	3.1	5.7
10	μ	0.815	1121	4437	7.0	15.4
	σ	0.079	196	1850	3.0	5.9
14	μ	0.819	1124	4537	7.3	15.6
	σ	0.078	197	1892	3.4	6.1
17	μ	0.816	1108	4545	7.2	15.3
	σ	0.079	198	1862	3.3	5.9
21	μ	0.816	1108	4545	7.2	15.3
	σ	0.079	198	1862	3.3	5.9
26	μ	0.816	1108	4545	7.2	15.3
	σ	0.079	198	1862	3.3	5.9
45	μ	0.811	1110	4706	7.0	15.0
	σ	0.079	202	1905	3.1	5.6

μ = Mean, σ = Standard deviation

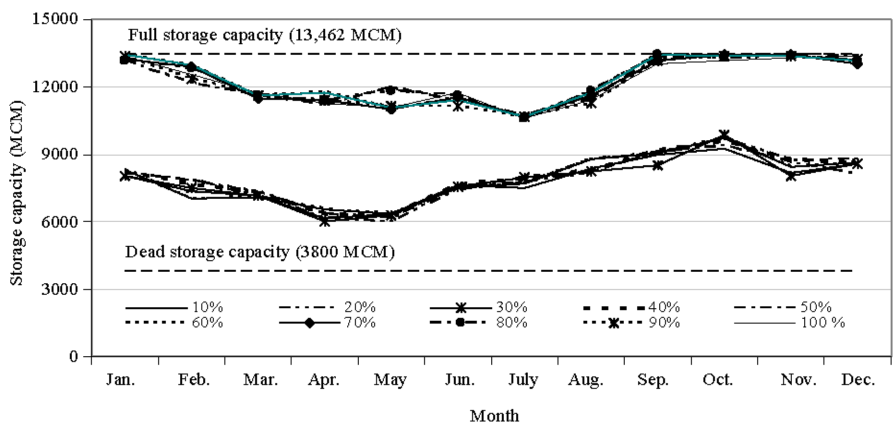

Fig. 4: Optimal rule curves of all initial capacities of the Bhumibol Reservoir

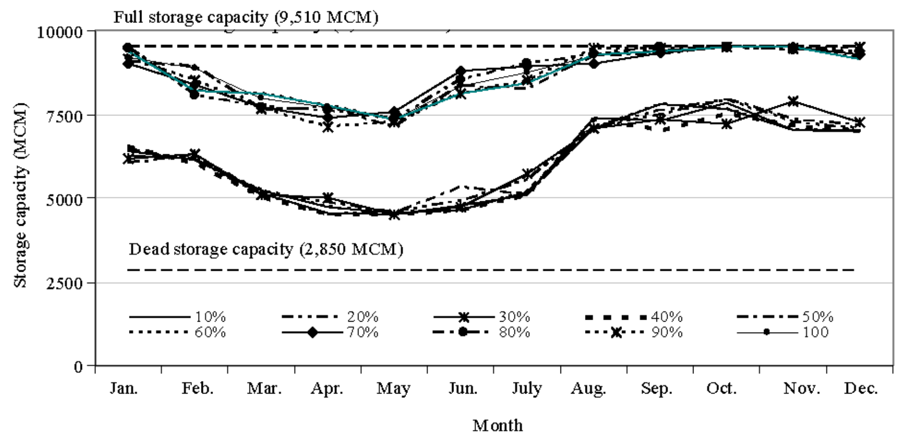

Fig. 5: Optimal rule curves of all initial capacities of the Sirikit Reservoir

Table 3: Frequency, magnitude and successive period of water shortage for all initial reservoir capacities

Initial capacity of reservoir (%)		Frequency (times/year)	Magnitude (MCM/year) Average	Magnitude (MCM/year) Maximum	Duration (year) Average	Duration (year) Maximum
10	μ	0.113	20	300	1.9	2.7
	σ	0.071	17	207	0.9	1.6
20	μ	0.114	20	306	1.9	2.7
	σ	0.072	18	204	0.9	1.8
30	μ	0.114	21	314	1.9	2.8
	σ	0.073	18	220	0.9	1.6
40	μ	0.118	21	316	1.9	2.8
	σ	0.072	18	227	0.9	1.6
50	μ	0.136	23	326	2.0	3.1
	σ	0.077	18	220	1.0	1.7
60	μ	0.126	22	313	1.9	2.9
	σ	0.072	18	206	0.8	1.5
70	μ	0.102	19	309	1.8	2.5
	σ	0.067	17	220	1.0	1.5
80	μ	0.137	24	323	2.0	3.1
	σ	0.076	18	206	1.0	1.7
90	μ	0.137	24	323	2.0	3.1
	σ	0.076	18	206	1.0	1.7
100	μ	0.137	24	323	2.0	3.1
	σ	0.076	18	206	1.0	1.7

μ = Mean, σ = Standard deviation

Table 4: Frequency, magnitude and successive period of excess release water for all initial reservoir capacities

Initial capacity of reservoir (%)		Frequency (times/year)	Magnitude (MCM/year) Average	Magnitude (MCM/year) Maximum	Duration (year) Average	Duration (year) Maximum
10	μ	0.812	1113	4579	7.0	15.1
	σ	0.080	195	1918	3.2	5.6
20	μ	0.812	1117	4574	7.0	15.1
	σ	0.079	197	1908	3.2	5.7
30	μ	0.812	1124	4637	7.0	15.1
	σ	0.079	203	1893	3.3	5.9
40	μ	0.816	1132	4532	7.2	15.4
	σ	0.079	202	1836	3.2	5.7
50	μ	0.819	1114	4497	7.4	15.7
	σ	0.080	196	1883	3.5	6.1
60	μ	0.815	1102	4477	7.1	15.2
	σ	0.079	195	1879	3.3	5.8
70	μ	0.817	1121	4558	7.4	15.7
	σ	0.080	205	1828	3.5	6.1
80	μ	0.816	1108	4545	7.2	15.3
	σ	0.079	198	1862	3.3	5.9
90	μ	0.816	1108	4545	7.2	15.3
	σ	0.079	198	1862	3.3	5.9
100	μ	0.816	1108	4545	7.2	15.3
	σ	0.079	198	1862	3.3	5.9

μ = Mean, σ = Standard deviation

generally agree with each other due to the seasonal effects on reservoir inflows and considered water demands. Moreover, the optimal rule curves using the different initial capacity are not different explicitly. These optimal rule curves were then evaluated to examine the situations of water shortage and excess release by the Monte Carlo simulation study.

Table 3 and 4, respectively show the assessment intervals of water shortage and excess release characteristics (e.g., frequency, magnitude and duration) for all initial reservoir capacities. They indicate that the situations of water shortage and excess release of all initial capacities are not different significantly.

Generally, the initial reservoir capacity is set at full capacity in all runs for simulating reservoir (Jain *et al*., 1998; Chaleeraktrakoon and Kangrang, 2007; Kangrang and Chaleeraktrakoon, 2007). However, the results of this study indicate that at any reservoir capacity the model can provide the outputs (rule curves) that are not different significantly. Further, the situations of water deficit and excess release using the obtained rule curves are not different significantly. Hence, it is concluded that the least initial capacity of reservoir for simulation model is 10% of reservoir capacity.

CONCLUSIONS

Rule curves are basic guidelines for long term reservoir operation. Generally, the optimal rule curves are searched by simulation model connected optimization techniques. Reservoir inflow is one of required data for operating reservoir. Often, some area lags long data record, it is the limitation of rule-curve search. Hence, this paper thus used the GAs embedded the simulation model to search the optimal rule curves for finding the suitable length of historic reservoir inflow. The model had been applied to determine the optimal rule curves of the Bhumibol and Sirikit Reservoirs (the Chao Phraya River Basin, Thailand). The optimal rule curves of each condition were used to assess by the Monte Carlo simulation. The results indicated that the shortest duration length of reservoir inflow records is 10 year.

The second objective is to find the effect on initial reservoir capacity for searching rule curves using simulation model embedded GAs technique. The results found that the obtained rule curves using the initial capacity over 10% of full capacity are not different significantly. The obtained rule curves of each condition were used to evaluate by the Monte Carlo simulation. The results showed that the situations of water deficit and excess release using the obtained rule curves are not different significantly. Hence, it is concluded that the least initial capacity of reservoir for simulation model is 10% of reservoir capacity.

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