An Optimal Objective Function for Searching Rule Curves by Genetic Algorithms Connected Simulation Model

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Abstract

The main objective of this paper is to find an optimal objective function for searching the optimal rule curves by using genetic algorithms (GAs) connected a simulation technique. The results indicate that an average water shortage is the optimal objective function for searching the optimal rule curves. It can be the proper representation for all situations of water deficit and excess release water. The average water shortage was used to determine the optimal rule curves of the Bhumibol and Sirikit Reservoirs (the Chao Phraya River Basin, Thailand). The obtained rule curves searched by the GAs connected the simulation model using the average shortage as the objective function can mitigate the situation of water deficit and excess release as compared with an existing rule curves.

1. Introduction

Rule curves of a reservoir system are necessary monthly guides for operation practice. The curves indicate the upper and lower bounds of required water levels, or those of desired storage volumes of each reservoir at any particular time of year. They are to be developed when initially implementing the reservoirs, and generally modified after being used for a certain period of time since total water requirements (e.g., water supply, industrial demand, and irrigation requirement) supported by the systems usually increase with time.

The searching of the rule curves is a non-linear optimization problem. Jain et al. [1] and EGAT [2] have used reservoir simulation approach for solving the referred problem. Often, a frequency of water shortage was used as the objective function for searching of this approach. However, an extreme maximum magnitude of deficit water possibly occurs because of regard the frequency only.

A dynamic programming (DP) is another optimization technique applied to search the non-linear problem [3-6]. But, the application of DP to multi-reservoir system is not that encouraging due to "curse of dimensionality". Chaleeraktrakoon and Kangrang [7] applied the DP with a principle progressive optimality to determine the optimal rule curves using a magnitude of water shortage and excess release as the objective function. However, this method does not guarantee to yield the suitable objective function.

Recently, genetic algorithms (GAs) embedded the simulation model (HEC-5) have proposed to search the rule curves for the reservoir system [8-11]. A shortage index (SI) was used as the objective function for searching the curves. This objective function considers only the deficit water, so it may not cover the situation of excess water. Tasaduak and Chittaladakorn [12] integrated the lowest and the highest levels of rule curves, the deficit and excess water into the objective function for searching rule curves using GAs technique. Unfortunately, the optimal parts of each parameter are required. However, the best part of GAs is that they can handle any type of objective function.

To evaluate the suitability of the derived rule curves, an appropriate objective function is required. Therefore, this paper is to find the suitable objective function for searching optimal rule curves using the genetic algorithm

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(GAs) with the simulation model. The proposed approach was applied to the Bhumibol and Sirikit Reservoirs (the Chao Phraya River Basin, Thailand).

2. Simulation Models

Simulation models (i.e., HEC-3, HEC-5) are generally used to study the efficiency of the reservoir operation. To connect easily the simulation into optimization (GAs) model, this study conducted the simulation model based on those concepts. The developed simulation model can be used to determine both reservoir storage requirements and operational strategies for flood control or conservation. The multi-reservoir operating policies are based on the rule curves of individual reservoirs and the principles of water balance concept.

A reservoir system is operated along the standard operating policy expressed in Eq.(1) and Fig.1.

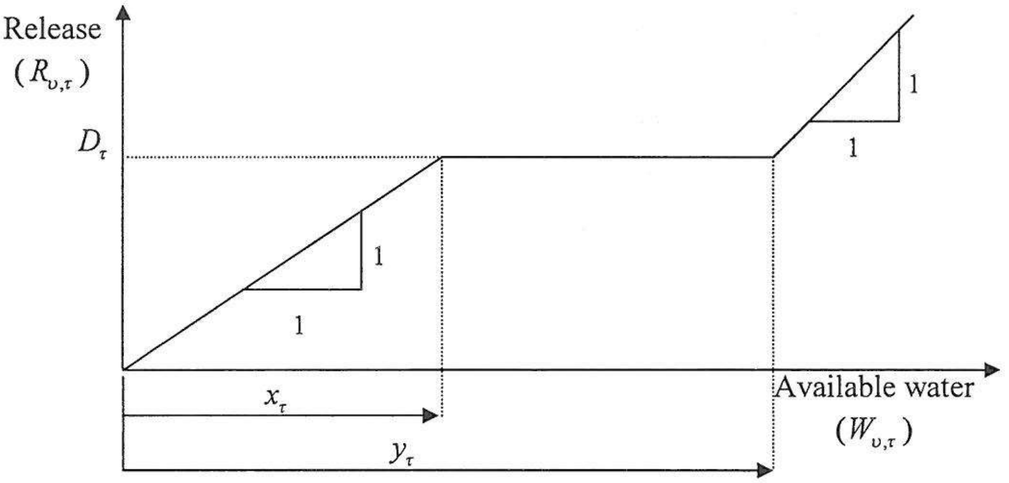

Fig. 1 Standard operating rule

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

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, y_τ 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 $S_{\upsilon,\tau}$ is the stored water at the end of month τ, $Q_{\upsilon,\tau}$ is monthly reservoir inflow, E_τ is average value of evaporation loss, and *DS* is the minimum reservoir storage capacity (the capacity of dead storage). In the mention figure and 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 $0 \leq W_{\upsilon,\tau} < x_\tau - D_\tau$.

At the end of simulation program, the number of failure year, the number of excess release water, the average annual shortage will be recorded. Figure 2 shows the characteristic of water shortage and excess release water for understanding the reservoir simulation.

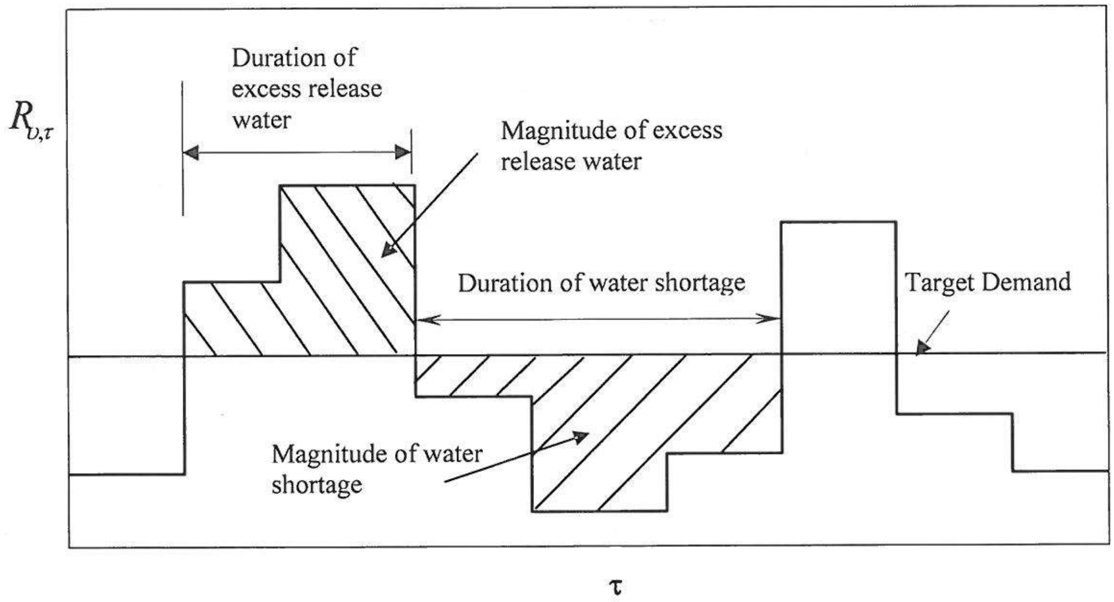

Fig. 2 Characteristics of water shortage and excess release water

3. Genetic algorithms

The genetic algorithms are search and optimization techniques based on the principles of national selection and genetics. They are a robust method for searching for the optimum solution of a complex problem and can provide the near global optimal solutions. The GAs was first proposed by John Holland and his co-workers to mimic the behavior of nature that evolves itself in order to survive. The idea was inspired by natural selection theory of Charles Darwin.

There are many versions of GAs but this study will focus on the standard version of GAs. The general procedure of GA is as follows:

```
randomly generate initial population {A}
do until convergence is observed
apply selection operator to {A} to create {B}
apply crossover operator to {B} to create {C}
apply mutation operator to {C} to create {D}
replace {A} by {D}
end do
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The whole process of running the GA is called as a *run*, {A} is *current populations*, {B} is *parents*, {C} is *intermediate offsprings*, and {D} is *offsprings*. After {D} is created, they will replace {A} and become the current populations of next generation.

4. Integration of the GAs and Simulation Model

The algorithms of connection the developed simulation model into the GAs are described as follows. GA requires encoding schemes that transform the decision variables into chromosome. Then, the genetic operations (reproduction, crossover, and mutation) are performed. These genetic operations will generate new sets of chromosomes. The most common encoding schemes use binary strings as indicated in Fig.3. Each bit of the binary string is called a gene. The chromosome in Fig.3 contains five decision variables, each represented by six bits. In this study, each decision variable represents a monthly level of the rule curves of a reservoir.

000000, 000001, 000010, 000011, 111111

Fig. 3 Chromosomes of represented variables

After the chromosomes (rule curves) of the initial population have been determined, the release of the system in every period is calculated by the developed simulation model corresponding to each chromosome. The release of the system for each chromosome is retuned to the GA to evaluate its fitness. The situation of water shortage of the system is defined as fitness function in this study. Next, the reproduction including selection, crossover and mutation is performed for creating a new rule curve parameters in next generation. This procedure is repeated until the criterion is satisfied as described in Fig.4. Each parameter of the fitness functions is applied into the model to find the suitable objective function. The objective function of each search is to minimize the parameter of the fitness functions. There are 48 parameters (rule curve levels) of two reservoirs which are represented by the chromosomes. This study used population size = 80, crossover probability = 0.9, mutation probability = 0.01.

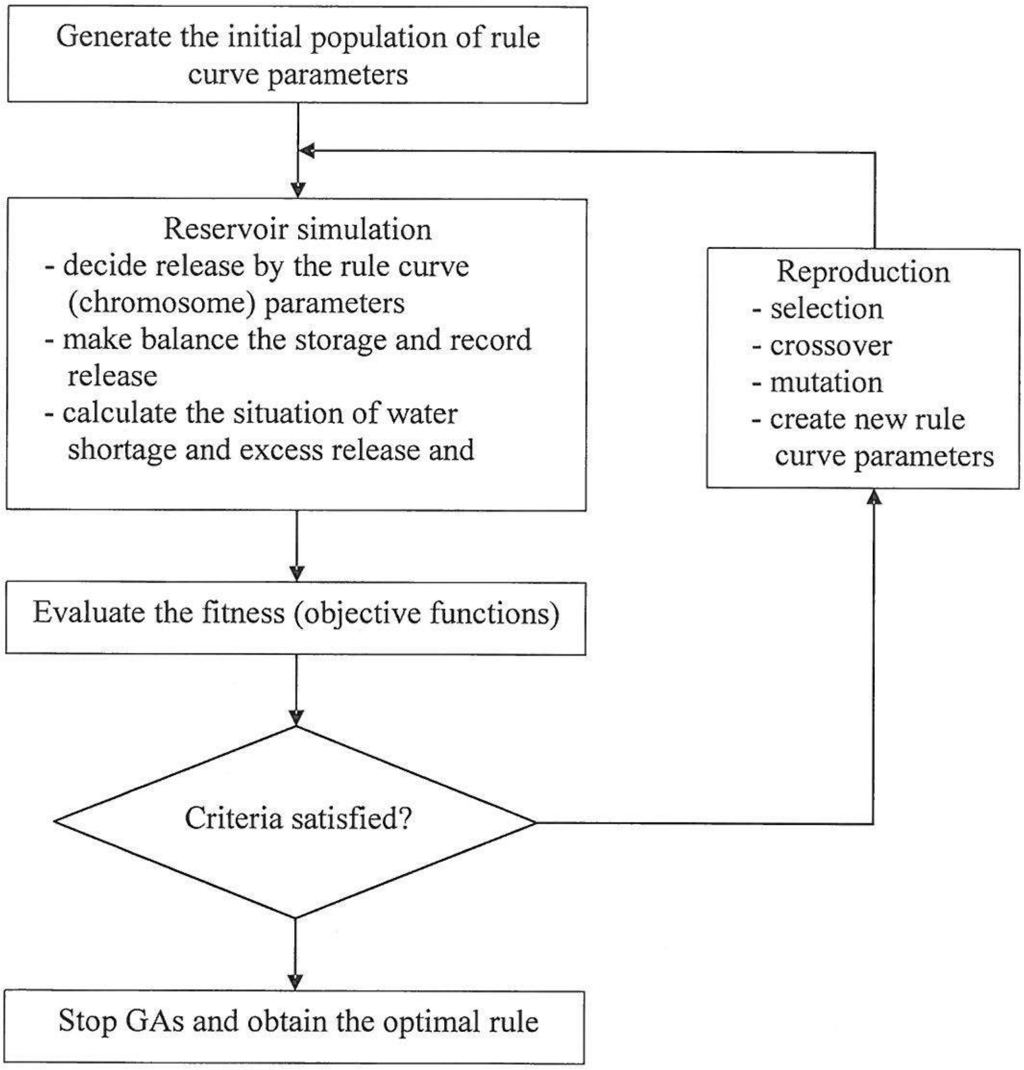

Fig. 4 Integration of GAs and simulation model

There are six objective functions which chosen for searching the optimal rule curve. First, the shortage index (SI) which proposed by the US Army crops of Engineers [13] and can be summarized as

$$SI = \frac{100}{N}\sum_{i=1}^{N}\left(\frac{Sh_i}{D_i}\right)^2 \quad (3)$$

in which N is the total number of periods, Sh_i is water deficit during the period i, D_i is target demand during the period i. A month is taken as the period of reservoir operation.

The others are the average water shortage (*Aver*--MCM/year), the maximum magnitude of water shortage (*Max*--MCM/year), Frequency of water shortage (*Fre*, times/year), Total square deficit (*RMS*--MCM^2), and sum of above mention (*SUM*) which described as follows:

$$Aver = \frac{1}{n}\sum_{\upsilon=1}^{n} Sh_\upsilon \quad (4)$$

$$Max = Maximum\left(Sh_\upsilon\right), \quad \text{for } \upsilon = 1,\dots,n \quad (5)$$

$$Fre = \frac{p_i}{n} \quad (6)$$

$$RMS = \sum_{\upsilon=1}^{n}\left(D_i - R_i\right)^2 \;,\; \forall R_i < D_i \quad (7)$$

$$SUM = \frac{1}{4}\left(\frac{Aver}{\text{full}(Aver)} + \frac{Max}{\text{full}(Max)} + Fre + \frac{RMS}{\text{full}(RMS)}\right) \quad (8)$$

where n is the total number of considered year. Sh_υ is water deficit during year υ, p_i be total number of annual failure (year that release does not met 100% of target demand), R_i is supply water during the period i.

5. Illustrative Application

The proposed approach was applied to search the optimal rule curve of multi-purpose storages (the Bhumibol and Sirikit Reservoirs) locating in the watershed area of the Chao Phraya River (Thailand). Figures 5 and 6 present the location of the Chao Phraya River and the schematic diagram of water resource systems within the drainage basin. The solid lines represent the systems where they are considered in the application. They include the discharges of the two reservoirs, and the side flows of River Wang and River Yom. The dashed lines stand for the systems in which they are ignored. For example, these are the discharges of River Sakae Krang and River Tha Chin, the releases of the Pasak Reservoir and the return flows of irrigation projects.

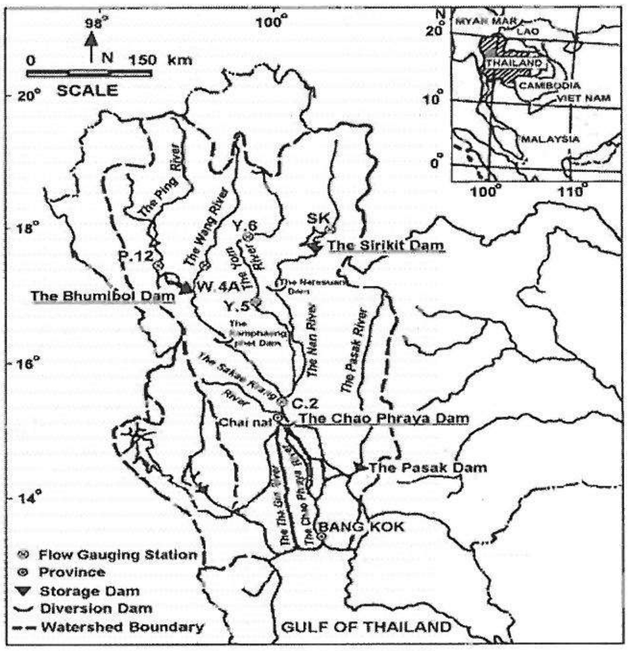

Fig. 5 Location of the Chao Phraya River

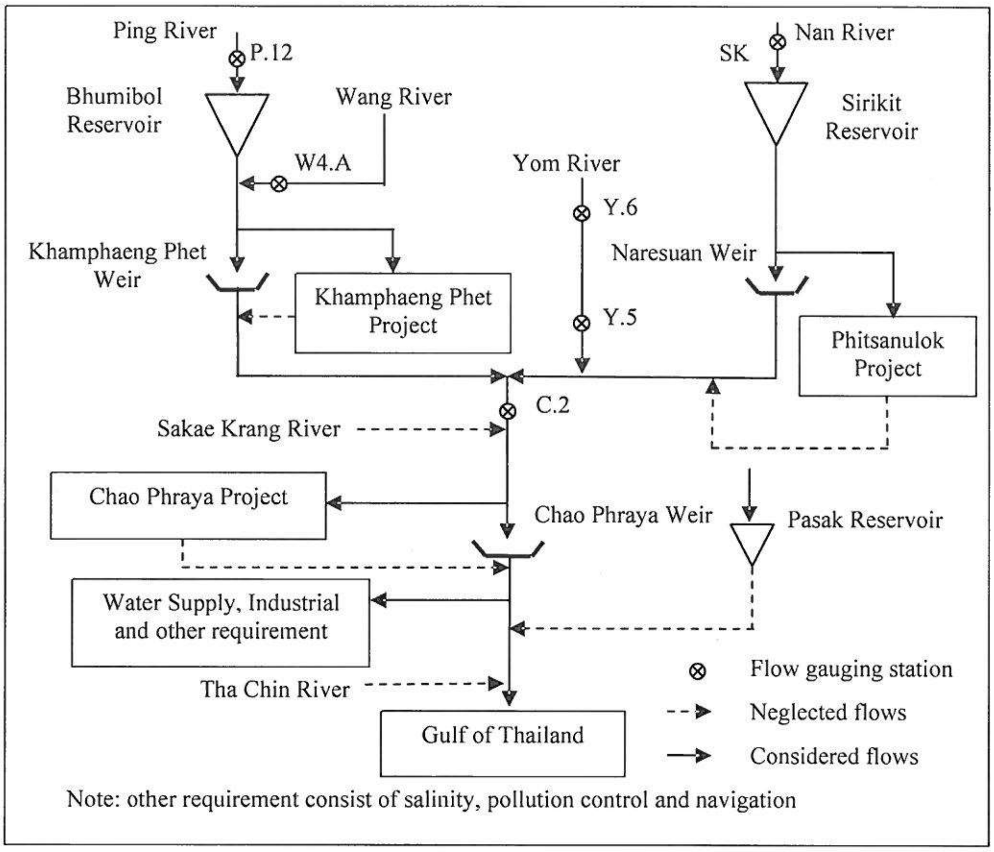

Fig. 6 Schematic diagram of water resource systems in the Chao Praya River Basin

Two sequences of 21-year (1975-1995) monthly-flow records of stations P.12 and SK covering several dry and flooding years were commonly used for searching the optimal upper and lower rule curves. 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 (Wang River) and Y.5 (Yom River). The report of the Electricity Generating Authority of Thailand [2] was used to provide for the considered water-requirement information of the applied basin. The total monthly demands (irrigation demand, water supply demand, industrial demand, and demand for secondary purposed) of the lower Chao Phraya River Basin were used to evaluate the simulation run of the system. The lower basin is considered downstream from Nakhonsawan province to the gulf of Thailand. Results of the illustrative application are presented as follows.

6. Suitable objective function

The search for optimal rule curves in this study is divided into two cases. The first case is a separate search that the optimal lower rule-curve is searched firstly by fixing the upper rule-curves at full storage level. Then the optimal upper rule-curve is searched by fixing the lower level at optimal lower rule-curve. The second case is a simultaneous search that the upper and the lower rule-curve are searched simultaneously.

Tables 1 and 2 show the results of searching optimal rule-curve of the Bhumibol and Sirikit Reservoirs which using all objective functions in case of the simultaneous search. Further, tables 3 and 4 also show the results of the separate search. They indicate that the Chao Phraya River Basin has available water that is approximately adequate for its water-use activities. In addition, the situation of water shortage and excess release water (Magnitude) of the simultaneous search is less than the separate search. Therefore, the simultaneous search is more suitable for providing the optimal rule curve than the separate search.

Figures 7 and 8 respectively present the optimal rule curves of the Bhumibol and Sirikit Reservoirs using all objective functions in the case of simultaneous search. The figures appear that the patterns of the rule curves between the two reservoirs generally agree with each other due to the seasonality effects on reservoir inflows and considered water demands. However, there are large variations of the intervals between the upper and lower rule curves.

Table 1 Situation of water shortage for using all objective functions (simultaneous search)

Objective functions	Frequency (times/year)	Magnitude (MCM/year)		Duration (year)	
		Average	Maximum	Average	Maximum
SI	0.238	114	861	2.5	4.0
Fre	0.143	206	1,735	3.0	3.0
Aver	0.238	60	472	2.5	4.0
Max	0.571	145	419	6.0	9.0
RMS	0.286	97	684	3.0	5.0
SUM	0.190	92	610	4.0	4.0

Table 2 Situation of excess release water for using all objective functions (simultaneous search)

Objective functions	Frequency (times/year)	Magnitude (MCM/year)		Duration (year)	
		Average	Maximum	Average	Maximum
SI	0.667	784	3,476	7.0	12.0
Fre	0.619	875	4,594	4.3	7.0
Aver	0.619	935	3,395	4.3	7.0
Max	0.714	983	5,483	3.8	7.0
RMS	0.619	1,103	5,541	4.3	7.0
SUM	0.619	769	2,543	4.3	7.0

Table 3 Situation of water shortage for using all objective functions (separate search)

Objective functions	Frequency (times/year)	Magnitude (MCM/year)		Duration (year)	
		Average	Maximum	Average	Maximum
Fre	0.286	181	1,536	2.0	4.0
Aver	0.571	135	1,295	3.0	9.0
Max	1.000	155	523	21.0	21.0
RMS	0.762	162	586	4.0	9.0
SUM	0.238	99	716	2.5	4.0

Table 4 Situation of excess release water for using all objective functions (separate search)

Objective functions	Frequency (times/year)	Magnitude (MCM/year)		Duration (year)	
		Average	Maximum	Average	Maximum
Fre	0.619	948	5,214	4.3	7.0
Aver	0.714	617	3,006	5.0	12.0
Max	0.762	955	2,714	5.3	13.0
RMS	0.762	822	3,026	5.3	12.0
SUM	0.619	718	2,560	4.3	7.0

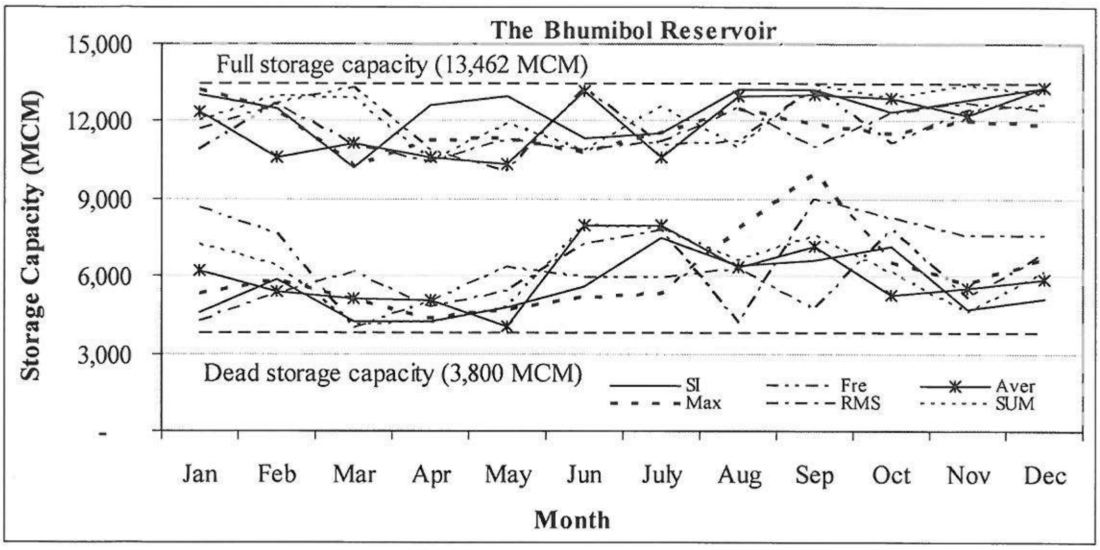

Fig. 7 Optimal rule curves of all objective functions of the Bhumibol Reservoir

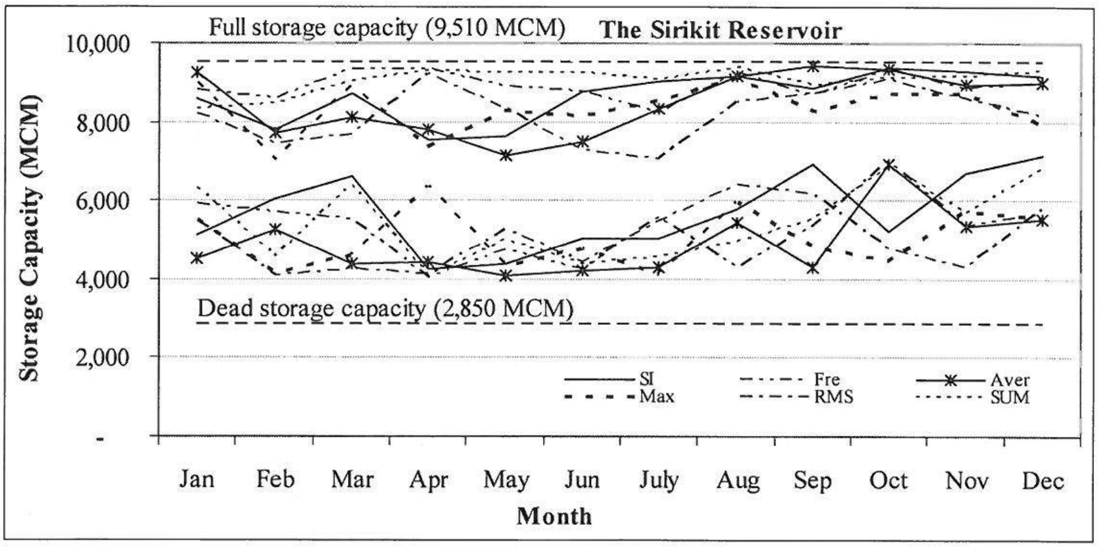

Fig. 8 Optimal rule curves of all objective functions of the Sirikit Reservoir

The rule curves searched by each objective function were then assessed to examine the situations of water shortage and excess release of the lower Chao Phraya River Basin by considering related characteristics (e.g., frequency, magnitudes, duration and SI). A Monte Carlo simulation study against 500 samples of generated monthly flows of stations P.12 and SK [14] was used to compute the interval (mean ± standard deviation) of the referred statistics for the assessment. In the following, the obtained assessment results of the considered water- deficit and excess-release properties for each objective function are presented.

Figures 9 and 10 show the assessment intervals of water shortage characteristics for all objective functions. Further, Figs 11 and 12 also show the assessment intervals of excess release characteristics. They indicate that the rule curves of using the average water shortage (Aver) as the objective function gives the water deficit bounds that are generally less than using the others. Especially, the range of the average and maximum shortage of the Aver are 15 to 42 MCM and 105 to 308 MCM respectively that are lower than the other bounds. In addition, the excess release bounds of using the above objective function are less than using the others. Therefore, the average water shortage (Aver) is the most suitable for using as an objective function of searching rule curve.

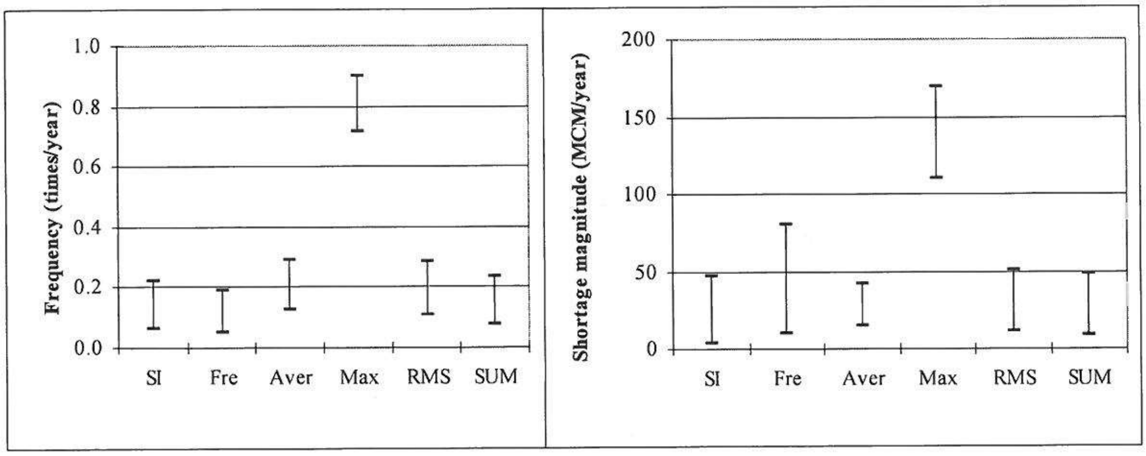

Fig. 9 Frequency and magnitude of water shortage for all objective functions

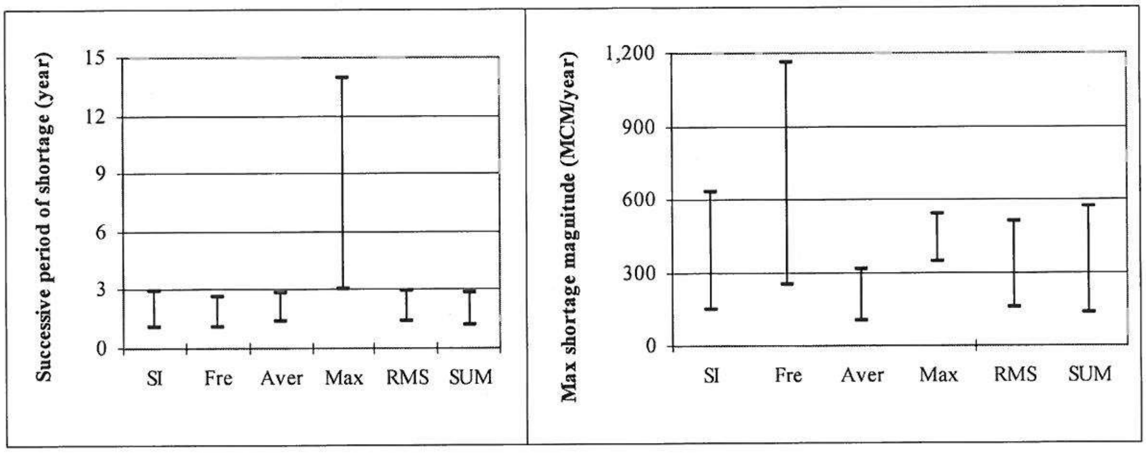

Fig. 10 Successive period and magnitude of water shortage for all objective functions

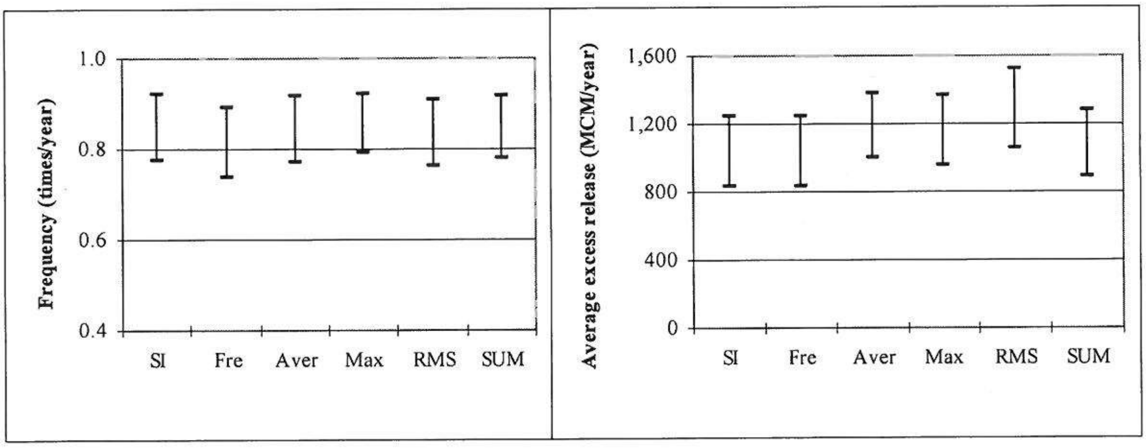

Fig. 11 Frequency and magnitude of excess release for all objective functions

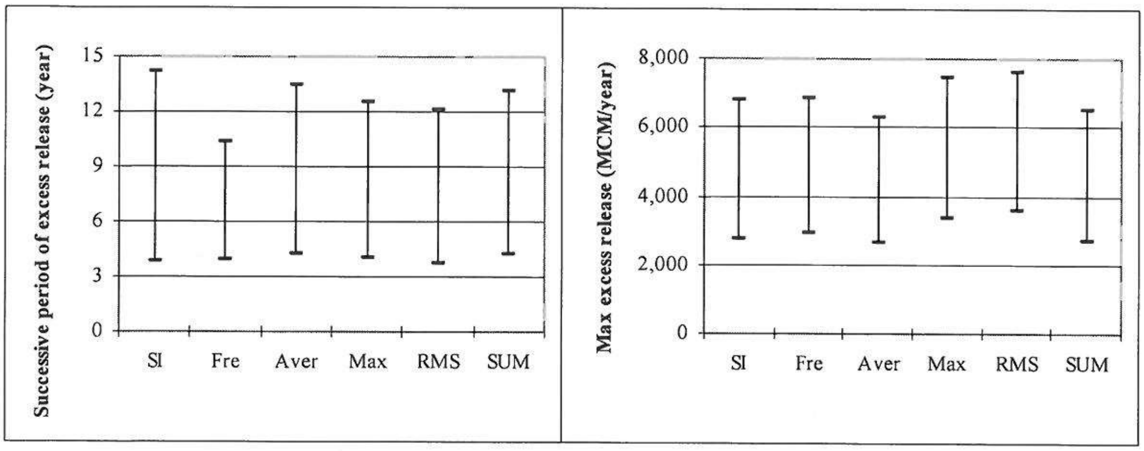

Fig. 12 Successive period and magnitude of excess release for all objective functions

7. Assessment the suitable objective function

The rule curves generated by GAs connected simulation approach using Aver-objective function were then applied in the operation simulation model and their performance is evaluated. Further, their results were compared with the performance of existing rule curves of the HEC-3 [15] simulation approach [2]. Figures 13 and 14 present the optimal rule curves of GAs connected simulation model using Aver-objective function as well as the existing curves of the Bhumibol and Sirikit Reservoirs respectively. The results of evaluation are presented as the following.

Table 5 shows the assessment intervals of water-shortage characteristics for the GAs connected simulation model and the HEC-3 simulation approach. It appears that the rule curves of the GAs connected simulation model gives the water deficit characteristics which are smaller than the existing one does. Table 6 presents the referred statistics of excess releases for the two curves. It is evident that the GAs connected simulation techniques do not yield greater excess releases, as compared with the existing one.

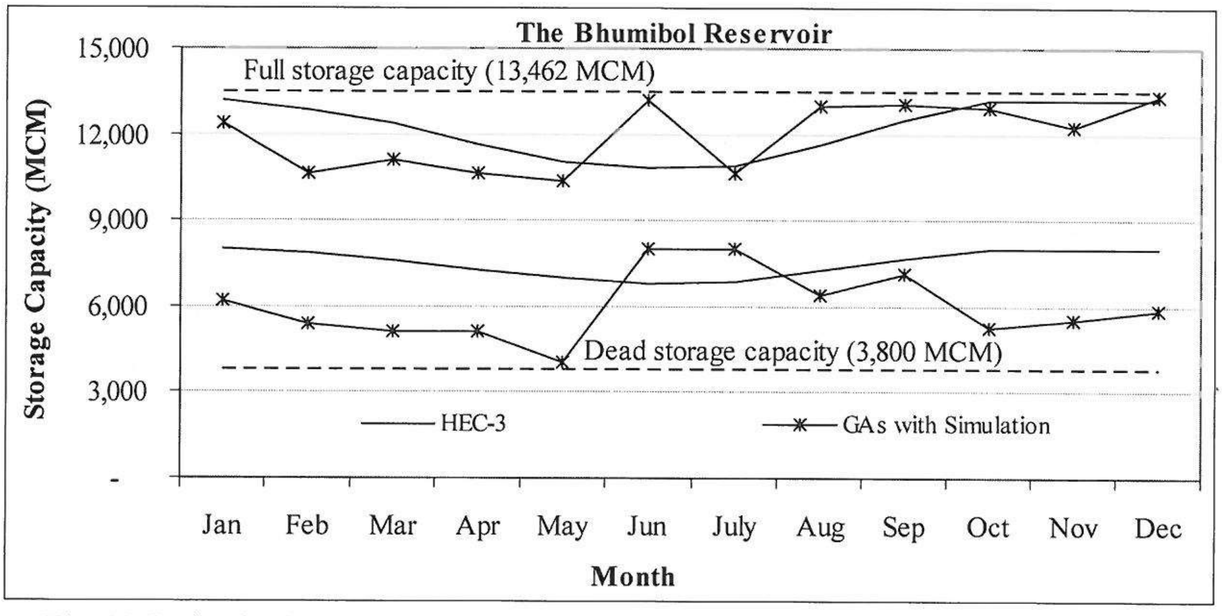

Fig. 13 Optimal rule curves of the GAs connected simulation techniques and the HEC-3

simulation approach (the Bhumibol Reservoir)

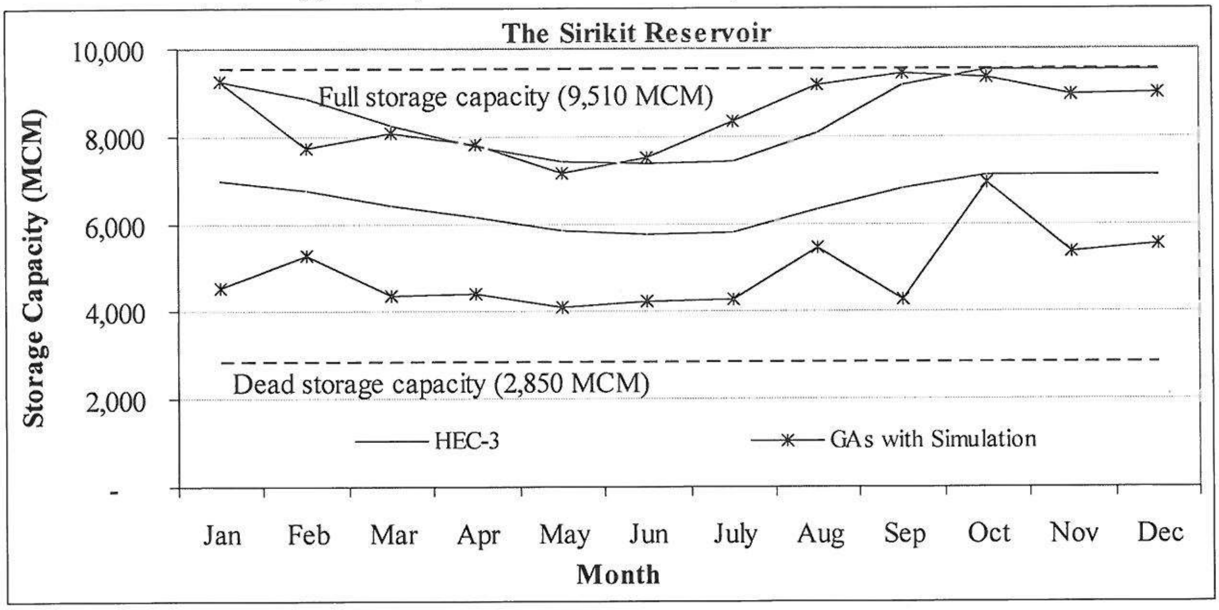

Fig. 14 Optimal rule curves of the GAs connected simulation techniques and the HEC-3 simulation approach (the Sirikit Reservoir)

Table 5 Frequency, magnitude and successive period of water shortage for the GAs connected simulation algorithm and the HEC-3 simulation approach

Techniques		Frequency (times/year)	Magnitude (MCM/year)		Duration (year)	
			Average	Maximum	Average	Maximum
HEC-3	μ	0.098	43	804	1.7	2.3
	σ	0.066	39	606	0.9	1.4
GAs connected Simulation	μ	0.208	29	207	2.1	3.8
	σ	0.082	14	102	0.7	1.8

Note: μ = mean, σ = standard deviation

Table 6 Frequency, magnitude and successive period of excess release for the GAs connected simulation algorithm and the HEC-3 simulation approach

Techniques		Frequency (times/year)	Magnitude (MCM/year)		Duration (year)	
			Average	Maximum	Average	Maximum
HEC-3	μ	0.847	1,201	4,538	8.8	17.7
	σ	0.073	209	1,795	5.0	7.1
GAs connected Simulation	μ	0.843	1,188	4,446	8.8	17.2
	σ	0.073	194	1,825	5.6	7.0

Note: μ = mean, σ = standard deviation

8. Conclusions

This study used the GAs connected simulation technique to find the optimal objective function for searching the optimal rule curves. The obtained curves of all objective functions are compared, and assessed on the properties (frequency, magnitudes, and consecutive duration) of water deficit and excess release using the Monte Carlo simulation. The results show that the average water shortage is the optimal objective function for searching the optimal rule curves. It can be the representation for all situations of water deficit and excess release.

The obtained rule curves of the GAs connected simulation model which used the average shortage as the objective function are used for evaluating the existing rule curves. Results demonstrate that the optimal rule curves of the GAs technique are more mitigate the situation of water deficit and excess release than the existing rule curves especially in magnitude term.

9. Acknowledgements

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References

[1] K. S. Jain, K. M. Goel and K. P. Agarwal, "Reservoir Operation Study of Sabamati System, India", Journal of Water Resources Planning and Management, Vol. 124, No. 1, 1998, pp. 31-38.

[2] EGAT (Electricity Generating Authority of Thailand), "Manual for operating the Bhumibol and Sirikit Reservoirs", EGAT Research Report, Bangkok, Thailand, 2004. (in Thai).

[3] R. Bellman, "Dynamic Programming", Princetion University Press, Princeton, New Jersey, 1959.

[4] S. Yakowitz, "Dynamic Programming Applications in Water Resource", Water Resources Research, Vol. 18, No. 4, 1982, pp. 673-696.

[5] O. A. Esogbue, "Dynamic Programming for Optimal Water Resources Systems Analysis", Prentice Hall, Englewood Cliffs, New Jersey, 1989.

[6] W. J. Labadie, "Combining Simulation and Optimization in Reservoir Basin Management", Stochastic Hydrology and Its Use in Water Resources Systems Simulation and Optimization, NATO ASI Series, Kluwer Academic Publishers, The Netherlands, 1993, pp.345-371.

[7] C. Chaleeraktrakoon and A. Kangrang, "A Dynamic Programming for Searching Rule Curves", The proceeding of International Conference on World Water and Environmental Resource Congress, Anchorage, Alaska, USA, 2005.

[8] C. L. Chang and C. C. Yang, "Optimizing The Rule Curves for Multi-Reservoir Operations Using A Genetic Algorithm and HEC-5", Journal of Hydroscience and Hydraulic Engineering, Vol. 20, No. 1, 2002, pp. 59-75.

[9] J. F. Chang, S. J. Lai and S. L. Kao, "Optimization of Operation Rule Curves and Flushing Schedule in A Reservoir", Hydrological Processes, Vol. 17, 2003, pp. 1623-1640.

[10] L. Chen, "Real Coded Genetic Algorithm Optimization of Long Term Reservoir Operation", Journal of the American Water Resources Association. Vol. 39, No. 5, 2003, pp. 1157-1165.

[11] J. F. Chang, L. Chen and C. L. Chang, "Optimizing Reservoir Operating Rule Curves by Genetic Algorithms", Hydrological Processes, Vol. 19, No. 11, 2005, pp. 2277-2289.

[12] S. Thasaduak and S. Chittaladakorn, "Determination of Reservoir Rule Curve by Genetic Algorithms", Proceedings of the 9th National Conference on Civil Engineering, Thailand, Vol. 2, WRE-(29-33).

[13] Hydrologic Engineering Center (HEC). Hydrologic Engineering Methods for Water Resources Development, Vol. 8, Reservoir Yield. US Army Corp of Engineers:Davis, California, U.S.A., 1975.

[14] C. Chaleeraktrakoon, "Stochastic Procedure for Generating Seasonal Flows" Journal of Hydrologic Engineer, ASCE, Vol. 4, No. 4, 1999, pp. 337-343.

[15] HEC-3 (US Army Corp. of Hydrologic Engineering Center). "HEC-3 Reservoir System Analysis for Conservation", User's Manual, California, U.S.A., 1974.