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EXPERT PARTICIPATION WITH OPTIMIZATION TECHNIQUE FOR IMPROVING OPTIMAL RULE CURVES OF RESERVOIR

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Abstract

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Rule curves are monthly guideline for long-term reservoir operation. Often, they have not been used practical operation because of lacking expert participation. The expert operators were director on reservoir operation, senior operations engineer and technical operations engineer. The expert participation processes were interviewing, observation, focus group discussion and workshop. Their suggestions were performed for adjusting the final rule curves until the new adjusted rule curves accepted. Then these accepted rule curves were used to run with the 500 samples of synthetic inflow for evaluating the differential evolution with expert participation (Expert-CDE) technique. Comparison of the CDE model and the Expert-CDE model as well as the existing model was performed with these synthetic inflows to demonstrate the effectiveness of the developed method. The Lampao reservoir located in Kalasin province, in the northeastern Thailand were considered in this study. The result was found that the accepted rule curves had a lower frequency and smaller magnitude of water shortage than the existing rule curve, whilst the flood frequency of excess water release, the average excess water release, and the maximum excess water release were reduced. Compared to the differential evolution technique, the differential evolution with expert participation provided a similar pattern of rule curve but the new rule curves of differential evolution with expert participation were acceptable to operate reservoir.

Key words: expert participation, reservoir rule curves, differential evolution algorithms, optimization technique

Introduction

Reservoir is one of important tool for flood and drought control. The use of dam for flood mitigation is aim to impound water in a reservoir during periods of high flow in order to maintain safe downstream discharges (Smith and Ward, 1998). Nowadays, water requirements for agriculture, water supply, industry, power generation, ecology and environment increase in concert with population growth, lifestyle changes and economic expansion. This is especially true in the northeast region of Thailand where the population faces annual problematic droughts and floods. As such, a criterion of optimal water operation for storage reservoirs should be established that recognizes that the amount of water storage in the area is limited. A reservoir operation that uses rule curves can improve water budgeting, had better respond to water requirements, provide positive solutions to flood problems, and achieve long-term operation planning (Kangrang et al., 2011).

Generally, reservoir operating systems function with a water release budget. The stored water is released under certain conditions for a multitude of purposes that are defined by water use criteria and reservoir operating rule curves. The

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reservoir operating rule curves have been found to provide the best all around budgeting solution. Typically, reservoir operating systems have been large and complex. The searching of the optimum rule curves is a non-linear optimization problem. Years ago, the optimization technique being applied to search the optimal rule curves was performed with a reservoir simulation model (Jain et al., 1998). The rule curves obtained by this method are not guaranteed to yield the optimal curves because of human adjustment in the trial and error process. Later "dynamic programming" (DP) was applied to solve non-linear problems in water resource areas (Esogbue, 1989; Kumar and Baliarsingh, 2003). However, DP method suffered from computational overburden for its large dimensionality (Hota et al., 2009). The "dynamic programming with the principle of progressive optimality" (DP/PPO) was developed to search the optimal rule curves of single and multiple reservoirs (Chaleeraktrakoon and Kangrang, 2007).

The "genetic algorithm" (GA) has been widely used to solve complex problems (Chen et al., 2002; Muttil and Chau, 2006; Wang et al., 2009; Chau et al., 2005; Yeh, 1997). The best part of the GA is that it can handle any type of objective function of the search. The GA was applied to the reservoir operation model, studied in this paper, as it has been in several studies (Chang et al., 2003; Chang et al., 2005; Hormwichian et al., 2009). In the last decade, a "simulated annealing algorithm" (SA) was applied to solve the optimization problem (Locatelli, 2000; Teegavarapu and Simonovic, 2002; Lamom et al., 2008). Rather, the SA does not always guarantee the globally optimal solution. Sometime, they can produce sub-optimal or near globally optimal solution (Hota et al., 2009). More recently, the SA has been applied to search the optimal reservoir rule curves (Kangrang et al., 2011).

The "differential evolution algorithm" (DE) is a new heuristic approach for minimizing possible nonlinear and non-differentiable continuous space function. It will be demonstrated that the new method converges faster and with more certainty than Adaptive simulated annealing as well as the Annealed nelder and Mead approach, both of which have a reputation for being very powerful. The differential evolution requires few control variables, but it is robust and easy to use especially in the more difficult functions, and lends itself very well to parallel computation. It uses a simulation of natural evolution, the same as the GA (Price and Storn, 1997). The DE is a search technique based on the mechanism of natural selection and genetics. It has a robust random search capability and an approach to global optimum values. The DE structure is less complex than that of the GA. As a result, the DE finds the answer efficiently and faster than GA for solving complex equations in the mathematics field. When comparing DE with another well known method such as GA, SA, Nelder-Mead simplex search method (SM), and Least squares technique (LS). It can obtain optimum solutions more easily than other can (Wang and Ye, 2009). The DE uses fewer control parameters, namely, number of population including a scaling factor, combination coefficient and crossover rate (Karaboga and Okdem, 2004; Bardsiri and Rafsanjani, 2011; Li et al., 2011). The DE can evenly solve both single and multi-objective optimization problems (Adeyemo and Otieno, 2009; Adeyemo et al., 2010). The DE has been used to the model calibration in the water resource field (Liu and Sun, 2010). Therefore, it can be said that the DE is a suitable alternative technique used to find the optimal rule curves within the limited boundaries of reservoir operation.

Integrated water resources management is the practice of making decisions and taking actions while considering multiple viewpoints of how water should be managed. These decisions and actions relate to situations such as river basin planning, organization of task forces, planning of new capital facilities, controlling reservoir releases. The need for multiple viewpoints is caused by competition for water and by complex institutional constraints. The decision-making process is often lengthy and involves many participants (GWP, 2000). There are great challenges in a transition to participatory decision-making in water systems management especially public participation (Song et al., 2011). Effective public participation is the key factor to improve the efficiency of the river basin's water resource management and succeed in its comprehensive management (Jingling et al., 2010; Zaharani et al., 2011). Mathematical models and algorithms have to be re-considered within a methodological framework, in which stakeholder participation and cross-disciplinary approaches are given a central role. The combination between traditional control techniques with preference and subjective aspects of decision-making promotes to get the effective and efficient management of water systems. These can reduce the gap between theories and practice (Castelletti et al., 2008). A participation of stakeholders is the procedure to promote an optimization approach in order to accept for performing by operators who working on reservoir operation.

This paper involved expert participation into optimization model for searching reservoir rule curves. The expert operators were director on reservoir operation, senior operations engineer and technical operations engineer. The differential evolution algorithm connected with the reservoir simulation model was performed for searching the operating rule curves. A conditional constraint was applied to the search process to reduce the fluctuation of the obtained operating rules, and a minimum average water shortage was adopted to be the objective function of the search process. Comparison of the conditional differential evolution model (CDE) and the expert participation-conditional differential evolution model (Expert-CDE) as well as the simulation model was shown to demonstrate the effectiveness of the proposed model. The reservoir operation model was applied to determine the optimum rule curves of the Lampao reservoir in the Northeast region of Thailand.

Materials and Methods

The differential Evolution Algorithm (DE) is similar to the Genetic Algorithms (GA) used for solving non-liner problems. Both algorithms discover the optimum point using the concept of the genetic process of the theory of evolution, or survival theory of Charles Darwin (Darwin, 1959). The theory was created to help people understand the natural operation of the evolution of life and provides the guidance people need to identify and solve problems by viewing minimum or maximum points. All life is composed of good and bad characteristics. In life, good characteristic transfer to the genetic makeup, while bad characteristics are held for further consideration. This operation is presented in the pattern of chromosomes, which uses the Fitness function that judges the objective function in each chromosome. The chromosome will consider which chromosome should generate or should not. So the algorithm will base on natural genetic transferring by mutation, crossover and selection. It is assist to find diverse answer that cover in all answer of problem.

Reservoir Simulation Model

Generally, a reservoir system comprises available water that flows into the reservoir with a single or multipurpose downstream service area. The reservoirs usually operate under water usage criteria and reservoir rule curves. The reservoir rule curves have been found to offer the most equitable solution to all operational problems. A new reservoir operation model was constructed on the concept of water balance, and it can be used to simulate reservoir operation effectively (Hormwichian et al., 2009). The reservoir operating policies are based on the reservoir rule curves and the principles of a water balance concept. The reservoir system operated along the standard operating policy as expressed in Chaleeraktrakoon and Kangrang (2007).

There are policies for releasing water from a reservoir: if available water is in a range of the upper and lower rule level, then requirements are satisfied in full; if available water is over the top of the upper rules level then the water is spilled from the reservoir to the downstream river in order to maintain the water level at the upper rule level so, the excess release will be found in this case; and if available water is below the lower rule level the release water is reduced from requirement for this reason, the water deficit will be met in this case.

The release water of the reservoir based on above policies was used to calculate the situations of water shortage and excess water release, namely, the number of failures in a year, the number of excess water releases, as well as the average annual shortage. These are shown in Figure 1. The results will be recorded for use in the developed CDE and Expert-CDE model.

Development of Conditional Differential Evolution Model

The developed CDE for the simulation model is described as follows. The CDE requires encoding schemes that transform the decision variables into chromosome (lower rule curves and upper rule curve-- x_τ , y_τ). Then, the differential evolution operations (reproduction, mutation and crossover) are performed. These CDE operations will generate new sets of chromosomes. The most common encoding schemes use binary strings. In this study, each decision variable represents a monthly level of the rule curves of reservoirs that described in the mentioned release policies.

After the chromosomes of the initial population have been determined, the release water is calculated in simulation model using these rule curves. Then, the release water is used to calculate the objective function for evaluating DE fitness. Next, the reproduction including selection, mutation and crossover is performed for creating new rule curves parameters in the next generation. This procedure is repeated

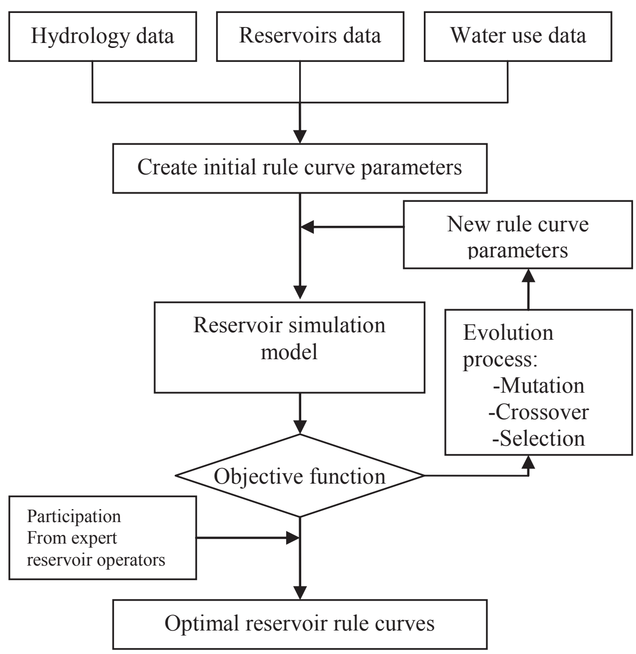

Fig. 1. Integration of Expert-CDE and Simulation Model

until the criterion is satisfied as described in Figure 1. The chromosomes represent 24 parameters (rule curve levels). The objective function of searching the optimal rule curves is the minimum of the average water shortage (MCM/year) obtained from the simulation model as following.

$$f_i\ (x_\tau , y_\tau) = \mathrm{Min}\left(\frac{1}{n}\sum_{v=1}^{n} Sh_v \right), \tag{1}$$

$$\text{if } R_t < D_t\,;\text{Then } Sh_v = \sum_{t=1}^{12}\left(D_t - R_t\right), \tag{2}$$

$$\text{Else } Sh_v = 0\,,$$

where R_t is the release discharges from the reservoir during year ν and period τ (τ = 1 to 12, representing 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; n is the total number of considered year. Sh_υ is water deficit during year ν (year that releases do not meet 100% of target demand) and i is iteration number of each generation.

The boundary of the search for each generation is limited in order to reduce the fluctuation of the obtained rule curves. The range of searching for the lower and upper rule curves is fixed on the dead storage and normal high water level respectively.

Expert participation in optimization model for searching accepted rule curves

Stakeholders who were expert on in the reservoir operation section will consider the optimal rule curves were provided from CDE. This developed model was called Expert-CDE. The expert operators were director on reservoir operation, senior operations engineer and technical operations engineer. Surveying, interviewing, observation, focus group discussion and workshop were used in expert participation process. Their suggestions were performed for adjusting the final rule curves. Then these adjusted rule curves were used to run again in simulation model for evaluating the objective function. These situations were sent to the expert operator again for approving the new adjusted rule curves. This process was done until the new adjusted rule curves accepted by the expert operators. Then these accepted rule curves were used to run with the 500 samples of synthetic inflow for evaluating the expert-CDE technique. Comparison of the CDE model and the Expert-CDE model as well as the existing model was performed with these synthetic inflows to demonstrate the effectiveness of the developed model.

Illustrative Application

In this study, the Lampao reservoir was considered. It is an important reservoir in the northeast of Thailand located on the Lampao basin as shown in Figure 2. The capacity of the reservoir is 1,430 MCM (million cubic meters) with an irrigation covering area of 502 square kilometers. Figure 3 shows a schematic diagram of the Lampao basin and the average yearly rainfall is approximately 1,400 mm per year. The average inflow of the reservoir is 2,230 MCM / year and maximum flood volume at 500 years of return period is 5,482 cubic meters per second. Monthly inflow data of the Lampao reservoir from 1986 to 2008 (23 years) as presented in Figure 4 were used in simulation model.

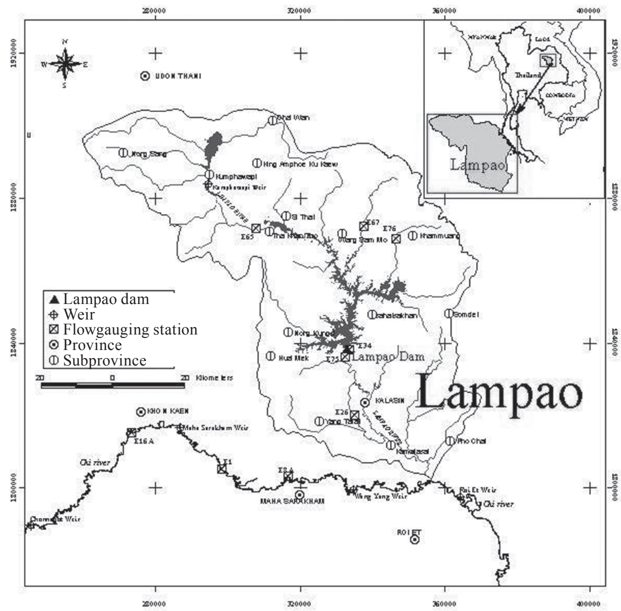

Fig. 2. Location of the Lampao reservoir

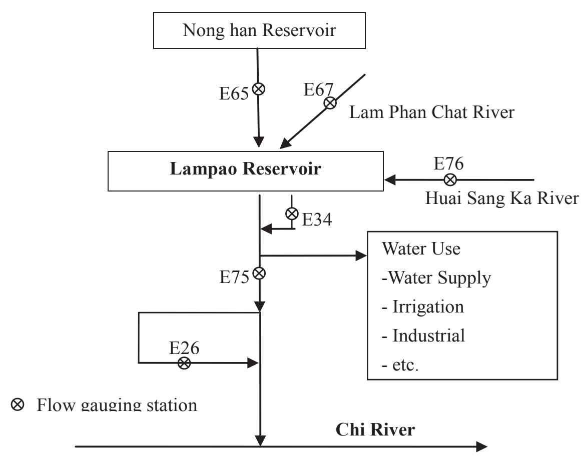

Fig. 3. Schematic diagram of flows in the Lampao river basin

The study used a DE algorithm in connection with a reservoir operation model to find optimal rule curves through the Matlab toolbox (CDE). The optimal rule curve can then be applied to an actual scenario depending on whether the rule curve can be used to cover every case or event that might occur. Thus, "HEC-4 Monthly Streamflow Simulation" (HEC-4) model was used to create synthetic inflow data into the monthly inflows of the reservoir as a synthetic data set of 500 events as presented in Figure 5. Then, input synthetic inflow data were used to assess the efficiency of the new rule curves and compare them with the existing rule curves and between the CDE and Expert-CDE models under the same conditions (objective function and constraints). Moreover, the new rule curves were assessed in various other situations, i.e., water requirement increases, and inflow decreases to judge the impact of how these things will effect to future operations.

Results and Discussion

These data of inflow, evaporation, water requirement and monthly rainfall were imported for processing in the simulation and the CDE models, the optimal rule curves were obtained from those models. The Expert-CDE was performed for finding accepted rule curves. These new rule curves of two methods were plotted in order to compare them with the existing rule curves as shown in Figure 6. The results show that the patterns of accepted rule curve obtained from the Expert-CDE and the CDE are similar. There are slightly different only some month such as lower rule curves of May, July and August. The operators based on their experiences because the mentioned lower rule curves adjusted these differences. These adjustments of participation process lead to an acceptation of stakeholders that the accepted rule curves will be used to operate by the operator according to the previous studies (Song et al., 2011; Jingling et al., 2010). Moreover, the acceptation of rule curves from Expert-CDE can reduce the gap between theory computation and practical operation according to the study of Castelletti et al. (2008).

The obtained rule curves also indicated that the water storage levels of the new lower rule curves of Expert-CDE is higher than the rule curves of CDE in May in order to reduce water release for maintaining water for next month. Whereas, the lower rule curves of Expert-CDE during July-August are lower than the lower rule curves of CDE in order to release water on demand. This will help alleviate water shortages in these months.

The performance of the Expert-CDE model was evaluated with monthly synthetic inflow data, these results are shown in Table 1. The results indicate that, the average frequency of water shortage was 0.451±0.085 times per year, the average magnitude of water shortage was 108.89±22.48 million cubic meters per year and the maximum magnitude of water shortage was 476.27±118.63 million cubic meters per year. These are close to the results of using the CDE rule curves; however, they are still smaller than the results of using the existing currently rule curves. The average frequency of excess water

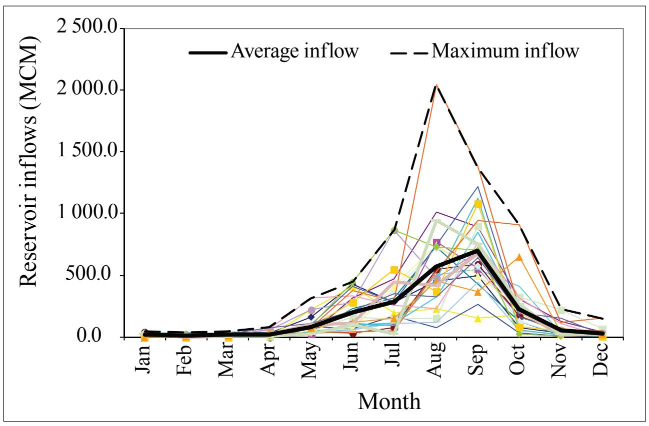

Fig. 4. The observed inflows of Lampao reservoir

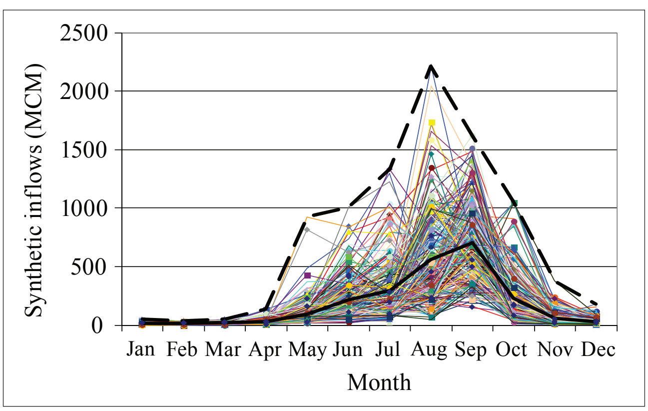

Fig. 5. Synthetic inflows of Lampao reservoir

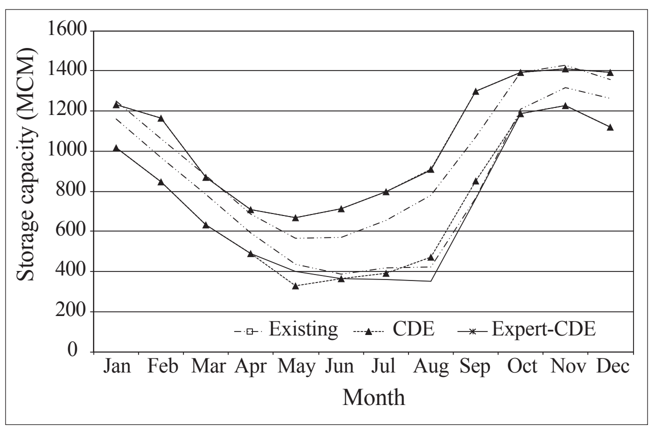

Fig. 6. Optimal rule curves of the Lampao reservoir (new and existing system)

release was 0.795±0.061 times per year, the average magnitude of excess water release was 691.02±27.66 million cubic meters per year and the maximum magnitude of excess water release was 2,584.17±580.94 million cubic meters per year. This is less than when using the existing curves. These results are also close to those using the rule curves of CDE.

Table 2 shows the situations of water shortage and excess release using the rule curves from the proposed new reservoir operation model and the existing model when the water requirements were increased by 10%, 20% and 30%. The results indicate that the water shortage situation increased when the water demands were increased. Water shortage and excess release were the greatest when the water demands were increased to 30%. The results also indicate that the situations of water shortage and excess release of water, using the Expert-CDE's rule curves are close to the situation of using CDE's rule curves. In addition, their situations are smaller than the situations of the existing rule curves when increasing the water requirement. All runs of searching by DE were fast, because the DE method has a different structure model with the GA, and the parameters used are real numbers according to the study of Karaboga and Okdem (2004).

Conclusions

This study incorporated the expert operators to participate in optimization model in order to find the optimal rule curves for accepting to practice. The reservoir operation model conducted on a differential evolution algorithm and reservoir simulation model. The Lampao reservoir located in Kalasin province, Thailand was considered in this study. The synthetic inflow 500 sample were used to evaluate the performance of the proposed method, and the results were compared with those of the existing model and those of the optimization model without expert participation.

The result was found that the pattern of accepted rule curves of the differential evolution with expert participation (Expert-CDE) were similar to the pattern of rule curve of the conditional differential evolution. Moreover, the new rule curves of Expert-CDE were accepted to perform in reservoir operation. In addition, the new rule curves of Expert-CDE provided lower frequency and smaller magnitude of water shortage than the existing rule curve, whilst the flood frequency of excess water release, the average excess water release, and the maximum excess water release were reduced too. It was also found that with a 20% increase of water demand, the new reservoir operation model's rule curve yielded lower average water shortage than the existing rule curve with the current water requirement. This indicated that the rule curve obtained from the proposed method could effectively support the increasing water requirement for the near future. In conclusion, the proposed expert participation with optimization model could enhance the performance of Lampao reservoir, and it might be applied to other reservoirs by adjusting the objective functions, constraint equations of the reservoir and operator participation.

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Table 1
Frequency, magnitude and duration of water shortage and excess water release of the reservoir systems

Situations	Rule curves		Frequency (times/year)	Magnitude (MCM/year)		Duration (year)	
				Average	Maximum	Average	Maximum
Water shortage	Existing	μ	0.926	327.21	669.93	13.02	16.36
		σ	0.049	20.65	85.66	6.37	4.79
	CDE	μ	0.402	96.8	411.6	2.1	3.7
		σ	0.056	20.2	97.3	0.7	1.3
	Expert-CDE	μ	0.451	108.89	476.27	2.65	4.32
		σ	0.085	22.48	118.63	0.80	1.58
Excess release water	Existing	μ	0.979	922.58	2738.02	18.16	20.07
		σ	0.029	25.19	565.68	6.27	4.28
	CDE	μ	0.817	707.5	2,631.0	4.8	10.8
		σ	0.063	28.1	582.4	1.9	3.4
	Expert-CDE	μ	0.795	691.02	2584.17	4.40	8.50
		σ	0.061	27.66	580.94	1.67	2.95

Note: μ = mean, σ = standard deviation

Table 2
Frequency, magnitude and duration of water shortage and excess water release of the reservoir systems when the water requirements were changed up

Situations		Rule Curves		Frequency	Magnitude (MCM/year)		Duration (year)	
				(times/year)	Average	Maximum	Average	Maximum
Water shortage	increase demands 10%	Existing	μ	0.966	403.06	773.14	18.31	20.13
			σ	0.032	21.09	92.33	5.80	3.75
		CDE	μ	0.670	183.60	618.60	3.70	6.90
			σ	0.076	24.80	128.10	1.20	2.40
		Expert-CDE	μ	0.666	182.08	606.63	3.65	6.86
			σ	0.078	24.87	125.53	1.22	2.43
	increase demands 20%	Existing	μ	0.982	487.07	883.93	21.59	22.06
			σ	0.023	22.43	97.25	3.43	2.14
		CDE	μ	0.869	285.20	774.10	8.50	13.00
			σ	0.054	25.70	136.70	4.40	4.30
		Expert-CDE	μ	0.869	282.66	757.07	8.52	13.02
			σ	0.054	25.39	131.87	4.42	4.30
	increase demands 30%	Existing	μ	0.994	581.46	1008.10	22.78	22.82
			σ	0.015	23.82	111.59	1.02	0.54
		CDE	μ	0.953	389.10	922.30	18.10	19.90
			σ	0.033	26.30	142.20	5.80	3.90
		Expert-CDE	μ	0.972	479.01	976.87	19.63	20.92
			σ	0.029	25.00	120.09	5.25	3.38
Excess release water	increase demands 10%	Existing	μ	0.955	841.27	2637.23	14.04	17.39
			σ	0.040	24.95	558.22	6.64	4.90
		CDE	μ	0.742	620.10	2476.70	3.60	7.30
			σ	0.062	29.60	576.80	1.20	2.60
		Expert-CDE	μ	0.742	618.98	2479.64	3.58	7.25
			σ	0.062	29.60	577.21	1.20	2.61
	increase demands 20%	Existing	μ	0.915	768.14	2548.40	10.01	14.32
			σ	0.052	26.66	560.61	5.46	4.68
		CDE	μ	0.700	565.60	2394.10	3.20	6.50
			σ	0.064	30.90	572.30	1.00	2.40
		Expert-CDE	μ	0.696	563.74	2392.46	3.14	6.45
			σ	0.063	30.59	572.96	1.04	2.36
	increase demands 30%	Existing	μ	0.882	706.20	2460.18	7.67	12.29
			σ	0.057	27.19	546.02	4.23	4.36
		CDE	μ	0.659	513.60	2310.90	2.80	5.80
			σ	0.067	31.10	571.00	0.80	2.00
		Expert-CDE	μ	0.774	599.93	2347.43	4.12	8.18
			σ	0.063	32.24	552.03	1.52	2.84

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