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Reliability Based Multireservoir System Operation for Mae Klong River Basin

Areeya Rittima* and Varawoot Vudhivanich

ABSTRACT

Because of the uncertainty of hydrologic process and the increasing trend of water demand, the reliability-risk concept was adopted for evaluating a long term multireservoir system operation characteristics. The reliability based multireservoir operation model of Mae Klong River Basin was developed in term of limit state function by using the daily hydro-meteorological data from 1985 to 2004. The reliability concept was applied to classify the failure domain in terms of load and resistance. The failure domain was classified into 3 modes namely flood mode, shortage mode, and energy mode. The objective of this study was to evaluate the reliability indices of the existing and future system states and also to forecast the maximum possible firm yield of Mae Klong multireservoir system at the various reliability levels. The result showed that the existing operation at 6,975 mcm/yr of average water demand gave the good performance with the reliability of 98.60%, 99.80-100%, and 73.60% for mode 1, 2, and 3 respectively. If there was 25% increase of the average water demand, the reliability of shortage mode would decrease to 95.60% and the reliability of energy mode would decrease to 51%. However, it did not influence to the reliability of flood mode. The result of possible firm yield forecasting considered from shortage mode indicated that at the reliability of 80%, 85%, 90%, and 95%, the maximum possible firm yields were 10,979, 10,672, 10,114, and 9,451 mcm/yr respectively. In other words, if the higher shortage risk was allowed, the higher firm yield could be utilized.

Key words: multireservoir system operation model, reliability based multireservoir system operation model, Mae Klong river basin

INTRODUCTION

According to the global temperature has risen up in the past century, the global warming has become a huge issue that many agencies have realized the effects. One worldwide mention in the past few years is the climatic change. The discussion on the world stage emphasizes the important of sensitivity of climate variation together with hydrological uncertainty and its effect to human living especially in the regional scale. These changes have serious implications for water resource system management.

It is well known that the hydrological uncertainty of water resource systems is beyond the certain expectation in quantity and time scale. Consequently, it makes a water resource management becomes a tough task to the right operation. It is often heard about the mismanagement output of water resource systems

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appeared as the severe drought events and flood damage in many local areas. Moreover, the tendency of water requirement which is likely to be increasing in response to the economic growth, even though the rising populations also enlarges these mismanagement impacts higher. Therefore, to make a success of sustainable water management, the operators must be taken these limitations into account for setting the appropriate work plan according to each local state.

In Thailand, it can say that the high variation of rainfall amount and number of rainy day brought a regional drought comes to more effects particularly in the north-east. Many times the reservoir system operation in this region is performed under uncertainty of these hydrologic conditions and its encompassing factors. Therefore, it is necessary to construct the measurement for water resource systems performance evaluation by using the information of uncertainty.

In general, the calculated uncertainty may be expressed in term of probability. The probability of failure of an event is the risk while the probability of success may be called the reliability (Chow *et al.*, 1988; Srdjevic and Obradovic, 1997). In the other words, reliability is the complement of probability of failure or risk. Failure of any system can basically be classified as structural failure and performance failure. Structural failure involves damage of the structure whereas the performance failure relates to inability of the system to perform as desired within the period of interest. Therefore, the definition of reliability in term of performance failure is the probability of a system performing its function adequately for the intended time under the intended operating conditions (Koutsoyiannis, n.d.). The objective of a reliability study is to derive suitable measures of successful performance on the basis of component failure information and system configuration.

Reliability and risk are typical modern performance indices in evaluation of long term dynamical reservoir behavior likewise resiliency and vulnerability. Since 1980s, the reliability-risk analysis was widely informed especially in water resources management. For example, Srdjevic and Obradovic (1995) applied the reliability-risk concept in evaluating the control strategies of multireservoir water resources system. Tsheko (2003) calculated reliability and vulnerability of rainfall data to define the severity and frequency periods of droughts and floods in Botswana. In Thailand, there were many researches about an assessment of water resource management using reliability, vulnerability, and resiliency indices accompanied by the simulation approach. For example, Jin (1985) measured these performance indices in order to assess water resource system management of the eastern seaboard development project. Rittima (2002) developed the probability based rule curve of Mun Bon and Lam Chae reservoirs and brought three types of these performance indices to evaluate the reservoir simulation result. However, it was observed that most of researches dealt with reservoir performance descriptor. Therefore, instead of evaluating a reliability of reservoir operation by these descriptors, this study proposed a reasonable technique to analyze reliability indices by limit state function derived from a reliability based multireservoir operation model. Apart from evaluating the reliability indices, the developed model also helped to forecasting the maximum possible firm yield in Mae Klong river basin.

MATERIALS AND METHODS

Required data

(1) The daily hydro-meteorological data comprising of rainfall, net inflow, evaporation, and seepage data supported by the Royal Irrigation Department (RID) and the Electricity Generating Authority of Thailand (EGAT) from 1985 to 2004.

(2) The physical reservoir data such as

the elevation-storage-area curves, the tail water rating curves, and the capability-discharge-efficiency curves gathered from various documents and reports.

(3) The water demand sectors and existing demand pattern.

(4) The existing multireservoir operation data comprising of water release, reverse pumping water, surplus release, and hydropower generation from 1985 to 2004.

Methods

(1) The collected data was checked in parts of the abnormality and inconsistency via time series plots and filled up the missing data by the average value. For the rainfall data, the double mass curve method was used for the preliminary data analysis.

(2) Develop the daily multireservoir system operation model of the Mae Klong river basin both the current and future demand pattern by simulation technique.

(3) Develop the reliability based multireservoir system operation model in the limit state function forms of flood mode, shortage mode, and energy mode by applying the reliability concept.

(4) Evaluate the reliability indices and forecast the maximum possible firm yield using the reliability based multireservoir system operation model.

Description of the study area

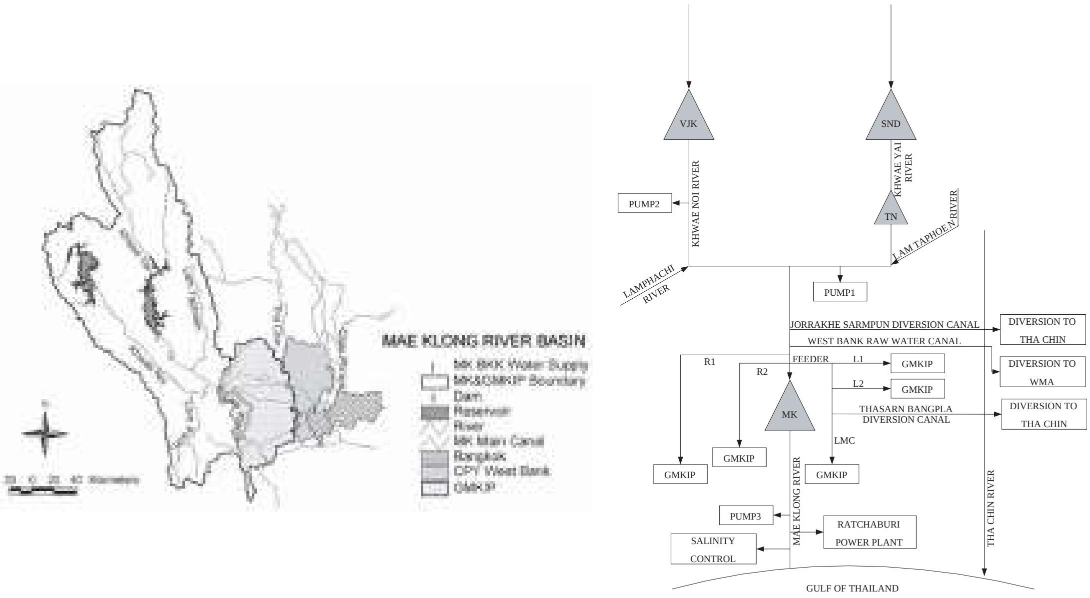
The Mae Klong river basin development project was formulated in 1963. The basin is located in the western part of Thailand covering a total catchment area of 30,800 km.^{2} in eight provinces namely Kanchanaburi, Ratchaburi, Nakhon Pathom and some parts of Suphanburi, Samut Songkhram, Samut Sakhon, Phetchaburi, and Uthai Thani. The large storage dams; Srinagarind (SND) and Vajiralongkorn (VJK) have been constructed on KhwaeYai and Khwae Noi river respectively. At the downstream of SND dam, there is the Tha Thung Na (TN) re-regulating dam which its function is to regulate for reversible turbines of SND reservoir and also to control downstream release to Mae Klong river in the lower basin area. These two major tributaries are converged to Mae Klong (MK) diversion dam which ends at the gulf of Thailand and its function is set up for diverting water to the canal system.

The operating policy is focused on the irrigation especially in the Greater Mae Klong Irrigation Project (GMKIP), domestic and industrial water supply, salinity control, and transbasin diversion to Tha Chin river basin and Bangkok Metropolitan Water Works Authority (MWA) serving for city water supply. In addition, this project can be utilized for the hydropower generation with total installed capacity of 1,058 MW. The descriptions of Mae Klong river basin including dam, irrigation project location, and its configuration diagram are shown in Figure 1.

Water supply and water demand of Mae Klong river basin

Respecting the water supply of Mae Klong river basin, the main source was the net inflow of two storage dams, SND and VJK. It was about 78% of total water supply or 9,892 mcm/yr. For the rest, it was net side flow component came from two subcatchment area namely the area between TN and MK dam and between VJK and MK. Hence the average annual total supply of Mae Klong river basin between 1985-2004 was 12,638 mcm as presented in Table 1. However, the result of water year classification showed that total water supply in critical dry year ran from 5,375 mcm/yr to 9,054 mcm/yr while it climbed up to 19,442 mcm/yr in wet year. From this, it reflected a large variance of water supply which made the reservoir operation a complicated task.

In consideration of water demand sectors in 2003, it could say that the available water supply was allocated to several water activities within



a) Dam and irrigation project location

b) Configuration diagram

Figure 1 Mae Klong river basin.

Table 1 Water supply and water demand of Mae Klong river basin.

Water supply & water demand	Volume (mcm/yr)
1. Water supply	12,638
- Net inflow	9,892
- Net side flow	2,746
2. Water demand sectors	8,200
- Irrigation water demand of GMKIP and pumping project area	5,853
- Domestic and industrial water supply	20
- Transbasin diversion to Tha Chin	506
- Diversion to Bangkok Metropolitan Water Works Authority	244
- Salinity control	1,577

basin and nearby basin. About 91% of total water demand was served for the inner basin on the purpose of domestic and industrial water supply, irrigation, and salinity control. Additionally, 71% of total water demand was drawn to 3,230,360 rai of irrigable project area in GMKIP. For the transbasin diversion to Tha Chin and Bangkok Metropolitan Water Works Authority, water demand of this sector was only 9% of all and it tended to be higher according to the MWA's plan in the near future.

By comparison between water supply and water demand of Mae Klong river basin, it indicated that the available water supply was still high potential enough for serving to the existing water demand side throughout the year. However, it might be confronted the water shortage characteristics in some drawdown periods especially the critical dry year. Thus, an operating strategy of how to refill reservoir storage during the drought period by the abundant water supply in wet season should be carried out.

RESULTS AND DISCUSSION

Model formulation

1. The daily multireservoir system operation model

The purposes of daily multireservoir operation model here were to duplicate the multireservoir behavior and tried to store some savable water to fulfill a long term operation. The active storage of VJK, (5,848 mcm) was less than SND reservoir, (7,470 mcm) while the net inflow of VJK was much bigger especially in the wet period. Hence, to avoid flooding situation of VJK reservoir and to save water storage of SND, it was optimal to regulate the multirservoir system by swapping a release ratio between VJK and SND in that period. Consequently, the release ratio of VJK was raised up to take advantage of decreasing flood flow. Accordingly, another purpose of model development was to decrease flood encountering VJK.

To formulate the daily multireservoir operation model, the water balance approach was used and the operating rule curve was employed being an operating rule for SND and VJK reservoirs. The decision release of SND and VJK was controlled under the operating rule which offered some guidance for a reservoir operation. Actually, the EGAT had developed the operating rule curves of SND and VJK since the beginning of development project and continued to improve them related to a real use. The latest rule curves were updated in 2001 by HEC-3 simulation technique and were used in practice since 2002 till now. For the real operation of TN and MK reservoirs, it appeared that both attempted to keep the upstream water level at the constant value all the time, 58.65 m.msl. for TN and 22.50 m.msl. for MK reservoir. Therefore, controlling the constant water level in upstream was determined as an operating rule of TN and MK.

Besides, it was necessary to create two vital submodels: (1) hydropower generation and (2) reverse pumping submodel, to accomplish the development of multireservoir operation model. For hydropower generation, the power was produced by release flow rate via the turbines of SND, VJK, and TN reservoirs. Therefore, hydropower production was the product of head, efficiency, and release flow rate. If the reservoir created a higher head per unit volume of storage, it gave higher generation efficiencies as well as flow rate resulting the higher hydropower production. Since the special function of TN reservoir was for regulating reversible turbines of SND made. The reverse pumping submodel was designed. To resemble its behaviors in respect to the quantity and occurrence based probability of reverses pumping water, the study started with the consideration of all involved variables such as the release of SND and TN reservoir including reverse pumping volume and their relationships. The result was found that the volume of reverse pumping water per day related to the daily release of TN at the various ratio. Hence, the reverse pumping water here was expressed as a ratio of daily release of TN accompanied with the generated probability of extended events according to its real occurrence.

The physical features of Mae Klong river basin in Figure 2 help formulating model framework easier. Each reservoir was balanced and a release decision was made with its operating rule as mentioned above. The daily release of SND and small part of side flow became the major sources of TN's net inflow. Some part of water storage at TN was pumped back to SND reservoir, consequently the reverse pumping submodel was employed. A large flow rate coming from the net daily release of TN and VJK including unexpected side flow were combined on the downstream basin and became the net inflow to MK. It took one day and two days of traveling time from TN an VJK respectively. The available water at MK dam was

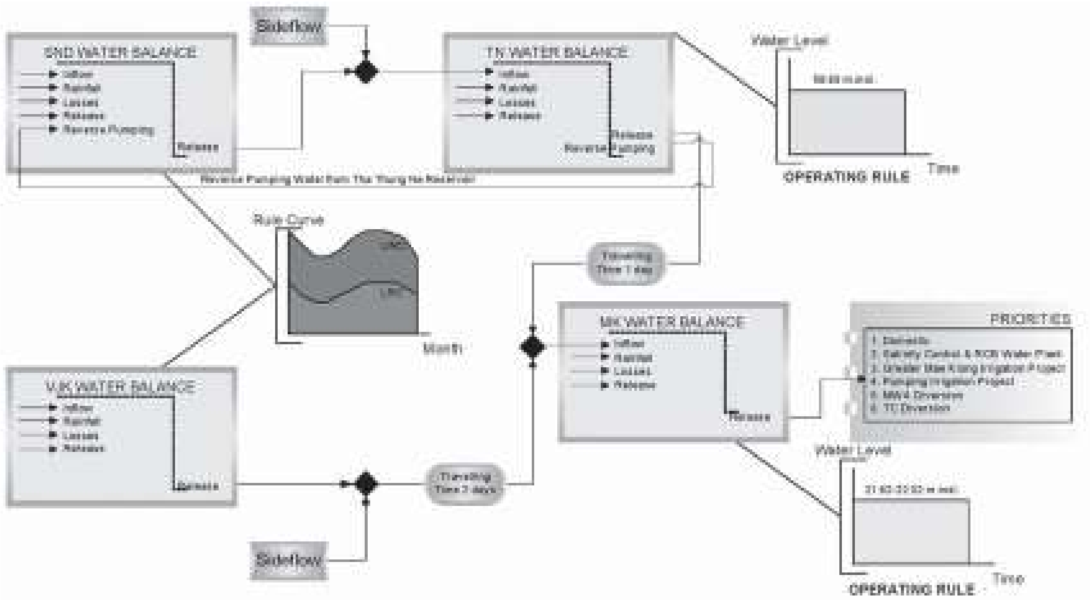


Figure 2 Multireservoir system operation model of Mae Klong river basin.

allocated for the various demand sectors as prescribed in the previous section. The priorities of all demand sectors were arranged as follow; domestic and industrial water supply, salinity control, irrigation, and transbasin diversion respectively.

In this study, the simulation model was divided into two cases: (1) the existing case and (2) future case. The first case represented the current reservoir operation of Mae Klong river basin. The daily record between 1985-2004 was input to the model including the essential data of SND, VJK, TN, and MK. Because the current demand pattern tended to be gradually high, so its pattern was used for the existing case. The second case represented the reservoir operation in the future which the tendency of demand pattern was supposed to be stable according to the full potential development plan. The input data of the future model was synthesized by the suitable stochastic model such as AR, ARMA, ARX, and ARMX models.

2. The reliability based multireservoir system operation model

In stead of evaluating a reliability of reservoir operation by the performance indicator, this study developed a reasonable technique for evaluating reliability indices from the limit state functions. To obtain these required functions, the reliability based multireservoir system operation model was formulated. The structural reliability concept was applied to define the failure behaviors in terms of load and resistant. The main steps of methodology were as follows:

(1) Classification of state variables and their combinations

The model development here began with the examination of the hydrological condition in order to classify state variables and to point out their key role on the multireservoir operation system. The independent characteristics of these state variables were basically investigated by the correlogram test. The statistical characteristics in terms of mean and standard deviation of all variables both the existing and future case of simulation were computed as shown in Table 2.

Table 2 Probability density function and statistic characteristic of the selected state variables.

Random variables	Probability density function	Statistic characteristics			
		Existing case		Future case	
		Mean	Stdev.	Mean	Stdev.
1. X1; Net reservoir inflow of SND	Gumbel	11.34	18.22	11.34	18.22
2. X2; Net reservoir inflow of VJK	Gumbel	14.00	28.57	14.00	28.57
3. X3; Net reservoir inflow of TN	Gumbel	0.31	1.06	0.31	1.06
4. X4; Net reservoir inflow of MK	Gumbel	6.81	13.63	6.81	13.63
5. X5; Water demand	Gumbel	19.62	5.75	22.88	6.70

The best fit probability density function (PDF) of all variables was analyzed together with categorizing the combinations of these variables to be the data input of risk analysis simulation model.

From the preliminary analysis, the observed hydrologic condition and established water demand were considered as the state variables; X1, X2, X3, X4, and X5. The variable X1 represented net reservoir inflow of SND calculated from unexpected inflow, rainfall, and losses components. By the same token, X2, X3, and X4 represented net reservoir inflow of VJK, TN, and MK respectively. Variable X5 was the established water demand calculated from all demand sectors of the system.

It can be said that the selected stated variables played an important role on the multireservoir operation in Mae Klong river basin because they gave information of water supply and water demand throughout the system. Additionally, the property of randomness of both water supply and water demand also made the strategy of multireservoir operation proposed in the different ways according to these incoming variables. Consequently, it took the effect to the reservoir performance in term of reliability indices directly.

The result of correlogram test indicated that X1-X5 were the uncorrelated variables because the coefficient values (rk) of each variable was within the probability limit at 1% significance level. Besides, the result of goodness-of-fit by using Smirnov-Kolmogorov test could be concluded that Gumbel distribution was fitted to all variables. Both the independent characteristic of all variables and their probability density function would be taken into account in the limit state function.

Furthermore, X1-X5 were determined as [X1;X11, X12, X13], [X2;X21, X22, X23], [X3;X31, X32, X33], [X4;X41, X42, X43], and [X5;X51, X52, X53] multiplied by the coefficient factors (ai). For example, the variable X1 was composed of X11, X12, X13 calculated from a11X1, a12X1, and a13X1 respestively. The criteria of setting the coefficient factors were imposed by the possibilities of variable occurrence. These variables were grouped later on to be the combinations of input in the next step.

(2) Simulation method

In this method, the dynamic behaviors of the system were simulated by the combinations of variable using risk analysis simulation model. It could say that risk analysis model was part of the reliability based multireservoir system operation model which defined the failure behaviors as load (Q) and resistant (R). In general, to analyze of structural reliability, a piece of any structures was defined as load and resistance effects. The failure behavior would be occurred when load exceeded the resistance. For example, in bridge structures, failure could be happened when the inability of structure to carry traffic load. It was sometimes helpful to think of load as a demand and resistance as the capacity (Kijawatworawet, 1998; Nowak, 2000). As a case in point, these criteria could basically be applied for an analysis of reservoir reliability. Each mode of failure behavior in this study was specified separately as flood mode, shortage mode, and energy mode which was summarized in Table 3.

In case of flood mode, the daily downstream release of SND, VJK, TN, and MK reservoir were defined as load and maximum capacity of Khwae Yai river at the downstream of SND reservoir, Khwae Noi river, Khwae Yai river at the downstream of TN reservoir, and Mae Klong river were defined as resistance respectively. If the daily release of any reservoir was beyond its river capacity, flood failure could be taken an effect. The second was shortage mode which was split into two types; type 1 and type 2. The established water demand of both types was defined as load, while the resistance was the available water supply subjected to the net reservoir inflow for type 1 and added to unexpected side flow for type 2. The last was energy mode which the full potential of hydropower generation was taken into account to define the energy failure. The hydropower head at any time was compared with the designed head defined as the maximum water level which could be produced a full potential energy. Therefore, the energy failure would be occurred when the hydropower head at the beginning of any time was less than design head of each reservoir.

(3) Allowable risk specification

The allowable risk was specified with reference to the preceding study of Raudkivi in 1979 (Koutsoyiannis, n.d.). This specific allowable risk became important part of limit state function which was supposed to be required resistance of the performance function.

(4) Limit state function analysis

The simulation results obtained from risk analysis simulation model were risk values at the various combinations of input. The values that approached the specific allowable risk were selected to find the relationship between their risk values and combinations of input variables (Xi) in forms of linear equation (ciXi) at the constant allowable risk line. It could say that the function of input variables in linear forms was load effect of limit state function. Hence, the required limit state function (g(X)) in each failure mode was given by the required resistances (R) and load effects (Q) in the following expression: $g(X) = R-Q = 0$

(5) Reliability testing

The Monte Carlo simulation technique was brought for the reliability testing with 500 iteration results. In details, it was necessary to calibrate the limit state functions before leading them to evaluate reliability indices or even to forecast the maximum possible firm yield. In calibration, the reliability testing was firstly carried out by generating the probability density function of two random variables; load and resistant effect. However, the required resistance here was specified as the constant values, only the load effect comprising the function of input variables; X1, X2, X3, X4, and X5 was generated by Gumbel distribution function. The probability that load effect exceeded the required resistant or $g(X)\geq 0$ was actual reliability indices. The reliability

Table 3 Specifications of three modes of reliability based multireservoir system operation model.

	Mode	Load*	Resistance*	Allowable risk
1.	Flood mode	Release (Rt)	River capacity (C)	3%
2.	Shortage mode	Water demand (Dt)	Water supply (WS)	
	-Type 1	Dt	WS=St	5%
	-Type 2	Dt	WS=St+SF	5%
3.	Energy mode	Hydropower head (Ht)	Designed head	30%

* (Duckstein *et al.*, 1987)

indices of flood mode, shortage mode, and energy mode were evaluated using the limit state function as developed in preceding section and compared them with each mode of actual reliability. If both came close to each other, it showed that these limit state functions represented performance function of Mae Klong multireservoir system well and were ready for application. On the other hand, the new parameter (ci) of load effect term should be searched again until there was no difference between the reliability indices obtained from the limit state function and the real operation analysis.

Simulation results

The simulation results from daily multireservoir operation model were investigated comparing with the actual operation with respect to the average release, average energy, and available storage. In parts of average release, it included the total release of SND, VJK, TN, and MK together with the total release of the system, total reverse pumping, and total surplus release. The average energy of SND, VJK, TN, and the whole energy of the system was considered over the intended period. Furthermore, the available storage at the end of simulation particularly the large storage dam, SND and VJK from the model was also scrutinized in comparison with the real operation.

The multireservoir operation since 1985 to 2004 in Table 4 showed that an average release of SND reached 5,046 mcm a year, a 3.59% higher than VJK's release, with the release of 4,865 mcm a year. However, the simulation result showed the average release of SND dropped to 4,983 and 4,962 mcm/yr for model simulation and calibration respectively. In contrast, the average release of VJK increased to 4,941 mcm/yr for the simulation and improved to 4,945 mcm/yr when the revised rule curve was used for model calibration. In other words, the proportion of storage of SND went up to 1.67% from the actual operation while the proportion of release of VJK fell to 1.64% which was coincident with the EGAT's policy to decrease flooding situation of VJK and to keep the savable water of SND in the meanwhile. The simulation result also showed that the hydropower energy was unchanged from the actual operation, it ranged from 1,970 to 2,010 GWh per year. Moreover, the simulation result also gave lower surplus release at the downstream of Mae Klong dam. The reduction of total release over the system made an available total storage higher at the end of simulation. Besides, there was no difference in the performance indices; time based reliability, quantity based reliability, occurrence based reliability, and flood reliability, among the several kinds of simulation techniques in the current situation and real performance. In the similar manner, every component of validation result was rechecked against the operation record from 2001 to 2004. The result pointed out that the total release of the system went up about 23.69% in the last four years comparing with the long term operation. Moreover, the increasing water demand in the future encouraged the shortage performance in term of the time base reliability came to more effects inevitably.

Limit state function

As mentioned earlier, the reliability based multireservoir system operation model in the limit state function forms of flood mode, shortage mode, and energy mode were derived from risk analysis simulation model. The limit state functions (g(X)) were expressed as a function of specific allowable risk, net reservoir inflow, and water demand as follow:

$$g(X) = D_i - [c1X1 + c2X2 + c3X3 + c4X4 + c5X5] = 0 \quad \text{............}(1)$$

in which

Δ_i = The specific allowable risk of each mode

ci = Coefficient of the limit state function came from the fitted result between the selected combination of input variables and specific allowable risk value

Table 4 Multireservoir simulation results.

Reservoir states	Reservoir operation record		Multireservoir operation model			
			Existing case			Future case
	1985-2004	2001-2004	Operating rule curve			Operating rule curve
			Simulation[1]	Calibration[2]	Validation[3]	Simulation[2]
1. Average release (mcm/yr)						
1.1) Total release of SND	5,046	5,704	4,983	4,962	6,052	5,330
1.2) Total release of VJK	4,865	5,883	4,941	4,945	6,207	6,001
1.3) Total release of the system	9,911	11,586	9,924	9,907	12,259	11,331
1.4) Total release of TN	4,068	4,938	4,086	4,080	5,016	4,225
1.5) Total release of MK	10,907	12,619	11,397	11,382	10,826	12,215
1.6) Total Reverse pumping	978	766	985	991	1,095	1,108
1.7) Total surplus release	4,494	4,693	4,402	4,446	2,702	4,075
1.8) otal water demand	6,975	8,234	6,975	6,975	8,234	8,760
2. Average energy (GWh/yr)						
2.1) Total energy of SND	1,176	1,176	1,274	1,289	1,592	1,353
2.2) Total energy of VJK	645	645	587	581	771	707
2.3) Total energy of TN	148	148	149	147	176	149
2.4) Total energy of the system	1,970	1,970	2,010	2,017	2,539	2,209
3. Available storage at the end of simulation (mcm)						
3.1) Storage of SND	14,217	14,217	16,007	16,169	15,052	14,491
3.2) Storage of VJK	7,025	7,025	5,635	5,548	5,811	6,044
3.3) Total storage of the system	21,242	21,242	21,642	21,717	20,863	20,535
4. Performance indices						
4.1) Time based reliability	0.8769	0.9999	0.8856	0.8615	0.9799	0.7334
4.2) Quantity based reliability	1.5200	1.5300	1.5940	1.5910	1.3150	1.3950
4.3) Occurrence based reliability	0.4988	0.4988	0.5011	0.5010	0.5000	0.5007
4.4) Flood reliability	0.9998	1.0000	0.9987	0.9986	1.0000	0.9982

[1] Simulated by the existing rule curve.

[2] Simulated by the revised rule curve in 2001.

[3] The data from 2001 to 2004 was used for validation.

X1, X2,.., X4 = Net reservoir inflow of SND, VJK, TN, and MK respectively

X5 = Water demand of the system

It could say that the limit state function was a performance function which was the boundary between safety and failure performance. The specific allowable risk represented the resistance effect (R), whereas the function of net reservoir inflow and water demand (ciXi) represented the load effect (Q) in meaning of structural reliability. Thus, if $g(X)\geq0$ it indicated that the multireservoir system operation would be safe or it gave a satisfied performance in practice, on the contrary if $g(X)<0$ the multireservoir system operation gave a unsatisfied performance. Hence, the reliability indices (RI) were equal to the probability that the satisfied performance was occurred as presented in the following equation

$$RI = Prob[g(X)>0] \qquad ....(2)$$

The figure 3 showed the coefficient of three modes of limit state function both existing and future cases. The coefficient value of each mode was different depending on each considerate mode and involved state variables. In case of flood mode and two types of shortage mode, the coefficient of all variables; X1, X2, X3, X4, and X5, were significant on their limit state functions because it gave the high value fluctuated during zero in both two cases. It signified that all variables of multireservoir system played an important role for flood and shortage reliability analysis. Only the net reservoir inflow of SND, VJK, and TN variables; X1, X2, and X3, were important on the limit state function analysis of energy mode. In other words, the net reservoir inflow of MK (X4) and water demand (X5) were not the significant factors for the capability of hydropower generation of Mae Klong configuration system which was actually controlled by the rule curve operating rule.

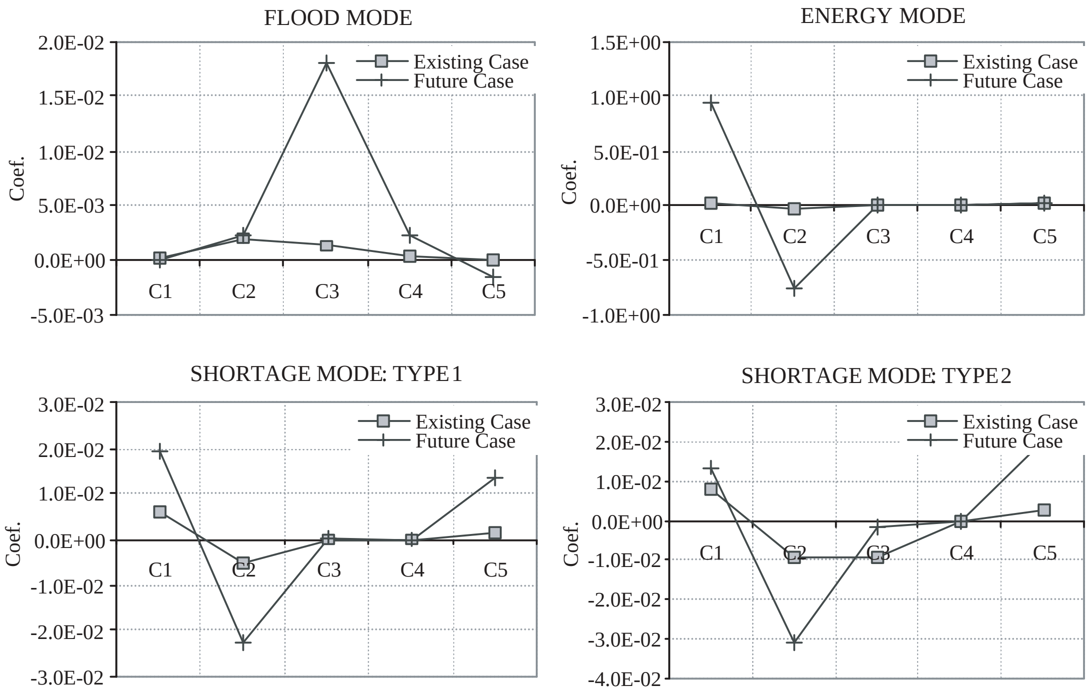


Figure 3 Limit state function coefficient.

Reliability indices evaluation

The result of reliability indices evaluation in Table 5 showed that the existing multireservoir operation at water demand of 6,975 mcm/yr gave a good performance of 98.60%, 99.80-100%, and 73.60% of reliability for flood mode, shortage mode, and energy mode respectively. The percent error of reliability indices was quite small ranging from 0% to 1.26% in comparison with actual performance. However, the increasing water demand in the future affected on the reliability indices of shortage and energy mode which tended to be lower. On the other hand, the recessive reservoir storage according to rising established demand conducted the flood reliability indices higher. Besides, two types of shortage reliability indicated that if side flow was considered as the main source of water supply system combined with net reservoir inflow, the reliability indices of shortage mode would be increased because of the higher water supply of the system.

To extend the study result in parts of the reliability indices tendency, the various ratios of water supply and water demand were settled up as the input of reliability based multireservoir operation model. When the water supply ratios were varied, the water demand ratios remained constant. On the other hand, if the water demand ratios were varied, another ratio was constant. As a case in point, 0.80, 0.90, 0.95, 1.00, 1.10, and 1.20 were selected for flood mode and energy mode ratios and 0.80, 0.90, 0.95, 1.00, 1.10, 1.20, and 1.25 for two types of shortage mode. It was observed that the specific ratios covered the possibility of water supply and water demand both current and future situations.

From the result of existing and future cases in Figure 4, it could be explained that there was an increase in flood risk when water supply of the system was risen up. It was possible that water release during the refill periods was drawn more than ever by way of reservation some vacancy storage for unexpected inflow. Hence, the probability of flood failure would be increased. The increment of water supply ensured that it would be sufficient in response to established demand and benefit to the hydropower generation. Accordingly, the reliability of shortage mode was gradually increased in the similar manner with the reliability of energy mode. The rising water demand enabled flood risk hardly to happen. Consequently, the flood reliability remained stable when water demand ratios were varied higher. The reliability indices of both shortage and energy mode fell dramatically when water demand was risen up.

Maximum possible firm yield forecasting

To answer the question of how much available water supply of Mae Klong river basin could be drawn at most, the reliability based multireservoir operation model was brought for the forecasting in term of the maximum possible

Table 5 Reliability indices evaluation.

Mode	Reliability indices (RI, %)		
	Reservoir operation record	Limit state function	
		Existing case	Future case
1. Flood mode	97.88	98.60	100.00
2. Shortage mode			
- Type 1: WS=St	100.00	99.80	95.60
- Type 2: WS=St+SF	100.00	100.00	98.40
3. Energy mode	72.34	73.60	51.00

firm yield. Table 6 showed the result of two types of this. For the first type, the accomplishment of multireservoir operation serving to the irrigation purpose without any shortage condition was taken into account, thus the maximum possible yield was anticipated from the limit state function of shortage mode. The hydropower generation purpose was considered for the latter type, so the limit state function of energy mode was used. It appeared that the water demand of 6,626 mcm/yr could be satisfied without any problematic shortage. Additionally, 35% of water demand increasing from 6,975 to 9,451 mcm/yr was satisfied at 95% of allowable reliability. In other words if 5% of shortage risk was allowed, the available water supply of 9,451 mcm/yr could be utilized. However, the increment of water demand significantly effected on the reduction of reliability of the energy mode. It could be extended that the increment of possible firm yield made reliability indices changed rapidly. Therefore, at 70% of allowable reliability of energy mode, the maximum possible firm yield of 7,055 mcm/yr could be responded.

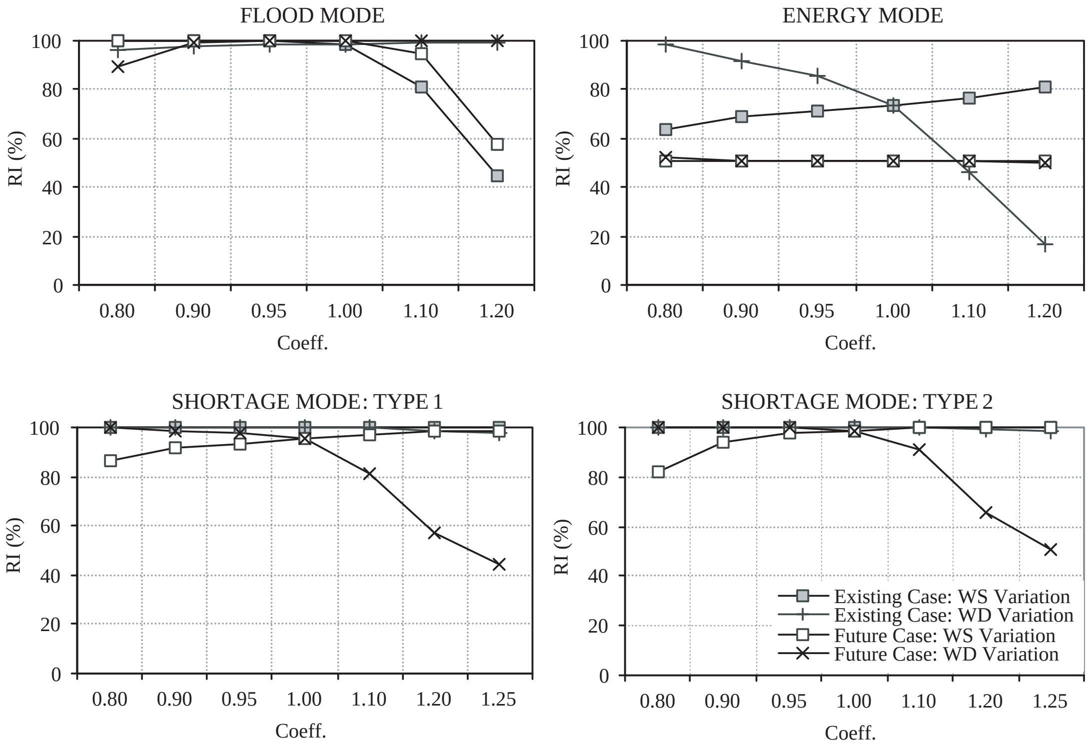


Figure 4 Reliability indices evaluation.

Table 6 Maximum possible firm yield forecasting.

(I) Shortage mode		(II) Energy mode	
Reliability indices (%)	Max. possible firm yield (mcm)	Reliability indices (%)	Max. possible firm yield (mcm)
90	10,114	50	7,554
95	9,451	60	7,268
100	6,626	70	7,055

CONCLUSION

In consideration of the maximum possible firm yield of Mae Klong river basin, it could be summarized that the available water supply was sufficient enough for serving to the existing water demand side. Though the basin might be faced the water shortage characteristics in some critical periods, the water supply availability particularly in wet season was abundant for overall utilization. Because of the high potential of water supply in the basin, many agencies consequently planed to supply it to the nearby basin. Therefore, the point of how much water could be drawn without any problematic shortage within the basin became more important issues. In this study, the reliability based multireservoir system operation model in the limit state function form was developed to measure the safety of multireservoir operation in terms of reliability indices. Furthermore, it could also be answered in reference to the maximum possible firm yield with reasonable technique based on the reliability-risk analysis.

ABBREVIATIONS

SND = Srinagarind reservoir
GWh = Gigawatt-hour
VJK = Vajiralongkorn reservoir
MW = Megawatt
TN = Tha Thung Na reservoir
RI = Reliability indices
MK = Mae Klong reservoir
NHWL = Normal high water level
cms = Cubic Meter Per Second
MWL = Minimum water level
km^2 = Square kilometer
FCRC = Flood control rule curve
mcm/yr = Million cubic meter per year
URC = Upper rule curve
mm/yr = Millimeter per year
LRC = Lower rule curve
m.msl. = Meter above mean sea level

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