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Development of Probability Based Rule Curves for a Reservoir

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ABSTRACT

The probability based rule curves were developed for Mun Bon and Lam Chae reservoirs, Nakhon Ratchasima province, using 50 synthetic generated monthly inflow sequences of 48 years each. There were 4 levels of risk including 0.05, 0.10, 0.20 and 0.30 for each of the upper and the lower rule curves. Mun Bon reservoir used the actual water use for developing the probability based rule curves. Since Lam Chae reservoir was the newly constructed reservoir, only some part of the project was irrigated. Three water use scenarios were used for developing the probability based rule curves.Those were 100%, 75% and 50% of upland crop area. The probability based rule curves of Mun Bon and Lam Chae reservoirs were used in reservoir operation simulation using the proposed reservoir operating rules and the 48 years of monthly historical data, 1952-1999. The standard operating policy was also used in Mun Bon and Lam Chae reservoir operation simulation using the same set of data in order to see the effectiveness of the developed probability based rule curves. The simulation result showed that the failure indices in terms of the number of months, sum and sum squared of water shortage of the probability based rule curves were smaller than those of the standard operating policy.

Keywords: rule curves, reservoir operations, risk, probability, Mun Bon, Lam Chae

INTRODUCTION

Reservoirs are the man-made mechanism built on a stream or river on purpose to control the stream or river flow to meet the demand. The excess water is stored in the reservoir and will be delivered to various purposes during the time of deficit. Some are designed as a single purpose reservoir, ie., for irrigation, hydropower, domestic and industrial water supply, etc. Others are the multipurpose reservoir (Vudhivanich, 2002). Most of the large reservoirs in Thailand are the multipurpose type such as the reservoirs of Bhumibol and Sirikit dams. The reservoirs are usually operated by the experienced engineer using some kinds of rule curves or operating policy.

The rule curve or guide curve are commonly used in the reservoir operations. This rule curves defined the release decision according to the present reservoir storage. They are usually constructed from the data in the critical period. Thus it gives a confidence to the reservoir operators that the reservoir will have enough water to meet the future demand provided that the reservoir inflow must not less than the past. Once the reservoir operators know the present state of the system, they can make a release decision according to the rule curves and their experiences(Vudhivanich. 1986).

Standard Operating Policy (SOP) is the simplest policy that releases only the demand in each period, if possible. If sufficient water is not available to meet the demand, the reservoir empties.

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If water is in excess, the reservoir will fill and then spills the excess water. Standard Operating Policy is the optimal operating policy with an objective to minimize the total deficit over the time horizon(Stedinger, 1984). Some rule curves indicate the zones of reservoir storage for different purposes. The release decision depends on the present state of the system and the period of operation(Chaiyasing, 1997).

Neelakantan and Pundarikanthan (2000) discussed the hedging rule in reservoir operation which allowed water shortage to be distributed for a long duration in order to reduce the critical water shortage. They proposed the multiple hedging rule which divided the reservoir storage into 4 zones. The rule indicated the release at 100, 80, 66 and 50% of the demand according to the reservoir storage in zone 1 (high storage), 2 (medium to high storage), 3(low to medium storage) and 4 (low storage). The multiple hedging rule could reduce the overall deficit index (sum squared deficit) comparing to the standard operating rule.

Hashimoto *et al*. (1982) presented 3 performance indicators to measure the effectiveness of reservoir operations. Those were reliability, vulnerability and resiliency. Reliability and vulnerability defined the frequency and magnitude of failure of the system. Resiliency defined how fast the system could be recovered. Fontane (2001) defined the reliability and vulnerability as temporal and volume reliability and defined these 3 indices mathematically in term of probability. Duckstein *et al*. (1987) proposed 9 reservoir performance indices related to the risk in reservoir operations. Vudhivanich (1986) proposed the methodology for inclusion of risk in multireservoir operations. The reservoir operation periods called "Anticipated Decision Influence Periods or ADIP" were first identified. The Monte Carlo simulation was used to generate the risk of failure at the end of ADIP as the function of the present state of the reservoir system.

Although the risk or the probability of failure is very important in reservoir operation decision and there were many studies related to the risk in reservoir operations, none has worked effectively in practices. Vudhivanich (2000) has proposed the new concept of the probability based rule curves which has a very high potential of success in the actual reservoir operation practices.

The objectives of this study were to develop reservoirs operating rules which can include the risk of water shortage and water spillage. Mun Bon and Lam Chae reservoirs, Nakhon Ratchasima province, were selected as the case study.

MATERIALS AND METHODS

Required data

(1) The monthly inflow, storage volume, seepage loss rate and evaporation rate of Mun Bon and Lam Chae reservoirs.

(2) The monthly rainfall data of station 25112 (Khonburi) and 25093 (Chokchai) and the monthly climatological data of Nakhon Ratchasima station during 1952-1999.

(3) The elevation-area-storage curves of Mun Bon and Lam Chae reservoirs.

(4) The existing cropping pattern and water demand for non-agricultural uses.

Methods

(1) Calculate the potential evapotranspiration from the climatological data using CROPWAT version 7.0 (Allen *et al.*, 1998) and estimate the monthly water demand from Mun Bon and Lam Chae reservoirs. The crop water requirements were estimated by using WUSMO version 5.0 (Booranareungsak,1999). Since the Lam Chae reservoir was newly constructed, the irrigable area in both wet and dry season was not fully utilized yet. Three water use scenarios which represented the 100%, 75% and 50% of the area for upland crop cultivation in wet season and the dry season area for scenario 1, 2 and 3 respectively were assumed.

(2) Generate 50 synthetic sequences of 48 year-monthly inflow to Mun Bon and Lam Chae reservoirs using Autoregressive and Moving Average stochastic model , ARMA(1,1).

(3) Develop the probability based rule curves (Vudhivanich, 2000) for Mun Bon and Lam Chae reservoirs for the specified risk of 0.05, 0.10, 0.20 and 0.30.

(4) Evaluate the effectiveness of the probability based rule curves for reservoir water allocation.

The Study area

Mun Bon and Lam Chae reservoirs are the main sources of water for Mun Bon irrigation project, Nakhon Ratchasima province. The main purposes of this project are to deliver water for agriculture, domestic-municipal and industrial water supply and downstream control. Mun Bon and Lam Chae reservoirs have the storage capacity of 141 and 275 million cubic meter(mcm) respectively.

The general characteristics of Mun Bon and Lam Chae reservoirs are shown in Table 1.

At the present, Mun Bon and Lam Chae reservoirs can allocate water to the designated irrigation area in both wet and dry seasons. Mun Bon has the total irrigated area of 45,136 and 17,933 rai in wet and dry seasons respectively, which is about the full potential utilization of the water resources from Mun Bon reservoir. On the other hand for Lam Chae reservoir, only some part of the irrigation area has been cultivated, since it is newly developed. In this study, therefore, 3 water use scenarios for Lam Chae reservoir are assumed. Scenarios 1,2 and 3 assume that the wet season upland crops are 34,125, 25,594 and 17,063 rai according to the 100%, 75% and 50 % of the potential upland crops area respectively. The dry season upland crop area is assumed at 64,260 , 48,195 and 32,130 rai on the same basis. In all scenarios, the wet season rice of 81,893 rai is assumed. The detail irrigation area in different scenarios is shown in Table 2.

Table 1 The general characteristics of Mun Bon and Lam Chae reservoirs.

	Mun Bon reservoir	Lam Chae reservoir
1. Catchment area (km^2)	454	601
2. Capacity at the normal pool level (mcm)	141	275
3. Capacity at the minimum pool level (mcm)	7	7
4. Annual rainfall (mcm)	9.98	18.29
5. Annual inflow (mcm)	93.88	229.29

Table 2 Scenario of irrigation area for Mun Bon and Lam Chae reservoirs.

Reservoirs	Total irrigation area (rai)			
	Wet season		Dry season	
	Rice	Upland crop	Rice	Upland crop
1. Mun Bon reservoir	44,801	335	17,545	388
2. Lam Chae reservoir				
-Scenario 1	81,893	34,125	-	64,260
-Scenario 2	81,893	25,594	-	48,195
-Scenario 3	81,893	17,063	-	32,130

In addition, Mun Bon reservoir must allocate 0.0025 mcm per month for Charakae Hin subdistrict municipality, Khon Buri district and 0.40 mcm per month for the downstream control. Lam Chae reservoir must allocate 5.13 mcm per month for the downstream control.

Theoretical development of the probability based rule curves

The probability based rule curves are the reservoir rule curves which incoperated the risk of failure in reservoir operations. This risks are simply the exceedence probability or non-exceedence probability of the specified events in case of spillage or shortage respectively(Vudhivanich, 2000). The method to derive the probability based rule curves is given in the following sections.

• Development of upper rule curves

The upper rule curve was defined as the maximum allowable reservoir water level for the given risk of flooding. In this study, the flooding means reservoir having insufficient storage to accommodate the incoming flood.

Let $NRI_t = I_t - O_t$ (1)

I_t = reservoir inflow in month t.

O_t = reservoir outflow in month t.

NRI_t = net reservoir inflow in month t having $f(NRI_t)$ as the probability distribution function as shown in Figure 1. The $f(NRI_t)$ was determined from the 50 synthetic generated reservoir inflow sequences of 48 years period each by the standard procedure of frequency analysis (Vudhivanich, 2002).

And VFC_t = volume of flood control reserve in month t.

Once the $f(NRI_t)$ was known, the VFC_t for the specified risk of 0.05 , 0.10 , 0.20 and 0.30 could be determined as shown in Figure 1 or by the following equation.

$$P(NRI_t > VFC_t) < Risk \quad (2)$$

Finally the upper rule curves were determined by the following equation:

$$VURC_t = VNP_t - VFC_t \quad (3)$$

Where

VURCt = reservoir upper rule curve volume in month t.

VNP_t = normal pool volume in month t.

• Development of lower rule curves

The lower rule curve was defined as the minimum allowable reservoir water level for the given risk of water shortage. In identification of the lower rule curve, the definition of wet and dry season must be clearly defined. The dry season is the period when NRI_t is less than or equal to 0 and the wet season is the period when NRI_t is greater than 0 as shown in Figure 2. By this definition, the dry season means the water shortage period while the wet season means the excess period. After the wet and dry season was defined, the cumulative volume of NRI_t for the dry season was calculated.

Let $\sum_{i=t}^{D} NRI_i$ = cumulative volume of NRI_t

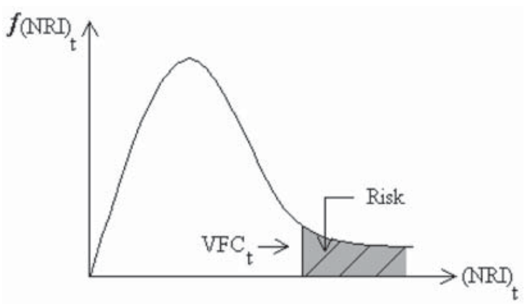


Figure 1 Probability distribution of NRI_t and definition of VFC_t.

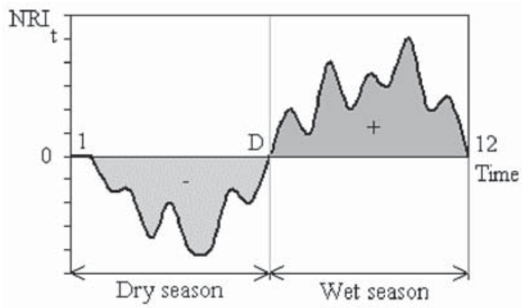


Figure 2 Definition of the wet and dry season.

for dry season having $f(\sum_{i=t}^{D} NRI_i)$ as the probability distribution function as shown in Figure 3. The $f(\sum_{i=t}^{D} NRI_i)$ was determined from the 50 synthetic generated reservoir inflow sequences of 48 years period each by the same procedure as mentioned in the above section.

D = the end of dry season month.

$VBUF_t$ = volume of buffer zone in month t.

Once the $f(\sum_{i=t}^{D} NRI_i)$ was known, the $VBUF_t$ for the specified risk of 0.05, 0.10, 0.20 and 0.30 could be determined as shown in Figure 3 or by the following equation.

$$P(-\sum_{i=t}^{D} NRI_i > VBUF_t) < Risk \qquad (4)$$

The $VBUF_t$ for the specified risk is the lower rule curve.

• The proposed reservoir operating rules

For the given probability based rule curves, the reservoir releases can be decided by the following proposed operating rules which is divided into 5 cases as follow.

Let V_{t+1} = reservoir volume at the beginning of month t.

D_t = water demand of month t.

R_t = reservoir release of month t.

SP_t = spilled volume in month t.

DEF_t = deficit in month t.

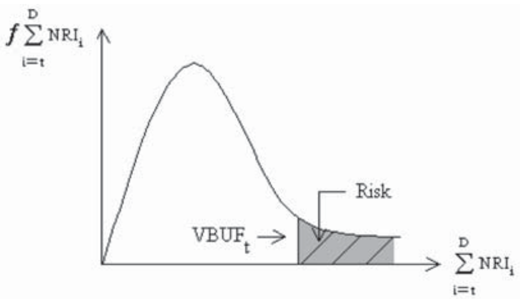


Figure 3 Probability distribution of $\sum_{i=t}^{D} NRI_i$ and definition of $VBUF_t$.

SUR_t = surplus release in month t.

V_{max} = maximum or normal pool volume.

V_{min} = minimum volume.

V_{URC} = upper rule curve volume.

V_{LRC} = lower rule curve volume.

Case 1 : If $V_{t+1} > V_{max}$

$$SP_t = V_{t+1} - V_{max}$$

$$R_t = D_t + SP_t \qquad (5)$$

Case 2 : If $V_{URC} < V_{t+1} < V_{max}$ (6)

$$R_t = \frac{[V_{t+1} - V_{min}]}{[V_{URC} - V_{min}]} D_t$$

$$SUR_t = \{\frac{[V_{t+1} - V_{min}]}{[V_{LRC} - V_{min}]} - 1\} D_t$$

Case 3 : If $V_{LRC} < V_{t+1} < V_{URC}$

$$R_t = D_t \qquad (7)$$

Case 4 : If $V_{min} < V_{t+1} < V_{LRC}$ (8)

$$R_t = \frac{[V_{t+1} - V_{min}]}{[V_{LRC} - V_{min}]} D_t$$

$$DEF_t = \{1 - \frac{[V_{t+1} - V_{min}]}{[V_{LRC} - V_{min}]}\} D_t$$

Case 5 : If $V_{t+1} < V_{min}$

$$R_t = 0 \qquad (9)$$

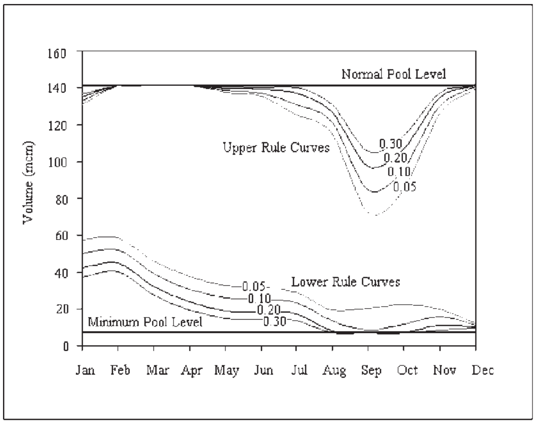
$$DEF_t = D_t$$

RESULTS AND DISCUSSION

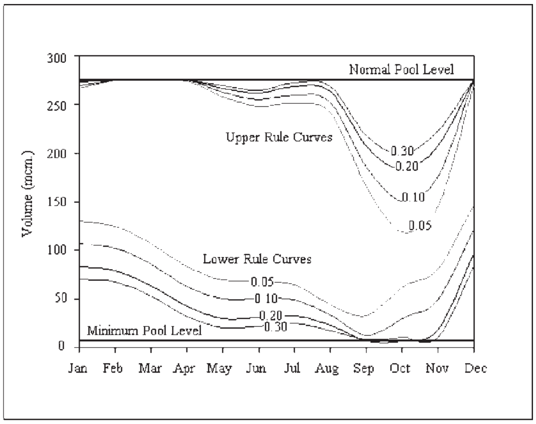
Probability based rule curves

Figure 4 showed the probability based rule curves developed for Mun Bon and Lam Chae reservoirs using 50 synthetic generated inflow sequences. There were 4 upper and 4 lower rule curves in each figure according to the 4 risk levels of 0.05, 0.10, 0.20 and 0.30. The upper rule curves of Mun Bon reservoir (Figure 4(a)) indicated the required flood control reserve in wet season, June to December, with the maximum required volume in September. The volume of flood control reserve varied inversely with the risk level. In case of Mun Bon, the maximum flood control reserve varied between 34-66 mcm depending on the risk level. The higher risk level, for example 0.30, required a smaller flood control reserve comparing to the lower risk level of 0.05. This implied that if the reservoir operator would like to reduce the risk of flooding, he had to select the upper rule curve at the lower risk(0.05) in his operation decision. On the other hand, the lower rule curves showed the required buffer storage for most month of the year, particularly during January to July. The maximum buffer storage to reduce the risk of water shortage was between 40-60 mcm depending on the risk level. The maximum required buffer storage took place in February. Similarly to the case of flooding, the higher risk level required a smaller buffer storage.

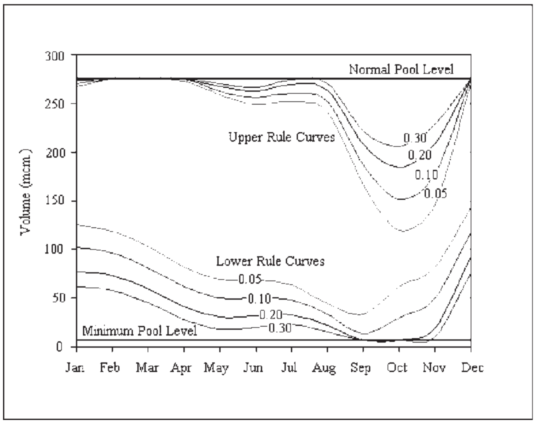
For Lam Chae reservoir, there were 3 probability based rule curves according to the 3 water use scenarios (100%, 75% and 50% of upland crop area) used in this study. The 3 water use scenarios almost did not have any effect on the upper rule curves but they had some effect on the lower rule curves as shown in Figure 4(b)-4(d). The upper rule curves of Lam Chae reservoir look different from those of Mun Bon reservoir. In all the scenarios, it showed the required flood control reserve during April to December. The maximum required volumes were between 70-150 mcm in



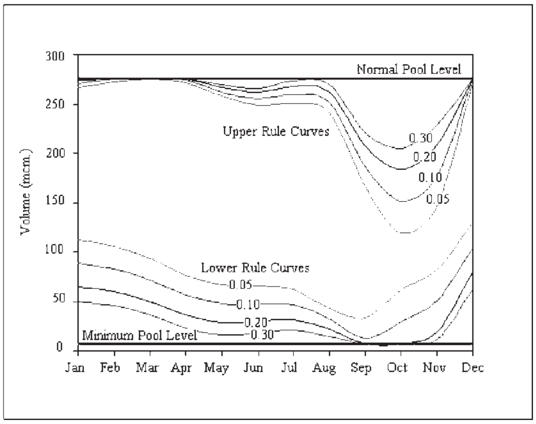
(a) Mun Bon



(b) Lam Chae (Scenario 1)



(c) Lam Chae (Scenario 2)



(d) Lam Chae (Scenario 3)

Figure 4 Probability based rule curves for Mun Bon and Lam Chae reservoirs.

October depending on the risk level.

The lower rule curves of Scenario 1 (100%) indicated a few percent higher buffer storage than Scenario 2 (75%). Similary, Scenario 2 indicated a few percent higher buffer storage than Secnario 3 (50%). The lower rule curves of Lam Chae reservoir look different from those of Mun Bon reservoir. The maximum required buffer storage varied between 80-145 mcm in the month of December depending the risk level.

These probability based rule curves showed the risk associated with the decision to maintain water in the reservoir. There would be a higher risk of operation failure to maintain the water either above the upper rule curves or below the lower rule curves. Therefore, the reservoir operator could use these rule curves in making reservoir release decision. Whenever the reservoir storage exceeded the upper rule curves, some additional release should be made to avoid the critical flooding in the future. Similary, whenever the reservoir storage dropped below the lower rule curves, the release should be reduced to avoid a serious water shortage in the future.

Evaluation of probability based rule curves performance

The probability based rule curves of Mun Bon and Lam Chae reservoirs in Figure 4 were used in reservoir operation simulation using the proposed reservoir operating rules as mentioned before. The 2 reservoirs were simulated using the 48 years of monthly historical data, 1952-1999. In order to see the effectiveness of the developed probability based rule curves, the standard operating policy was also used in Mun Bon and Lam Chae reservoir operation simulation using the same set of data. The simulation result in term of the number of months, sum and sum squared of water shortage and spill was shown in Table 3.

In case of water shortages which related directly to the lower rule curves, it could be seen clearly in Table 3(a)-3(d) that the standard operating policy gave considerably smaller number of months of water shortages than the probability based rule curves. Besides, the total water shortages or sum of the water shortages during 576 months simulation period were also smaller than those of the probability based rule curves. This agreed to the conclusion of Stedinger (1984) which stated that the standard operating policy gave the smaller total water shortages. However, the figure in Table 3 indicated that the sum squared shortages of the probability based rule curves were smaller than those of the standard operating policy. It could be noticed that the smaller risk level gave the smaller sum squared shortages. This came from the fact that the smaller risk probability based rule curves maintained more water in the reservoir in order to avoid the critical water shortages in the future. Whenever the water shortages dropped below the lower rule curves, the release would be reduced. Some water shortages took place, however, it was the smaller shortages. By this logic, the probability based rule curves would gave a higher frequent with smaller shortage while the standard operating policy would gave a lower frequent with larger shortages. Therefore the sum squared shortages of the lower risk probability based rule curves were smaller than the other rules.

On the other hand, the case of reservoir spill which related to the upper rule curves, the probability based rule curves were more effective in reservoir operations than the standard operating policy. As seen in Table 3, the number of months of spill, sum of spill and sum squared of spill of the probability based rule curves were smaller than those of the standard operation policy. The smaller risk level gave smaller shortages both in term of number of months, sum and sum squared. By the same logic as the lower rule curves, whenever the water in the reservoir exceeded the upper rule curves, the additional releases were made in order to avoid the heavy spill in the future. This mechanism would try to maintain the flood control reserve in the wet season, particular when the large inflow was expected. The failure index therefore was smaller. This simulation result showed the effectiveness of the probability based rule curve.

Table 3 Reservoir simulation results.

(a) Mun Bon reservoir

Operating Rules	Shortage (Months)	Spill (Months)	Σ(Shortage) (mcm)	Σ(Shortage)^2	Σ(Spill) (mcm)	Σ(Spill)^2
1. Probability Based Rule Curves						
-risk 0.05	29	56	172	1,851	1,307	45,358
-risk 0.10	25	68	169	1,899	1,393	48,875
-risk 0.20	23	69	167	1,914	1,454	51,649
-risk 0.30	23	73	166	1,914	1,486	53,185
2. Standard Operating Policy	16	74	163	1,971	1,528	55,442

(b) Lam Chae reservoir (Scenario 1)

Operating Rules	Shortage (Months)	Spill (Months)	Σ(Shortage) (mcm)	Σ(Shortage)^2	Σ(Spill) (mcm)	Σ(Spill)^2
1. Probability Based Rule Curves						
-risk 0.05	51	41	572	10,814	1,888	152,314
-risk 0.10	40	50	531	11,127	2,366	190,626
-risk 0.20	33	58	513	11,433	2,692	218,903
-risk 0.30	29	61	512	11,554	2,794	229,156
2. Standard Operating Policy	25	65	510	11,812	2,975	249,040

(c) Lam Chae reservoir (Scenario 2)

Operating Rules	Shortage (Months)	Spill (Months)	Σ(Shortage) (mcm)	Σ(Shortage)^2	Σ(Spill) (mcm)	Σ(Spill)^2
1. Probability Based Rule Curves						
-risk 0.05	46	53	496	9,196	2,427	195,729
-risk 0.10	33	66	467	9,647	2,927	239,398
-risk 0.20	27	70	462	9,929	3,225	270,746
-risk 0.30	27	72	460	9,935	3,350	286,374
2. Standard Operating Policy	24	75	457	9,957	3,538	311,807

(d) Lam Chae reservoir (Scenario 3)

Operating Rules	Shortage (Months)	Spill (Months)	Σ(Shortage) (mcm)	Σ(Shortage)^2	Σ(Spill) (mcm)	Σ(Spill)^2
1. Probability Based Rule Curves						
-risk 0.05	38	68	430	8,098	3,016	241,388
-risk 0.10	27	79	416	8,383	3,482	285,844
-risk 0.20	27	80	411	8,512	3,752	321,529
-risk 0.30	26	84	408	8,581	3,886	340,631
2. Standard Operating Policy	22	91	405	8,652	4,099	369,001

CONCLUSION

The probability based rule curves were developed for Mun Bon and Lam Chae reservoirs using 50 synthetic generated monthly inflow sequences of 48 years each. The rule curves consisted of the upper and the lower rule curves for 4 risk levels of 0.05, 0.10, 0.20 and 0.30. The risk of the upper rule curves was the exceedence probability that the reservoir storage exceeded the maximum level and flooding might occur. The risk of the lower rule curves was the probability that the water shortage might occur. Three water use scenarios (100%, 75% and 50% of upland crop area) were used for developing the probability based rule curves for Lam Chae reservoir while the actual water use was used for Mun Bon reservoir. The probability based rule curves of Mun Bon and Lam Chae reservoirs were used in reservoir operation simulation using the proposed reservoir operating rules using the 48 years of monthly historical data, 1952-1999. The standard operating policy was also used in Mun Bon and Lam Chae reservoir operation simulation using the same set of data in order to see the effectiveness of the developed probability based rule curves. The simulation result in term of the number of months, sum and sum squared of water shortage and spill was shown. The probability based rule curves gave a higher frequent with smaller shortage while the standard operating policy gave a lower frequent with larger shortages. On the other hand, the case of reservoir spill which related to the upper rule curves, the probability based rule curves were more effective in reservoir operations than the standard operating policy. The number of months of spill, sum of spill and sum squared of spill of the probability based rule curves were smaller than the standard operation policy.

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