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Assessing Flood Risk Using Reservoir Flood Control Rules

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ABSTRACT: The application of conventional flood operation regulation is restricted due to insufficient description of flood control rules for the Pubugou Reservoir in southern China. Based on the requirements of different flood control objects, this paper proposes to optimize flood control rules with punishment mechanism by defining different parameters of flood control rules in response to flood inflow forecast and reservoir water level. A genetic algorithm is adopted for solving parameter optimization problem. The failure risk and overflow volume of the downstream insufficient flood control capacity are assessed through the reservoir operation policies. The results show that an optimised regulation can provide better performance than the current flood control rules.
KEY WORDS: reservoir flood control operation, parameters optimization of rules, risk assessment.

0 INTRODUCTION

Reservoir is the major structural measure that is operated to mitigate the downstream flood damage. In practice, the release rules for reservoir flood control in China are usually based on predefined operating policies through simulation techniques, corresponding to reservoir water levels and reservoir inflows. However, these predefined operation rules have proven inadequate to operate various floods properly. This is because the knowledge of complete information concerning the flood event is not fully considered and subjective management practices are used in operation rules (Hejazi et al., 2008). Use of existing flood control rule curves degraded reservoir system efficiency.

In recent years, the optimization models to solve reservoir operation problems are more attractive for reservoir flood risk management. These techniques can be classified into two main categories: (1) Mathematical programming techniques, which are applied to quantitative information with well-structured algorithmic processes, such as network flow optimization (Lee et al., 2009; Lund and Ferreira 1996), linear programming (Wei and Hsu, 2009), and dynamic programming (Kumar et al., 2009; Tingsanchali and Boonyasirikul, 2006), etc.. (2) Heuristic programming techniques, which are employed with both quantitative and qualitative information in this paper, based on experience and various analogies, such as genetic algorithms (Huang and Hsieh, 2010; Malekmohammadi et al., 2009; Chang, 2008), fuzzy optimization (Chen and Hou, 2004), particle swarm optimization (Fu et al., 2014, 2011) and shuffled frog leaping algorithm (Li et al., 2010) and so on. Finding powerful method to optimise the rule curves is vitally important. Good operating rules will increase the system performance and decrease undesired deviation from a release target (Wu and Chen, 2013, 2012; Nardini et al., 1992).

As a non-structural failure mode for implementing reservoir operation, performance failure risk is described as the probability that the failure occurs based upon performance function of flood risk management (Fu et al., 2013; McMahon et al., 2006). When an optimal operating policy is derived based on a known objective, the policy itself does not, in general, indicate a measure of the reservoir operation performance (Suresh and Mujumdar, 2004). Therefore, it is important that performance indicators with an operating policy be studied to indicate the performance characteristics of reservoir flood control. The primary objective of this study is to optimize flood control rules with punishment mechanism by defining different parameters of flood control rules in response to flood inflows forecast and reservoir water level. The flood risk is then assessed using the optimized release rules and existing rules by conducting the real-time operations in historical floods. The developed methodology is applied to the Pubugou Reservoir in China.

1 PUBUGOU RESERVOIR SYSTEM

The Pubugou Reservoir completed in 2009 is located at the Dadu River in southwestern China. The Dadu River is 1 062 km long with a drainage area of 77 400 km^2 (see Fig. 1). The Pubugou multipurpose reservoir is primarily for flood control and hydropower generation. The flood control limited water level in flood season is 841 m. The dead water level and the normal water level are 790 and 850 m, respectively. The storage capacity of the reservoir is 5.39 billion m^3 with a flood control capacity of 0.73 billion m^3. The hydropower generation capacity is 3 300 MW with an annual average of 14.58 billion kWh.

The existing operation rules adopt the release look-up

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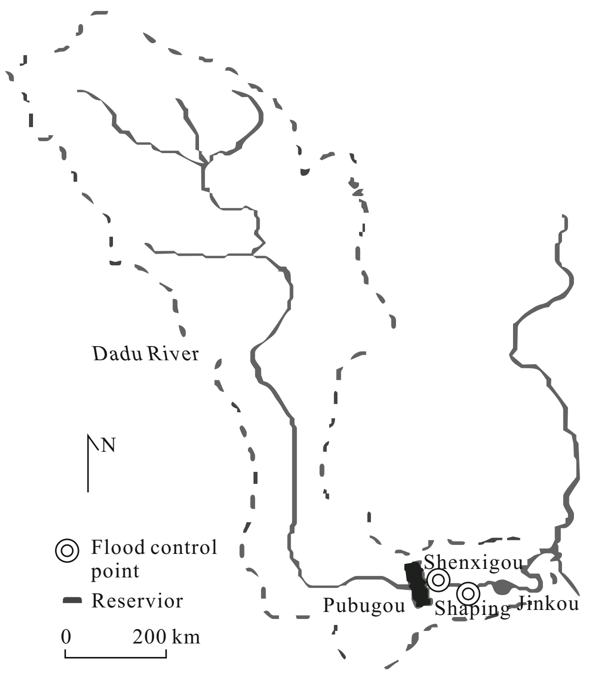

Figure 1. Location of the Pubugou Reservoir in the Dadu River basin.

tables during flood. The reservoir release tables are graded by the reservoir inflow and the observed storage level during the rise period and the recession period. Operation of the Pubugou Reservoir follows the predetermined rules shown in Table 1.

The Pubugou Reservoir was expected to reduce the downstream flooding at the selected downstream control points. The target value for preventing downstream from flooding consists of three grades, which is set as 4 000, 4 980, and 5 810 m^3/s, respectively, for protecting downstream flood-prone areas selected. For small flood less than 5% exceedance probability, the reservoir operation aims to keep the water level of the downstream flood control point at the Shaping below warning water level. The maximum allowable reservoir release is 4 000 m^3/s. For 5% exceedance probability flood, the maximum allowable reservoir release is 4 980 m^3/s for safe protection of downstream town at the Shenxigou control point. For 1% exceedance probability flood, the maximum allowable reservoir release is 5 810 m^3/s to protect the downstream railway from flooding at the Jinkou. The existing reservoir operation rules are used to compare the results with the optimized release rules for flood risk assessment.

2 METHODS

2.1 Parameters Optimization of Reservoir Flood Control Rules

In the present release look-up tables, the amount of water released for flood control depends on to which zone the reservoir inflow and storage level belong. The development of these rules from largely an empirical exercise was inadequate to operate a wide variety of floods. For this system, more complex and flexible rules are required. To achieve more detailed operating rules, the number of zones for the reservoir inflow and storage level should be increased.

The operational parameters defined are summarised in Table 2. To achieve more detailed and efficient operating rules, the reservoir inflow is increased into six intervals using optimal operation (see Table 2) compared with four intervals using existing operation (see Table 1) during the rise period. The two zones of storage level corresponding to each inflow interval are generated during the rise period and the recession period. Therefore, the total number of parameters to be optimised is 10 except for given threshold values of reservoir releases and levels. The parameters for flood control rules consist of the seven reservoir releases (X_1, X_2, X_3, X_4, X_5, X_6, X_7) and the three reservoir levels (Y_1, Y_2, Y_3). The feasible parameter space for these parameters is shown in Table 3.

In real-time operation, a longer forecast period can result in a better operation but may not be realistic (Wei and Hsu, 2008). Generally, the limited future information can be evaluated by specifying the number of hours of foresight on inflows. The inflow forecast accuracy descends with the increase of forecast period (Braga and Barbosa, 2001). Thus, the 48 h ahead reservoir inflow forecast is employed to determine the reservoir releases in the case study.

To determine the proper reservoir release rules according to limited future hydrological information during floods, the reservoir operation optimization model is presented to determine optimal parameters while meeting operational constraints.

The optimization model is formulated as follows

$$F = \text{Min}\,\frac{1}{N}\left(\omega_1\sum_{i=1}^{N}\frac{Q_i^p}{I_i^p} + \omega_2\sum_{l=1}^{L}H_{i,l}/H_{\max}\right) \tag{1}$$

subject to

$$V_{i,t+1} = V_{i,t} + (I_{i,t} - Q_{i,t})\Delta t \tag{2}$$

$$H_{\min} \le H_{i,t} \le H_{\max} \tag{3}$$

Table 1 Pubugou Reservoir existing release rules during flood periods

No.	Period	Reservoir inflow I (m^3/s)	Storage water level H (m)	Reservoir release Q (m^3/s)
1	Rise period	$I \le 3\,000$	$841.00 \le H \le 848.41$	$Q=I$
2		$3\,000 < I \le 8\,230$	$841.00 \le H \le 848.41$	$Q=1\,500+0.5I$
3		$3\,000 < I \le 8\,230$	$848.41 < H \le 850.00$	$Q=5\,810$
4		$I > 8\,230$	$H > 848.41$	$Q=f(H)$*
5	Recession period	$6\,960 < I$	$841.00 \le H \le 850.00$	$Q \le f(H)$
6		$I \le 6\,960$	$841.00 \le H \le 850.00$	$Q \le 4\,980$

* $f(H)$ is the reservoir release capacity corresponding to storage water level H.

Table 2 Definition of operational parameters

No.	Period	Forecasted reservoir peak inflow I (m^3/s)	Reservoir level H (m)	Reservoir release Q (m^3/s)
1	Rise period	$I \le 4\,000$	$841.00 \le H \le 848.41$	$Q=1\,500+0.5I$
2		$4\,000<I\le 5\,000$	$841.00\le H<Y_1$	$Q=X_1$
3			$Y_1\le H<850.00$	$Q=X_2$
4		$5\,000<I\le 6\,000$	$841.00\le H<Y_2$	$Q=X_3$
5			$Y_2\le H<850.00$	$Q=X_4$
6		$6\,000<I\le 7\,000$	$841.00\le H<Y_3$	$Q=X_5$
7			$Y_3\le H<850.00$	$Q=4\,980$
8		$7\,000<I\le 8\,230$	$841.00\le H<848.41$	$Q=X_6$
9			$848.41\le H<850.00$	$Q=X_7$
10		$I>8\,230$	$848.41\le H<850.00$	$Q=X_7$
11			$850.00\le H$	$Q=f(H)^*$
12	Recession period	$8\,230<I$	$850.00\le H$	$Q=f(H)^*$
13			$H<850.00$	5 810
14		$6\,960<I\le 8\,230$	$847.00\le H<850.00$	$Q=X_7$
15			$841.00\le H<847.00$	$Q=X_6$
16		$I\le 6\,960$	$844.50\le H<850.00$	$Q=4\,980$
17			$841.00\le H<844.50$	X_5

Table 3 Feasible parameter space of regulation

Variable	X_1 (m^3/s)	X_2 (m^3/s)	X_3 (m^3/s)	X_4 (m^3/s)	X_5 (m^3/s)
Feasible parameter space	3 000–3 500	3 800–4 300	3 500–4 000	4 200–4 800	4 000–4 500
Variable	X_6 (m^3/s)	X_7 (m^3/s)	Y_1 (m)	Y_2 (m)	Y_3 (m)
Feasible parameter space	4 500–4 980	5 000–5 810	844.50–846.00	845.00–847.00	845.50–847.50

$$S_i^e \le S_T \tag{4}$$

where N is the number of floods considered during optimization, Q_i^p is the peak outflow of ith flood, I_i^p is the peak inflow of ith flood, ω_1, ω_2 are weights assigned to the two objectives, $H_{\max}$ is maximum allowable water level of dam for dam safety in the flood season. $H_{\min}$ is dead water level of reservoir, $H_{i,t}$ is reservoir water level at the tth time step of the ith flood season, $H_{i,l}$ is reservoir water level exceeding target value of dam safety at the lth time step of the ith flood season ($H_{i,l}$= $H_{i,t}$ if $H_{i,t}$>$H_{\max}$). L is the number of time step that the target value is unsatisfactory. $V_{i,t}$ is the initial storage volume at the beginning of period t of ith flood, $I_{i,t}$ is the inflow into reservoir during period, $Q_{i,t}$ is the outflow from reservoir during period t of ith flood, which includes the power release and spillway release. S_i^e is the final reservoir storage as the flood operation stops, S_T specifies the upper limit for reservoir conservation storage at the end of the flood operation.

The model includes three objectives. The first objective minimizes the peak flow at a selected downstream control point in Eq. (1). The second objective guarantees the safety of a dam for the worst possible flood, which is considered as penalty for not meeting constraint in Eq. (3). The third objective meets the target reservoir storage as the flood operation stops, which is satisfied by Eq. (4). In Eq. (1), the first weight equals to 1. In order to increase penalty for violating the law, the second weight equals to 5.

The genetic algorithm is used to search optimal solutions for reservoir flood operation (Chang, 2008), which starts with a set of coded variables. The objective function corresponding to each variable set is calculated through reproduction, crossover and mutation. The parameters of genetic algorithm include the sample-size population and the probabilities of crossover and mutation. The good parameter values that consistently lead to good results in this study are chosen. The population size, crossover, and mutation probabilities are 100, 0.8, and 0.01, respectively. An optimal solution can be obtained by the final winner of the evolution process.

2.2 Flood Risk Assessment

The reservoir flood operation can reduce a risk to particular areas downstream including small towns, railways and small-scale farms. The flood risk is sensitive to the operating policies. A flood risk assessment is presented here for the Pubugou Reservoir to measure risks associated with optimal operation rules and existing operation rules. In this study, the flood risk consists of the probability that reservoir operation failure occurs and the consequences of flooding.

The probability of failure is defined as the proportion of intervals of time that the target value is unsatisfactory during the study time (McMahon et al., 2006). The failure measure for flood control is defined as

$$P_k = \frac{1}{T}\sum_{t=1}^{T} Z_t^k \quad (5)$$

where k is the index of downstream control points, P_k is the probability of failure, T is the total number of intervals during the entire simulation period, Z_t^k is an indicator function, which is defined as a binary variable at time t.

In Eq. (5), binary variable Z_t is expressed as

$$Z_t^k = \begin{cases} 1 & \text{for } q_t^k > q_{\max}^k \\ 0 & \text{for } q_t^k \le q_{\max}^k \end{cases} \quad (6)$$

where q_t^k and $q_{\max}^k$ are channel flow and maximum allowable flow at the kth control point, respectively. Muskingum method is used for the channel flow routing from the reservoir to the downstream control-point.

The consequence of failure for flood control is defined as the overflow volume during the failure period as follows

$$OV_k = \frac{\sum_{j=1}^{fp}\left(q_j^k - q_{\max}^k\right)}{fp} \quad (7)$$

where OV_k is the overflow volume at the kth control point, and fp is the total number of failure intervals during the entire simulation period.

3 RESULTS AND DISCUSSION

In order to optimize the parameters for flood control rules, twenty-four floods are chosen: the observed 1965, 1982, 1992 and 1998 floods and twenty design floods with 0.01%, 0.2%, 1%, 2%, and 5% exceedance probability floods based on the hydrographs of the 1965, 1982, 1992 and 1998 floods. The hydrograph of these floods are unfavorable for protecting the downstream part from flooding. The optimum solutions are presented with maximum objective value for the Pubugou reservoir in Table 4.

Table 4 The optimal values of the flood control parameters

Variable	X_1 (m^3/s)	X_2 (m^3/s)	X_3 (m^3/s)	X_4 (m^3/s)	X_5 (m^3/s)
Optimum solution	3 330	3 960	3 980	4 310	4 430
Variable	X_6 (m^3/s)	X_7 (m^3/s)	Y_1 (m)	Y_2 (m)	Y_3 (m)
Optimum solution	4 950	5 800	845.05	846.58	846.42

To validate the optimal flood control rules, six new extreme floods (0.01%, 0.2%, 1%, 2%, and 5% exceedance probability floods based on the hydrographs of the 1981 flood and the observed 1981 flood) that are not used in the previous optimization are tested to examine the efficiency of the optimal parameters.

The 0.2% exceedance probability flood shows a high peak inflow about 9 460. The flood operation for the extreme flood started with flood limited water level of 841 m. As shown in Fig. 2, maximum reservoir level of optimal operation is 849.5 m while value of existing operation rules is 850.4 m. Thus, the maximum water level reduction reached 0.9 m.

A comparison is carried out between the optimal parameters-based flood operation and the present reservoir regulation. Table 5 displays these comparisons including maximum reservoir level and peak outflow. The results show that the optimal parameters-based flood operation can reduce peak outflow and the maximum water level of the reservoir for large floods, which is better than those obtained under the present regulation.

The present and optimal parameter-based flood control rules are both used to compute flood risk for the six floods. The maximum allowable releases are defined according to downstream flood-prone areas selected, which are equal to 4 000, 4 980, and 5 810 m^3/s, respectively. Figures 3 and 4 show failure probability and overflow volume for different exceedance probabilities based on 1981 flood. The two figures clearly show that the failure probability and overflow volume decrease monotonically with increase in exceedance probability of flood.

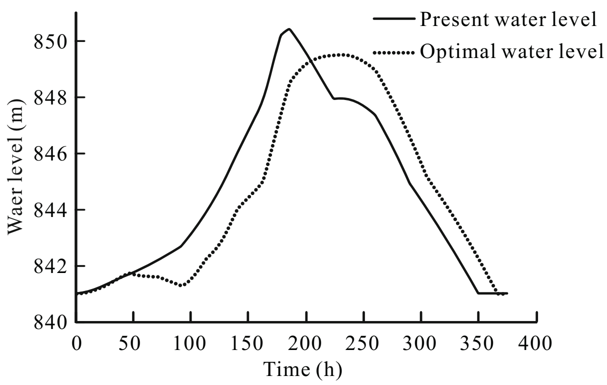

Figure 2. Reservoir water levels for 0.2% exceedance probability flood.

Table 5 Comparison of results for the floods using the present regulation and the optimal parameters-based flood operation, respectively

Flood	Peak inflow (m^3/s)	Peak outflow (m^3/s)		Maximum reservoir level (m)	
		Present operation	Optimal operation	Present operation	Optimal operation
1981 flood	5 340.0	4 980.0	4 430.0	844.7	845.1
5% flood	6 980.0	4 980.0	4 920.0	847.2	846.0
2% flood	7 690.0	5 810.0	4 980.0	847.8	847.0
1% flood	8 230.0	5 810.0	5 800.0	849.1	847.3
0.2% flood	9 460.0	8 405.7	5 800.0	850.4	849.5
0.01% flood	11 600.0	9 355.6	8 942.0	852.5	851.6

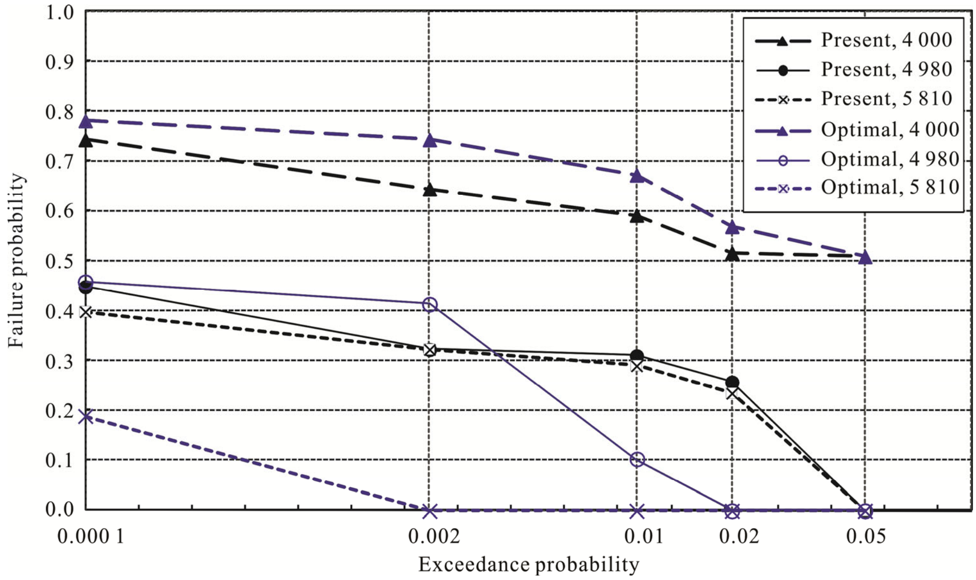

Figure 3. Failure probability for diffenrent exceedance probability based on 1981 flood. Downstream target value was set to 4 000, 4 980, and 5 810 m^3/s.

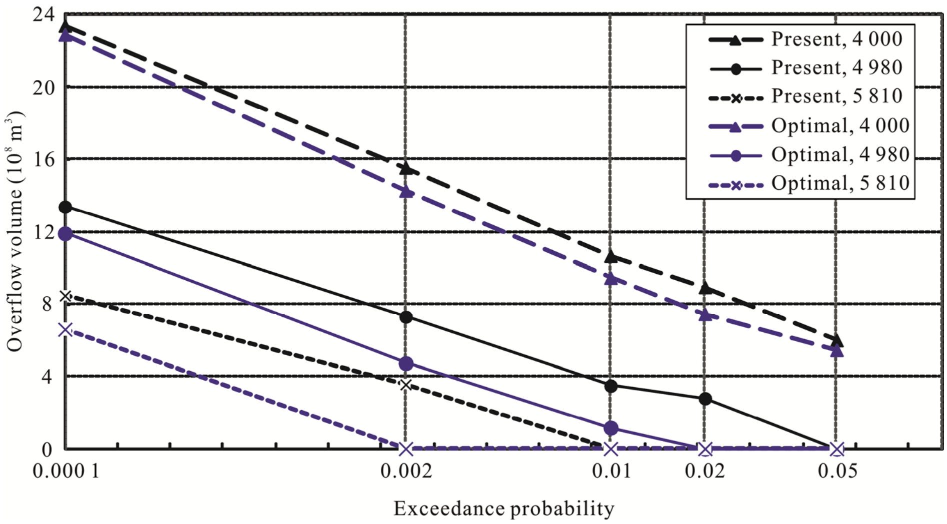

Figure 4. Overflow volume for diffenrent exceedance probability based on 1981 flood. Downstream target value was set to 4 000, 4 980, and 5 810 m^3/s.

The failure probability and overflow volume are influenced by the operating policy and downstream target flow. It is seen from the figures that the optimized operation increases failure probabilities above the present regulation values, but has a lower overflow volume than the present operation at low downstream target flow. For high downstream target flow, the lower failure probabilities and overflow volume resulting from optimal operation. Figures 3 and 4 also indicate that optimal operation decreases flood risk indicators such that the risk indicators are lower than those resulting from present operation during extreme flood events. This is due to the nature of the multi-objective function chosen for Parameters optimization, where it is set to minimize two objectives that involve peak outflow and dam security (see Table 1). A tradeoff between failure probability and overflow volume is achieved for low and moderate downstream target flow.

4 CONCLUSIONS

This study focuses on assessing flood risks using reservoir flood control rules for the Pubugou reservoir in southwestern China. The methodology presented in this paper consists of two parts: parameters optimization of reservoir flood control rules and flood risk assessment. The multiobjective optimization for parameters of the rule curves is solved through genetic algorithm. It aims to secure downstream flood control and reservoir security. The optimal parameters-based flood operation shows better flood control compared to the present reservoir regulation.

The optimised regulation can maintain a lower water level in the reservoir, and at the same time reduce the downstream flood peak. Flood risks for both optimal parameter-based and present reservoir regulations have been achieved. Analysis shows that lower overflow volume is achieved at the cost of failure probability increment for a given low capacity of the downstream flood control point, followed by better flood control objective with the optimal policy as compared to the current policy. For moderate and high capacity of the downstream flood control points, better results for both the failure probability and overflow volume are achieved, which also benefits flood control objective using the optimal policy. In an ongoing study, the flood risk of the multi-reservoir flood control will be estimated in a real-time flood control operation system.

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