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Optimisation of Hydropower in a Multi-Objective Context

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ABSTRACT: Application of optimisation techniques to reservoir operation has become a major focus of water resources planning and management. Traditionally, reservoir operation has been based on heuristic procedures, embracing rule curves and, to a certain extent, subjective judgements by the operator. More efficient solutions, however, can be obtained by coupling a simulation model with an optimisation algorithm for optimising reservoir operation in a multi-objective context. The focus of the present study is the operation of the Hoa Binh reservoir in Vietnam, considering hydropower production and downstream flood control including the protection of the capital Hanoi. Using the hydrodynamic simulation model MIKE 11, the existing operation rules were incorporated in the model, and the reservoir performance evaluated in comparison with alternative operation strategies suggesting a scope for improvement of both hydropower production and downstream flood control. Subsequently, the Shuffled Complex Evolution (SCE) algorithm was coupled with MIKE 11, and through Pareto optimisation it was shown that choosing a balanced optimum would result in an increase of the hydropower production without compromising the downstream flood protection. Finally, the possibility of using real-time information on forecasted reservoir inflows to improve short-term operation was addressed, and it was indicated that flexible, real-time optimisation procedures can further improve the performance of the reservoir operation in comparison to a strict application of the optimised rule curves.

INTRODUCTION

Reservoir operation is a complex problem that involves a number of often conflicting objectives, including flood control, hydropower generation, water supply for various users, navigation control etc. Traditionally, fixed reservoir rule curves are used for guiding and managing the reservoir operation. These curves specify reservoir releases according to the current reservoir level, hydrological conditions, water demands and time of the year. Established rule curves, however, are often not very efficient for balancing the demands from the different users (Oliveira and Loucks, 1997; Chang *et al.,* 2005). Moreover, reservoir operation often includes subjective judgements by the operators. Thus, there is a potential for improving reservoir operating policies, and even small improvements can lead to large benefits. The combined use of simulation models and numerical optimisation techniques has shown to be a powerful tool to analyse existing reservoir operation policies and derive more efficient solutions.

In the present project operation of the Hoa Binh reservoir in Vietnam is considered. Initially, the hydrodynamic simulation model MIKE 11 (DHI, 2005a) was set up for the Red River including the Hoa Binh reservoir for representing the effect of reservoir operation decisions on downstream floods and hydropower generation (Ngo *et al.,* 2007a). The existing operation rules (rule curves) were incorporated in the model, and the reservoir performance evaluated in comparison with alternative operation strategies suggesting a scope for improvement of both hydropower production and downstream flood control.

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Subsequently, a global optimisation tool, the Shuffled Complex Evolution (SCE) algorithm (Duan *et al.*, 1992), as implemented in the AUTOCAL software (DHI, 2005b), was coupled with the simulation model for optimising reservoir performance (Ngo *et al.*, 2007b). Using two objective functions (maximise hydropower potential and minimise downstream flooding) the Pareto front of non-dominated solutions was derived representing the range of efficient regulation strategies. Also the trade-off between hydropower production during the flood season and the reservoir level at the end of the season was analysed using Pareto optimisation. It was shown that choosing balanced optima would result in an increase of the hydropower production without compromising the downstream flood protection and that more water could be saved for the dry season.

The possibility of using real-time information on forecasted reservoir inflows to improve shortterm operation was finally addressed (Ngo *et al.*, 2007c). Incorporating penalty functions for long-term deviations from the optimised rule curves into the objective functions, multi-objective optimisation of short-term reservoir operations was undertaken for selected inflow sequences indicating that flexible operation strategies based on short-term forecast could offer a potential for further improvements. The real-time optimisation procedure improves the performance and enhances the flexibility of the reservoir operation in comparison to a strict application of the optimised rule curves.

EVALUATION OF CURRENT OPERATION RULES FOR THE HOA BINH RESERVOIR

The Red River basin, which is one of the largest in Vietnam, is located in the northern and north-eastern part of the country (see Figure 1). The total catchment area is 169,000 km^2 of which 48% is in China and less than 1% is in Laos. Three major upstream tributaries Da, Thao and Lo join and form the Red River near Hanoi. The river delta covers about 16,500 km^2 of which more than half is less than 2 m above mean sea level (Tinh, 2001). The mean annual rainfall varies from 1200 mm to 5000 mm. There is a significant seasonal variation in rainfall. Only about 20% of the annual rainfall occurs in the dry season, from November to April. The remainder falls in the rainy season, from May to October. The delta region is exposed to typhoons from June to October, and most of the floods occur in July and August. The average discharge of the Red River is about 3700 m^3/s. The minimum recorded discharge is 370 m^3/s, while the maximum is 38,000 m^3/s (in 1971).

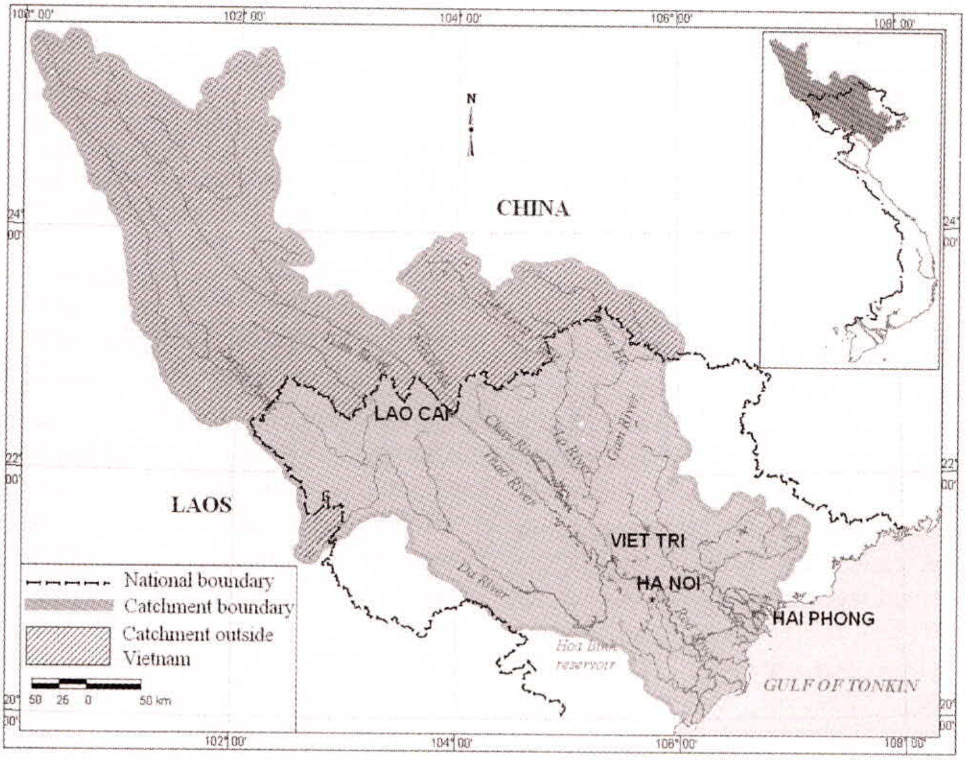


Fig. 1: The Red River basin

The Hoa Binh reservoir on the Da tributary, which was completed in 1989, has a storage capacity of 9.5 billion m^3, and an active storage of 5.6 billion m^3. It is designed to reduce the peak flood level of the most extreme historical flood that occurred in 1971 by 1.5 m at Hanoi (from +14.8 m to +13.3 m). The reservoir has 8 turbines with a maximum capacity of each turbine of 240 MW corresponding to a total power generating capacity of 1920 MW. It produces on average 7.8 billion KWh per year. It is a multipurpose reservoir providing flood control, hydroelectric power generation, and water supply. The Central Committee for Flood and Storm Control (CCFSC, 2005) takes responsibility for operation of the reservoir during the flood season by regulating the outflow.

In order to ensure both flood protection and efficient hydropower generation, three regulation periods have been defined (CCFSC, 2005):

(a) Pre-flood season : From 15 June to 15 July;
(b) Main flood season : From 16 July to 20 August;
(c) Post-flood season : From 21 August to 15 September.

The target water levels in the reservoir before storing water for flood control are shown in Figure 2 (flood control curve). In the pre-flood season a target water level of 95 m is defined. In the main flood season the flood control capacity is increased and a target water level of 93 m is defined. In the post-flood season, operation is reviewed in consideration of rainfall forecasts with the goal of ensuring a full reservoir and maximum power generation before the dry season. However, in order to prevent late floods, the maximum water level before 25th August must not exceed 103 m and before 31st August not exceed 108 m. Until the end of September the water level in the Hoa Binh reservoir can be increased but must not exceed 117 m.

Because hydropower generation is the second objective of the reservoir in the flood season, the reservoir is operated to get as much hydropower as possible within the constraints of the flood control rules. A control scheme is used to define how much water is supplied in the model for hydropower generation, which consists of three curves (upper, lower, and critical limit) as shown in Figure 3. The reservoir operations for hydropower generation are described as follows (see Figure 3):

1. When the water level is above the upper limit, hydropower generation is operated with maximum discharge through turbines. In the pre-flood and main flood season the maximum discharge through turbines is set to 2400 m^3/s. In the post-flood season, in order to save water for the following dry season, the maximum discharge through turbines is determined according to the present headwater level for the turbines to work at maximum capacity. This gives a maximum discharge less than 2400 m^3/s.
2. When the water level is between the lower and upper limits, hydropower generation is operated with a discharge through turbines that varies linearly between the minimum downstream discharge requirement (680 m^3/s) and the maximum.
3. When the water level is between the critical and lower limits, hydropower generation is operated with a discharge through turbines that meets the minimum downstream discharge requirement (680 m^3/s).
4. When the water level is below the critical limit, hydropower generation is halted.

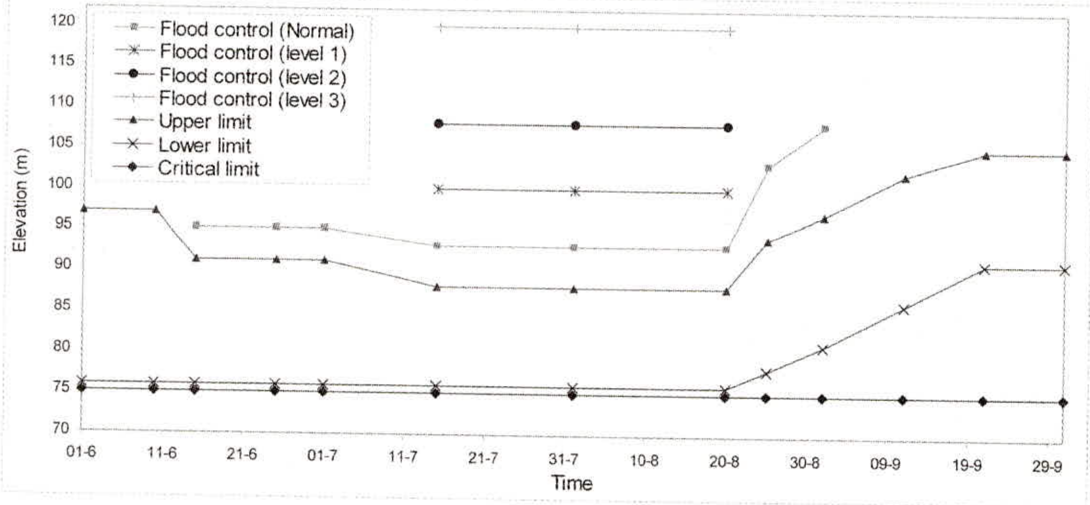


Fig. 2: Time varying reservoir level rule curves for the Hoa Binh reservoir

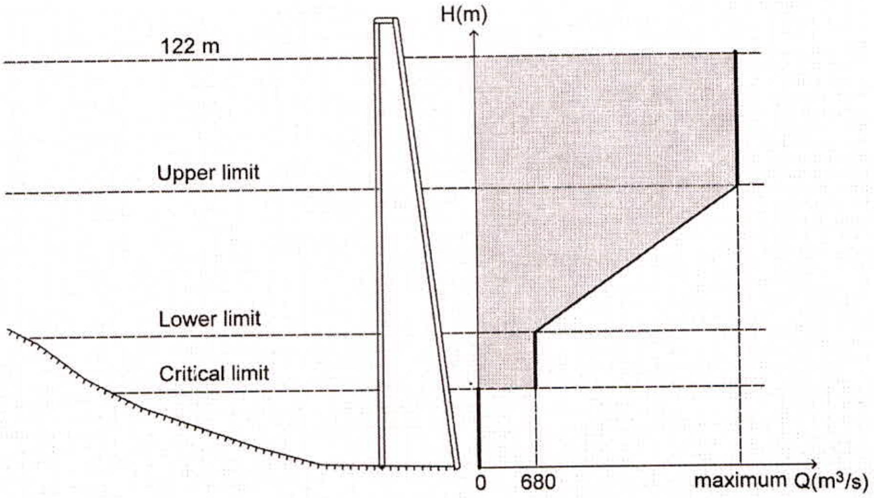


Fig. 3: Rule curves for discharge through turbines for hydropower generation

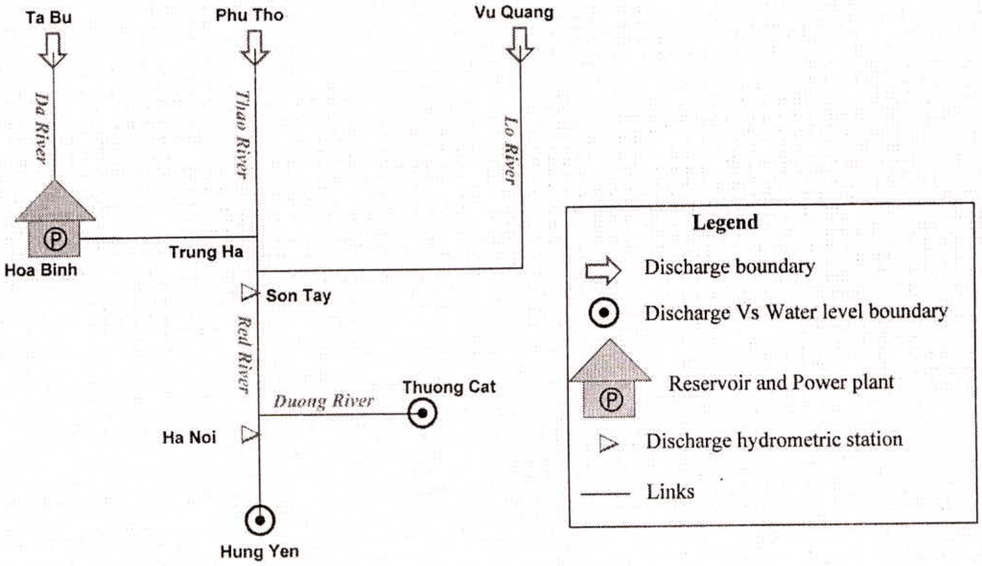


Fig. 4: MIKE 11 model setup of the lower Red River basin, including the Hoa Binh reservoir

The MIKE 11 modelling system (DHI, 2005a) is set up for the lower part of the Red River basin to simulate inflow to the Hoa Binh reservoir and water flow in the downstream part (see Figure 4). To simulate the releases from the Hoa Binh reservoir, operational structures including bottom sluice gates, spillways and turbines are specified as control structures in MIKE 11. The control structures are implemented with control strategies that determine how the structures are operated based on the reservoir level and the water level at a downstream flood control point in Hanoi. The operations consist of specifying the discharge through turbines as well as opening and closing bottom gates and spillways. The control strategies are defined using a list of logical statements according to priorities of the different controls.

After set-up and calibration of the model, it is possible to study various options for reservoir operation. The following three cases are analysed in detail:

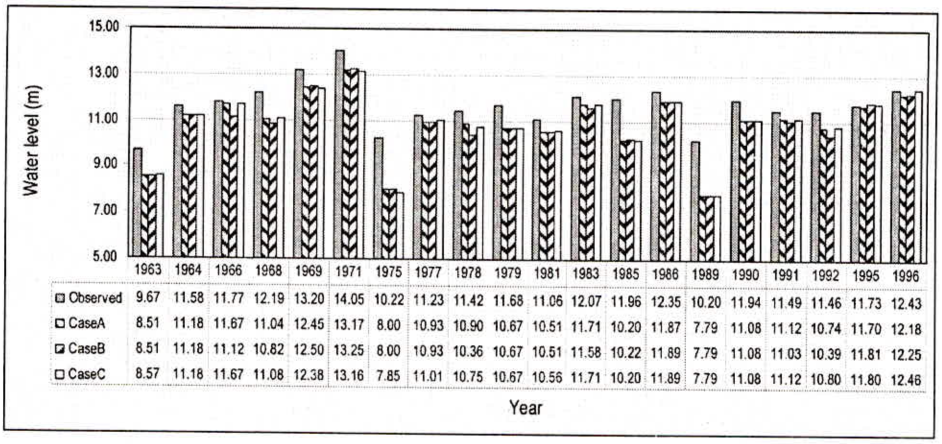
1. *Case A*: The Hoa Binh reservoir is operated strictly in accordance with the present operation rules.
2. *Case B*: The reservoir starts its operation for regular flood alleviation when the 24 hour forecast of the water level in the Red River at Hanoi exceeds 10.5 m (11.5 m in the present regulation).
3. *Case C*: The water level in the reservoir in the main flood period is set to 95 m before storing water for flood cutting (2 m higher than in the present regulation).

For the analysis, data from 20 flood seasons are used. The following results are obtained:

One of the most important issues of flood control for the downstream part of the Red River basin is reduction of the peak flood level at Hanoi. By using the MIKE 11 model the effects of alternative reservoir operation policies on flood control are evaluated quantitatively. Figure 5 gives the peak flood levels at Hanoi that would occur in the twenty years of flood seasons corresponding to, respectively, Case A, Case B and Case C reservoir operation policy in comparison to the observed water level. It should be emphasised that the reservoir did not start its operation before 1990, and hence only the water levels that are measured in Hanoi after 1990 have been obtained with the actual regulation of the Hoa Binh reservoir. Case B is seen to be more effective than case A and C in most years, but not all.

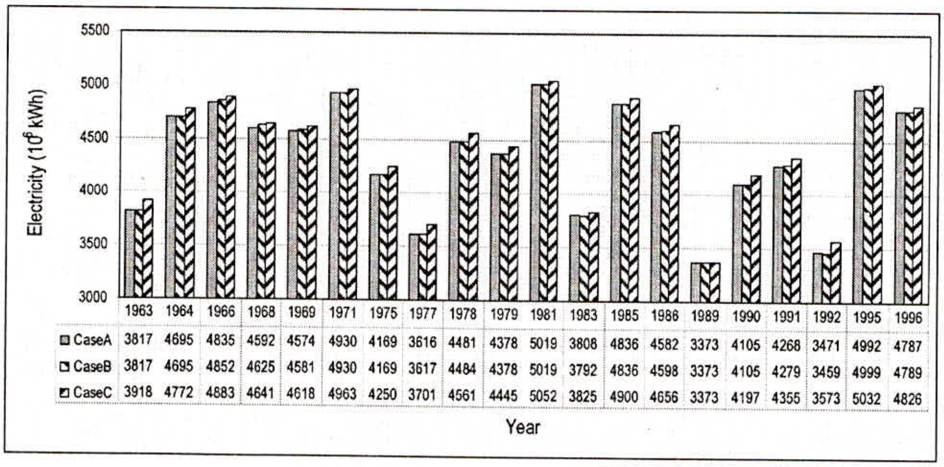
Figure 6 presents the total hydropower generation that could be obtained from the twenty flood seasons. From this figure it can be seen that there is an increase in hydropower generation under the Case B and Case C strategies in comparison with the Case A strategy. Especially, the Case C alternative seems to be predominating. However, with higher water levels in the reservoir before storing water for flood control in the main flood season, this alternative strategy will reduce the potential for flood control.

Figure 7 shows that the present regulation (Case A) is dominated by the Case B regulation, and hence, case B is better with respect to both flood control and hydropower generation. The total power generated under Case C would be valued at approximately \$217.6 million per flood season (based on the power price in Vietnam), 1.4% (\$3.0 million) and 1.3% (\$2.8 million) more than Case A and B, respectively. It can be stated that if the benefits of improved flood control with Case B compared to Case C are valued at more than \$2.8 million per year, Case B should be preferred over Case C. Alternatively, if the flood control benefits of Case B compared to Case C are worth less than \$2.8 million per year, Case C should be preferred over Case B. The results of this preliminary analysis will be helpful for proposing alternatives for Hoa Binh reservoir operation. The obvious way to proceed, however, is to pursue an off-line optimisation of the operation rules.



	1963	1964	1966	1968	1969	1971	1975	1977	1978	1979	1981	1983	1985	1986	1989	1990	1991	1992	1995	1996
▨ Observed	9.67	11.58	11.77	12.19	13.20	14.05	10.22	11.23	11.42	11.68	11.06	12.07	11.96	12.35	10.20	11.94	11.49	11.46	11.73	12.43
☐ CaseA	8.51	11.18	11.67	11.04	12.45	13.17	8.00	10.93	10.90	10.67	10.51	11.71	10.20	11.87	7.79	11.08	11.12	10.74	11.70	12.18
◪ CaseB	8.51	11.18	11.12	10.82	12.50	13.25	8.00	10.93	10.36	10.67	10.51	11.58	10.22	11.89	7.79	11.08	11.03	10.39	11.81	12.25
☐ CaseC	8.57	11.18	11.67	11.08	12.38	13.16	7.85	11.01	10.75	10.67	10.56	11.71	10.20	11.89	7.79	11.08	11.12	10.80	11.80	12.46

Fig. 5: Maximum water level at Hanoi



	1963	1964	1966	1968	1969	1971	1975	1977	1978	1979	1981	1983	1985	1986	1989	1990	1991	1992	1995	1996
▨ CaseA	3817	4695	4835	4592	4574	4930	4169	3616	4481	4378	5019	3808	4836	4582	3373	4105	4268	3471	4992	4787
◪ CaseB	3817	4695	4852	4625	4581	4930	4169	3617	4484	4378	5019	3792	4836	4598	3373	4105	4279	3459	4999	4789
◩ CaseC	3918	4772	4883	4641	4618	4963	4250	3701	4561	4445	5052	3825	4900	4656	3373	4197	4355	3573	5032	4826

Fig. 6: Hydropower generation

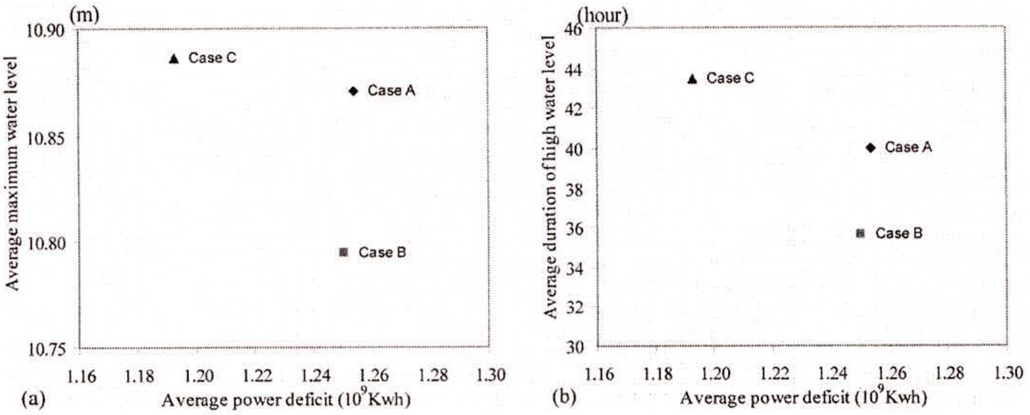


Fig. 7: Solutions in term of flood control and hydropower generation

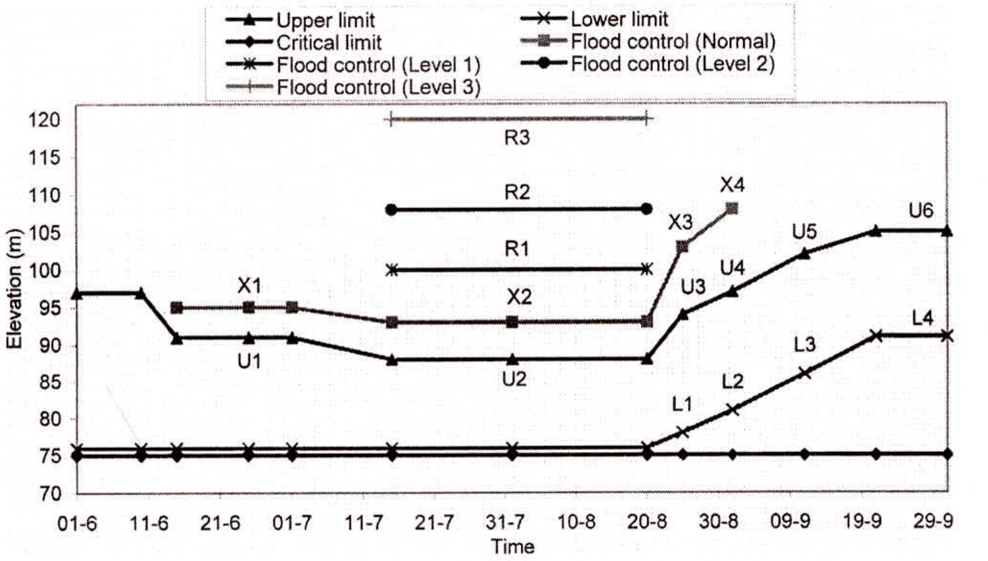


Fig. 8: Target reservoir water levels for defining flood control and hydropower rule curves

OPTIMISATION OF FLOOD PROTECTION AND HYDROPOWER PRODUCTION

Optimisation of Reservoir Rule Curves

The control variables to be optimised consist of the reservoir water level curves and water level targets at the flood control point at Hanoi specified in Figure 8 and Table 1. These include the flood control variables X_1, X_2, R_1, R_2, R_3, H_1 and H_2 (X_3 and X_4 in Figure 8 are not optimised) and the hydropower control variables U_1, U_2, U_3, U_4, U_5, U_6, L_1, L_2, L_3 and L_4. The rule curves are optimised using a two-step optimisation by combining the MIKE 11 simulation model with the Shuffled Complex Evolution (SCE) algorithm (Duan *et al.*, 1992). First, the flood control variables are optimised with respect to two objectives: (1) flood control in terms of downstream water level, and (2) hydropower potential in terms of reservoir level. In the second step the hydropower control variables are optimised with respect to: (1) the hydropower generation in the flood season, and (2) the reservoir level at the end of the flood season (used as a surrogate for hydropower generation in the low flow season). For the optimisation, selected data from the historical record are used as input to the MIKE 11 model.

The main purpose of the optimisation is to highlight the trade-offs between the flood control and hydropower objectives. Multi-objective optimisation seeks the non-dominated or Pareto-optimal set of solutions with respect to the given objective functions for evaluation of these trade-offs. A set of solutions are identified where none of the objective functions can be improved without violating one or more of the others. From this curve (denoted the Pareto front) the decisionmaker can choose a preferred strategy. One important benefit of using Pareto optimisation is that different objective functions measured in different units can be optimised simultaneously without the need to use a common monetary unit, which is often difficult to apply.

Table 1: Control Variables for Flood Control. The Numbers in Brackets Correspond to the Present Operation Rules. H_{HN} Denotes the Actual Water Level at Hanoi and $H_{HN(t+24)}$ the Forecasted Water Level with a Lead Time of 24 Hours

Operational Status		*Water Level at Hanoi*	*Period*	*Reservoir Water Level (H_{Res})*
Normal		$H_{HN(t+24h)} < 11.5$ m	1 Jun – 15 Jul	$H_{Res} \leq X_1$ (95 m)
			16 Jul – 20 Aug	$H_{Res} \leq X_2$ (93 m)
			21 Aug – 25 Aug	$H_{Res} \leq 103$ m
			26 Aug – 31 Aug	$H_{Res} \leq 108$ m
			01 Sep – 30 Sep	$H_{Res} \leq 117$ m
Flood control	Level 1	$H_{HN} < 11.5$ m		$H_{Res} < R_1$ (100 m)
	Level 2	$H_{HN} < H_1$ (12.0 m)		$H_{Res} < R_2$ (108 m)
	Level 3	$H_{HN} < H_2$ (13.1 m)		$H_{Res} < R_3$ (120 m)
Dam protection		$H_{HN} \geq H_2$ (13.1 m)		$H_{Res} \geq R_3$ (120 m)

The results of the optimisation of flood control variables are shown in Figure 9. The optimisation problem is defined as minimisation of the hydropower deficit compared to the maximum hydropower generation capacity (denoted hydropower objective in Figure 9) and minimisation of the maximum water level at Hanoi (denoted flood control objective in Figure 9). As expected, a significant trade-off is observed between the two objectives. That is, an improvement in hydropower generation (decrease of hydropower deficit) can only be obtained by an increase in the maximum water level at Hanoi, and vice versa. In the figure is shown a balanced optimum solution obtained as part of the optimisation, which is seen to provide a proper balance between the two objectives. In the figure is also shown the point corresponding to using the present reservoir regulations. Importantly, the optimisation provides Pareto-optimal solutions that are better with respect to both hydropower generation and flood control. Thus, more efficient flood control rules can be implemented that provide an increase in hydropower production in the flood season without violating the basic flood control objective.

The results of the optimisation of hydropower control variables are shown in Figure 10. The two objective functions measure, respectively, the hydropower deficit in the flood season (denoted hydropower objective in Figure 10) and the deviation of the water level at the end of the flood season compared to a target level of 117 m (denoted reservoir level objective in Figure 10). Also, in this case a significant trade-off between the two objectives is observed, i.e. an increase in hydropower production (decrease in hydropower objective function) in the flood season can only be obtained by a decrease of the water level at the end of the flood season, and vice versa. The results of this optimisation show that Pareto-optimal solutions can be chosen that are better with respect to both objectives compared to the present regulations, i.e. more efficient solutions can be chosen to provide increased hydropower production in the flood season as well as increased hydropower potential in the low flow season (larger reservoir level at the end of the flood season).

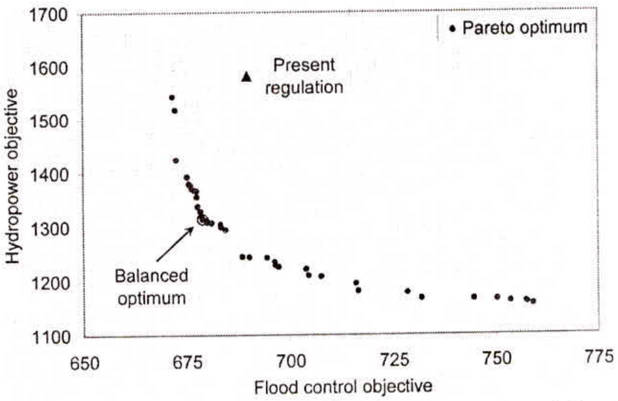


Fig. 9: Pareto optimal solutions for optimisation of flood control variables compared to the present regulations

Simulation with Optimised Rule Curves

The generated hydropower in the analysed flood seasons using the optimised operation strategies (balanced optimum) is shown in Figure 11 in comparison to using the present operation rules. In most flood seasons the balanced optimum solution provides an increase in hydropower production compared with the present regulations. On average an increase of 1.8% is obtained, corresponding to 80 million kwh per year.

The simulated water level at the end of the flood season using the two operation strategies is shown in Figure 12. In most seasons the balanced optimum solution provides an increase in water level compared to the present regulations. Importantly, the balanced solution provides a substantial increase in water level

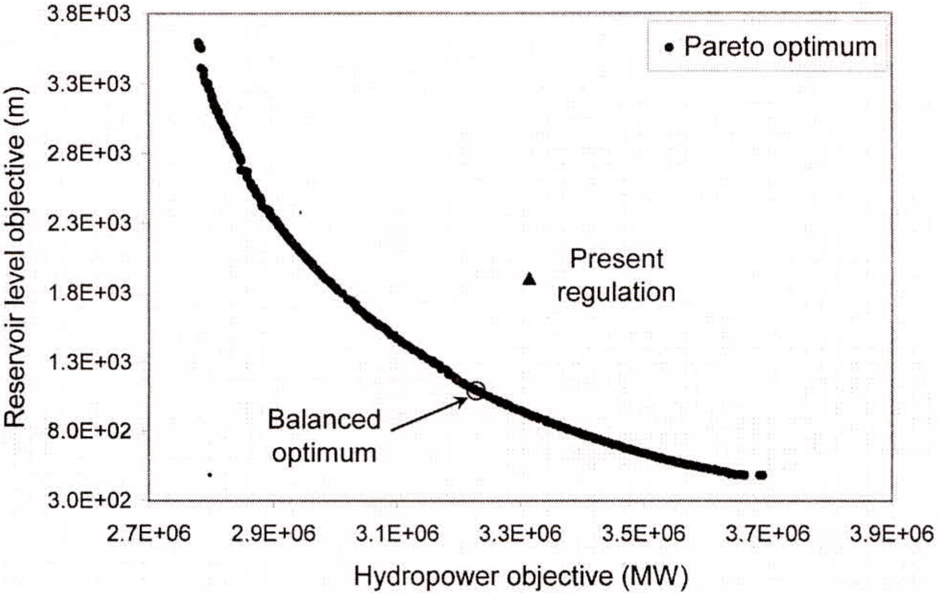


Fig. 10: Pareto optimisation results for optimisation of hydropower control variables compared to the present regulations

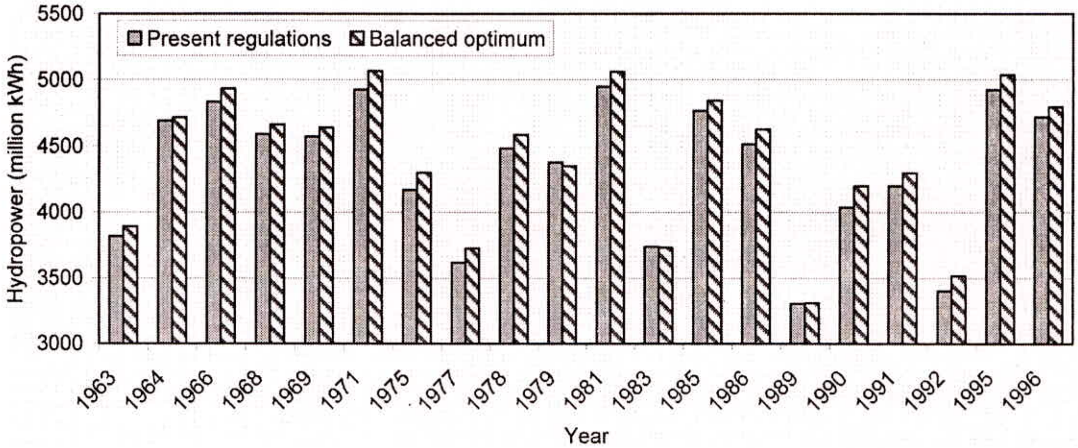


Fig. 11: Simulated hydropower generation in the flood season using, respectively, the present regulations and the balanced Pareto-optimal rule curves

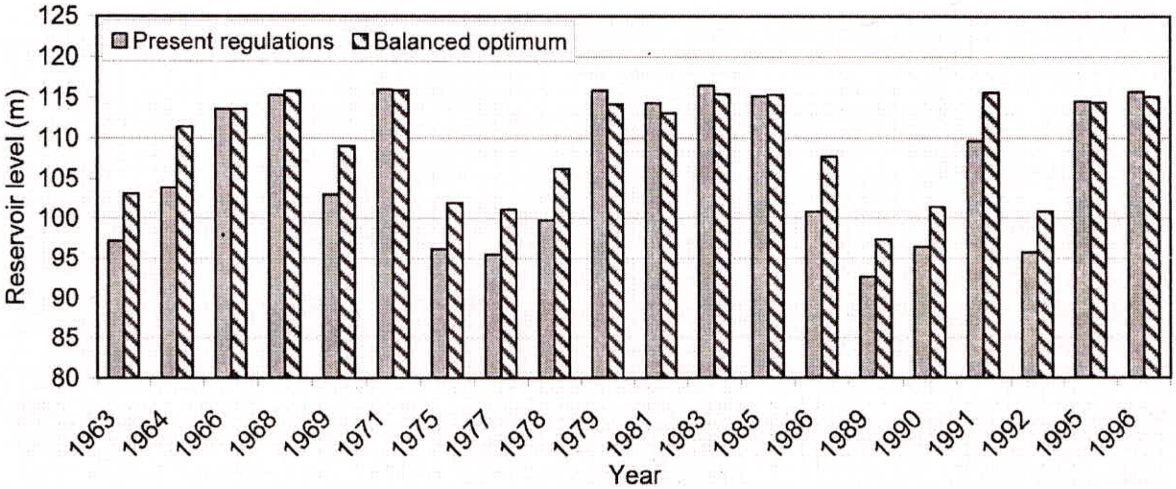


Fig. 12: Simulated water level at the end of the flood season using, respectively, the present regulations and the balanced Pareto-optimal rule curves

in the dry years. On average an increase of about 3 m is obtained. The increase in water level at the end of the flood season provides an increased hydropower potential in the low flow season, corresponding to about 130 million kWh per year on average. Thus, in total the balanced optimum solution offers an increased hydropower production of 210 million kWh on average per year.

As shown in Figures 9–10, other Pareto-optimal solutions exist, which are better with respect to all objectives considered as compared to the present regulations. The decision-maker may choose an optimum solution according to other criteria not used in the optimisation that put focus on some objectives at the costs of others. For instance, by choosing a Pareto solution to the left of the balanced optimum point in Figure 10, a larger hydropower production on average in the flood season is obtained at the cost of a decrease in water level at the end of the flood season and hence a smaller hydropower potential in the low flow season.

REAL-TIME OPTIMISATION

Operation of reservoir systems using optimised rule curves will provide a general optimal operation of the system. To further improve the performance, real-time optimisation can be adopted, where real-time and forecast information about reservoir levels, reservoir inflows and water demands for various users are utilised. In this case, the reservoir system is optimised with respect to the short-term operation, using both short-term and long-term objectives. Often there is a conflict between short-term and long-term benefits, and hence the inclusion of long-term objectives in the optimisation is important.

For the Hoa Binh reservoir, a real-time optimisation strategy has been implemented. The control variables that include discharge through turbines and opening and closing of bottom gates and spillways are optimised at 6 hour time intervals in a 3 day forecast period. Short-term objectives are defined in terms of hydropower production and flood risk at Hanoi in the forecast period. Long-term objectives are implemented by penalizing the deviation of the reservoir level at the end of the forecast period from the target levels defined by the optimised rule curves. Thus, short-term optimisations resulting in operations that provide large deviations in reservoir level compared to the rule curves are penalized. In the Pareto optimisation the trade-off between short-term operation objectives and long-term penalizing terms is evaluated. From the Paretooptimal set the decision-maker can then choose a preferred solution taking other considerations into account. For a flood situation the Pareto optimal solutions are shown in Figure 13.

A real-time optimisation test is carried out in a situation where a large flood is forecasted in the Da River as inflow to the Hoa Binh reservoir (see Figure 14). The forecasted inflow show a peak about 12 hours after time of forecast, followed by a decrease in the remaining forecast period. Thus, in this case a

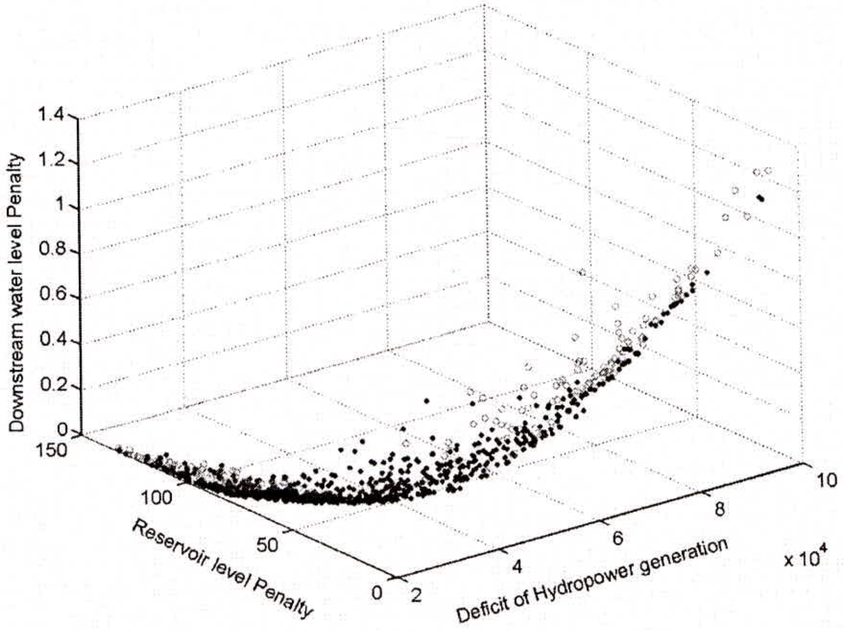


Fig. 13: Three-dimensional plot of evaluated points. Solid points indicate Pareto-optimal solutions

preferred operation strategy is to try to keep as much water in the reservoir in order to reduce downstream flood risk. That is, a Pareto-optimal solution is chosen that allows a larger water level in the reservoir at the end of the forecast period compared to the flood control rule curve to reduce the water level at Hanoi. The Pareto solutions with a water level at Hanoi lower than the alarm level are shown in Figure 15, in which a balanced solution can be identified.

It is seen that a Pareto optimal solution can be chosen, which allows a larger water level in the reservoir at the end of the forecast period compared to the flood control rule curve to reduce the water level at Hanoi. At the same time an increase in hydropower production during the forecast period is obtained. The results of this preferred solution is shown in Table 2 and compared with the results obtained by operating the reservoir according to the optimised rule curves. Real-time optimisation provides an increase in hydropower production in the forecast period of 5.5 GWh (4.3%) and a decrease in the maximum water level at Hanoi of 0.81 m.

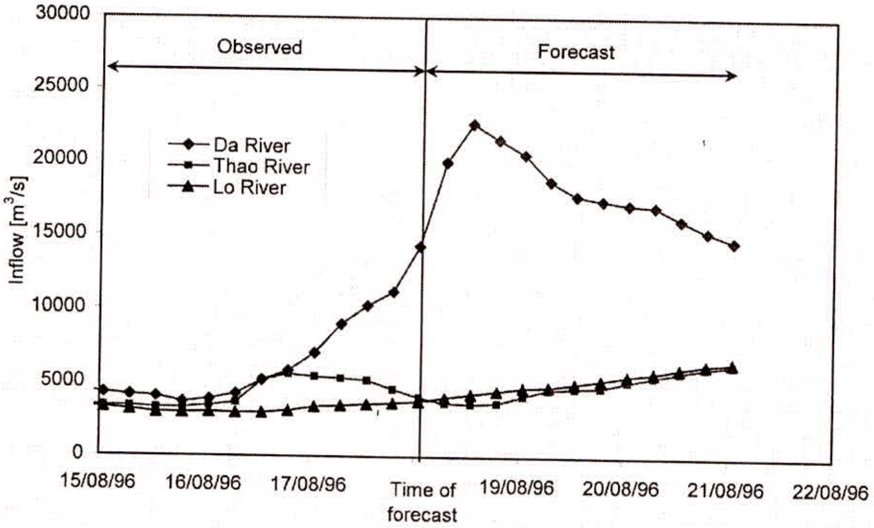


Fig. 14: Inflow forecasts at the three upstream tributaries used for optimising short-term reservoir operations

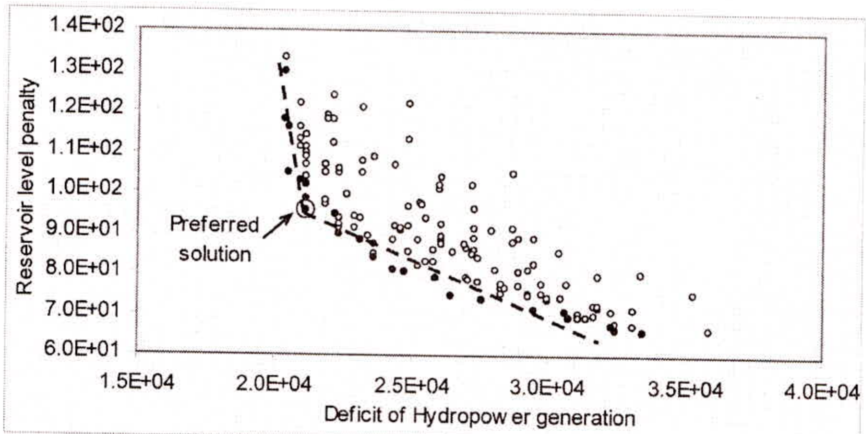


Fig. 15: Two-dimensional plot of 3-D Pareto-optimal solutions, which meet a zero downstream penalizing objective. Solid points indicate Pareto-optimal solutions in the 2D subspace. The dashed line indicates the trend of Pareto solutions

Table 2: Comparison of Simulation Results Using, Respectively, the Optimised Rule Curves and the Real-time Optimal Solution

	Reservoir Level at the End of the Period [m]	*Hydropower Generation [GWh]*	*Maximum Water Level at Hanoi [m]*
Optimised rule curves	110.7	127.3	12.29
Real-time optimal solution	116.8	132.8	11.48

CONCLUSIONS

A combined flow prediction and control system has been developed for optimisation of multipurpose reservoir operation. The system combines the MIKE 11 modelling system for simulation of river flow and reservoir operation with a numerical optimisation tool. The optimisation tool includes a general multi-objective optimisation framework for estimation of Pareto-optimal solutions.

The simulation-optimisation procedure has been applied to optimisation of the operation of the Hoa Binh reservoir in Vietnam, considering flood control and hydropower generation. A twostep procedure was adopted for optimisation of flood control and hydropower rule curves. The results showed that Pareto-optimal solutions can be chosen that are better with respect to both flood control and hydropower generation in the flood season. In addition, the water level at the end of the flood season can be increased with the optimised rule curves, hence providing a larger hydropower potential in the low flow season. By using the rule curves of the balanced optimum solution increase in hydropower production of about 210 GWh on average per year is obtained compared with the present regulations.

To further improve the reservoir operation, and hence increase the hydropower potential, a realtime optimisation system has been developed that utilises real-time and forecast information about reservoir levels, reservoir inflows and water demands. In this case, short-term operation for a 3 day forecast period is optimised considering the trade-off between short-term hydropower and flood control objectives and long-term objectives in terms of deviations from the optimised rule curves. The analysis demonstrates that the real-time optimisation and control system improves the performance and enhances the flexibility of the reservoir operation in comparison to a strict application of the rule curves.

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