Real-time optimisation of the Hoa Binh reservoir, Vietnam

Bertrand Richaud, Henrik Madsen, Dan Rosbjerg, Claus B. Pedersen and Long L. Ngo

ABSTRACT

Multi-purpose reservoirs often have to be managed according to conflicting objectives, which requires efficient tools for trading-off the objectives. This paper proposes a multi-objective simulation-optimisation approach that couples off-line rule curve optimisation with on-line real-time optimisation. First, the simulation-optimisation framework is applied for optimising reservoir operating rules. Secondly, real-time and forecast information is used for on-line optimisation that focuses on short-term goals, such as flood control or hydropower generation, without compromising the deviation of the long-term objectives from the optimised rule curves. The method is illustrated for optimisation of the Hoa Binh reservoir in Vietnam. The approach is proven efficient to trade-off conflicting objectives. Selected by a Pareto optimisation method, the preferred optimum is able to mitigate the floods in the downstream part of the Red River, and at the same time to increase hydropower generation and to save water for the dry season. The real-time optimisation procedure further improves the efficiency of the reservoir operation and enhances the flexibility for the decision-making. Finally, the quality of the forecast is addressed. The results illustrate the importance of a sufficient forecast lead time to start pre-releasing water in flood situations.

Key words | flood control, hydropower, multi-objectives, real-time optimisation, reservoir optimisation, rule curves

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INTRODUCTION

Reservoir operation is often a multi-purpose problem where trade-offs exist between numerous stakeholders such as flood control, hydropower generation, irrigation, or industrial and domestic water use. Fixed operating rules are usually applied for guiding the reservoir releases according to current reservoir level, hydrological conditions, water demand, and time of the year. Designed by experience or by trial-and-error (Oliveira & Loucks 1997) they are often not efficient for balancing the demands from different users. Many studies reviewing techniques to optimise rule curves have shown that small improvements on the reservoir operation can lead to large benefits (e.g. Oliveira & Loucks 1997; Ngo *et al.* 2007). Methods using genetic algorithms have been used to optimise management of multi-reservoir systems (e.g. Oliveira & Loucks 1997; Wardlaw & Sharif 1999; Chang *et al.* 2005; Kim *et al.* 2006; Reddy & Kumar 2006). Recently, Ngo *et al.* (2007) showed the large potential for improving the reservoir operating rules by using multi-objective optimisation.

To further improve the efficiency of reservoir operation many studies have demonstrated the effectiveness of real-time operating systems (e.g. Hamlet *et al.* 2002; Hsu & Wei 2007). The reservoirs are operated by making decisions on release when forecasted information becomes available (Mays & Tung 2002). Assuming that forecasted inflows are available, the regulation focuses on short-term objectives whereas the

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optimal set of rule curves designs the long-term guidelines. Thus, the main objective of the real-time optimisation is to improve short-term objectives without compromising long-term goals. As Oliveira & Loucks (1997) demonstrated, real-time operation of reservoir system will clearly benefit from optimisation in identifying alternative policies compared to the use of pre-defined optimal rule curves.

The quality of flow forecasting is often quantified in terms of lead time and accuracy. The lead time of the forecast is defined as the time interval between the issuing of the forecast and the time when the forecasted event is expected (Mays & Tung 2002). The accuracy is defined as the difference between the forecasted and the actual reservoir inflow. Dong *et al.* (2006) demonstrated that with inflow forecasting (assuming 100% accuracy forecasts) the benefits (in terms of electricity generated) increase with the extension of forecast lead time. Labadie (2004) concluded that even with the presence of error, the use of flow forecasting is preferable.

This paper considers real-time optimisation of operation of the Hoa Binh reservoir, Vietnam. Its multi-purpose operation is primarily a matter of dispute between hydropower generation and downstream flood control at Hanoi during the flood season. In addition, the amount of water stored at the end of the flood season to accommodate water uses in the dry season is in conflict with both the hydropower and the flood control objectives (Ngo *et al.* 2007). Multi-objective optimisation is introduced to resolve the trade-offs between the different objectives and provide balanced optimal solutions. An 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. A two-step simulation–optimisation procedure is applied. First, an optimisation is carried out using historical data for optimisation of operation rules of the reservoir. Secondly, for real-time optimisation, the simulation model is applied for evaluating the short-term benefits using available forecast data during a period of days after the time of forecast, and penalising deviations from the long-term operation goals given by the optimal rule curves.

The paper is organised as follows. First, the Hoa Binh reservoir and present operation rules are described. Then the implementation of the simulation–optimisation framework for rule curve and real-time optimisation is presented. Finally, the results illustrating the optimisation framework are given.

CASE STUDY

The Hoa Binh reservoir, Vietnam

The Hoa Binh reservoir is located on Da River, which is one of the main tributaries of the Red River. The Red River basin situated in the Northern part of Vietnam (see Figure 1) comprises more than 500 tributary rivers and springs. The total area of the catchment is 169,000 km^2, where the main part is in China and Vietnam (less than 1% is in Laos) (Tinh 2001). The confluence of the three main tributaries – Da, Thao and Lo rivers – forms the Red River near Hanoi. The Da River contributes 51% of the Red River flow on average (Tinh 2001).

With a tropical to sub-tropical climate, the rainy season in the basin occurs from May to October with about 80% of the annual rainfall. The mean annual rainfall varies from 1200 mm to 4800 mm (Tinh 2001). The flood season occurs from June to September, with the highest intensity in August.

The Hoa Binh reservoir is the largest reservoir in Vietnam with an active storage of 5600 million m^3. Designed after the historical event of the year 1971 (return period of 100 years) it aims at reducing downstream flood peaks below 13.3 m at Hanoi (Tinh 2001). Near Hanoi a system of dykes has been constructed along the river. It consists of secondary dykes of height 12 m and main dykes of height 15 m. The system of dykes is expected to withstand a flood level of 13.5 m. The highest flood water level ever recorded is 14.8 m in 1971 (Tinh 2001).

Besides flood control, the reservoir has also the purpose of generating hydroelectric power. It consists of eight generators with an installed capacity of about 1920 MW. It produces on average about 8160 million kWh per year (EVN 2008). The Hoa Binh reservoir represents a major part of the Vietnamese electricity. Supplying the northern part of the country its production accounts for 46.2% of the total hydropower capacity of the country.

A third task assigned to the Hoa Binh reservoir is to store water at the end of the flood season in order to meet water

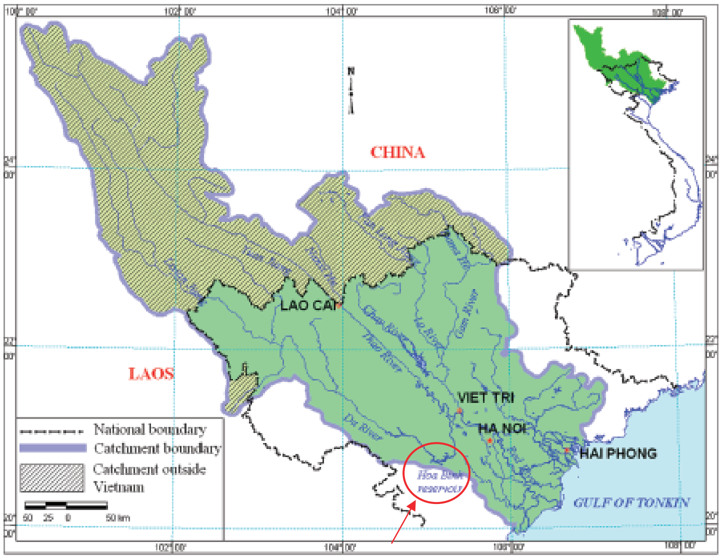


Figure 1 | The Red River catchment. The arrow shows the location of the Hoa Binh reservoir (Ngo 2006).

demands and reduce droughts in the following dry season. At that time a minimum flow has to be discharged for irrigation purposes (Ngo *et al.* 2008).

Operating rules for the Hoa Binh reservoir

The Central Committee for Flood and Storm Control (CCFSC 2005) has defined three regulation periods during the flood season between 15 June and 15 September: the pre-flood, the main-flood and the post-flood periods. For balancing conflicting objectives rule curves are used to operate the turbines, bottom sluice gates and spillways.

For flood control purposes the reservoir has to be operated in order to provide sufficient storage capacity in case of a flood event. Different operational modes have been defined. Normal operation occurs when the 1-day ahead forecasted water level at Hanoi is below 11.5 m. In this case the reservoir level has to be kept below the *Flood Control Limit* (see Figure 2). During the post-flood period, the target water level is raised to meet the irrigation demand in the next dry season. When the forecasted water level at Hanoi is above 11.5 m, operation status changes to flood control. In this case three flood control levels are defined (see Figure 2), depending on the water level at Hanoi. Finally, an emergency status is defined when the reservoir level is above the maximum allowed water level of 122 m (Ngo *et al.* 2008).

For hydropower generation, three operating rules have been defined with respect to the reservoir level. Below the *Critical limit*, hydropower generation is halted. Between the *Critical* and *Lower limits*, the discharge through turbines is set to meet the minimum downstream water demand. Then until the reservoir level reaches the *Upper limit*, the turbines are operated with a discharge that varies linearly between the minimum and maximum capacity with respect to the reservoir water level. If the water level is above the *Upper limit*, then turbines are operated at maximum discharge. In order to store water during the post-flood season, the maximum discharge through turbines is calculated according to the present head water level for the turbines to work at maximum capacity (Ngo *et al.* 2008).

METHODOLOGY

Simulation–optimisation framework

Ngo *et al.* (2007) has demonstrated the potential for improving the operation strategies of the Hoa Binh reservoir by using simulation and optimisation tools. This simulation–optimisation approach is adopted here for both rule curve (off-line) and real-time optimisation (on-line).

The framework is illustrated in Figure 3. Model simulation is used to evaluate the operations of a river and reservoir

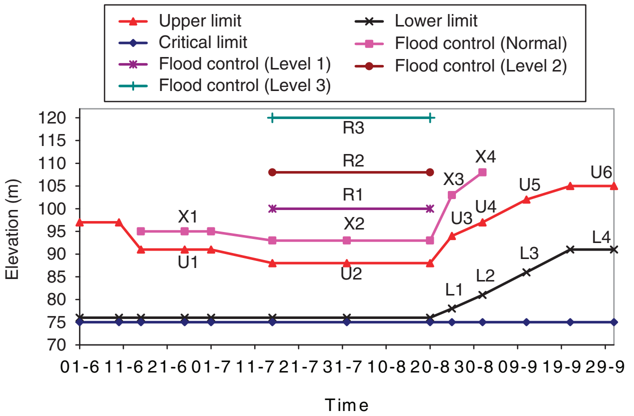


Figure 2 | Present reservoir rule curves representing reservoir water levels for flood control and hydropower generation (Ngo *et al.* 2007).

system, whereas optimisation is used to search for an optimal policy from an infinite number of feasible operation policies that are defined through decision variables.

The combination of simulation and optimisation is an effective method to find the optimal policy of the system. The methodology for solving such a problem starts by selection of a set of decision variables. These variables are applied to the simulation model of the system. The defined objective functions are evaluated according to optimisation targets. If the stopping criterion is fulfilled, the process is stopped, otherwise a new set of decision variables is generated by the algorithm and the same process is repeated. The procedure handles constraints that define the feasible space of the decision variables as well as equalities and inequalities between them.

In a multi-objective context, the simulation-optimisation approach seeks the non-dominated or Pareto optimal set of solutions with respect to the given objective functions for evaluation of the trade-offs. Cohon (1978) stated that a solution to a multiple objective programming problem is non-inferior if no other feasible solution exists that will yield an improvement in one objective without causing degradation in at least one other objective. The curve defined by the set of non-inferior solutions is named the Pareto front or more generally Pareto surface (if more than two objectives are considered).

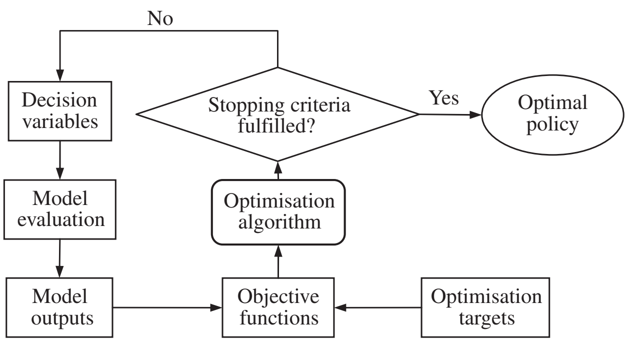


Figure 3 | Framework of simulation–optimisation modelling approach.

The MIKE 11 model developed by DHI (DHI 2008*b*) is here used for simulating the inflow to the reservoir, operation of the reservoir, and flow to the downstream part of the Red River (see Figure 4). Operating strategies of the Hoa Binh reservoir are defined as control structures. They consist of a list of logical statements including information such as reservoir status, downstream water level or time of the year. MIKE 11 can hereby simulate the operation of spillways, bottom sluice gates and turbines (DHI 2008*c*).

The heuristic global optimisation tool, Shuffled Complex Evolution (SCE) (Duan *et al.* 1992) as implemented in the AUTOCAL tool (DHI 2008*a*), is applied for the optimisation. The procedure consists of the optimisation of a single objective function, which is a weighted aggregate of the different objective functions defined. By performing several optimisation runs with different sets of weights, the entire Pareto surface can be explored. The SCE algorithm has proven to be effective in providing an efficient approximation of the Pareto front in a multi-objective context (Madsen 2000). Eventually, the decision-maker can express his/her choice to select a preferred optimum from the Pareto solutions.

Rule curve optimisation

In the first step the parameters defining the rule curves are optimised (see Figure 2). The flood control is defined by three curves: flood control reservoir level curve for normal operations (X_1, X_2, X_3 and X_4), reservoir level curves for Level 1, 2 and 3 flood control (R_1, R_2 and R_3) and corresponding water levels at Hanoi (H_1, H_2 and H_3). The hydropower generation is controlled by three curves: the upper limit (U_1, U_2, U_3, U_4, U_5 and U_6), the lower limit (L_1, L_2, L_3 and L_4) and the critical limit (see Figure 2). H_1, X_3 and X_4 are set to the present operation rules, thus the decision variables consist of a set of 17 parameters.

The objectives of the parameter optimisation are defined by three objective functions: (1) reduction of downstream

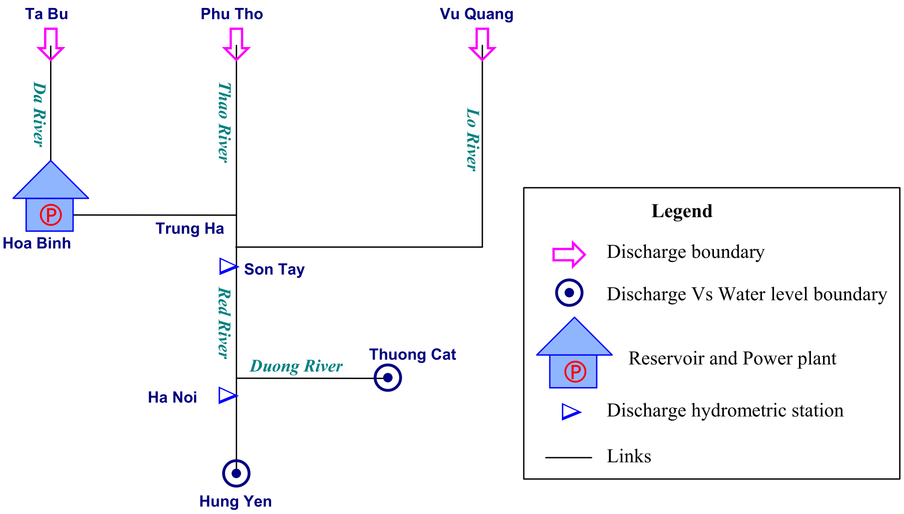


Figure 4 | MIKE 11 model setup of the lower Red River basin, including the Hoa Binh reservoir (Ngo *et al.* 2008).

flood peaks, (2) increase of the reservoir level at the beginning of the dry season, and (3) maximisation of hydropower generation. The objective functions are then aggregated into a single measure:

$$F = w_1 g_1 \sum_{i=1}^{N} (w_H (H_{max} - H_i)^2) + w_2 g_2 \sum_{i=1}^{N} \left(\frac{1}{D^2} \sum_{j=1}^{D} w_R (R_{max} - R_{ij})^2 \right) + w_3 g_3 \sum_{i=1}^{N} \left(\frac{1}{T^2} \sum_{j=1}^{T} (HP_{max} - HP_{ij})^2 \right) \quad (1)$$

where,

H_i, $i = 1, \ldots, N$, is the flood peak that occurs at Hanoi in the *i*th flood season (in metres),

R_{ij}, $i = 1, \ldots, N$, $j = 1, \ldots, D$ is the reservoir level in the *i*th flood season at the *j*th time step of the following dry season (in metres),

D is the number of time steps during the first 15 days of the following dry season (from 16 to 30 September),

HP_{ij}, $i = 1, \ldots, N$, $j = 1, \ldots, T$, is the hydropower generation at the *j*th time step of the *i*th flood season (in megawatts),

N is the number of flood seasons,

T is the number of time steps in a flood season,

w_1, w_2, w_3 are the weights assigned to the flood control, reservoir level and hydropower generation respectively,

w_H is the weight assigned to the Hanoi water level objective:

$$W_H = \begin{cases} 1 & \text{If } H_i \geq H_{max} \\ 0 & \text{if } H_i < H_{max} \end{cases}$$

w_R is the weight assigned to the reservoir level objective:

$$W_R = \begin{cases} 0 & \text{if } R_i > R_{max} \\ 1 & \text{if } R_i \leq R_{max} \end{cases}$$

H_{max} is the maximum accepted water level at Hanoi (13.3 metres),

R_{max} is the target reservoir level (117 metres) at the beginning of the dry season,

HP_{max} is the maximum hydropower capacity of the turbines (1920 megawatts),

g_1, g_2 and g_3 are transformation functions.

In Equation (1), the first term minimises the flood peak at Hanoi. The maximum value of the water level in the Red River at Hanoi is compared to the target value (13.3 m). In order to penalise the objective function value only when the maximum water level at Hanoi is higher than the target value, a weight w_H is defined. The second term maximises the reservoir level at the beginning of the dry season. The weighted average of reservoir level during the last 15 days of September is compared to the upper limit at this time of the year (117 m). The penalisation is applied only when the value is lower than the target. The last term minimises the hydropower deficit. The hydropower generated throughout the entire period is compared to the maximum value that the turbines are able to generate. Transformation functions are automatically calculated by AUTOCAL to compensate for the different magnitudes of the objective functions. The transformed objective functions will have similar influence on the aggregated objective function near the optimum (Madsen 2003). The weights w_1, w_2 and w_3 are specified by the user. To investigate the entire Pareto front several optimisation runs are performed using different sets of weights.

The input data that is used to force the reservoir and river model contains extreme flood and normal flood seasons. Extreme flood events are included in order to evaluate the flood control capacity of the Hoa Binh reservoir. By a flood combination method, three synthetically designed floods are generated based on the 1969, 1971 and 1996 flood seasons (Ngo *et al.* 2007). The extreme flood event of the year 1971 is also included.

During extreme flood years, the discharge through turbines is often at maximum capacity since the reservoir level is larger than the upper limit curve. Hence, five observed normal flood seasons (1963, 1977, 1983, 1989 and 1992) are added to the simulation-optimisation process for evaluating the hydropower generation. Thus, a total of nine different flood seasons are used to evaluate the objective functions.

Real-time optimisation

Operation of the reservoir system using the optimal operation rules will provide a general benefit, but improvement can be gained by utilising information about the current and future state of the system. When the reservoir is operated in real-time, the inflows to the three main tributaries of the Red River are forecast with a given lead time. Hence, the reservoir system is optimised for short-term operation using both short-term and long-term objectives. The control variables to be optimised in this case include reservoir releases for hydropower generation and operation of the flood control structures (bottom gates and spillways).

Assuming that forecasted inflows are available, the real-time optimisation aims at focusing on short-term objectives, yet they should not disregard long-term goals. According to Mays & Tung (2002), optimisation for real-time application should be able to consider the trade-off between long-term operational goals and short-term objectives. In other words, real-time optimal controls are designed to *track* optimal rule curves over a short-term horizon (Labadie 2004).

In this study, a three-day forecast is assumed available every six hours. As illustrated in Figure 5, the simulation is started using observed data. Then after the time of forecast (TOF) for the period covered by the lead time, forecasted inflows are used. If required, the optimisation period might be prolonged with an extended period where synthetic inflow data would be used.

Since the short-term objectives depend on the time of the year, two cases are defined: (A) normal and (B) flood control operation. Within *Case A*, no flood peak is forecasted for the given lead time, and the regulation focuses on hydropower generation. By contrast, *Case B* occurs when a flooding is forecasted, hence real-time operations aim at reducing downstream flood peaks at Hanoi.

Case A: normal operation

In normal inflow conditions the reservoir is operated for hydropower generation only. Spillways and bottom sluice gates are not used to release water from the reservoir. Therefore only the six-hour releases through turbines are optimised. Thus, 12 decision variables have to be considered for an optimisation period of three days.

Hydropower generation in the forecast period (short-term goal) and future hydropower potential (long-term goal) are the objectives to be considered. Thus, two objective functions are defined:

(1) Maximisation of hydropower generation throughout the forecast period,

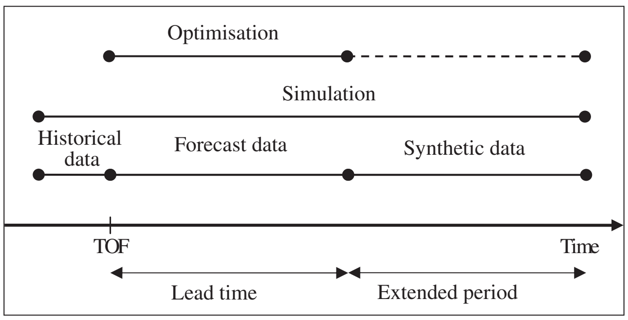


Figure 5 | Simulation–optimisation approach for real-time optimisation.

(2) Maximisation of the reservoir level at the end of the forecast period.

The long-term goal aims at reaching the upper limit at the end of the forecast period. A penalty is assigned to the second objective function only if the reservoir level is below the upper limit.

Case B: flood control

If a flood peak is forecasted, the reservoir will be operated for flood control. In this case, the turbines are operating at full capacity, thus the decision variables only include the operation of the bottom sluice gates. In total, 12 decision variables have to be optimised corresponding to the number of open bottom sluice gates every six hours within a period of three days.

Minimisation of the impact of the flood peak at Hanoi (1) is the short-term priority, which should aim at keeping the water level at Hanoi below the flood warning level of 11.5 m. However, the decision made during the forecast period should not compromise future operation of the reservoir. By reducing the flood peaks at Hanoi, the storage capacity of the reservoir may be reduced for the next forecast period. To ensure that, a second objection function (2) will penalise the deviation of the reservoir level from the reservoir level found using the optimal operation rules at the end of the forecast period. Moreover, the operation of the bottom sluice gates has to respect gate operation guidelines to minimise downstream fluctuations caused by reservoir releases. The last objective function (3) will penalise operation constraints where only one gate is operated every six hours if there are less than six gates open, else one gate can be operated every 15 minutes. Thus, three objective functions are defined:

(1) Flood peak at Hanoi,
(2) Reservoir water level at the end of the forecast period,
(3) Constraint on operations of bottom sluice gates.

To evaluate the effect of gate operations in the entire forecast period, the optimisation period is extended with a 1-day period, corresponding to the travel time from the reservoir to Hanoi during high flow events. During this extended period only the first objective will be evaluated (see Figure 5).

When aggregating these objective functions using a similar formulation as given by Equation (1), a weight of 1 is given to the first two objective functions whereas a weight of 0.1 is assigned to the third objective. The solution that gives the lowest aggregated value is chosen and used to operate the reservoir until the next forecast is available, and a new optimisation run is performed and so on (see Figure 6). For more details about the implementation of the real-time optimisation the reader is referred to Richaud (2008).

Lead time

One can intuitively foresee that the later the forecasted event occurs, the larger is the uncertainty of the forecast. The forecast is therefore balanced between lead time and uncertainty. Assuming a perfect forecast, a study is here carried out to evaluate the relationship between lead time and flood control. In this regard, real-time reservoir optimisation is analysed using forecasts with three-day and one-day lead times.

RESULTS AND DISCUSSION

Rule curve optimisation

To locate balanced solutions, the optimisation focuses on the central part rather than the entire Pareto surface. Hence, equal weights are assigned to the different objective functions, see Equation (1). During the off-line optimisation a total of 327 sets of parameters have been evaluated using historical data from nine flood seasons. Considering the trade-offs between the three objective functions previously defined, 78 non-dominated solutions, part of the Pareto surface, have been identified. In Figure 7, the two-dimensional sub-spaces of the three-dimensional Pareto surface are

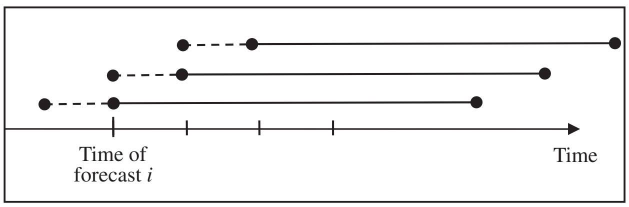


Figure 6 | Illustration of sequence of real-time optimisations. The dashed line shows the results of the ith optimisation used to start the $(i+1)$th optimisation. The dashed line combined with the full line represents the optimisation period.

shown. As expected, the figure highlights significant trade-offs between the three objectives. A preferred solution has to be chosen among these Pareto optimal solutions.

The rule curve optimisation aims at providing a solution that does not compromise flood control and at the same time improves both hydropower generation and irrigation capacity in the dry season. With respect to these goals, two optima have been singled out: Optimum 1 and Optimum 2 (see Figure 7).

Table 1 shows the objective function values of the two optimal solutions compared to the present regulation. Optimum 1 is selected as a result of its low aggregated objective function value, implying a good overall performance considering the three objective functions. Optimum 2 is chosen for its high performance regarding flood control, which is, however, balanced by a lower hydropower generation.

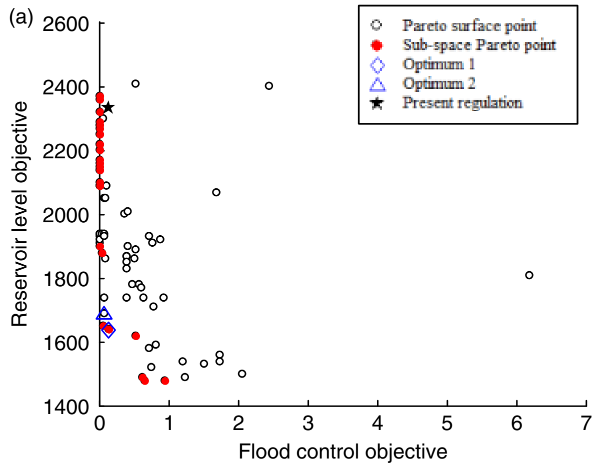
To select the preferred optimum, a set of 19 historical flood seasons is used for evaluating the performance of these operating rules. Table 2 compares the two Pareto solutions with the present regulations considering average maximum water level at Hanoi, average hydropower generation and average reservoir level at the end of the flood season for the 19 years. Optimum 1 and Optimum 2 provide the same flood control level at Hanoi compared to the present regulation. There is only one year (1971) out of 19 where the flood peak exceeds 13.3 m at Hanoi.

The optimal rule curves improve the hydropower generation and reservoir storage at the end of the flood season, without compromising the flood control. However, larger hydropower generation and slightly higher reservoir level at the end of the flood season are observed with Optimum 1 (see Table 2). For the following real-time optimisation, Optimum 1 is selected as the "preferred optimum".

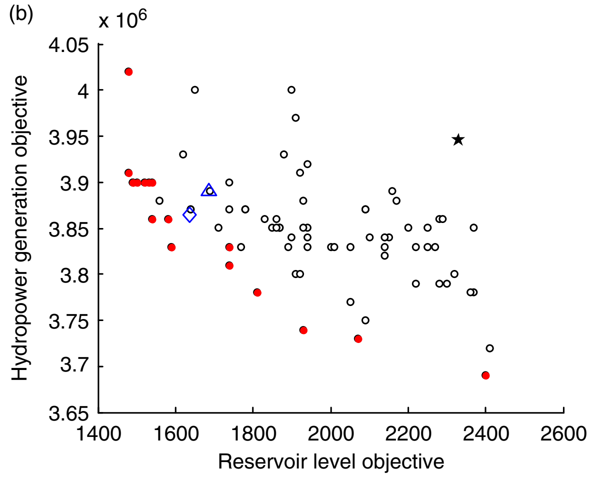
Ngo *et al.* (2007) found similar improvements using a two-step optimisation approach. However, the present approach is proven more appropriate since the three objective functions are optimised in the same optimisation run.

Real-time optimisation

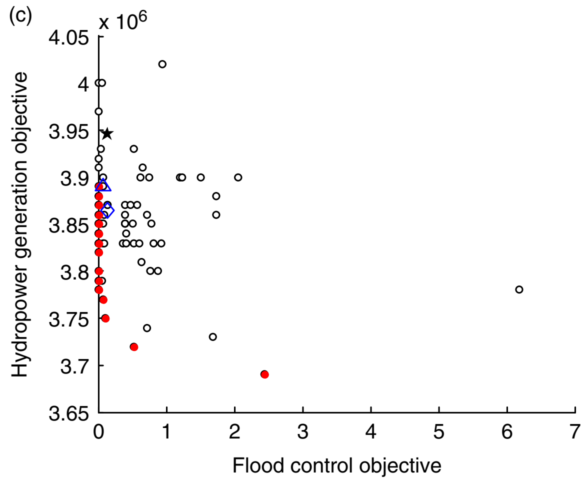
The reservoir is operated in real-time assuming a perfect forecast with three-day lead time. The historical data of the year 1996 is used to illustrate the implementation of real-time



Reservoir level objective versus Flood control objective.



Hydropower generation objective versus Reservoir level objective.



Hydropower generation objective versus Flood control objective.

Figure 7 | Representation in 2D the sub-spaces of the 3D Pareto surface. The 78 Pareto points from the rule curve optimisation are shown in these plots. In each sub-space the Pareto front is enlightened as well as Optimum 1, Optimum 2 and the evaluation of the present regulation.

Table 1 | Objective function values of the present regulation and two selected pareto optima from the rule curve optimization

	Flood control	Reservoir Level	Hydropower deficit
Present regulation	0.1351	2330	$3.95\ 10^6$
Optimum 1	0.1345	1637	$3.87\ 10^6$
Optimum 2	0.0752	1687	$3.89\ 10^6$

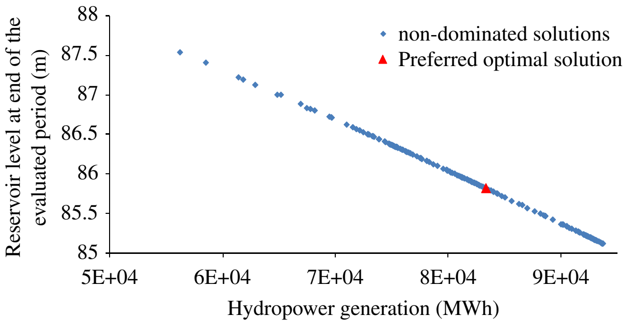


Figure 8 | Hydropower generation versus reservoir level at the end of the forecast period for the Pareto optimal solutions of the real-time optimisation under normal operation.

optimisation of the Hoa Binh reservoir. This year was not included in the rule curve optimisation.

Case A: normal operation

To illustrate the real-time optimisation under normal operation a single optimisation is shown. The optimisation run is executed using different combinations of weights for each objective function. A total of 832 sets of parameters have been evaluated and 182 non-dominated solutions were identified (see Figure 8).

Real-time optimisation provides a large range of Pareto optimal solutions (non-dominated solutions in Figure 8) that give different ratios between hydropower generation in the forecast period and future hydropower potential. The operation using the optimal rule curves is located on this Pareto front. However, the user can select a different policy according to his/her preference to increase immediate hydropower production or to raise the water level to increase hydropower potential. Under normal operation, Georgakakos (1993) found a similar trade-off between hydropower generation and reservoir level.

The choice made by the operating authority will be motivated by external parameters, which were not included in the optimisation objectives. Variation of the electricity market prices could be one incentive; this would be particularly interesting in a competitive market.

Table 2 | Comparison of the average simulation results regarding the flood control, hydropower production and the reservoir level at the start of the dry season (average value over 19 observed years)

	Present	Optimum 1	Optimum 2
Average maximum water level at Hanoi (m)	10.90	10.87	10.88
Average hydropower generation (10^6 MWh)	4.28	4.37	4.34
Average reservoir level at the start of the dry season (m)	102.69	105.14	105.09

Case B: flood control

The flood that occurred in 1996 had the highest inflow ever recorded in the Da River. This event is analysed in order to see to which extent flood mitigation can be ameliorated by introducing real-time optimisation, which in this case will be pursued as a sequence of several optimisation runs.

An optimisation run is performed when a new forecast is available, i.e. every six hours. A sequence of 12 optimisation runs is performed in order to cover a period of three days. As illustrated in Figure 6, only the first six hours of the short-term optimisation is implemented, then the operation is based on the next short-term optimisation. The first time of forecast is chosen on 16 August 1:00 when the operation changes to flood control.

After a sequence of 12 short-term optimisations, the overall regulation has been largely improved compared to rule curve operation (see Figure 9 and Table 3). Using real-time optimisation the reservoir is able to mitigate the flood peak observed in 1996 by keeping the water level in Hanoi below 11.5 m, see Figure 9(c). This is due to the pre-release of water from the reservoir as soon as the flood peak can be forecast, see Figure 9(b). If the set of optimal rule curves are strictly applied, the water level at Hanoi would reach 12.09 m.

The optimal solutions fulfil the gate operation requirements, see Figure 9(a). Regarding the long-term objective, the

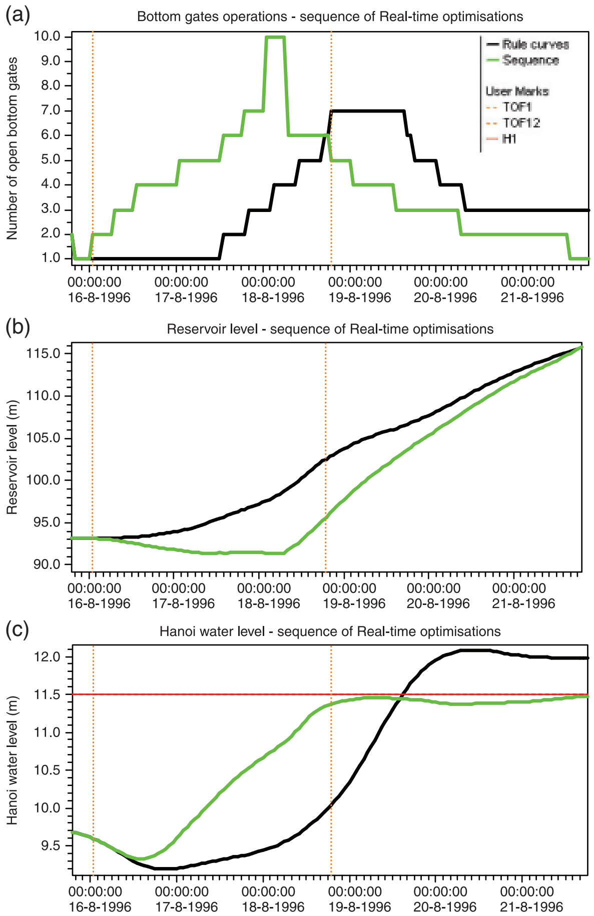


Figure 9 | Reservoir operation during the sequence of real-time optimisations under flood control operation: (a) operations of the bottom sluice gates, (b) reservoir level, and (c) water level at Hanoi. TOF1 and TOF12 are respectively the time of forecast used for the first and the twelfth run. H1 is the target water at Hanoi.

reservoir level is close to the one found using rule curves at the end of each run. As observed in Figure 9(c), the reservoir level is 0.16 m below the target at the end of the 12th run (see also Table 3).

The pre-release affects the hydropower generation. Within the three-day period when the optimisation sequence has been carried out, hydropower generation with real-time operation is about 4% lower than with rule curves (see Table 3).

Lead time

Like in Case B, a sequence of short-term optimisation is performed using a one-day lead time forecast. The results of

Table 3 | Comparison of real-time and rule curve operations between 16 August 1996 1:00 and 19 August 1996 19:00

	Rule curves	Real-time operations
Maximum water level at Hanoi (m)	12.09	11.5
Reservoir release (billion m^3)	3.95	3.98
Generated hydropower (10^3 MWh)	252	242
Reservoir level at the end of the optimised period (m)	115.69	115.53

both scenarios are illustrated in Figure 10. They both fulfil the gate operation requirements, see Figure 10(a). With a one-day forecast, the maximum number of open bottom gates is 5, whereas it is 10 with a three-day forecast. Figure 10(b) displays the variations of the reservoir level showing the pre-release prior to the inflow flood peak. In this first part, the amount being released is similar in both scenarios. However, the regulation with one-day forecast halts the pre-releases around 18 August 1996. Within the given lead time, the model is only able to forecast the water level at Hanoi within the next two days. The reduction in the pre-releases results in an increase in the downstream water level up to 11.85 m, see Figure 10(c). Assuming one-day forecasts is therefore not sufficient to keep the water level at Hanoi below the target value (11.5 m). However, the one-day lead time forecast still provides a reduction in water level in Hanoi compared to rule curve operation (12.09 m).

Regarding hydropower generation, the produced amount is higher for the one-day lead time case, Figure 10(d). Under flood control operation, the turbines are operating at maximum discharge, therefore only the hydraulic head affects the hydropower generation.

Use of flow forecasting is clearly more beneficial with three-day than one-day lead time, providing a reduction of the maximum water level at Hanoi of, respectively, 0.6 m and 0.25 m compared to the regulation using rule curves. Flow forecasting provides information to perform pre-release before the flood peak, and the longer the lead time, the more efficient is the pre-release.

The choice of lead time will be motivated by the physical conditions of the basin, the characteristics of the reservoir, and the available meteorological forecasts. Knowing that a

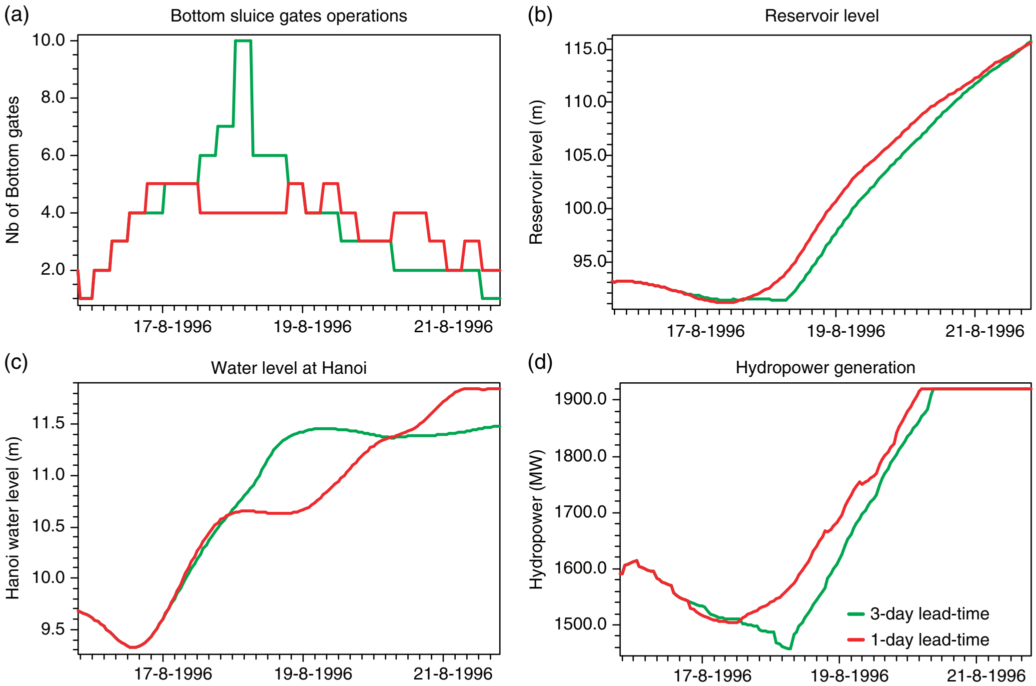


Figure 10 | Comparison of real-time operations with 3-day and 1-day flow forecasting: (a) Bottom sluice gates operation, (b) Reservoir level, (c) Water level at Hanoi and (d) Hydropower generation.

balanced lead time has to be found, a three-day forecast seems feasible with the current forecasting techniques.

CONCLUSION

A framework that combines off-line and on-line optimisations has been developed for real-time reservoir optimisation and applied for operation of the Hoa Binh reservoir in Vietnam. In the first stage, reservoir operating rules have been optimised considering trade-offs between flood control, hydropower generation and water supply for irrigation. From the set of 78 Pareto optimal solutions, a preferred optimal solution has been selected. This optimum improves hydropower generation on average by 2.2% during the flood season and leads to an increase of 2.45 m of reservoir level at the end of the flood season, without compromising the flood control level.

In the second stage, short-term optimisations are performed based on real-time and forecast information of the reservoir inflow. In normal flow situations the on-line optimisation provides a set of non-dominated solutions that trades-off the immediate and future hydropower generation. In flood situations, forecast information is used to adjust reservoir releases to enhance flood mitigation. A sequence of short-term optimisations has shown the benefit of using forecast data for reducing the impact of extreme flood events.

The quality of the forecast has been addressed at the end of the study, by considering the use of shorter lead time forecast. The benefit of using a three-day forecast for the reservoir inflow has been illustrated. Real-time optimisations using only one-day forecasts are not able to mitigate a flood peak such as the extreme flood peak that occurred in August 1996.

The application to the Hoa Binh reservoir proves how online computer simulation coupled to an off-line optimisation can effectively assist the decision-maker to safely operate the reservoir during severe inflow conditions, and to manage the water resources during normal inflow conditions.

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