A combined flow prediction and reservoir control system for optimising hydropower production

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Abstract

A combined flow prediction and control system is described for optimisation of multi-purpose reservoir operation. The system integrates a numerical model for simulation of river flow and reservoir operation with an optimisation tool. The optimisation tool includes a general multi-objective framework that searches for the set of non-dominated or Pareto-optimal solutions according to the trade-offs between the various objectives. The simulation-optimisation procedure is applied for optimisation of reservoir operation rule curves of the Hoa Binh reservoir, Vietnam, considering hydropower production and downstream flood control. Compared to the present regulations, Pareto-optimal rule curves are obtained that have both a smaller flood risk and a larger hydropower production. Simulations with a balanced optimum Pareto solution show a substantial increase of hydropower production of 210 million kWh on average per year. To further improve the operation, real-time optimisation is performed that utilises real-time and forecast information about reservoir levels, reservoir inflows and water demands. In this case, short-term operations are optimised considering both short-term hydropower and flood risk objectives and long-term objectives in terms of deviations from the rule curves. The real-time optimisation procedure offers a highly flexible optimal control framework, which is updated regularly with new forecast information.

1. 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. 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.

For optimisation of reservoir operation, procedures based on coupling simulation models with numerical search methods have been applied. Recent research has focused on direct coupling of simulation models with heuristic optimisation procedures (e.g. Oliveira and Loucks, 1997; Chang *et al.*, 2005). In this paper the MIKE 11 modelling system (DHI, 2005a) is adopted for simulating the flow in the river system including reservoir operations. The structure operation module in MIKE 11 allows implementation of complex control strategies, whereby reservoirs can be operated by defining a number of different control strategies with various conditions. The use of several control strategies makes it possible to simulate multi-purpose reservoirs, which take into account a large number of objectives, such as flood protection, hydropower production and water supply.

The MIKE 11 modelling system is combined with a numerical optimisation tool that is used for optimising different control variables defined for the reservoir operation strategies. The optimisation tool includes a general multi-objective optimisation framework that searches for the set of non-dominated or Pareto-optimal solutions according to the trade-offs between the various objectives. For solving the optimisation problem, the shuffled complex evolution (SCE) algorithm (Duan *et al.*, 1992) implemented in the AUTOCAL software (DHI, 2005b) is applied.

The simulation-optimisation procedure is used in an off-line mode for optimisation of reservoir rule curves using historical data. Implementation of the optimised rule curves with MIKE 11 then provides a base-line reservoir operation system. This operation system can be further improved in real-time by fine-tuning the reservoir releases using forecast information. In this case, the MIKE 11 modelling and reservoir control system uses weather forecasts to provide forecasts of reservoir inflows, which are combined with the optimisation tool to derive short-term, Pareto-optimal operation strategies. The simulation-optimisation approach is demonstrated on optimisation of operation of the Hoa Binh reservoir in Vietnam.

2. System description

Hoa Binh is the largest reservoir in Vietnam with a storage capacity of 9.5 billion m^3 and an active storage of 5.6 billion m^3. It is a multi-purpose reservoir providing flood control, hydropower and water supply. 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.

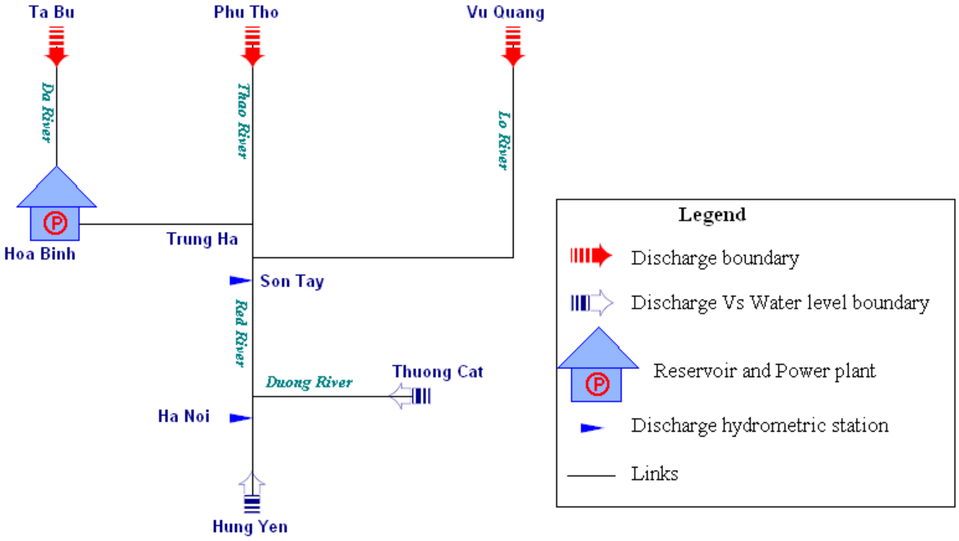

Fig. 1. MIKE 11 model setup of the lower part of the Red river basin, including the Hoa Binh reservoir.

The MIKE 11 modelling system 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 1). 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. In total, more than 100 logical statements are defined for the Hoa Binh reservoir operation.

Table 1. Control variables for flood control. The numbers in brackets correspond to the present operation rules. $H_{HN(t+24h)}$ is the forecasted water level at Hanoi with a lead time of 24 hours.

Operational status		Water level at Hanoi	Period	Reservoir water level
Normal		$H_{HN(t+24h)} < 11.5$ m	1 Jun – 15 Jul	$H_{Res} \le X_1$ (95 m)
			16 Jul – 20 Aug	$H_{Res} \le X_2$ (93 m)
			21 Aug – 25 Aug	$H_{Res} \le 103$ m
			26 Aug – 31 Aug	$H_{Res} \le 108$ m
			01 Sep – 30 Sep	$H_{Res} \le 117$ 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		$H_{HN} \ge H_2$ (13.1 m)		$H_{Res} \ge R_3$ (120 m)

Opening and closing of bottom gates and spillways for flood control are described according to flood control rule curves in terms of target water levels in the reservoir and water levels at the flood control point in Hanoi (see Figure 2 and Table 1). The discharge through turbines is defined according to hydropower control curves in terms of critical, lower and upper reservoir level curves (see Figure 2). When the water level is above the upper limit, hydropower generation is operated with a maximum discharge through turbines (up to 2400 m^3/s, depending of the headwater level). When the water level is between the lower and upper limits, hydropower generation is operated with a discharge through turbines that vary linearly between the minimum downstream discharge requirement (680 m^3/s) and the maximum. When the water level is between the critical and lower limits, hydropower generation is operated with a discharge through turbines to meet the minimum downstream discharge requirement. When the water level is below the critical limit, hydropower generation is halted.

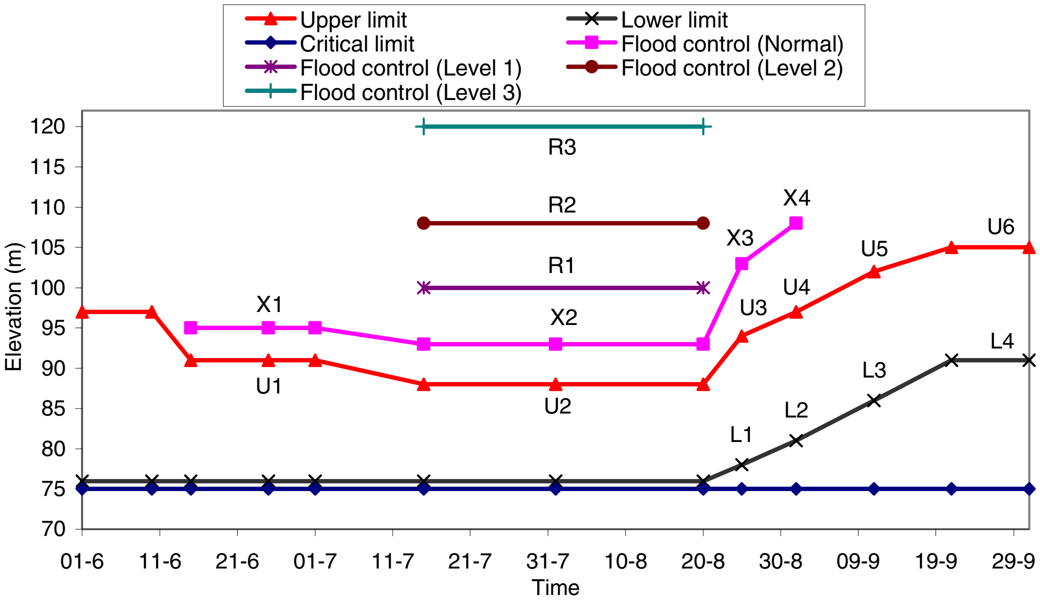

Fig. 2. Target reservoir water levels for defining flood control and hydropower rule curves.

3. Optimisation of reservoir rule curves

The control variables to be optimised consist of the reservoir water level targets and water level targets at the flood control point at Hanoi specified in Figure 2 and Table 1. These include the flood control variables X_1, X_2, X_3, X_4, R_1, R_2, and R_3 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 procedure. 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 the hydropower generation in the flood season and 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 decision-maker 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.

The results of the optimisation of flood control variables are shown in Figure 3. The optimisation problem is defined as minimisation of the hydropower deficit compared to the maximum hydropower generation capacity (denoted hydropower objective in Figure 3) and minimisation of the maximum water level at Hanoi (denoted flood control objective in Figure 3). 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 the balanced optimum solution obtained as part of the optimisation (see Madsen (2003) for details regarding definition of this solution), 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. The optimisation of the reservoir operations provides Pareto-optimal solutions that are better with respect to both hydropower generation and flood control.

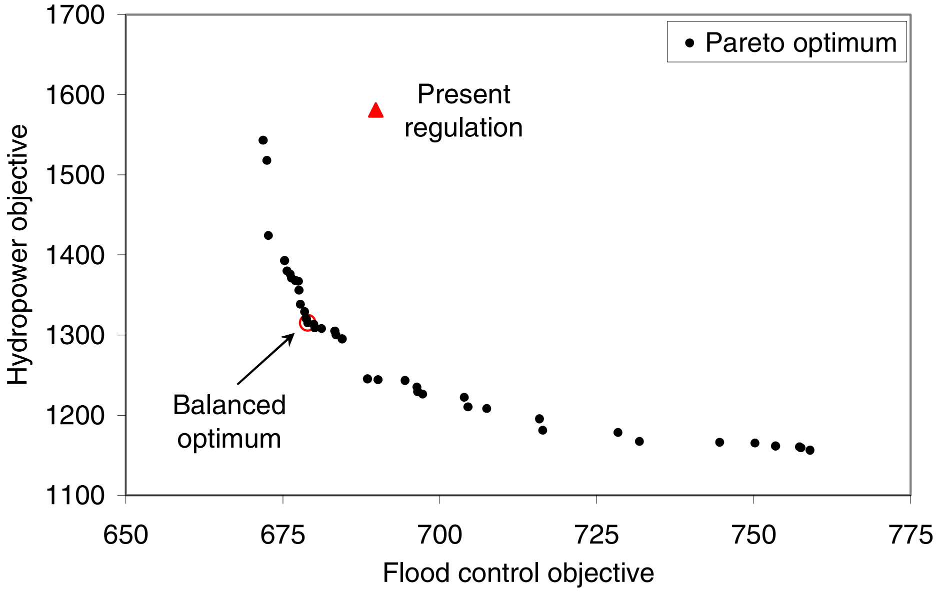

Fig. 3. Pareto optimisation results for optimisation of flood control variables compared to the present regulations.

The results of the optimisation of hydropower control variables are shown in Figure 4. The two objective functions measure, respectively, the hydropower deficit in the flood season (denoted hydropower objective in Figure 4) 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 4). 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 optimal 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).

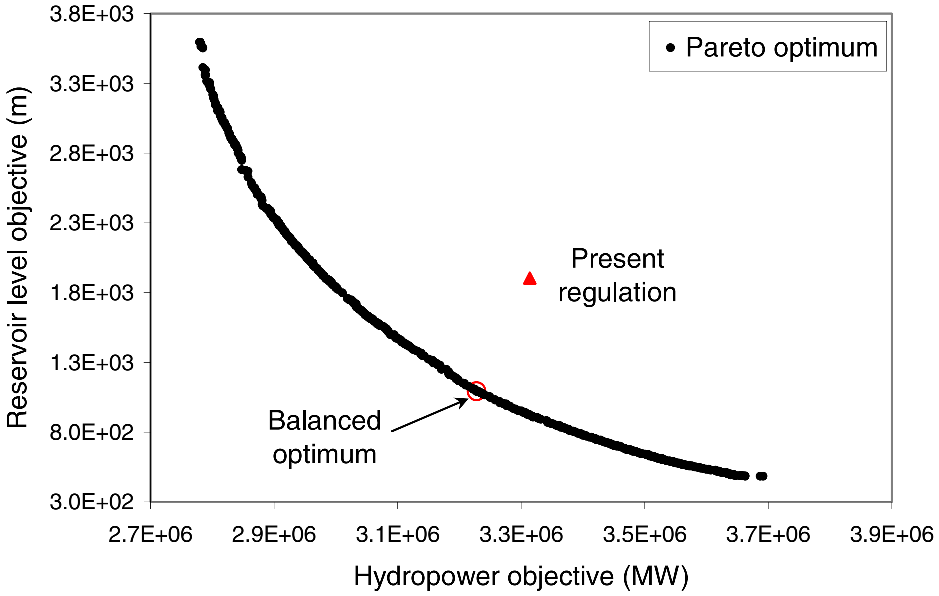

Fig. 4. Pareto optimisation results for optimisation of hydropower control variables compared to the present regulations.

4. Simulation with optimised rule curves

A 20-year historical record was used as input to the MIKE 11 model for simulation of reservoir operation using the present regulations and the balanced Pareto-optimal solution. The generated hydropower in the analysed flood seasons using the two operation strategies is shown in Figure 5. In most flood seasons the balanced optimum solution provides an increase in hydropower production compared to the present regulations. On average an increase of 1.8% is obtained, corresponding to 80 million kWh per year.

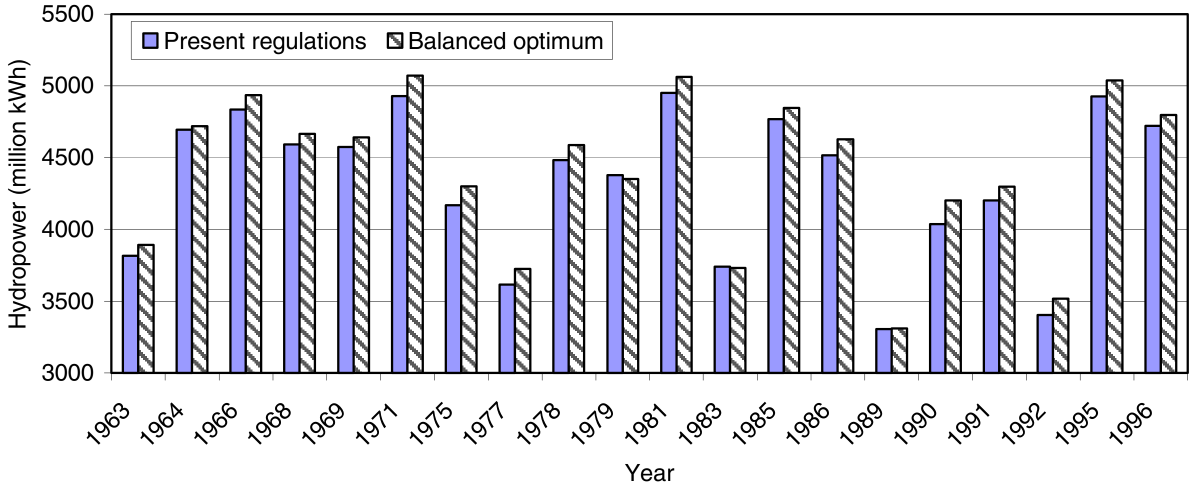

Fig. 5. Simulated hydropower generation in the flood season using, respectively, the present regulations and the balanced Pareto-optimal rule curves.

The simulated water level at the end of flood season using the two operation strategies is shown in Figure 6. 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 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.

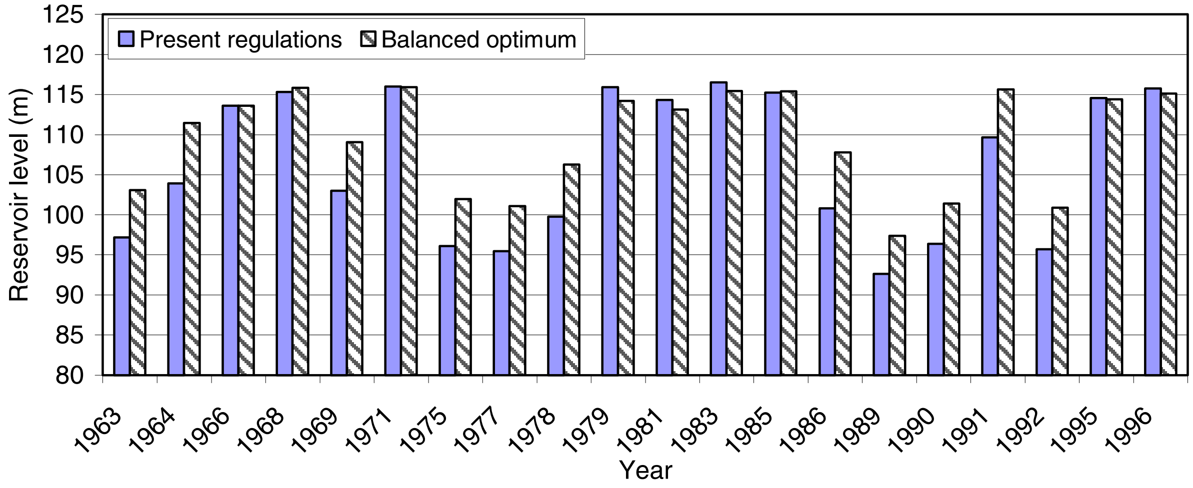

Fig. 6. Simulated water level at the end of the flood season using, respectively, the present regulations and the balanced Pareto-optimal rule curves.

As shown in Figures 3-4, other Pareto-optimal solutions exist that 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 4, 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.

5. 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 using an objective function that penalizes 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 Pareto-optimal set the decision-maker can then choose a preferred solution taking other considerations into account.

The results of a real-time optimisation test are shown in Figure 7. The figure shows the Pareto optimum solutions for optimisation of hydropower production (short-term objective) and penalizing of the deviation of the reservoir level at the end of the forecast period. The decision-maker can choose a preferred operation strategy from the set of Pareto-optimal solutions. If a certain hydropower production is specified for the forecast period, the consequence of this in terms of the reservoir water level can be seen from Figure 7. The reservoir operation using the optimised rule curves (balanced optimum solution) is close to the real-time Pareto set of solutions. In this case the reservoir is operated so that the reservoir level at the end of the 3-day forecast period is equal to the reservoir level at the time of forecast (87 m). Compared to reservoir operation using rule curves, real-time operation offers a highly flexible optimal control framework by efficient utilisation of current and forecast information. In addition, new information is regularly used to update the optimal operation strategies. For the Hoa Binh real-time optimisation system new optimisations are carried out every 24 hours.

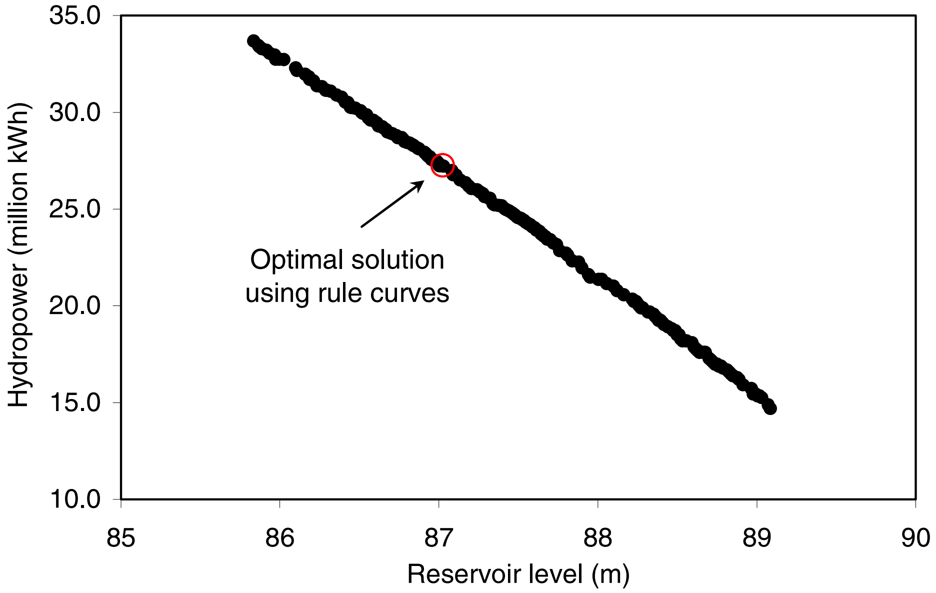

Fig. 7. Pareto optimum solutions for real-time optimisation in terms of hydropower generation in the 3-day forecast period and water level at the end of the forecast period compared to the optimal solution using rule curve operation. The reservoir water level at time of forecast is equal to 87 m.

6. Conclusions

A combined flow prediction and control system has been developed for optimisation of multi-purpose reservoir operation. The system combines the MIKE 11 modelling system for simulation of river flow and reservoir operation with the AUTOCAL 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 two-step 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 an increase in hydropower production of about 210 million kWh on average per year is obtained compared with the present regulations.

To further improve the reservoir operation, and hence increase the hydropower potential, a real-time 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 real-time optimisation procedure offers a highly flexible optimal control framework, which is updated regularly with new forecast information.

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