Chapter 66
Optimal Operation of Parallel Reservoirs System with Limited Storage Capacity for Flood Mitigation

Thanh Hao Nguyen and Philippe Gourbesville

Abstract In this research, a flood control operating strategy is developed based on a simulation–optimization model to reduce flood damage downstream of multi-reservoir systems by using spillway gates. For this purpose, an optimization algorithm is introduced, in which maximum water level at downstream control points is objective function and the level of the stages of spillway gates are the decision variables. A global optimization tool, Shuffled Complex Evolution (SCE) algorithm implemented in the AUTOCAL software was coupled with Mike 11 from the DHI simulation model for optimizing stages level of spillway gates. As a case study, the Vu Gia Thu Bon rivers catchment including multi-reservoirs of A Vuong, Song Tranh 2, Dak Mi 4 and Song Bung 4 is analyzed. Results obtained from the proposed model indicate a dramatic decrease in the expected flood damage. A comparison of findings with other studies shows that the proposed model has a better ability to control floods and minimize damage.

Keywords Optimization · Flood mitigation · Reservoir systems · SCE algorithm

66.1 Introduction

Optimization of the operation of a single reservoir or multi-reservoir system is a problem of close interest to the owners of these hydraulic facilities. Many optimization procedures have been developed to analyze the performance of future reservoir systems or to optimize the performance of the existing reservoir systems. Despite the

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multitude and specificity of each river reservoir system network, the formulations of the associated optimization problems are often in common.

Flood control and mitigation are significant concerns for the authorities responsible for the reservoir operation in the flood seasons. How to operate the reservoirs so that flood control and mitigation could be maximized are considered a key technology strategy in the flood protection management. Thus the focus is on optimizing the effective use of the available reservoir storage during flood events in particular and during flood seasons in general. Although reservoirs are not primarily built to provide full flood protection, effective use of the reservoir storage capacity can help to reduce the downstream flood levels and mitigate flood damages as well as to prevent major flood disasters.

The optimal operating strategy for a reservoir depends not only on the flood control decision of each reservoir but also on the respective content of each other reservoirs in the network [1]. In this current research, the optimal strategies for flood control of the multi-reservoir system in the Vu Gia Thu Bon catchment are considered.

For the operation of reservoir systems, a variety of optimization models were developed [2–5]. Several researchers have made efforts to control the floods of reservoir systems using optimization techniques, including Linear Programming (LP), Dynamic Programming (DP) and heuristic programming such as Genetic Algorithm (GA), Non-dominated Sorting Genetic Algorithm II (NSGA-II), Shuffled Complex Evolution (SCE), fuzzy logic and Artificial Neural Networks (ANN).

In the current research, due to the characteristics of the system and the targeted optional objectives, a flood control operating strategy has been developed based on coupled simulation–optimization to reduce downstream flood damage of the multi-reservoir system by using spillway gates. This model is applied to the optimal operation of a parallel reservoirs system with limited storage capacity in the Vu Gia Thu Bon catchment. The Mike 11 hydrodynamic model is utilized for flood routing in the reservoirs systems and the Shuffled Complex Evolution (SCE) algorithm for the optimization of operating spillway gates.

The SCE algorithm is one of the techniques that are robust optimization techniques to find the global optimum solution of complex problems with many functions such as non-convex, non-differentiable, and multi extrema functions [6]. In this research, the SCE algorithm, as implemented in the AutoCal [7] software, is adopted for optimizing the multi-reservoir system operation in the case study. A brief overview of the SCE algorithm is provided in the next section.

66.2 Methodology

According to the previous description the optimization of multi-reservoir system operation is a complex, multi-purpose optimization problem with different objectives such as irrigation, industrial water supply, hydropower generation, navigation and flood control. In order to achieve multiple objectives, procedures based on coupling simulation models with optimization algorithms have been proposed in

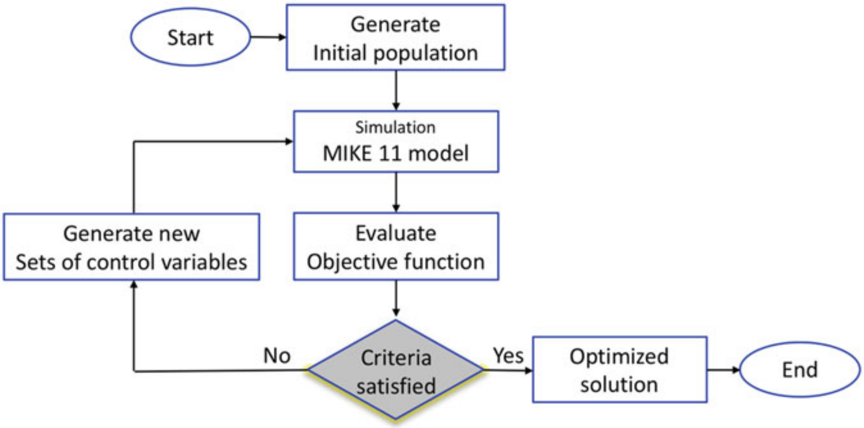


Fig. 66.1 Basic steps of the simulation–optimization framework

many previous studies. Figure 66.1 shows the framework of the simulation model coupled with the optimization model. The optimization of the operation of a multi-reservoir system during flood events can be formulated as a combination of a simulation model and an optimization model [8].

In this method, the hydrodynamic model is adopted for the simulation of the flow of the river network considering physical constraints of the system as well as operation policies. The optimization algorithms are applied to determine the best set of decision variables, such as reservoir release and storage. For the optimization of the multi-objective function, the optimization tool searches for the set of non-dominated or Pareto-optimal solutions according to the trade-offs between the various objectives [9].

First, the optimization model produces a release discharge hydrograph based on generating randomly a set of the decision variable (e.g., the method considers reservoir release as a decision variable that needs to be optimized). Next, the simulation model computes the flow discharges and water levels in the river network. After that, the optimization model evaluates the multi-objective functions based on the selected results from the simulation model. Then another set of control variables is generated through the optimization algorithm (Fig. 66.1). This process is repeated until the stopping criteria are satisfied. These include: the iteration number reaches a certain predefined, or the value of the objective function improves insignificantly over some iterations (i.e., less than 1%).

One of the main objectives of this research is the development of a methodology for optimizing the operation of the multi-reservoir system with multiple spillway gates in the Vu Gia Thu Bon catchment during flood events. Using different spillway gates has a significant impact on reservoir operation during the flood events [10]. The problem is formulated as an optimal control problem in which spillway gates levels of four major reservoirs represent the decision variables. Forty-two decision variables are used in the model to represent spillway operation.

The simulation–optimization framework that is adopted for determining the spillway gates operation strategy of the multi-reservoir system in the Vu Gia Thu Bon catchment during flood events is illustrated in Fig. 66.1. Once the sets of feasible solutions (spillway gates levels) are determined, decision variables are inputted into the Mike 11 hydrodynamic model to simulate the floods in the river systems. The main objective of the method is to control the flood elevations at critical locations downstream of a river-reservoir system (at Ai Nghia and Giao Thuy stations). The maximum water levels at downstream control points are objective functions for minimizing the vulnerability of flood in the downstream area (Fig. 66.2). If the objectives were not met, the model would repeat its optimization process using the SCE algorithm. Which means that a new set of control variables is generated for the simulation model. The processes repeat and continue until the stopping criteria are satisfied.

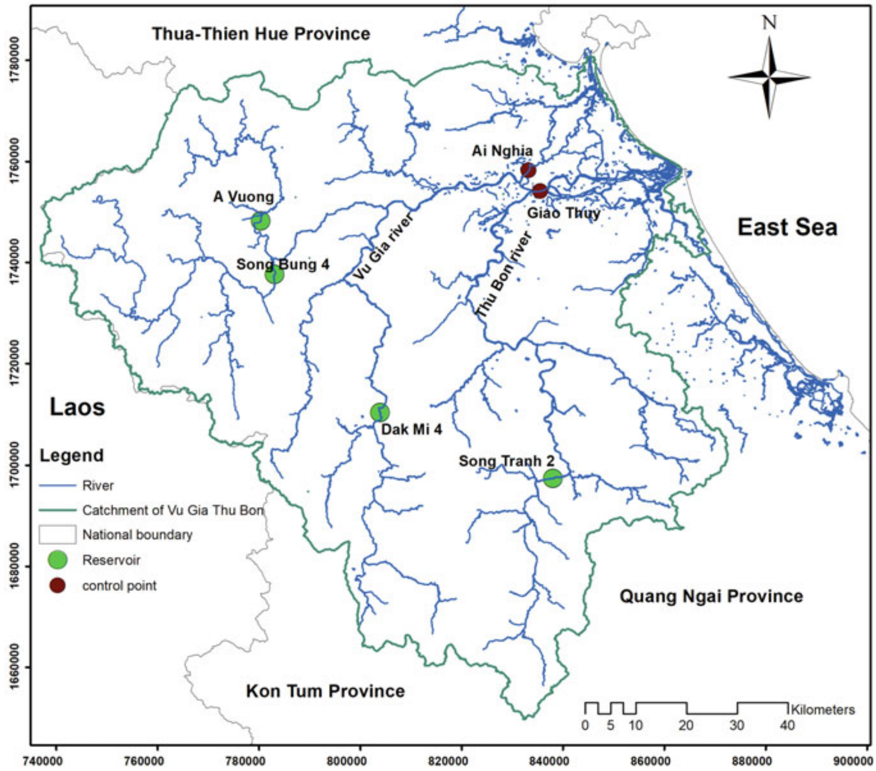


Fig. 66.2 Description of the Vu Gia Thu Bon river-reservoir system

66.3 Case Study: Vu Gia Thu Bon Reservoirs System

66.3.1 Multi-reservoir in Vu Gia Thu Bon Catchment

The steep slope of mountainous topography greatly limits the capacity of reservoirs in the central region of Vietnam in general and of reservoirs in the Vu Gia Thu Bon catchment in specific. Most projects are using dams for the impoundment of the river and using potential heads of the rivers to build a system of hydropower reservoirs cascade. All of these large hydropower reservoirs in the Vu Gia Thu Bon catchment are used a guiding channel for transferring water from the reservoir to the hydropower plant. Since 2015, eight large-medium sized dam projects have been constructed on the mainstream of the river basin. However, there are only four hydropower reservoirs with capacity flood control, including A Vuong, Dak Mi 4, Song Bung 4 and Song Tranh 2 (Fig. 66.2). These four reservoirs play the most important role in flood control in the Vu Gia Thu Bon catchment.

66.3.2 Objective Function

The major aim of this study is evaluation flooding mitigation capacity of the system, which regulated by flood peak at critical downstream gauging points. Hence, the objective is to minimize the flood peak at the control points that can be expressed by:

$$minimise\ F = max\left(\sum_{j=1}^{2} H_j^2\right)_{t\in[t_o,T]} \tag{66.1}$$

where

H_j is the flood peak that occurred at j station at the time step t of the flood event.

The subscripts j represents the number of the control points at Ai Nghia station and Giao Thuy station, respectively (Fig. 66.3).

T is the total number of time steps for flood events.

t_o is the initial operating time.

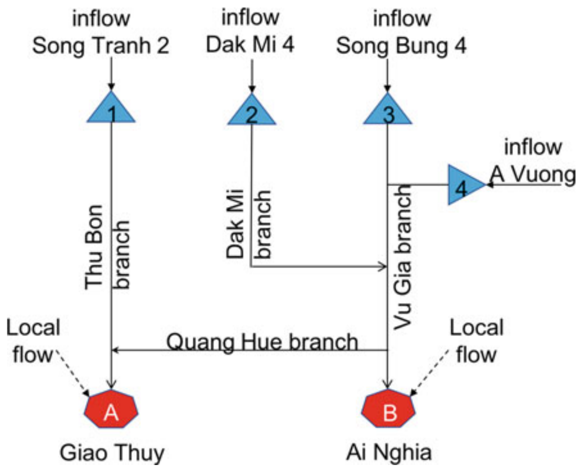


Fig. 66.3 Description of the four reservoirs and two control points in the Vu Gia Thu Bon catchment

66.4 Application and Results

On 4th of November 2017, typhoon Damrey (the typhoon n° 12 in Vietnam) made landfall in the southern province of Vietnam, bringing with it extreme rainfall. The rainfall recorded 804 mm in Tra My in 48 h between 3rd and 5th of November. At least eight other locations in the Vu Gia Thu Bon catchment recorded rainfall amount at around 500 mm during this period and consequently severe inundations appeared in the year of 2017.

According to Vietnam's Central Steering Committee for Disaster Prevention, Search and Rescue, the 2017 flooding caused significant damages to the Vu Gia Thu Bon river basin. Statistic data confirmed 13 people had lost their lives, and ten were missing. At least 10,620 people have been evacuated across affected areas. The damage caused by this disaster amounted to 542 billions VND.

At the time, four major reservoirs in the Vu Gia Thu Bon catchment have been operated according to the regulation of the Government.

66.4.1 Boundary and Initial Conditions

The recorded data of the inflow hydrograph in four reservoirs (A Vuong, Dak Mi 4, Song Bung 4, and Song Tranh 2) are shown in Fig. 66.4. Table 66.1 gives general information about them.

The time information of the given time series of a flood event is:

- Starting time: 10:00 a.m. 4 November 2017.
- Ending time: 1:00 p.m. 7 November 2017.
- Time step: 1 h.

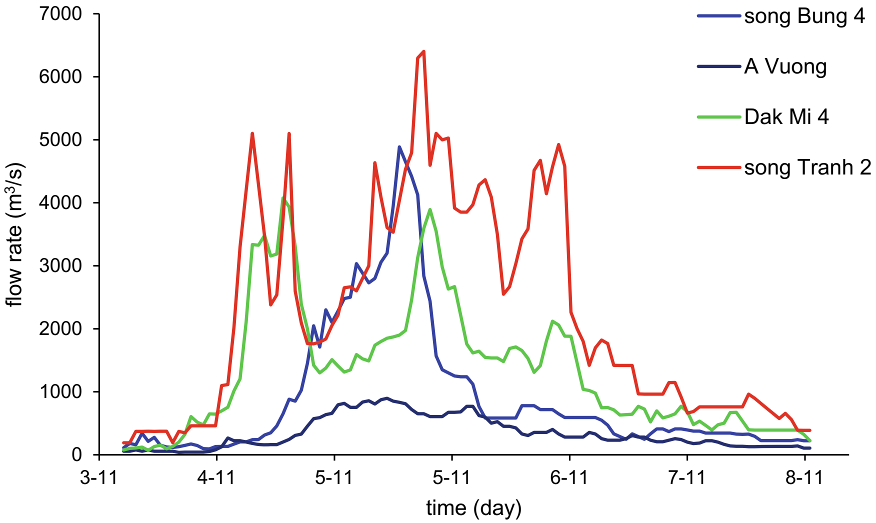


Fig. 66.4 Inflow hydrographs of four reservoirs in flood event 2017

Table 66.1 The flood event in 2017

Reservoir	Peak discharge (m^3/s)	Total volume (106 m^3)
A Vuong	897	138.49
Dak Mi 4	4075	534.64
Song Bung 4	4887	372.97
Song Tranh 2	6402	903.77

From Table 66.1, it can be seen that the runoff coming have a significant volume and peak discharge, in which the return periods corresponding are 25, 25, 20 years in Dak Mi 4, Song Bung 4 and Song Tranh 2 reservoirs, respectively, while a small volume in A Vuong reservoir.

The initial reservoir storages are also set to the historical levels, that is 243.59 million m^3, 243.57 million m^3, 534.81 million m^3, 413.78 million m^3, corresponding reservoir stage 368 m, 251 m, 165 m, 216 m in the A Vuong, Dak Mi 4, Song Tranh 2, and Song Bung 4 reservoirs, respectively.

66.4.2 Results

In order to show the significance of the simulation-based optimization model, the optimization strategies are applied simultaneously for the multi-reservoir system in the Vu Gia Thu Bon catchment. Here, comparisons with the downstream control points peak runoff and the maximum water level are made among two scenarios: (1)

the historical, and (2) the optimal operation. The simulated optimal gate operation of four reservoirs is compared to the actual rules during the flood event. Inflow and outflow hydrographs released for all reservoirs performed by the historical operation and proposed model are shown in Figs. 66.5 and 66.6.

Magnitude and duration of flooding in downstream critical control points obtained from the simulation of two scenarios that are: the historical operation rules and the application of the SCE algorithms for operating are compared to highlight the differences (Figs. 66.7 and 66.8). Table 66.2 illustrates that the peaks runoff and maximum water level at downstream derived from the simulation-based optimization model (proposed model) are lesser than from current rules.

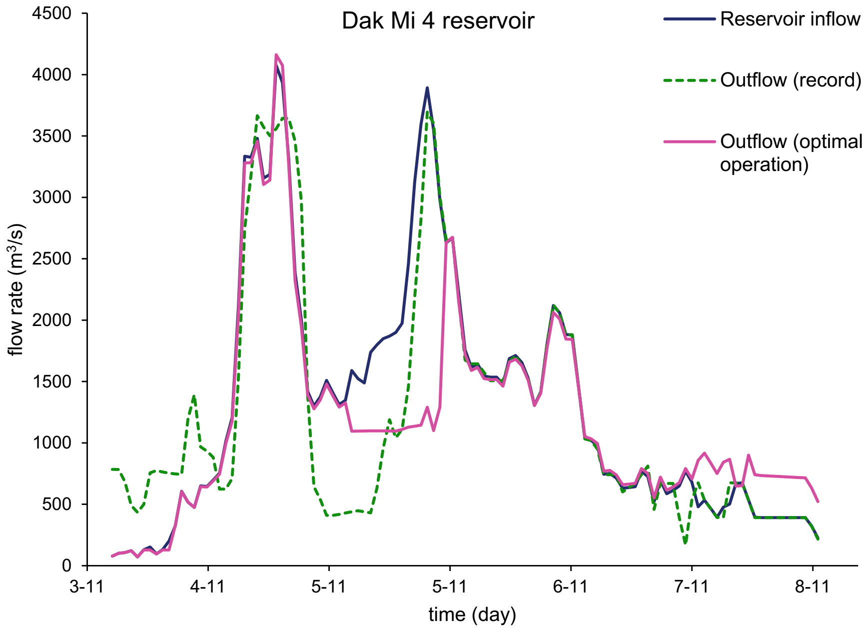
Results of the downstream peak runoff reduction rate (QR) and maximum level reduction rate (HR) during flood events were also calculated and listed in Table 66.2. The results of historical operation and proposed model are: (1) at Ai Nghia station for criterion QR by 19.11 and 31.11%, respectively; for criterion HR by 7.68 and 11.37%, respectively; (2) at Giao Thuy station for criterion QR by 19.89 and 26.43%, respectively; for criterion HR by 7.48 and 10.22%, respectively. From Table 66.2, once we can find that the two downstream control points peak runoff reduction rate (QR) and maximum level reduction rate (HR) derived from the proposed model are more significant than historical operation.

66.5 Conclusions

The primary purpose of flood control is to avoid downstream flood damages and to protect the reservoir itself. The main goal of the current research was to determine the optimal release during flood events for the multi-reservoir system in the Vu Gia Thu Bon catchment. To attain these goals, the simulation–optimization framework is adopted for determining the spillway gates operation strategy. The Structure Operation (SO) module in the hydrodynamic model Mike 11 is adopted for simulation of the operation multi-reservoir while the Shuffled Complex Evolution (SCE) algorithm is applied to determine the best set of spillway gates stages.

The method has been successfully implemented for the multi-reservoir system in the Vu Gia Thu Bon catchment.

The flood event in 2017 was selected for demonstration. In order to assess performance of the approach and for comparison purpose, three developed scenarios that are representing operations the reservoir system in the historical, the current rules and the proposed model have been used. The results indicate that the proposed model provides much better performance for all scenarios in terms of reducing the peak flow as well as reducing the maximum water levels at selected downstream control points compared to the rest scenarios. Our experiments obtained results find the agreement are in line with previous studies' results [11, 12]. Consequently, the SCE algorithm demonstrates its effectiveness for optimizing of complex reservoir systems.



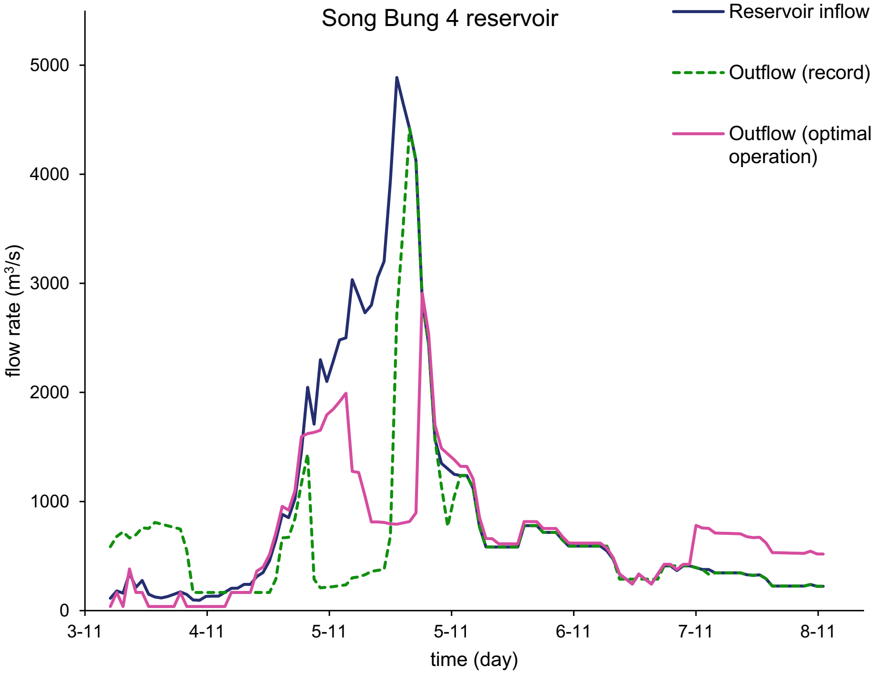


Fig. 66.5 Hydrographs of Dak Mi 4 and Song Bung 4 reservoirs in flood event 2017

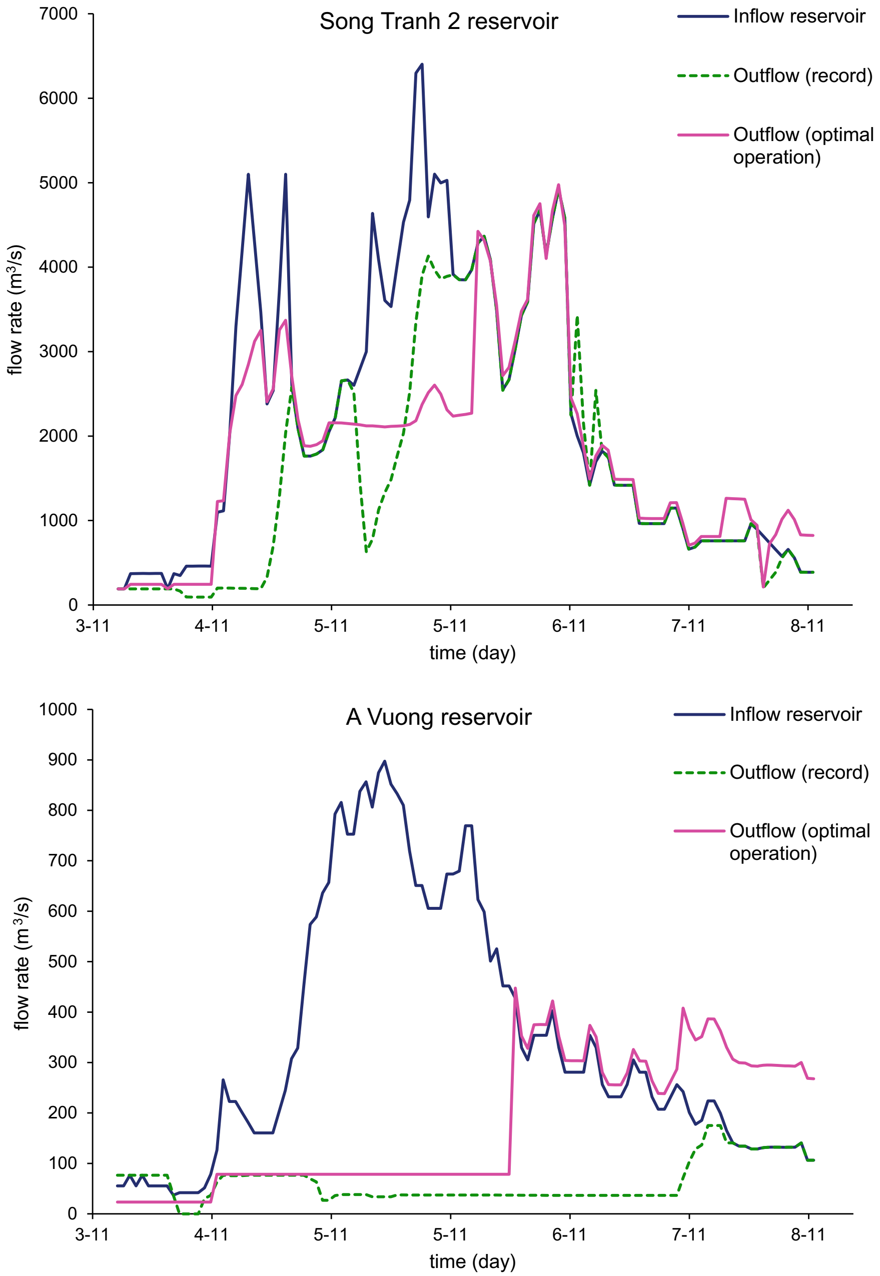
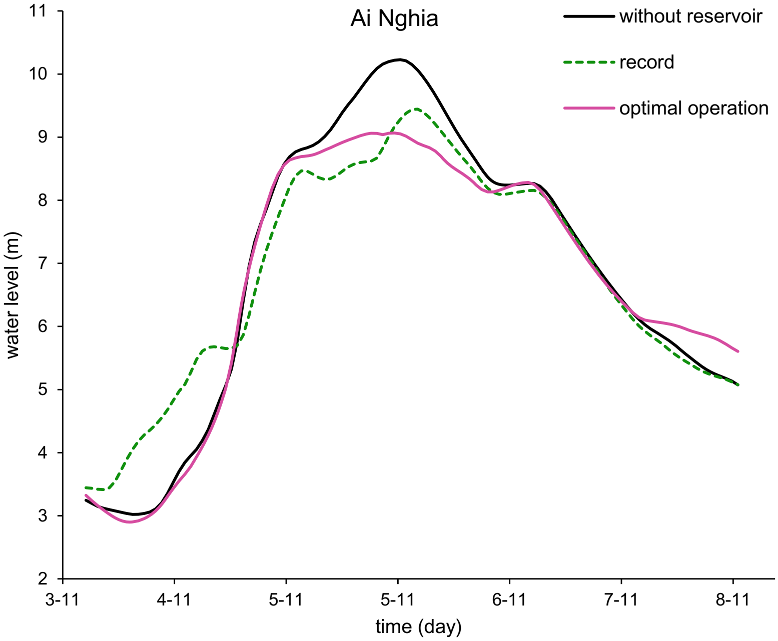


Fig. 66.6 Hydrographs of Song Tranh 2 and A Vuong reservoirs in flood event 2017



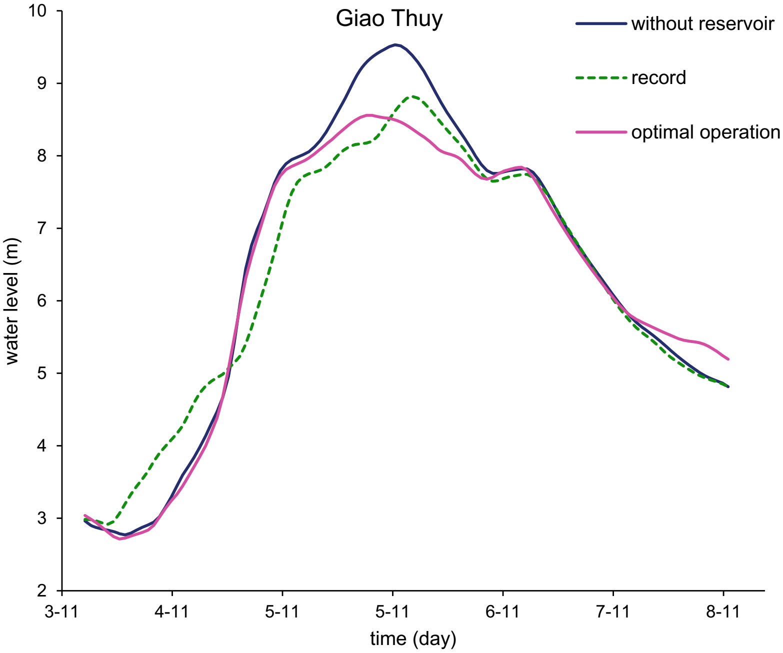
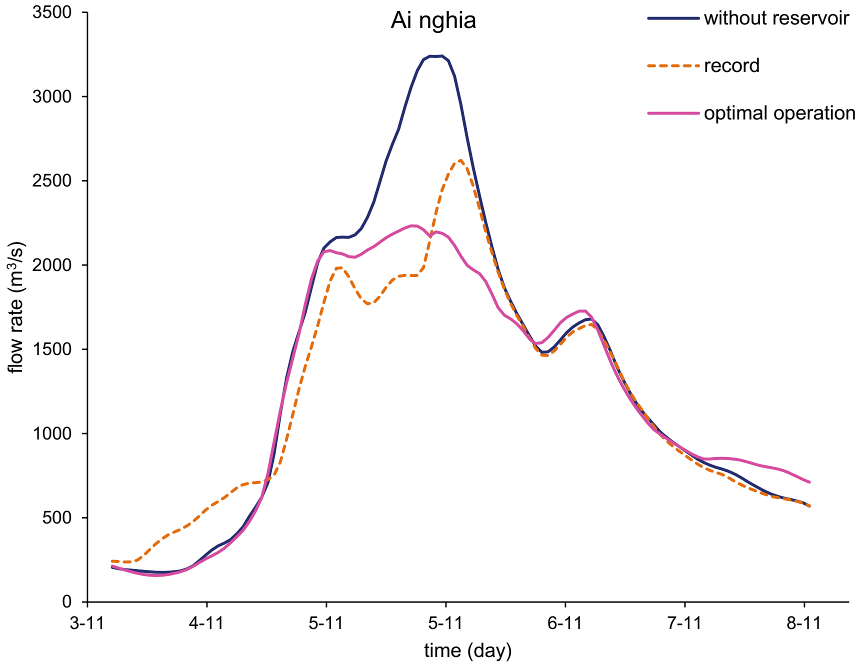


Fig. 66.7 Water level hydrograph of three scenarios at the control points in 2017 flood event



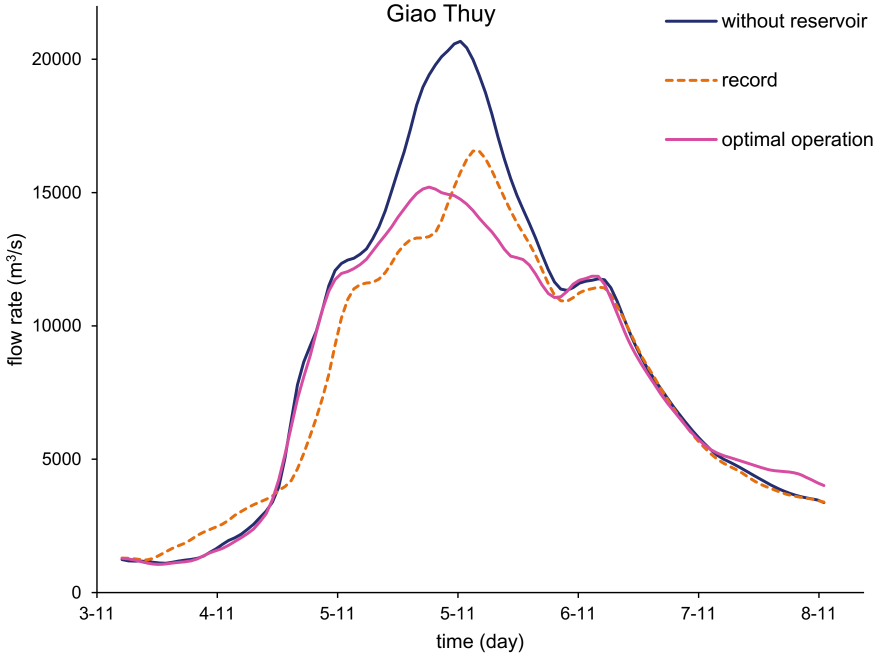


Fig. 66.8 Runoff hydrographs of flood events 2017 at the control points

Table 66.2 Comparison of the flood operating results among operators and the proposed model

Control point	Scenario	Downstream control-point			
		Maximum water level (m)	HR (%)	Peak runoff (m^3/s)	QR (%)
Ai Nghia	Operator	9.44	7.68	2621	19.11
	Optimal operation	9.06	11.37	2232	31.11
Giao Thuy	Operator	8.82	7.48	16,561	19.89
	Optimal operation	8.56	10.22	15,208	26.43

In respect to the obtained results, there are still several limitations which should be handled in future work. Specifically, estimating the flood damages in terms of economic indicators has not been proposed. Consequently, the exploration of the destruction concerning the floods to different regions, i.e., agricultural, residential and industrial areas, should be lighted up in detailed.

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