Optimal operation of multi-reservoir system for flood control and hydroelectric generation

Gestion optimale d'un système multi-réservoirs pour le contrôle des crues et la production hydroélectrique

Thanh Hao Nguyen[1]*, and *Philippe* Gourbesville[2]

[1]The University of Danang - University of Science and Technology, 54 Nguyen Luong Bang, Danang, Vietnam
[2]Polytech Lab, University Côte d'Azur, 06410 Biot, France

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 the maximum water level of the downstream control points and hydropower potential generation in the flood season are objective functions, 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 the Mike 11 from 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. The proposed method was demonstrated to provide an effective tradeoff between flood control and hydropower generation.

Résumé. Ce travail de recherche a comme objectif de développer les méthodes d'évaluation des opérations des retenues, nécessaires à la protection contre les crues du bassin versant Vu Gia Thu Bon. La stratégie de contrôle des crues est basée sur un modèle qui associe simulation-optimisation. La fonction objective consiste à minimiser les dégâts totaux d'inondation, qui dépend des débits ou des hauteurs d'eau dans les secteurs aval. La méthode proposée comporte trois composants majeurs : (1) la simulation des débits et des niveaux d'eau réalisée par un modèle hydraulique 1D ; (2) la simulation des opérations pour la production hydroélectrique réalisée par un module d'opération de structure ; (3) un modèle d'optimisation (algorithme Shuffled Complex Evolution) destiné à obtenir les règles optimales d'opération pour les retenues. La méthode a été

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* Corresponding author: nthao@dut.udn.vn

mise en œuvre avec succès pour le système multi-réservoirs dans le bassin versant du Vu Gia Thu Bon, Vietnam. Les résultats obtenus indiquent que les stratégies proposées par le modèle offrent de bien meilleures performances pour la réduction du débit de pointe et sur la diminution du niveau maximal de crue dans les secteurs aval.

1 Introduction

The Vu Gia Thu Bon river basin is the fourth largest in terms of potential hydroelectric capacity in Vietnam after the Da, Dong Nai, and Se San river systems [1]. This basin plays a significant role in the social and economic aspects of the central region of Vietnam. The Government of Vietnam has planned eight large-medium hydropower projects on Vu Gia Thu Bon catchment in the seventh National Power Development plan with a total power capacity of approximately 1,100 MW [2]. Besides undeniable benefits, operating of the hydropower reservoir system still has some limitations and the project is frequently judged to have increased natural disasters in recent years. Flood damages caused by hydropower operation could elicit public outrage, leading to increases stress for decision-makers in performing the flood control operation [3]. During the flood event in 2013, all hydropower reservoir operators stated that they had complied correctly with operational regulation. Still, the residents who suffered the severe flooding consequences did not absolve the responsibility of the operators [4]. In such difficult and conflicting situations, the analysis of multi-reservoir system operation typically with optimization and simulation models can provide quantitative information to improve operational water management.

The flood limit water level (FLWL) is an effective method to balance flood control and water conservation during the flood season [5], [6]. It is the maximum allowed water level required for flood control and also the maximum water level reserved for water conservation such as water supply, hydropower generation during the flood season [7], [8]. In the flood season, the reservoir water level must be maintained below the FLWL in order to leave enough room for flood storage. Once the flood peak passes and starts to recede, the reservoir stage must be reduced to the FLWL as soon as possible to provide adequate storage for the next flood events. This value is the most significant parameter of a trade-off between the activities of flood control and conservation [9]. The water level of reservoirs should not be too high during the flood seasons due to the likelihood that significant floods can occur, while the reservoir water level should not be too low due to water storage demands [10].

In the current research, an optimal design model for the FLWL boundary of a multi-reservoir is proposed to simultaneously optimize the flood control risk and hydropower generation potential of the reservoir system in the flood season. The popular Shuffled Complex Evolution (SCE) global optimization method that is used the AutoCal software, is coupled with the hydrodynamic Mike 11 model for optimizing the FLWL boundary. 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. The proposed model is applied to the four large multi-purpose reservoirs in the Vu Gia Thu Bon catchment using the hourly inflow data series for representative hydrological years.

2 Methodology

2.1 Multi-objective optimization framework

Multi-objective optimization of a multi-purpose multi-reservoir system refers to a problem that involves several objectives to be optimized simultaneously, such as flood control, water supply, hydropower generation. However, the objectives are often in conflict with each other and are calculated by different units [11]. Thus, when there are two or more performance measures, one of the most critical components of multi-objective problem solving is how to evaluate the parameter sets. The techniques to solve multi-objective optimization can be classified into two main groups: (i) aggregation approaches, and (ii) Pareto domination approaches.

An aggregate objective function method transforms a multi-objective optimization problem into a scalar optimization problem [12]. Usually, these aggregate functions use weighted sum, distance function, and utility function [13]. In contrast to the aggregation approach, there is a set of trade-off solutions, generally known as Pareto optimal solutions (also known as non-dominated). Such solutions are optimal in the sense that no other solutions are better than them in the creative potential, or can dominate them when considering all the objectives [14].

In the current approach, the aggregation approach has been chosen and is applied. The multi-objective optimization problem explores the entire Pareto front between the objective functions by performing several optimization runs using different weights. The weight allocated to the objective function in the combination of the various objective functions to be transformed into one aggregate calculation. Depending on the specific model application being considered, the assigned weights should reflect the relative priorities given to the different objectives. The defined objective functions are aggregated into one measure as follows:

$$f(X) = w_1 f_1(X_1, X_2, \dots, X_k) + w_2 f_2(X_1, X_2, \dots, X_k) + \cdots + w_q f_q(X_1, X_2, \dots, X_k) \quad (1)$$

where:
$f_1, f_2, \dots, f_q$, are the individual objective functions;
$w_1, w_2, \dots, w_q$, are weighting factors ($0 < w_i < 1$) and $\sum_{i=1}^{q} w_i = 1$;
$X_1, X_2, \dots, X_k$, are the parameter sets.

Transformation functions are used to account for variations in the magnitudes of the different units, so the weighted objective function can be changed, as shown below:

$$f(X) = w_1 g_1 f_1(X_1, X_2, \dots, X_k) + w_2 g_2 f_2(X_1, X_2, \dots, X_k) + \cdots + w_q g_q f_q(X_1, X_2, \dots, X_k) \quad (2)$$

where:
g_i is the transformation functions assigned to each objective function.

$$g_i(F_i) = \frac{F_i}{\sigma_i} + \varepsilon_i \quad (3)$$

σ_i is the standard deviation of the i^{th} objective function of the initial population used in the optimization algorithm;

ε_i is a transformation constant given by:

$$\varepsilon_i = max\left\{min\left\{\frac{F_j}{\sigma_j}\right\}, j = 1,2,\ldots,N\right\} - min\left\{\frac{F_i}{\sigma_i}\right\} \tag{4}$$

2.2 Simulation method

According to the above description, the computational core of the Mike 11 model consists of a hydrodynamic simulation engine and a wide range of additional modules [15]. Structure Operation (SO) is one of the add-one modules that can be used to define operating strategies for structures such as sluice gates, overflow gate, radial gate, pumps, and reservoir release, which may be included in the river network.

Control structures may be used whenever flow through a structure is to be regulated by the operation of movable gates, which forms part of the structure. They can also be used to control the flow directly without considering the moveable gate into consideration. Which is note as the simulation of a pump. With the SO module, control structures may be operated by choosing among an arbitrary number of different control strategies, which are presented as a sequence of ‘IF-THEN’ statements.

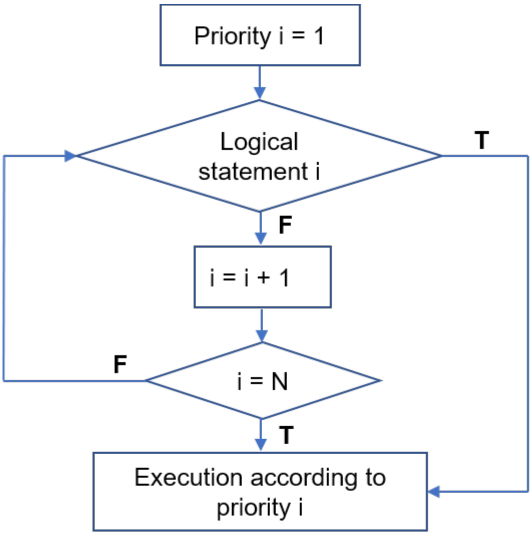

Fig. 1. Operational procedure on SO module.

The calculation of the gate operation is determined from a control strategy. A control strategy describes how the gate level depends on the value of control points. For a specific gate, it is possible to choose among an arbitrary number of control strategies by using a list of “IF” statements [16]. For each of these statements, it is possible to define an arbitrary number of conditions that all must be evaluated to True if the “IF” statement is to evaluate to True (Fig. 1). It is hereby to made probable to use different operating policies depending on the actual flow regime, reservoir stage, the water level at a control point, and time of the year, etc.

A control strategy consists of two parts: (1) conditions that must be fulfilled for the strategy to be executed and (2) a control strategy itself. The control strategy itself is a relationship between an independent variable (the value of the control points) and a dependent variable (values of the target points).

As mentioned above, it is possible to make Mike 11 model choose among an arbitrary number of control strategies. The control strategy belonging to the first of these statements that are evaluated to True will be executed (Fig. 1). Thus, it is important for the user to define which “IF” statement that is evaluated first, second, third, and so on. In this research, a simulation model that simulates the releases from the four reservoirs in the Vu Gia Thu Bon catchment, through the operational structures spillway gates, specified in Mike 11 model as a control structure.

2.3 Optimization model

The above objective functions are used to build a simulation-based optimization model with decision variables of FLWL. Fig. 2 shows the framework of the simulation model coupled with the optimization model. The optimization of FLWL, a multi-reservoir system, can be formulated as a combination of a simulation model and an optimization algorithm.

In this method, the SO module of the hydrodynamic model Mike 11 is adopted for the simulation of the operation multi-reservoir considering the physical constraints of the system as well as operation policies. The SCE algorithm is applied to determine the best set of decision variables, such as FLWL. In this study, the SCE algorithm, as implemented in the AutoCal [17] software, is adopted for optimizing FLWL of the multi-reservoir system in the case study.

In the first step, the SCE algorithm generates an initial population that meets all the constraints. Once the sets of FLWL are determined, the SO module is run to simulate the operation of a multi-reservoir and to determine the releases from all reservoirs. This hydraulic model also computes the flow discharges and water levels in the river network. Then, the optimization model evaluates the objective function based on the selected results from the simulation model. If one of the criteria for termination is satisfied, then stop the program; otherwise, return to execute the simulation model with a new set of FLWL generated by the SCE algorithm.

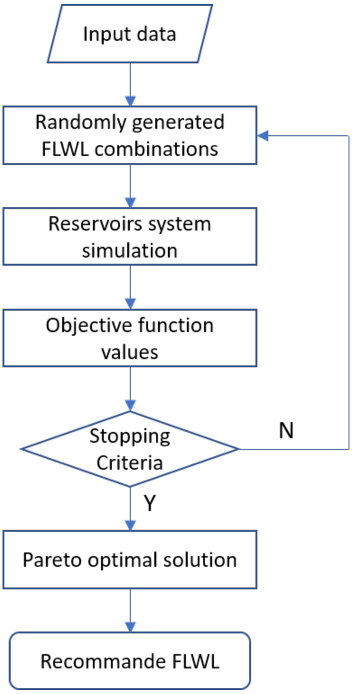

Fig. 2. Framework of the optimal scheduling model of FLWL.

3 Case study: Vu Gia Thu Bon reservoirs system

The Vu Gia Thu Bon is the biggest river basin in the central region of Vietnam which extending from 14°54'N to 16°13'N and 107°12'E to 108°44'E (Fig. 3). The catchment borders on the Cu De basin to the north and the Eastern Sea to the east. It shares borders Tra Bong basin to the south, with the Mekong basin to the west. The total catchment area is 10,350 km2, which 70% mountainous, and 30% is foothill and plain, located in the major area of Quang Nam province and Danang city as well as small parts of Kontum province.

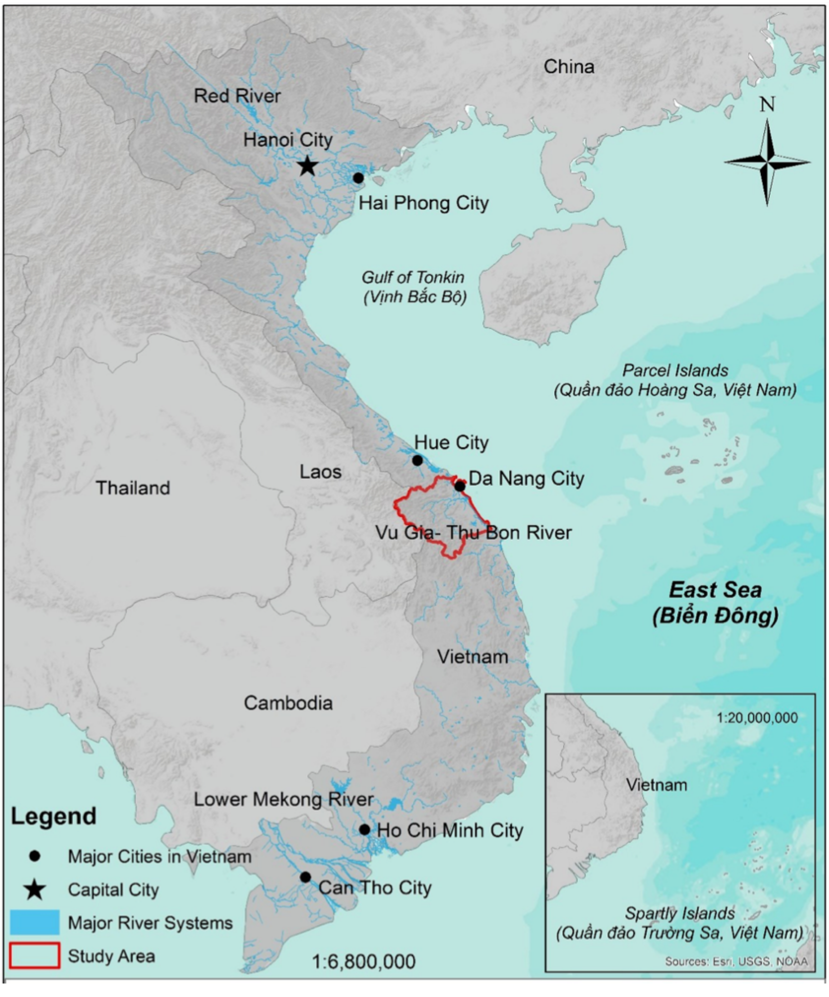

Fig. 3. Location of the Vu Gia Thu Bon catchment [18].

The catchment's natural topography divides the area into three major landscapes, the highlands, midlands, and lowlands (Fig. 4). The Truong Son mountain distinguishes the topography in the highlands with the highest elevation at over 2000 m and the Komtum mountain with mount Ngoc Linh as the highest mountain at 2598 m. On the one hand, the highland area presents steep sloping topography. The river is short and steep with narrow valleys, steep riverbanks, and many waterfalls and rapid flow. On the other hand, the midlands have lower hills ranging from 200 m to 800 m in comparison to the highlands [19], the river beds widen and shallow.

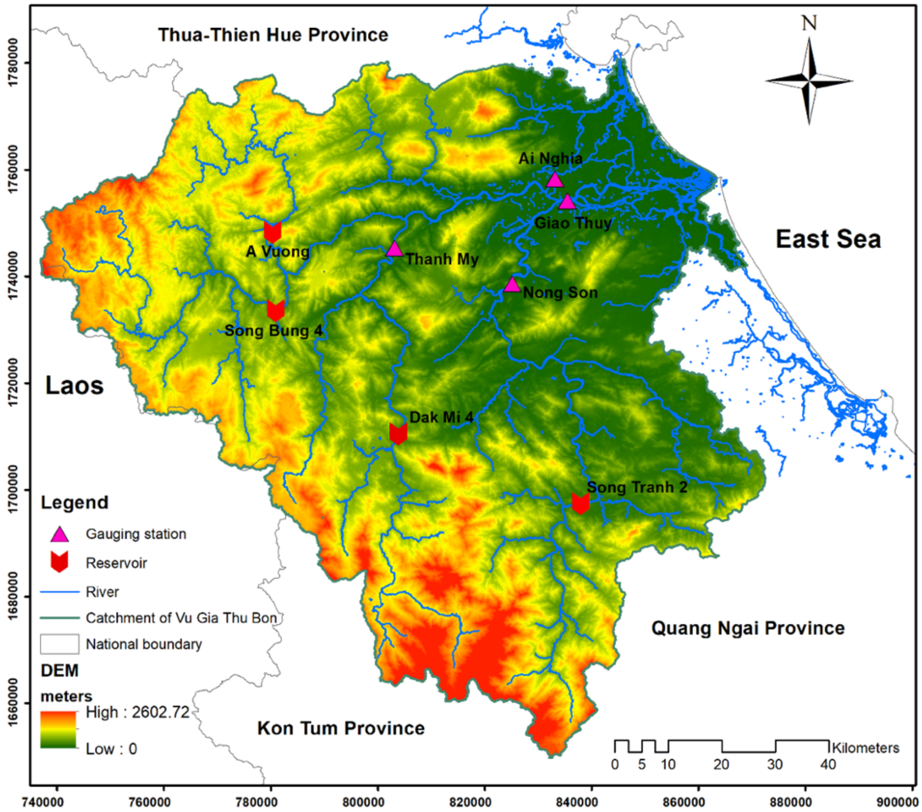

Fig. 4. Multi-reservoir system in the Vu Gia Thu Bon catchment.

The topographic conditions of this area are advantageous for the hydropower project development, as is the case where a large number of hydropower facilities have been built in recent years ago. Areas below 25 m characterize lowlands; the riverbanks become low, allowing overflows into the fields and villages during the flood season. In the lowlands, the river system has many different connected branches by natural and artificial canals.

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. 4). These four reservoirs play the most important role in flood control in the Vu Gia Thu Bon catchment.

3.2 Conventional operating rules

Flood control and hydropower generation that may be equally crucial in the operation of a reservoir system, correspond to two different water levels in the reservoir, FLWL and normal water level, respectively (see Fig. 5). The FLWL should not be surpassed by the reservoir water level during the flood season to maintain adequate storage for flood prevention. The normal water level is the highest water level under regular reservoir operation. Note that the storage volume defined between FLWL and the normal water level is called flood control storage, while the storage volume defined between the normal water level and the dead water level is the conservation storage (or active storage) and is used for hydropower generation (Fig. 5).

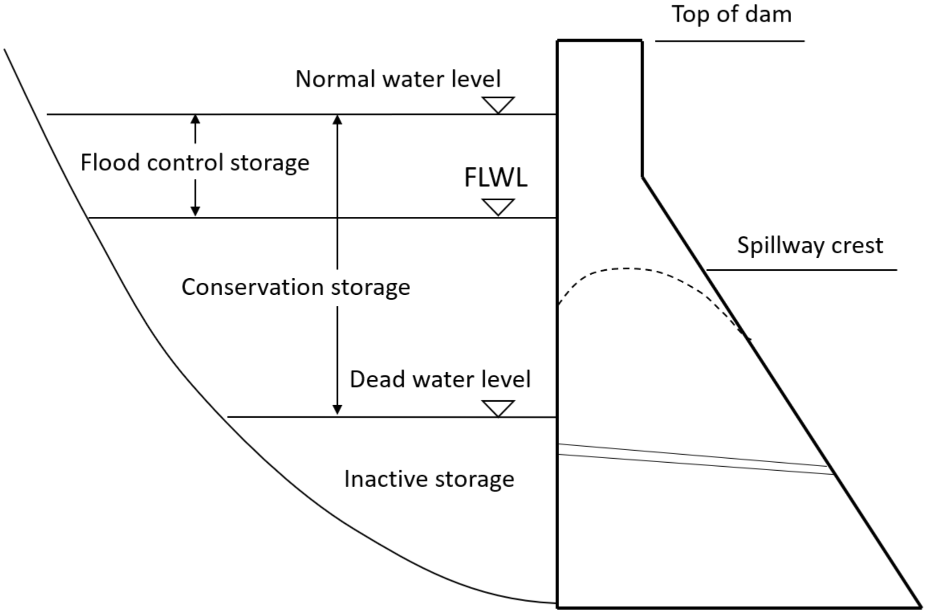

Fig. 5. Sketch of index water levels and storage zones of the reservoir.

The four major reservoirs in the Vu Gia Thu Bon catchment include A Vuong, Dak Mi 4, song Tranh 2, and song Bung 4, which have been put into operations since 2009, 2011, 2012 and 2014, respectively. Following the operational regulation, the flood season is normally from 1st September to 15th December of every year. During the flood season, the multi-reservoir system is operated in the following order of priority:

- Strictly ensuring the safety of the dams;
- Taking part in reducing downstream floods;
- Ensuring efficiency in hydropower generation.

The conventional operating rules of the four reservoirs in the Vu Gia Thu Bon catchment during flood season are as follows: the FLWLs have fixed values from the 1st September to 15th November (Fig. 6). When the reservoir inflows exceed the downstream safety discharge, retaining excess floodwater in flood storage reduces the flood peaks. One the flood has subsided, the reservoir stages should return to FLWL to keep adequate storage for other potential flood events. The reservoir is refilled to the normal water level from 15th November.

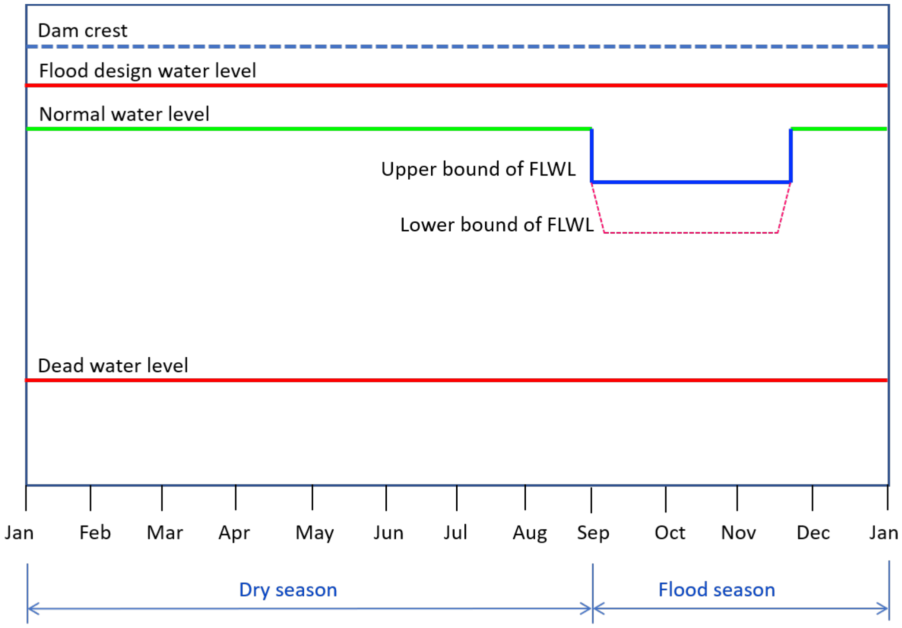

Fig. 6. Flood limit water level (Hypothesis: flood season from 1st September to 15th December).

According to the description above, the FLWL should not be kept high during the flood season to offer adequate storage for flood prevention. In the dry season, with hydropower generation, it is difficult to avoid possible shortages of water simultaneously. The problem is that precipitations are concentrated during the flood season, from September to December, and bring over 70% of annual rainfall volumes. However, the large amount of inflows generated during this season by these intense precipitations are usually released through spillway because the reservoirs do not have enough flood control capacities. Moreover, during flood season, the reservoir stage of the four reservoirs must be lowered to the upper bound of FLWL to secure additional storage for preventing possible flooding. As a result, the decision-makers should carefully select the most appropriate FLWL for the four reservoirs by considering potential shortages downstream and available water resources for the next year.

3.3 Objective function

The primary aim of this section is to deal with the trade-off between flood damages and hydropower generation of the reservoir systems in the Vu Gia Thu Bon basin. Two objectives that are to minimize the downstream flood peak and to maximize the hydropower potential, are introduced to reconcile these two conflicting aspects of reservoir systems operation.

After the determination of the dynamic control bounds, the simulation-based optimization model is used to find out a series of optimal combinations of the upper limit of FLWL in the multi-reservoir that can yield a good trade-off between the economic benefits of potential hydropower generation (i.e., maximizing the hydroelectricity) and risk rate of flood control (i.e., minimizing the flood damages).

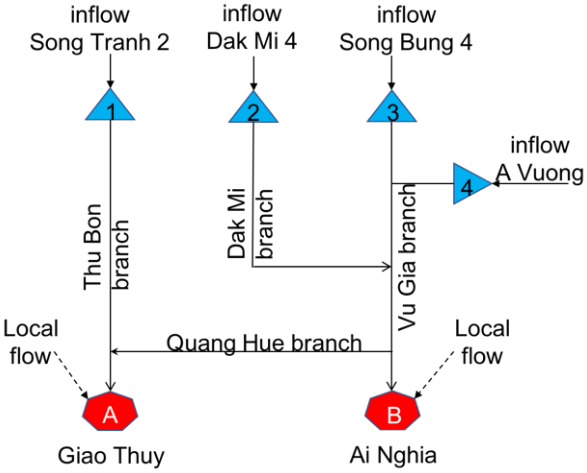

Fig. 7. The Vu Gia Thu Bon river-reservoir system.

**** Minimizing the flood damages***

$$\min F_1 = min\sum_{k=1}^{n} H_k^2 \tag{5}$$

where:

H_k is the maximum water level at the k^{th} control point. In the Vu Gia Thu Bon cactchment, the control points are selected at Ai Nghia and Giao Thuy stations (Fig. 7);

n is the number of control points.

**** Maximizing the hydropower generation***

$$\max F = max\sum_{t=1}^{T}\sum_{j=1}^{m} K_i Q_i^t H_i^t \tag{6}$$

where:

K_j is the hydropower generation efficiency of the j^{th} reservoir;

Q_j is release discharge for hydropower generation of the j^{th} reservoir in period t;

H_j is average hydropower head of the j^{th} reservoir in period t;

T is the total number of time steps;

m is the number of the reservoir; $m = 4$.

The hydropower head depends essential to the reservoir water level during the flood season (i.e., FLWL); therefore, maximizing potential hydropower generation can express as follows:

$$\min F_2 = \left(\sum_{j=1}^{m}\frac{1}{T}\sum_{t=1}^{T}\left(S_t^j - S_{max}^j\right)^2\right) \tag{7}$$

where:

S_t^j is the reservoir stage of the j^{th} reservoir in period t;

S_{max}^j is the maximum reservoir stage of j^{th} reservoir.

**** Multi-objective function***

The two single-objective functions can be then integrated into a multi-objective function using different weights as follows:

$$Minimize\ F = w_1 g_1\left(\sum_{k=1}^{m} H_k^2\right) + w_2 g_2\left(\sum_{j=1}^{m}\frac{1}{T}\sum_{t=1}^{T}\left(S_t^j - S_{max}^j\right)^2\right) \tag{8}$$

where:

w_i is the weight assigned to the i^{th} objective; $0 \le w_i \le 1$ and $\Sigma w_i = 1$.

The first term on the right-hand side in Equation (8) defines the optimal value for flood peak at downstream control points (F_1 is the minimization of the max water level). Whereas, the second term indicates the optimal value for the potential hydropower generation during the flood season (F_2 is the minimization of deviations of reservoir levels from the normal water levels of four reservoirs).

4 Application and results

Preliminary optimization tests showed that after around 500 model evaluations, the entire population converged around the global optimum. The following SCE parameters were selected: the maximum number of model evaluations was 500; the number of iteration loops was 5; the minimum relative change in the objective function was 0.001.

Seven scenarios run with different weight combinations (corresponding to a total of 3500 model evaluations) were carried out to analyze the trade-off between the two objectives and shows the Pareto front as Fig. 8.

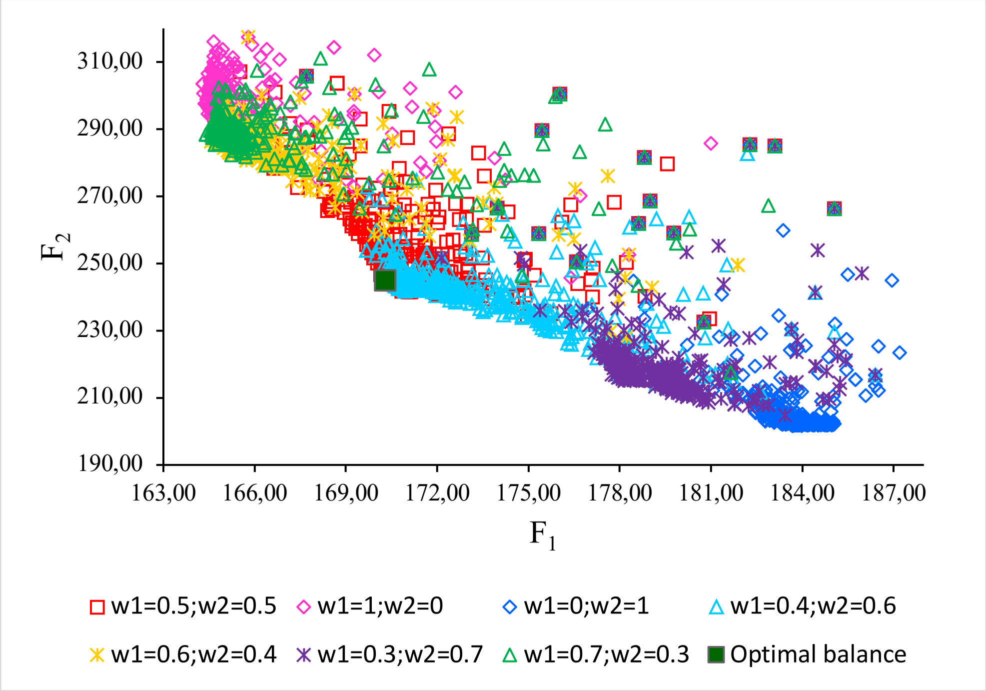

Fig. 8. Objective function values of evaluated decision variables sets.

Two scenarios were used to estimate the tails of the Pareto front. The solutions display in the objective function of only flood control (w_1=1; w_2=0) with points purple while objective function hydropower potential generation (w_1=0; w_2=1) with bleu points. The red points are the objective function using the same weight (w_1=0.5; w_2=0.5) to define balance optimum. The last four scenarios are applied to estimate the intermediary parts.

Table 1. The objective functions values of optimal the upper bound of FLWL using the SCE algorithm for different values of w_1 and w_2.

Objective function	Weights						
	w_1=1.0 w_2=0.0	w_1=0.7 w_2=0.3	w_1=0.6 w_2=0.4	w_1=0.5 w_2=0.5	w_1=0.4 w_2=0.6	w_1=0.3 w_2=0.7	w_1=0.0 w_2=1.0
F_1	164.29	164.39	164.55	170.3	170.73	178.14	183.69
F_2	303.42	288.42	286.26	244.65	242.45	214.97	201.73

Table. 1 shows the value of objective functions with different combinations of weights. It is indicated that the objective of flood control is monotonously increased with the w_1, and the objective of potential hydropower generation is monotonously increased with the w_2. The values of the upper bound of FLWL with different weights are shown in Table 2.

Table 2. The optimal values of the upper bound of FLWL for different combinations of weights.

Upper FLWL value	Weights						
	w_1=1.0 w_2=0.0	w_1=0.7 w_2=0.3	w_1=0.6 w_2=0.4	w_1=0.5 w_2=0.5	w_1=0.4 w_2=0.6	w_1=0.3 w_2=0.7	w_1=0.0 w_2=1.0
$FLWL_{AV}$	370.2	371.0	371.1	**375.8**	376.0	376.0	376.0
$FLWL_{DM4}$	250.7	251.3	251.4	**251.7**	252.7	252.9	255.0
$FLWL_{SB4}$	214.1	214.4	214.4	**215.6**	214.7	218.9	219.0
$FLWL_{ST2}$	167.2	168.6	168.8	**170.1**	171.4	171.7	172.0

In the Vu Gia Thu Bon catchment, flood control is the priority of the multi-reservoir system during the flood season. Therefore, the points mostly assemble on the top left side of Fig. 8 where a lower value of maximum water level is more favorable. The operator can decide a single solution among objectives according to other criteria. The determination of the FLWL was an optimization issue and was subject to balance both risk and benefits constraints. In this case, the most appropriate solution could be a balanced optimum (Fig. 8). The final optimization results of the upper FLWL boundaries for A Vuong, Dak Mi 4, Song Bung 4, and Song Tranh 2 reservoirs were 175.8 m, 251.7 m, 215.6 m, and 170.1 m, respectively (Tab. 3).

Table 3. The optimal values of the upper bound of FLWL for the balanced solution.

	Upper bound of FLWL			
Reservoir	A Vuong	Dak Mi 4	Song Tranh 2	Song Bung 4
Present value (m)	376	255	172	217.5
Balanced solution (m)	375.8	251.7	170.1	215.6

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