

## Developing a Web-based decision support system for reservoir flood management

Mokhtar Ghobadi and Hesam Seyed Kaboli

### ABSTRACT

Proper management of reservoirs in flood conditions minimizes flood damage and keeps the reservoir in a stable condition. This paper presents a Web-based decision support system of reservoir flood management (WDRFM) for reservoirs with gated spillways. WDRFM is capable of estimating the current situation of the reservoir and before the flood reaches the reservoir, provides the operator with suggestions to have optimal control over gates, using multistage simulation-optimization models to minimize flood damage downstream. Investigating the possibility of changing the dam's discharge gates, carrying out dam pre-release, and announcing relevant flood control warnings can all be performed by WDRFM, while allowing the operator to determine such observations and make final decisions on a time step basis. To assess the performance of WDRFM, 15 scenarios in four groups for flood management were defined on April 14, 2016 at Dez Dam, Iran. A comparison of one scenario with similar initial conditions with the occurrence of flood event has shown that a daily peak discharge shows 997 m<sup>3</sup>/s decrease from that recorded by the operator. The ability to examine different scenarios based on the conditions at any time in the WDRFM enables the decision-makers and operators to confront various circumstances.

**Key words** | dam gate operation, decision support system, flood control, Web-based

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### INTRODUCTION

Nowadays, the use of decision support systems (DSS) has developed dramatically, addressing complex and semi-structured issues of water resource management, and owing much of its increasing success to the speed and accuracy of these systems in calculating and proposing options to users, high-cost savings, ever-increasing hardware, and software advances in computer science, information processing limitations by human resources, theoretical and practical developments in applicable relevant areas such as hydrology and meteorology. DSS is a computerized management advisory system that provides decision-makers with timely management data by drawing upon databases, models, and dialog systems (Grigg 1996). After its confirmation as a practical management approach, DSS were widely used in water

resource management systems (Mysiak *et al.* 2005; Anzaldi *et al.* 2014). DSS benefit the decision-makers at different levels of management by providing them with a more efficient plan to manage water resources and, at once, forming a better vision for the future. As a leading researcher in this area, Loucks *et al.* (1985) pursued the development of a DSS for water resources management following an interactive water resources model. More recently, various specific applications of DSS in water resources and commercial software packages have been designed for facilitating water quality management (Camara 1990; Dingfei & Stewart 2004; Paredes *et al.* 2010), impact assessment of policy scenarios adopted by multiple scales of watershed authorities (Davis *et al.* 1991; Holmes *et al.* 2005), reservoir operational management (Simonovic

1992), sustainable water distribution system planning (Freund *et al.* 2017), regional water resources planning (McKinney *et al.* 1993), river flow forecasting (Bender & Simonovic 1994; Wang *et al.* 2017b; Mosavi *et al.* 2018; Yaseen *et al.* 2019), drought monitoring and management (Palmer & Tull 1987; Palmer & Holmes 1988; Chang *et al.* 1996), water allocation (Koutsoyiannis *et al.* 2003; Yang *et al.* 2017), flood control management (Ahmad & Simonovic 2001; Cheng & Chau 2004; Mioc *et al.* 2008; Fotovatikhah *et al.* 2018), integrated scenario-based multi-criteria decision support system (SMC-DSS) for planning water resources management in a river basin (Weng *et al.* 2010), and multi-reservoirs' operational management for securing regional water supply (Opricovic 2011).

Among the most efficient types of decision-making systems are Web-based systems with the following advantages: instant connection for collecting data from various sources, portability and availability, no need to install particular software which clogs system memory, the ability to instantly update and repair the system for all users, and finally, the ability to run on basic systems compared to other systems. Hence, local government and local stakeholders can access the Web-based DSS without the need to visit complex organizations. A Web-based DSS can also easily be transferred to other areas with similar features due to the flexible nature. Specific Web-based DSS applications have been designed for urban water resource management (Zeng *et al.* 2012), flood and fire management in and around urban areas (Kochilakis *et al.* 2016), irrigation network management considering user management experiences (Wang *et al.* 2017a), flood forecasting system (Li *et al.* 2006), single reservoir operation (Jahanpour *et al.* 2014), reservoir flood control (Yong *et al.* 2009), smart dam operation (Ahmad & Hossain 2019), real-time flood control (Zhu *et al.* 2017), and urban flood warning (Li *et al.* 2011). Considering the user's necessities in designing a DSS is essential (Fernandez & Trolinger 2007). A DSS is developed based on a specific purpose or application in order to provide timely management solutions, and to examine the effects of different decision-making scenarios. Therefore, the development of a Web-based DSS depends on the concept of decision-making that the users of the system need to rely on to be able to solve the problem. It is quite necessary for the DSS to have networking capabilities to log and

process simultaneously the collection of independent data coming from sources located in dispersed geographical locations or the sort recorded by the employees of the various departments. The networking capability of the DSS becomes especially relevant when the timing of flood management becomes a critical element in carrying out the necessary actions, especially to reduce flood damage and coordinating the organizations involved in crisis management with the timely information. Moreover, applying a DSS of flood management requires specialized knowledge of hydraulic and hydrological concepts, analyzing the needed data, and computer programming. It is a major challenge for reservoir operators, and it can have a negative impact on their performance, especially under flooding conditions. The capabilities of a Web-based system can overcome this challenge and make the system user-friendly. Therefore, Web-based DSS can be the most appropriate type of DSS for this purpose, as it simultaneously receives various data on flood management and, by imposing different management strategies and analyzing scenarios, provides the most appropriate solution to local and regional managers. Under such circumstances, the system appears to offer optimal functionality as it takes preventive measures such as alerting and evicting residents in downstream areas, blocking roads, warning hospitals and the Red Crescent, and hence providing those in charge of risk-managing organizations with timely information.

One of the most suitable nonstructural methods for reservoir flood control is the proper operation of dam spillway gates during floods. If a spillway gate is opened more than it should be, a great amount of flow will be released which, in its turn, damages the downstream of the reservoir, reducing the reservoir's role in controlling the flood. Conversely, if the spillway gates are opened less than the required size, the safety of the dam can be damaged, leading to the overtopping of the dam (Che & Mays 2015). In this respect, reservoir flood control has become a complex and semi-structured phenomenon due to the many uncertainties in the flood and multiple decision-makers at different levels of management and thus needs a DSS. Reservoir flood control is also very complicated if the reservoir system lacks a flood forecasting system and volume and peak flow rates are not known. In such a system, the experience and judgment of operators is an important factor in the operation

of dam spillway gates during floods. To optimize the operation of spillway gates in systems without a flood forecasting system, Acanal & Haktanir (1999, 2000) and Haktanir *et al.* (2013) proposed five, six, ten, and fifteen-stage performance policies. In these methods, the volume of reservoir flood control is divided into a small volume of storage, and for each small volume of storage, the reservoir water level and the spillway gate openings are determined on a trial-and-error basis; in this method, a large number of possible answers are given for the operation of spillway gates in times of flood so that an optimal solution can be finalized. Minimizing downstream damage is considered as an objective function to optimize spillway gates' operation (Qin *et al.* 2010; Valerino *et al.* 2010; Ahmed & Mays 2013). The objectives functions are the peak release discharge (Malekmohammadi *et al.* 2010) or the maximum inundation depth at points where downstream damage occurs (Bayat *et al.* 2011). Zargar *et al.* (2016) developed a simulation-optimization model based on a multi-stage method with the purpose of responding to floods where there is no prior knowledge of the shape and size of inflow flood hydrographs, and assuming that the reservoir is full. In this method, the decision as to how much of the discharge will be released at each critical level is made only on the basis of the reservoir water level and the objective function of the optimization problem is to minimize the expected annual flood damage. The number of stages and critical discharge values at each stage are determined independently of inflow hydrograph characteristics. It can prevent the sudden drops and jumps in outflow discharge which may cause a major problem in operating the spillway gates. Since all floods from small-to-large floods (a ten-year flood event to PMF) are investigated simultaneously with a single utilization policy by the optimization model, the operator does not need a flood forecasting system but does not use the entire flood control capacity for small floods while using this capacity may create better results in flood management.

The main objective of this research is to evaluate the feasibility of using a Web-based system for real-time flood management in Dez Dam reservoir, Iran. Therefore, the design of a Web-based decision support system of reservoir flood management (WDRFM) was considered. It provides a management instruction based on the current condition

of the reservoir for each flood event and before entering the dam reservoir; and the entire flood control capacity of reservoir will be used in flood management. Since the development of a real-time flood control system requires detailed hydraulic and hydrological data, this is a challenge for developing countries where data availability is still a major problem. Therefore, we have developed a method that can take advantage of a Web-based system considering all the limitations involved in developing a flood management system for the study area. Despite the operating instructions, the lack of a DSS of reservoir flood management for Dez reservoir led to a significant increase in the release from the reservoir to its maximum capacity, and downstream damages were estimated to be around \$2.5 million in the flood on April 14, 2016.

WDRFM is designed for specific objectives which are: (1) managing the real-time flood in Dez Dam reservoir, Iran; the system provides its suggested results to users before the flood enters the reservoir, according to the specified objective function during the flood; (2) managing all reservoir outlets by the system during flood management according to the limitation of using them; (3) checking the pre-release process when the flood control is not possible using all reservoir outlets; (4) to design a user-friendly system with easy access and no necessity to have sophisticated specialized knowledge for using it; (5) applying this system where the availability of detailed data in hydrologic, hydraulic, and use of forecasting and warning systems are major challenges, especially in developing countries; (6) announcing flood to the downstream area for preventive actions when it is not possible to manage the flood by the system due to the conditions of flood and reservoir. The user, moreover, can determine the objective function in terms of conditions and impose their own limitations at each decision-making interval on the system. The system is designed in a general framework, and the user can easily use the system to change the input data, under various conditions, or even for other reservoirs.

## SYSTEM DESIGN

The objectives for designing the WDRFM system include: user-friendliness and requiring no specialized and complex

knowledge; providing an approach for estimating the reservoir inflow flood hydrograph based on river flow rate measurements at the upstream station; providing a near real-time monitoring system of the reservoir conditions so that modification of the results of flood management strategies becomes possible at individual execution of the program; the ability to select the type of objective function and how to execute the program in terms of accuracy of the answer and determine the interval for the program to run automatically; determine how the gates open based on different scenarios and different suggestions and under probable limitations of using gates; prioritizing the usage of gates, allowing them to engage in the flood control process, and the feasibility of implementing for single-reservoir system. The WDRFM system consists of server-browser architectures, data mining terminals, web server, client browser, and communication system. The web server is developed using ASP.NET based on the C# programming language, the client browser page is written using HTML/CSS/JavaScript, and the data exchange uses Ajax technology. Ajax technology improves server performance and affects the efficient use of the Web by allowing the programmer to make Web applications more attractive, increasing the page loading speed, and decreasing bandwidth usage. Also, ASP.NET framework is purely server-side technology and is not limited to script languages, meaning any programming language (C#, J#, VB, etc.) which is completely suitable for your application, can be chosen. The advantages of C# are object-oriented, automatic garbage collection, strong memory backup, rich library, better integration, familiar syntax, Microsoft support, low-cost maintenance, and properties and indexers which are not available in Java language. These advantages can confirm the choice of C# programming in developing a DSS.

### Data requirement

The required project data are classified into four main categories: dam data, river discharge, parameters of the optimization algorithm, data related to the objective function and how the program is executed (see Table 1). Data that change at different times and need to be updated are automatically scanned by the web server. This information is applied to the system in real time, so the system is

continuously updating its results and the results are presented in accordance with the new conditions for new intervals.

## MODEL BASE MANAGEMENT SYSTEM

The model base in this system includes the following two sections: inflow flood hydrograph estimation based on the measurement of the flow discharge in an upstream station, and multistage simulation-optimization models to obtain the released hydrograph to achieve the target that has been defined by the user.

### Inflow flood hydrograph

Flood hydrographs are estimated by measuring the flow discharge at a station located upstream of the reservoir at specified intervals. First, a flow discharge as defined by the river is regarded as the threshold for floods, so that if the river discharge at the upstream station is smaller than or equal to it, it means there will be no flood and the condition is normal, and hence it will not be necessary to utilize a DSS. However, if the river discharge at the upstream station exceeds the specified threshold, the flood event is detected, and the flood hydrograph needs to be estimated for managing the reservoir under flood conditions. In this case, with each discharge measurement of the river at the upstream station, a flood hydrograph is formed with a peak discharge equal to the discharge recorded together with the peak time which equals the time recorded at the onset of the flood. If the flow discharge recorded at any time step is greater than or equal to the previous value, it means that the hydrograph is located in the rising limb; as a result, it is required to estimate the new flood hydrograph. However, if the river discharge shows a decrease compared to the discharge at a previous time step, it means that the hydrograph is located in the falling limb and there is no need to estimate the new hydrograph, but at any time after this, the falling limb of the hydrograph is modified based on the recorded values. Each estimated hydrograph has its own rising and falling limb, the rising limb is built based on the recorded river discharge values up to that moment, and the falling limb of the hydrograph for the next times is

**Table 1** | Data requirement description

		Unchanged data during system running	Data that need to be updated during system running
Reservoir specifications	Spillway threshold	*	
	Crest level of the dam	*	
	Spillway stage–discharge relationship	*	
	Reservoir volume–elevation relationship	*	
	Minimum and maximum powerhouse discharge	*	
	Minimum and maximum discharge of irrigation gates	*	
	Current discharge of spillway		*
	Current discharge of powerhouse gates		*
	Current discharge of irrigation gates		*
River specifications	Current water level in the reservoir		*
	River discharge at the upstream station		*
	Threshold flood discharge	*	
	Parameters $x$ and $k$ in river routing	*	
Required data in the selected optimization algorithm	An observed flood hydrograph	*	
	In GA: Population size, the number of iterations, percentage of crossover and mutation	*	
	In SA: Population size, the number of iterations, initial temperature, temperature drop coefficient	*	
	In PSO: Population size, the number of iterations, inertia weight ( $w$ ), inertia weight damping coefficient ( $W$ -damp), social parameter ( $C1$ ), cognitive parameter ( $C2$ )	*	
Data related to the objective function and how to execute the program	In the objective function: Peak discharge ratio ( $C$ ), a certain water level of the reservoir		*
	Number of stages in the multistage method (number of decision variables)	*	
	Maximum iteration	*	
	Prioritizing in the use of gates	*	
	Permission to use powerhouse gates and irrigation gates	*	
	Step amount of changing the discharge current	*	
	Step amount of changing the water level in pre-release	*	
	Permissible error		*
	Time step (automatic or manual)	*	

estimated by the logarithmic function as in Equation (1) (Banach 2011):

$$Q(t) = Q_r e^{-\alpha(t-t_k)} \quad (1)$$

In this equation,  $Q_r$  is the flow rate at time  $t$  [ $\text{m}^3/\text{s}$ ] (or the peak of the hydrograph);  $t_k$  the time to reach  $Q_r$  [h] (the same as the time of recording the discharge from the onset of the flood); and  $\alpha$  is a constant coefficient which depends on the catchment characteristics such as soil type, topography, and land use/land cover [1/h]. Where  $\alpha = -LnK$ , the value of  $K$  is expressed by three main

components related to three types of storage: surface storage, subsurface storage, and baseflow. The  $\alpha$  value was obtained based on the relationship presented in the study by Banach (2011) and with an observational hydrograph. Due to the falling limb correction at each time step, this method is the only reliable estimate of the inflow hydrograph to the reservoir.

To determine the inflow flood hydrograph to the reservoir, the estimated flood hydrograph at the upstream station is subjected to a Muskingum method for hydrological flood routing. If backwater effects and inertia influences are negligible in a river reach, the performance of Muskingum method can be best in routing a flood in river systems,



especially where the hydraulic behavior of the system is appropriately presented by choosing model parameters (O’Sullivan *et al.* 2012). The Muskingum model uses continuity and storage–discharge relationships in the river reach which are expressed as:

$$\text{Continuity } \frac{dS_t}{dt} = I_t - Q_t \tag{2}$$

$$\text{Storage } S = k[xI_t + (1 - x)Q_t] \tag{3}$$

where  $I_t$ ,  $Q_t$ , and  $S_t$  are amounts of inflow, outflow, and storage, respectively, at a given time  $t$ ,  $K$  is a storage constant which equates closely to the flood travel time through the river reach and  $x$  is a dimensionless weighing coefficient that describes the effect of inflow and outflow on the river storage; it can be from 0 to 0.5 for natural rivers. The Muskingum parameters, moreover, can be inserted into the system directly by the user, and the system can calculate them by inserting a recorded flood hydrograph at the upstream station and the reservoir through the loop in the storage curves (Yoo *et al.* 2017). More details can be found in O’Sullivan *et al.* (2012).

### Multistage simulation-optimization model

In the multistage simulation approach, as shown in Figure 1, the height of the reservoir between normal water surface level and dam’s crest elevation minus a freeboard (reservoir’s flood retention storage) is divided into a number of critical levels using similar increments. When the water

level in the reservoir reaches these levels during the flood, a predetermined constant discharge from each stage releases from spillway based on the type of flood hydrograph limb and the comparison of the critical flow rate of each stage and the inflow discharge to eventually be converted into an optimal hydrograph for satisfying objective function. Therefore, the main problem in this method is determining the critical flow rates of the stages based on the opening of the spillway gates in each stage. If the opening rate in stage  $k$  is represented by the variable  $\alpha_k$  and  $Q_{max,k}$  is maximum discharge released through the spillway in stage  $k$  while the gates are fully opened, according to the stage–discharge relationship, then the values of  $Q_{crk}$ , which are the critical outflows of the stages, are defined by Equations (4) and (5):

$$Q_{cr1} = \alpha_1(Q_{max1}) \tag{4}$$

$$Q_{crk} = Q_{crk-1} + \alpha_k(Q_{maxk} - Q_{crk-1}) \tag{5}$$

$\alpha_k$  are coefficients between 0 and 1 which are determined by the optimization model. If the coefficient  $\alpha_k = 0$  is selected, the outflow is zero, which means closing the spillway gates. If  $\alpha_k = 1$  is chosen, the flow rate is equal to the maximum spillway capacity in the open-gate mode.

By having a population of  $\{\alpha_1, \alpha_2, \dots, \alpha_k\}$ , we can obtain a specific population of critical discharges for stages such as  $\{Q_{cr1}, Q_{cr2}, \dots, Q_{crk}\}$ , which for the specific inflow hydrograph creates a special outflow hydrograph. Therefore, by creating different populations of gate openings it is possible to study various outflow hydrographs, searching for the optimal

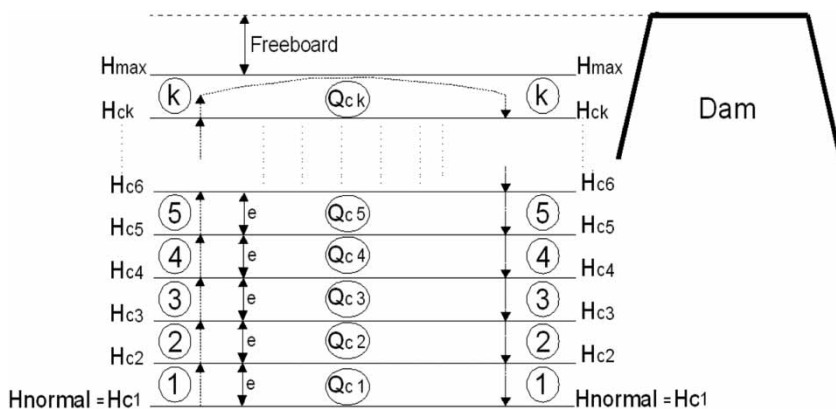


Figure 1 | Multistage method scheme to control the floods (Zargar *et al.* 2016).

hydrograph based on the objective function. Increasing the number of stages leads to an increase in the number of decision variables in the optimization model and reduces the processing speed of the program and, in effect, gradually imposes the gate opening, which prevents a sudden jump in the outflow discharge from the spillway. The number of stages is the input parameters of the program, which the user inserts into the system according to their own discretion. Appropriate values  $\{\alpha_1, \alpha_2, \dots, \alpha_k\}$  are achievable for the purpose of maintaining the desired goal through evolutionary optimization algorithms, such as genetic algorithm (GA) (Che & Mays 2015; Olukanni *et al.* 2018), particle swarm optimization (PSO) (Afshar 2012; He *et al.* 2014; Moeini & Babaei 2017), and simulated annealing (SA) (Teegavarapu & Simonovic 2002). Three powerful algorithms of optimization were addressed, namely, PSO, GA, and SA, to obtain decision parameters or the percentage of gate opening in each water level. However, only one of these three algorithms can be used at each run, but the existence of all of these algorithms allows for the user to select the desired algorithm according to individual expertise and knowledge. Therefore, considering these three algorithms has increased the flexibility and user-friendliness of the system. Here, two objective functions can be chosen according to the user's choice: (a) decision variables should be determined in such a way that not only the peak outflow discharge be smaller than the peak of the inflow flood hydrograph but also reflects the user's desired ratio; (b) the decision variables should be determined in such a way that the reservoir water level reaches a certain amount. In a particular situation for a reservoir or its inflow flood hydrograph, it may not be possible to maintain the intended objectives, and the optimization algorithm getting into an infinite loop. These include the following: (a) an increase in the ratio of the peak of the inflow flood hydrograph to the peak of the outflow hydrograph from the spillway in the objective function; (b) choosing a low reservoir water level into the objective function while the inflow flood hydrograph has a very high peak discharge; (c) the initial reservoir water level from the spillway threshold is so low that the final reservoir water level either does not reach the spillway threshold or rises above the spillway threshold to an insignificant amount while expecting a high flow spillway; (d) choosing a very high water level of the reservoir

into objective function while the inflow flood hydrograph has a low peak discharge. In this situation, a certain number of repetitions as a failure to achieve a goal under the current conditions is recorded by the user to the system, in the sense that if this number is repeated, it can be assumed that under current conditions it is impossible to achieve the intended purpose for subsequent repetitions. Therefore, in the current condition of the reservoir, it is necessary to consider the possibility of changing the other gate's discharge according to the prioritization and to consider the pre-release process. If there is no possibility of changing the current conditions of the reservoir for flood control, the system will alert the relevant organizations and provide the necessary time for preparation and preventive measures.

Figure 2 shows the multistage simulation and optimization combination for achieving the outflow discharge for each water level in each time step. The reservoir water surface level is determined using the flood routing in the reservoir of the dam. After calculating the water level of the reservoir at each time step and comparing it with the critical levels, the released hydrograph from the reservoir can be determined using Appendix A in the Supplementary Material. More details can be found in Zargar *et al.* (2016).

### System management

In the WDRFM system, first, it is tried to control the flood only by opening the spillway gates and not changing the discharge of the other outlets. If the spillway alone is not able to control the flood, based on prioritization and permission, a step-by-step change is made to the discharge outflow of the irrigation outlets or the powerhouse gates, as well as to the outlets' discharge capacity; after each step of change of outflow discharge, reservoir conditions for flood control will be fully investigated. If the first priority outlet is not able to control the flood, then the second priority outlet will intervene in a similar manner. Eventually, if the flood control process was not completed by engaging the powerhouse or irrigation gates or both at their maximum discharge capacity, then the pre-release procedure will be considered. In this way, the water level of the reservoir is reduced step-by-step until it is possible to control the flood at a specific reservoir water level. In this case, the pre-release volume will be calculated

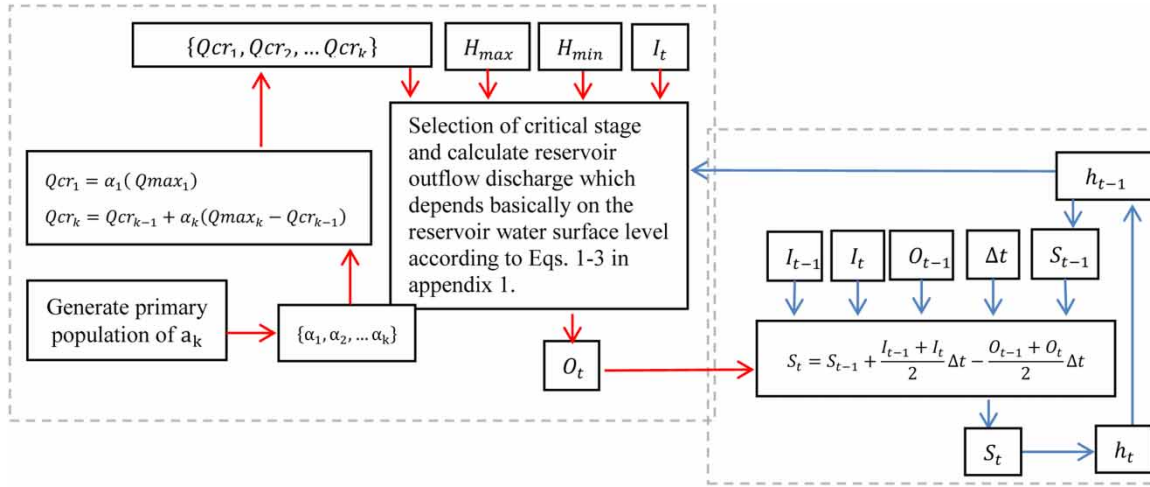


Figure 2 | Flowchart of the multistage simulation-optimization models in each time step.

for the desired water level. If the reservoir pre-prelease procedures cannot be completed before the flood reaches the reservoir, the system will send alerts. The flowchart of the flood management system is presented in Figure 3. Figure 4 shows a view of the WDRFM.

## SYSTEM APPLICATION

### Case study

One-third of Iran's surface water, about 40 billion cubic meters of water, flows into Khuzestan province in the southwest of Iran, which should be managed by dams in this province. The Dez River, as an important branch of the Karun River, is of great importance in the management of downstream floods. Dez River is the result of the confluence of Sezar and Bakhtiari Rivers, and after running for 120 km joins Karun River in the Bande-Ghir region downstream of Dez Reservoir. Dez Dam is a multi-purpose reservoir located on the Dez River, 23 km northeast of Andimeshk city in Khuzestan province, Iran (Figure 5). The main purpose of constructing the dam was to generate hydroelectric power, flood control, and water regulation for irrigation purposes. Recorded data from the floods (Table 2) show that flood inflow can be very severe, and it is a priority for flood management to reduce downstream damage. Conversely, due to the

lack of infrastructure facilities such as flood forecasting and flood alert systems, the use of a system that could provide acceptable results under these conditions was targeted.

By constructing the dam, a 203 m long lake was formed, running for 65 km in length, and hosting a total capacity of 3.3 billion cubic meters of water. There are two outflow tunnels in the eastern side of the lake, measuring 400 m long and slightly spaced from the body of the dam. The diameter of the first tunnel is 14 m and the second tunnel runs for 12.6 m. Each of the tunnels is able to discharge 3,000 m<sup>3</sup>/s. Moreover, two main water tunnels were created on the western side of the lake, each divided into smaller branches whereby water flows into the turbines. The maximum flow discharge of each of the main water tunnels is 240 m<sup>3</sup>/s. In the middle of the dam body at a height of 222.7 m above sea level, there are three cone irrigation gates. The maximum flow discharge of each of these irrigation gates is 60 m<sup>3</sup>/s.

Since the purpose of this research is to develop a Web-based flood management system for critical conditions, the April 14, 2016 flood data were considered to demonstrate the effectiveness of the WDRFM system for managing this flood. On April 14, 2016, a flood with a daily peak discharge of 5,841.75 m<sup>3</sup>/s (maximum hourly discharge exceeding 8,000 m<sup>3</sup>/s) entered the Dez Dam reservoir, which was unprecedented in its lifetime. The spillway discharge capacity of the dam is 6,000 m<sup>3</sup>/s,



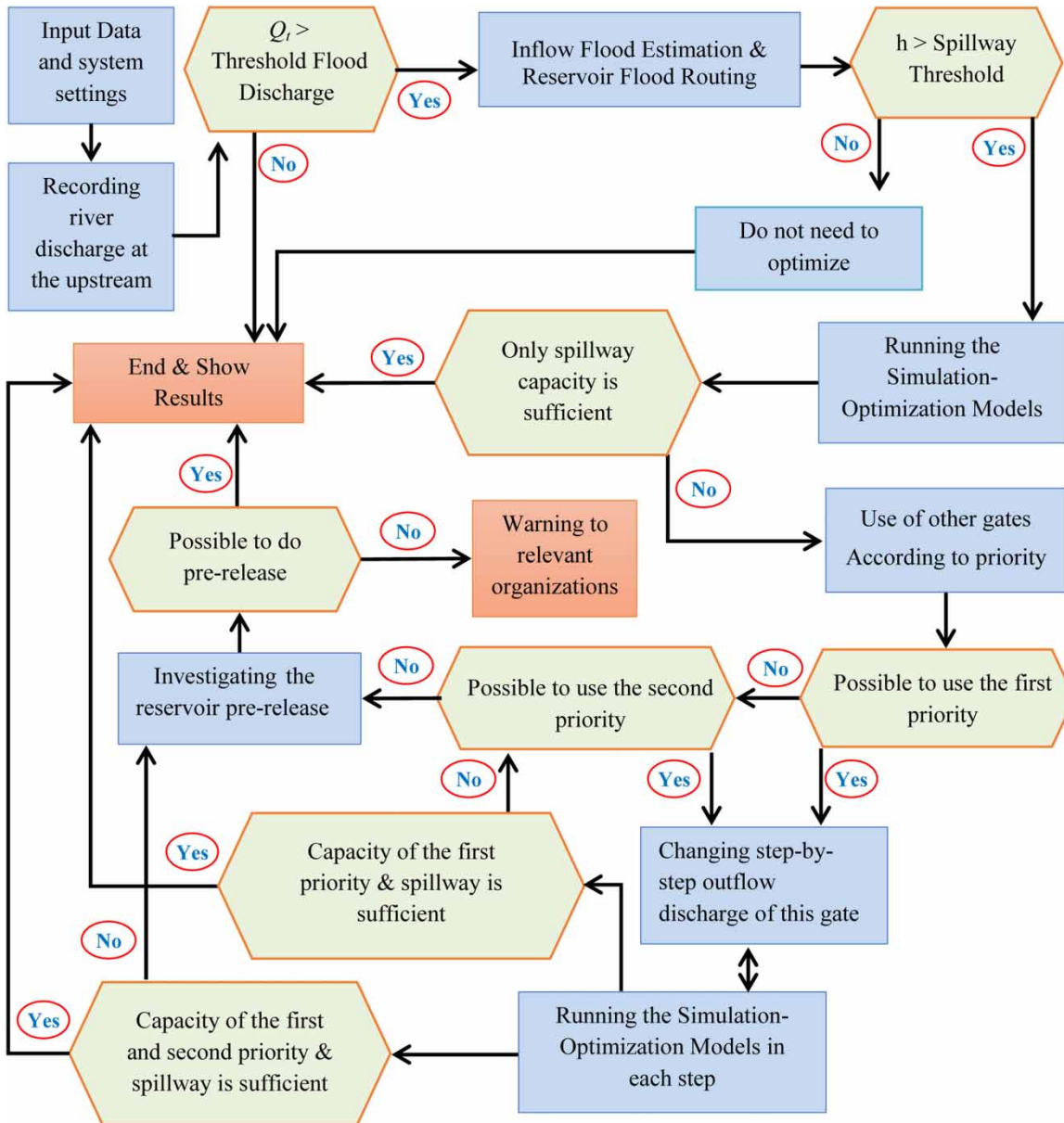


Figure 3 | Flowchart of the WDRFM system in each time step.

which was fully utilized to manage this flood and caused extensive damage downstream of the dam, especially in the city of Dezful. The river flow rate recorded at the Talezang hydrometric station located at the upstream of the reservoir (Figure 5) was used to estimate the flood hydrograph. Talezang station is located at the confluence of the two rivers Cesar and Bakhtiari on the Dez River, where hydro measurements can be effective in managing the

Dez reservoir. The distance between the Talezang station and the reservoir is about 35 km, when water level is located at 352 m above sea level.

#### Analysis of flood control operation in DEZ dam

Analysis of historical recorded floods at the Talezang station show that 57% of floods occur in March and April

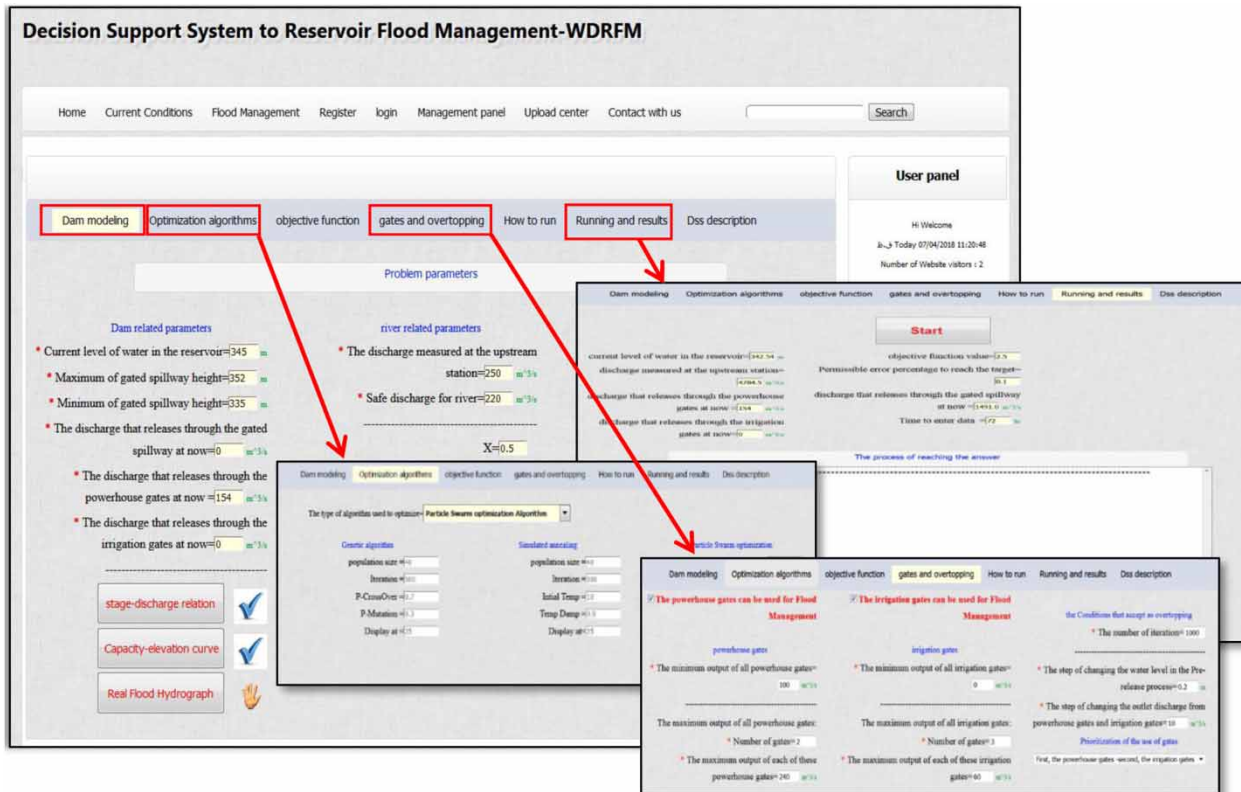
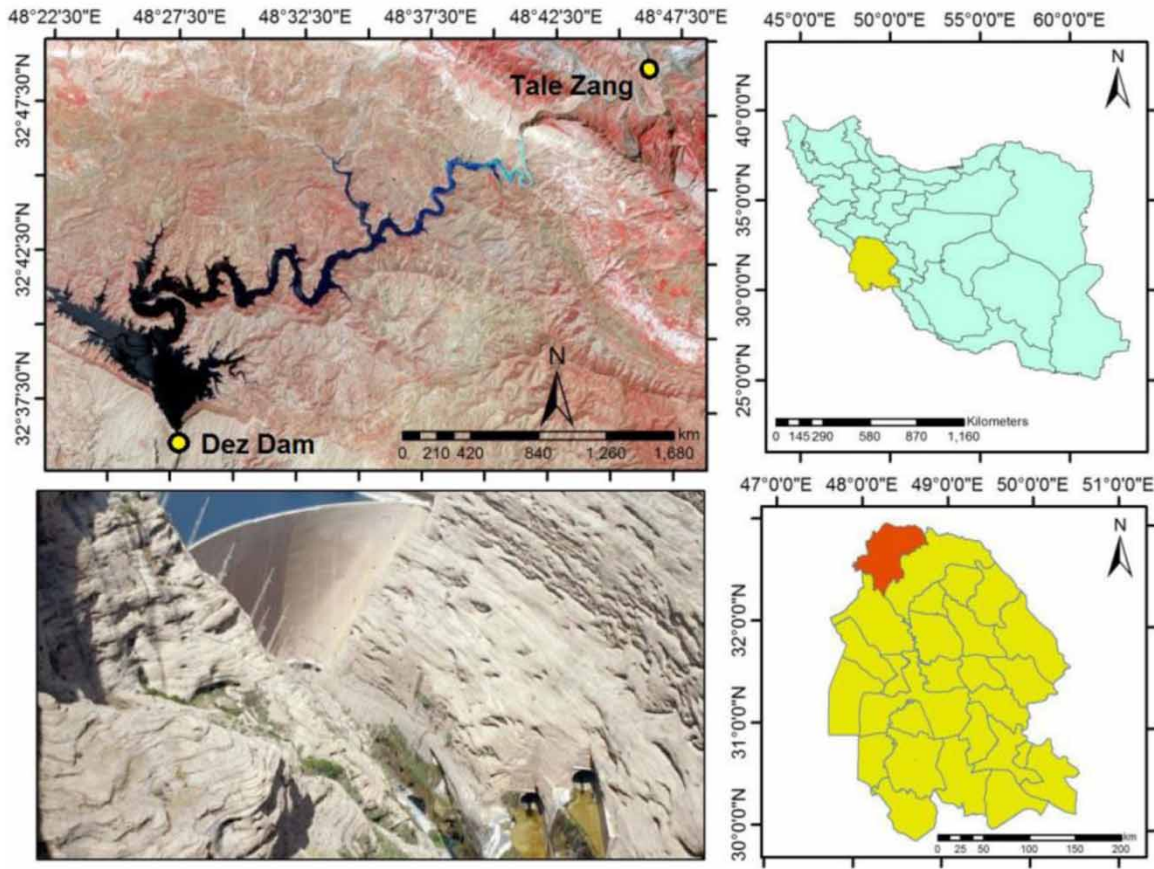


Figure 4 | A view of the WDRFM system.

(Farvardin and Ordibehesht in Persian calendar) (Figure 6). Additionally, as shown in Table 2, there have been floods with peak discharges that exceed the maximum capacity of the dam's spillway, which doubles the significance of gates' operation in this dam. Figure 7 illustrates the minimum and maximum normal reservoir level as an operation rule curve which is calculated by considering downstream demands and hydropower generation. Figure 7 depicts the maximum normal reservoir level on March 20 as 338 m, and 345 m above sea level on April 21. Usually, due to water scarcity issues, the reservoir water level is kept much higher than the maximum normal reservoir level.

Based on the average daily data recorded in the period March 20 to May 20 (Figure 8(e)), the water level of the reservoir on March 20, 2016 was 341.9 m. According to the operation rule curve, the average reservoir water level is about 5 m above the maximum normal reservoir level. Even if this subject can be overlooked in recent years as a result of a slight drought, there are points worth

highlighting: according to Figure 8(b), until April 12 (square marker) there was no considerable flood taking place in this interval, only a small flood (circular markers) with a mean peak of  $624.25 \text{ m}^3/\text{s}$  occurring on March 29. According to Figure 8(a), during the small flood event, the spillway has been completely closed and according to Figure 8(d), the powerhouse discharge was fixed on the range between  $153 \text{ m}^3/\text{s}$  and  $173 \text{ m}^3/\text{s}$ . On April 11, that is the day before the sudden increase in reservoir inflow discharge that was caused by the large flood, the powerhouse discharge capacity has fallen by about  $133 \text{ m}^3/\text{s}$ , which is one of the factors contributing to increasing the reservoir's water level. As Figure 8(c) shows, the irrigation outlets were completely closed during this period. As shown in Figure 8(e), due to the previous small flood, the reservoir water level had increased from 342.52 m to 347.3 m at the time of the large flood, which, according to the operation rule curve (Figure 7), had exceeded the maximum normal reservoir level.



**Figure 5** | Location of Dez Dam and Talezang station.

At these critical times (April 13), one should note, as [Figure 8\(b\)](#) shows, although the daily inflow discharge has reached the value of  $1,477 \text{ m}^3/\text{s}$ , the spillway in the above interval was closed as shown in [Figure 8\(a\)](#), allowing for the powerhouse gates to slightly increase the discharge rate to a value of  $221.8 \text{ m}^3/\text{s}$ , as shown in [Figure 8\(d\)](#) (triangle marker in charts). This eventually led to an increase in the water level:  $349.4 \text{ m}$  (that is only  $4.86 \text{ m}$  to the dam crest). In this case, there was only  $4.86 \text{ m}$  in terms of the height of the reservoir to store any possible flood; and, as shown in [Figure 8\(b\)](#), on April 14 the flood peak reaches the reservoir and increases the daily inflow discharge to  $4,397 \text{ m}^3/\text{s}$ , and as a result, passes the maximum level of water storage, eventually threatening the stability of the dam with flow overtopping. In this case, as [Figure 8\(a\)](#) illustrates, the operator of the dam had to open the spillway at a daily discharge of  $3,230.4 \text{ m}^3/\text{s}$ , and to bring the

powerhouse discharge, as shown in [Figure 8\(d\)](#), to a value of  $280.1 \text{ m}^3/\text{s}$ , and even at certain moments of the day the irrigation outlets opened at a daily discharge of  $34.5 \text{ m}^3/\text{s}$ , as shown in [Figure 8\(c\)](#). In other words, on this day the total daily discharge from the reservoir was equal to  $3,545 \text{ m}^3/\text{s}$ .

Given that the amounts discussed above are the daily values and the instantaneous values are greater than the above values, the sudden discharge of this rate has caused a great deal of damage. According to the study of [Malek Mohammadi et al. \(2010\)](#), assuming the same outflow peak discharge, the damage will be about 299.55 billion rials (\$2.5 million). Such issues double the need for a DSS that helps the operator to manage and control floods. A DSS could, in the first stage, prevent the excessive increase in reservoir water level due to the small flood and even if the water level reached  $347.32 \text{ m}$  in the reservoir, an optimal gate



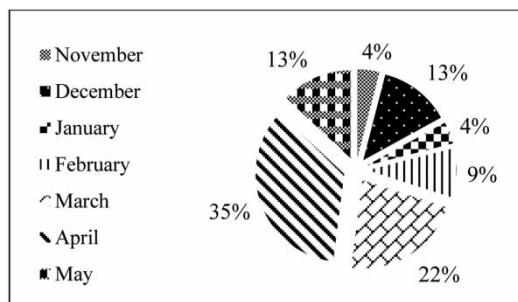


Figure 6 | Percentage of flood occurrence in a year at the Talezang station.

Table 2 | Critical floods recorded at the Talezang station

Time	Duration (day)	Maximum ( $\text{m}^3/\text{s}$ )			
		Direct runoff	Base-flow	Hourly runoff	Daily runoff
11/22/1994	17	6,418	386	6,804	4,529
04/10/1990	10	5,841	539	6,380	2,689
03/27/1998	14	5,680	873	6,560	5,525
02/23/1992	13	5,100	250	5,350	2,757
05/02/1986	14	4,953	457	5,410	3,181
12/25/1978	15	4,257	336	4,593	2,521
02/01/1993	6	4,129	405	4,534	2,744
02/07/1993	11	4,036	995	5,031	3,172
03/02/1989	18	3,917	523	4,440	2,832
12/05/1994	7	3,880	130	4,010	3,183
01/01/1986	16	3,829	85	3,914	2,039
02/03/1969	15	3,667	211	3,878	2,884
01/06/1993	10	3,621	400	4,022	2,813
02/02/1966	5	3,524	943	4,467	2,920
12/22/1987	15	3,509	224	3,733	2,416

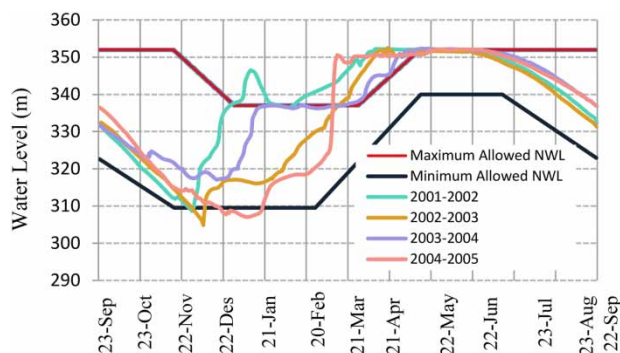


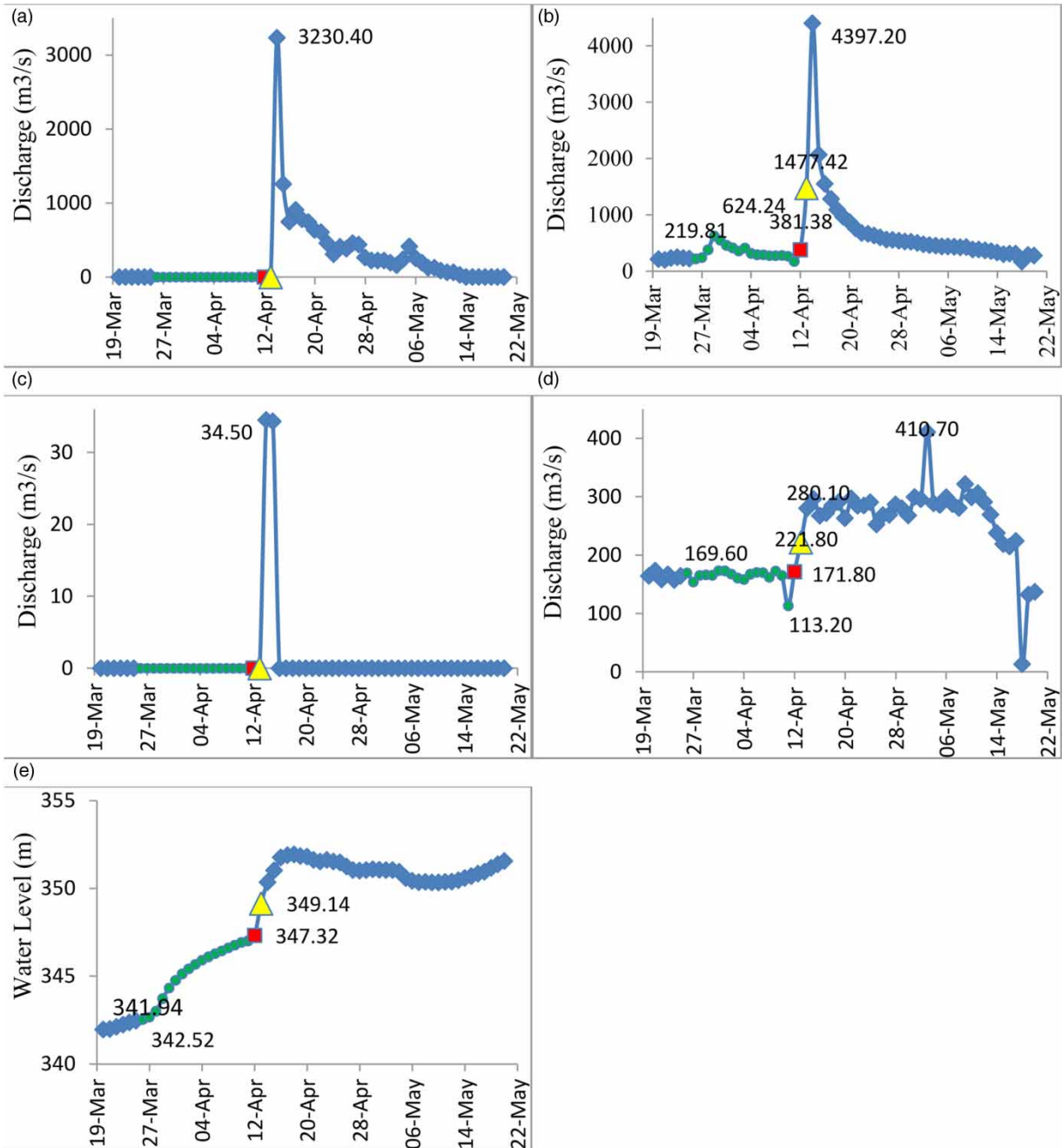
Figure 7 | Reservoir operation rule curve of Dez Dam and water level due to the dam operation in 2001–2004.

operation will be provided to minimize the peak of the outflow hydrograph, hence significantly reducing the damage.

### Values of used parameters

Embedding different algorithms in the WDRFM system is only to increase the system's capability. Therefore, based on which algorithm the user of the system is familiar with, the parameters of that algorithm can be entered and used. Due to the collaboration and sharing of information between particles, high convergence speed, better flexibility against local optimal problems of the PSO algorithm, this algorithm was selected for system evaluation in the Dez Dam reservoir management 2016 flood. The values of its parameters are given in accordance with Table 3.

In order to consider the more critical conditions, the value of  $x$  is equal to 0.5 and  $k$  is equal to 2 hours which is equal to the observed flood travel time between the Talezang station and the reservoir. In fact, the river storage effect will not be considered in the flood routing. The number of stages or the number of decision variables equals 10 which is sufficient to prevent sudden jumps in the water level and the outflow hydrograph from the reservoir. The amount of outflow from the spillway and irrigation gates are considered zero and are assumed to be closed at the start of flood management. The priority of using outlets is to use the gates of the powerhouse at first and after that the irrigation outlets, because opening the irrigation gates discharges the sediment and has environmental limitations. The amounts of changing discharge in these outlets are step by step and  $10 \text{ m}^3/\text{s}$ . Decreasing water level for estimating the pre-release is performed with a step of 0.1 m. The lower the discharge and water elevation steps, the lower the processing speed. The permissible 5% error is defined to achieve optimal solutions. The flood start threshold for the Dez River is set at  $220 \text{ m}^3/\text{s}$ , which is safe discharge. The  $\alpha$  parameter used in estimating the falling limb of the inflow hydrograph is set to 0.0123 using observational hydrograph analysis. Finally, the parameters of the optimization algorithm are determined, with the constants C1 and C2 referring to the learning factors. The PSO algorithm works better when the values of C1, C2 are equal or have a moderate balance. Each time the loop is repeated, it uses a W damping coefficient to reduce the particle velocity so



**Figure 8** | Reservoir operation March 20 to May 20, 2016: (a) Daily spillway release, (b) inflow flood hydrograph, (c) daily release from the irrigation gates, (d) daily powerhouse discharge, (e) water surface level of the reservoir.

that the algorithm does not have any convergence problems.  $W$  is the speed factor at the start of the optimization process. The maximum iteration is assumed as 1,500, which means that the algorithm is not capable of achieving the optimal solution in the next repetitions.

### Scenarios' description

In this system, it is possible to define different scenarios based on several factors such as the objective functions, the initial water levels in the reservoir, outflow from the



**Table 3** | The values of common system parameters in all scenarios

Step amount of changing the discharge	10 m <sup>3</sup> /s
Step amount of changing the water level in pre-release	0.1 m
Prioritization of the use of gates	1. powerhouse gates; 2. irrigation gates
Number of stages	10
Permissible error (%)	0.05
Initial spillway discharge	0
Initial discharge of irrigation gates	0
Time step	2 hours
Threshold flood discharge	220 m <sup>3</sup> /s
$\alpha$ (Equation (1))	0.0123
PSO algorithm	Population size Maximum iteration
	60 1,500
	W
	1
	W-damp
	0.8
	C1
	2
	C2
	2

powerhouse. Also, there are additional limitations on the use of these gates during flood management. In this research, the system capabilities were evaluated for different situations through different scenarios. According to Table 4, for different factors, abbreviations are considered so that different scenarios can be defined accordingly.

For example, the defined scenario (WL1-C1-QH1-Lim1) means that the water level at the start of flood control is 340 m, and the ratio of the inflow flood peak discharge to the outflow peak discharge is equal to 1.5, and the powerhouse discharge at the start of flood control is 171.8 m<sup>3</sup>/s.

In this case, the powerhouse inlets can be fully used, and the irrigation gates do not have the ability to change the flow discharge. In fact, to study the effect of the ratio of the inflow flood peak discharge to the outflow peak discharge in the objective (C), different scenarios were defined as Group 1. In this group, the initial water level (W), powerhouse discharge (QH), and the applied limitations on gates (Lim) were considered constant but the objective function was varied. Group 2 scenarios are similar to Group 1 but the initial water level is increased to evaluate its impact. Group 3 scenarios are similar to the reservoir's condition during the April 14, 2016 flood, and in these scenarios, the possibility of flood management under different objective functions and the effect of initial powerhouse discharge are considered. Finally, in Group 4 scenarios, the limitations in using the gates for flood management are evaluated. Generally, the scenarios used in this study and the purpose of defining different scenarios are presented in Table 5. This study is limited to examine only these scenarios. However, other scenarios can also be defined with respect to the capabilities of the Web-based DSS.

## RESULTS

It should be noted that how the gates open at any interval completely depends on the conditions of the reservoir at the beginning of that period, which itself depends on the proposed management performance of the system in the prior period. Therefore, the condition of opening in stages varies during the flood control process and in different intervals. As shown in Figure 9, by comparing reservoir water level of the scenarios of Group 1, with the increase of the

**Table 4** | Abbreviation of factors for scenarios' definition

Factor name	Factor number			
	1	2	3	4
Water level (m) (WL)	340	345	347.32	–
Peak discharge ratio (C)	1.5	2	2.5	3
Initial powerhouse discharge (m <sup>3</sup> /s) (QH)	171.8	100	50	0
Limitations (Lim)	Powerhouse inlets	Full use	Use of one gate	Unchangeable
	Irrigation outlets	Unchangeable	Unchangeable	Full use

**Table 5** | Defined scenarios and purpose of defining each group

	Group 1	Group 2	Group 3	Group 4
Abbreviated name for scenarios identification	WL1-C1-QH4-Lim1, WL1-C2-QH4-Lim1 WL1-C3-QH4-Lim1 WL1-C4-QH4-Lim1	WL2-C1-QH4-Lim1, WL2-C2-QH4-Lim1, WL2-C3-QH4-Lim1, WL2-C4-QH4-Lim1	WL3-C3-QH1-Lim1, WL3-C3-QH2-Lim1, WL3-C3-QH3-Lim1, WL3-C2-QH3-Lim1	WL3-C3-QH2-Lim2, WL3-C3-QH2-Lim3, WL3-C2-QH3-Lim3
Purpose of each group	Effect of peak discharge ratio (c)	Effect of initial water level	Effect of initial discharge	Effect of limiting the use of gates

C ratio, it is clear that the outflow discharge is expected to be lower than the spillway, the final water level of the reservoir increases. In any case, this final water level does not exceed the defined value of 352 m, which is the upper level of the spillway. Regarding the reservoir water levels, in these scenarios, it can be seen that during the intervals when the reservoir inflow discharge exceeds the total discharge from the dam, the water level is increasing. Spillway outflow hydrograph shows that in the rising limb of the spillway outflow hydrograph, the spillway outflow discharge can be reduced compared to the previous time frame, and it is not necessary to be strictly increasing; as in a specific time period, the gates' opening pattern is presented in such a way that if the pattern is applied to the spillway operation, the amount of outflow discharge from the spillway will decrease compared to the previous interval. In this case, the chart of the water level, due to an increase in inflow relative to outflow, has a mutation in increasing the water level. Also, any fluctuations in the falling limb of the spillway outflow hydrograph are also found to be oscillations at the reservoir water level.

According to Figure 10 for Group 2 scenarios at initial water level 345 m, the peak discharge ratio of 3 does not meet the objective function and pre-release is necessary. In this case, the initial water level is high, and the final reservoir water level exceeds the above threshold (352 m), so spillway must be performed at its maximum capacity (6,000 m<sup>3</sup>/s) to prevent the dam overtopping. However, the objective function can never be satisfied arising from the choice of a large amount for the C ratio in the objective function. Under such circumstances, therefore, the system first considered the possibility of using the full capacity of the powerhouse gates, which again was not possible to achieve the given objective. Therefore, the

only possible solution was to pre-release the flood and reduce the initial level of water in the reservoir, which the system proposes.

Comparison of Group 2 scenarios with initial reservoir water level of 345 m compared to the first group scenarios with initial reservoir water level of 340 m shows that achieving a higher peak discharge ratio (C) would be more difficult by increasing the initial reservoir water level. It is not possible to use the 3-peak discharge ratio in the initial water level of 345 m, unlike the 340-m initial water level. This indicates that the initial reservoir water level has a very influential role in determining the peak discharge ratio. At the beginning of the flood, the higher the peak discharge ratio can be used in the lower the initial reservoir water levels. In addition, due to the amount of powerhouse discharge in these conditions, with the initial water level of 345 m, compared with the scenarios with a 340 m initial water level, it is shown that as the peak discharge ratio increases, so does the powerhouse discharge, while in the scenario WL2-C3-QH4-Lim1 the powerhouse discharge has reached 400 m<sup>3</sup>/s. In the case of the WL1-C4-QH4-Lim1 scenario, the increase in the powerhouse discharge peaked to 320 m<sup>3</sup>/s. In general, the desired peak discharge ratio can be entered at each time the program performs *t* hours. It is generally more acceptable to use low peak discharge ratios in the initial time intervals. In the early moments of the flood, the peak of the inflow flood hydrograph is lower than the safe discharge of the river downstream. Consequently, with a lower ratio of C and even being closer to 1, the water level in the reservoir shows an insignificant increase, and even shows a decrease in some cases; in the future, it can have a critical role in controlling floods by increasing reservoir storage capacity. For example, for the Dez Dam where the peak outflow from the dam is less than 668.25 m<sup>3</sup>/s, there is no damage to

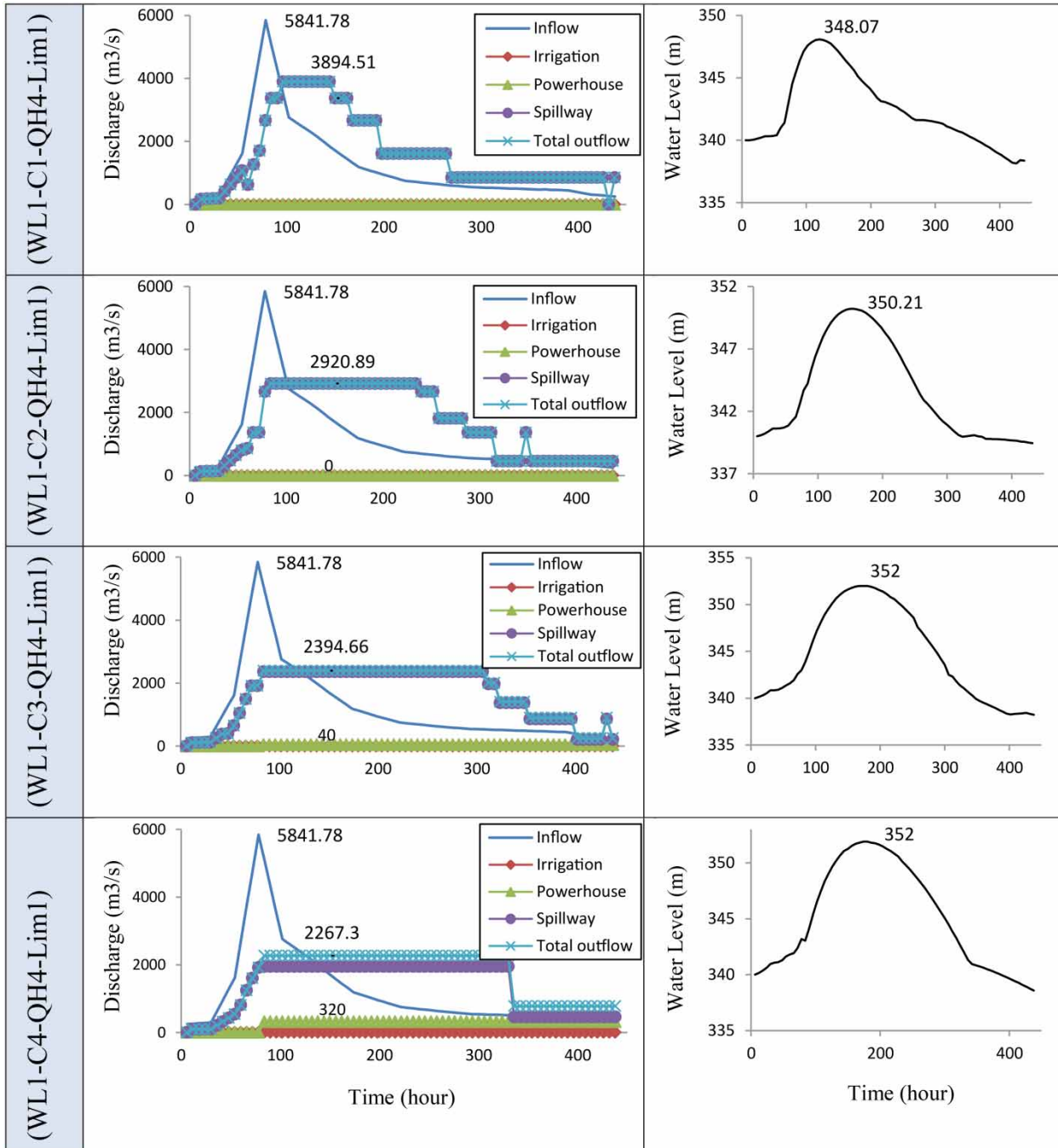


Figure 9 | Release hydrographs and reservoir water level under Group 1 scenarios.

the downstream areas (Malekmohammadi *et al.* 2010). Therefore, for inflow discharges smaller than this value, a peak discharge ratio ( $C$ ) can be used in the objective function that the peak discharge of the total outflow hydrograph is smaller or equal to  $668.25 \text{ m}^3/\text{s}$ .

As shown in Figure 11, in Group 3 scenarios, at the initial time intervals, the reservoir’s water level has been steadily decreasing, which also allows the system to control the flood. In these scenarios, the initial reservoir water level is  $347.32 \text{ m}$ , a ratio of 2.5 is considered as the objective

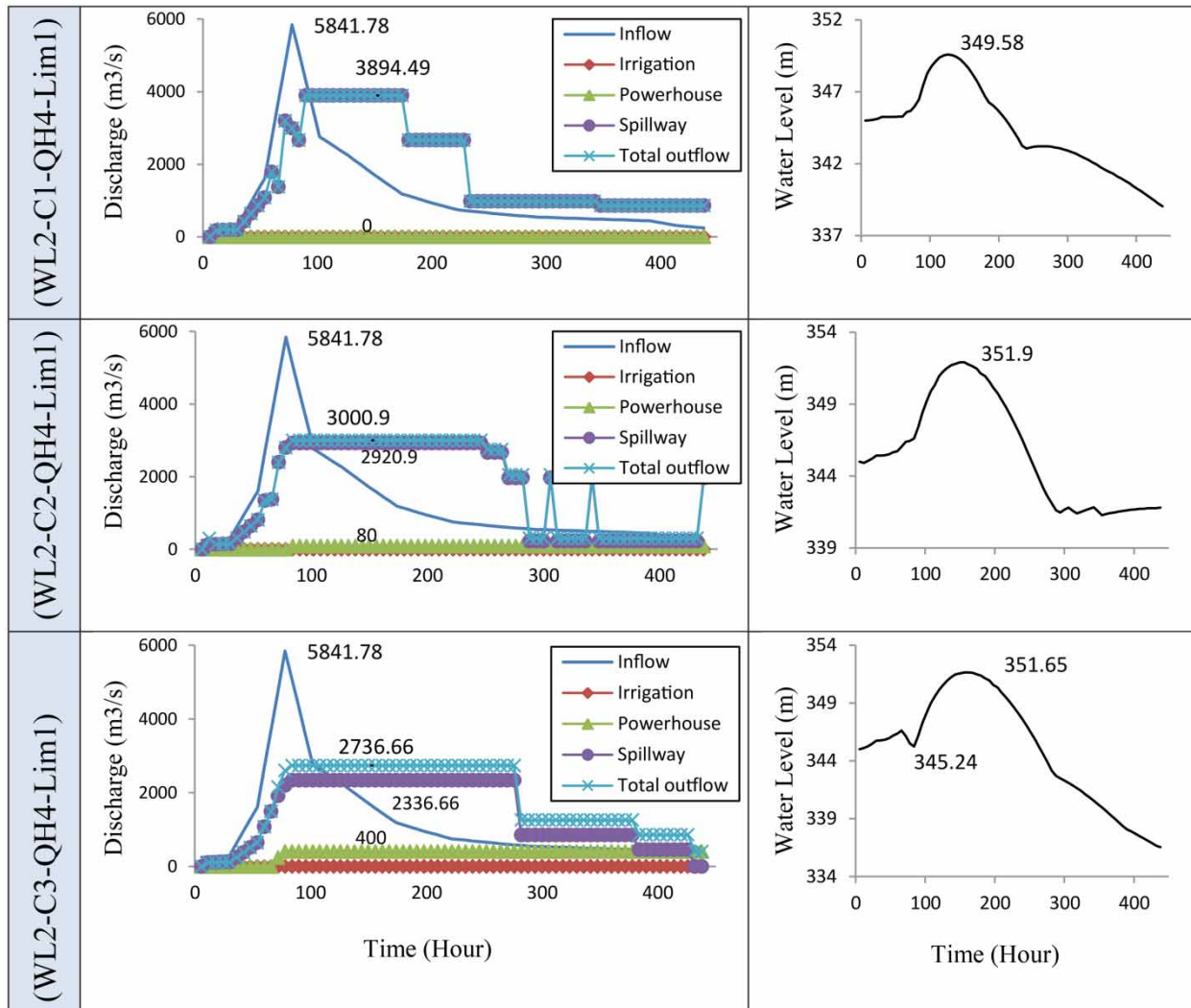


Figure 10 | Release hydrographs and reservoir water level under Group 2 scenarios.

function, in which the gates of the powerhouse can release, but the irrigation outlets cannot. The high initial water level of the reservoir has become a major challenge in this case, and the system can only manage the flood if the initial water level is reduced to a level of 344.5 m in the early steps. In the WL3-C3-QH1-Lim1 scenario the powerhouse discharge flow is  $171.8 \text{ m}^3/\text{s}$ . The system manages the flood by using the spillway outflow without changing the outflow from the powerhouse. In this scenario, in the early moments of the flood the sum of outflow discharge from powerhouse and spillway, exceeded the reservoir outflow discharge, so that the water level of the reservoir was

reduced, which is why the system was able to manage the flood. But in the WL3-C3-QH2-Lim1 scenario, the discharge flow from the gates of the powerhouse is  $100 \text{ m}^3/\text{s}$ . The system initially tries to manage the flood through the outflow from the spillway without changing the outflow from the powerhouse, but the decreased water level is not what it has to be. Therefore, it has increased the discharge rate of the powerhouse until the water level reaches a level that can be managed. The results show the effectiveness of the initial outflow discharge from the reservoir in flood management, so more powerhouse discharge at the start of the flood makes flood control easier. It can be concluded that



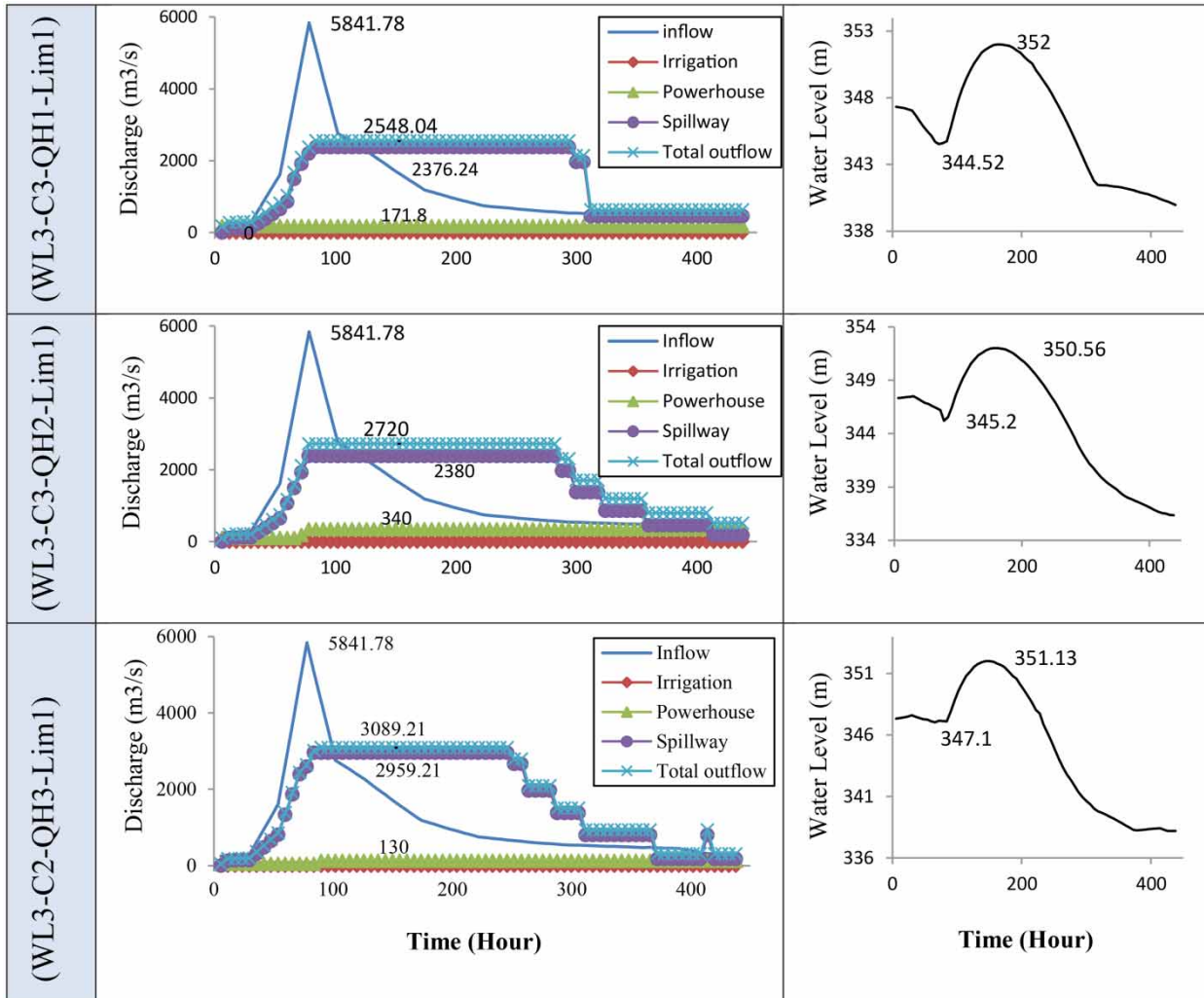


Figure 11 | Release hydrographs and reservoir water level under Group 3 scenarios.

any safe release discharge from the above-mentioned gates and other available dam gates at the beginning of the flood, could be very helpful.

Group 4 scenarios were defined to examine possible constraints on the use of dam gates in flood control. For example, due to dispatching center orders and repairs or overhaul of the equipment or any other reason there are limitations in using the powerhouse gates. Irrigation gates are also facing another form of limitation, as their functionality in being fully open has been marred due to environmental concerns, although sometimes the opening of these gates will be a priority during flood events due to the possibility of flushing operation. Opening the

irrigation gates causes large volumes of sediment to flow downstream and creates problems for aquatic life, agricultural land, and irrigation and water supply networks (Moridi & Yazdi 2017). Therefore, the opening of irrigation gates is subject to limitations and, in this assessment, it is assumed that sedimentation from the reservoir will not occur during the flood. Only in the fourth group scenario (Lim3) has the use of irrigation gates been investigated, where the aim was to investigate the limitation on the maximum capacity utilization of powerhouse gates. Figure 12 shows that limiting the operation of gates on the selection of the peak discharge ratio in the objective function and flood control has a



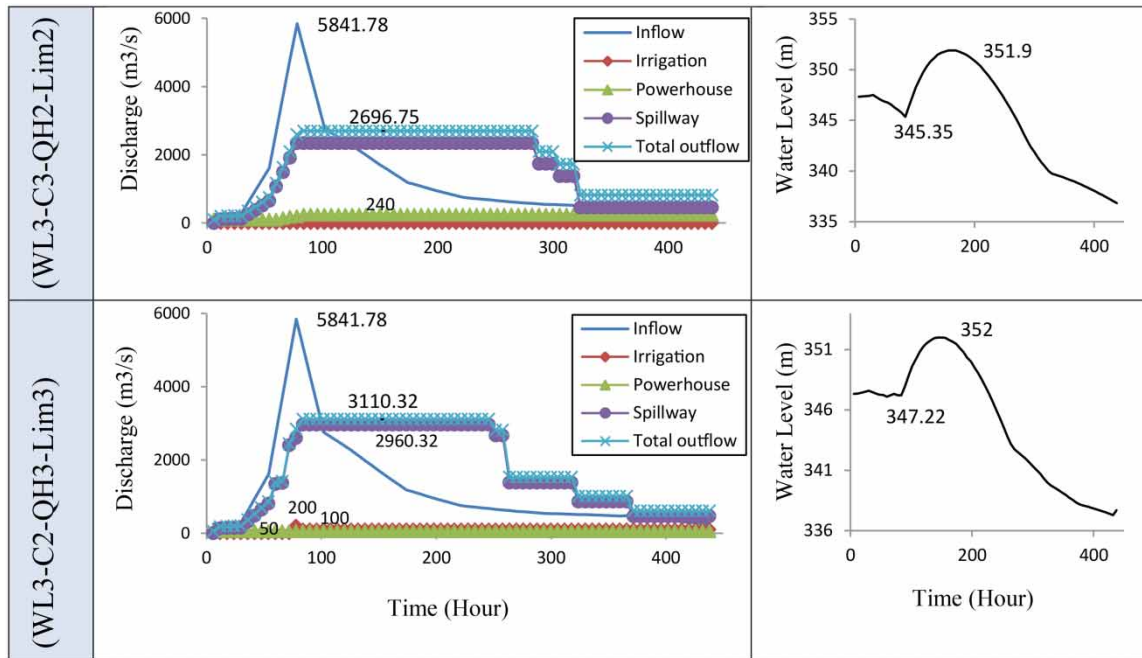


Figure 12 | Release hydrographs and reservoir water level under Group 4 scenarios.

significant effect, and the system is not able to manage the flood for some constraints based on the objective function. In these two scenarios, by selecting a ratio of 2.5 as the objective function, the initial reservoir water level (347.32 m) and initial discharge flow from the powerhouse (100 m<sup>3</sup>/s), there are two different limitations of Lim2 and Lim3 in using gates. In Lim2, powerhouse gates can discharge up to 240 m<sup>3</sup>/s and irrigation outlets cannot be changed. In Lim3, powerhouse discharge cannot be changed, and irrigation outlets can operate with any three drain outlets (maximum discharge is 180 m<sup>3</sup>/s). The WL3-C3-QH2-Lim2 scenario allows flood management to be done for the desired objective function by increasing the discharge to 240 m<sup>3</sup>/s, but if the powerhouse discharge cannot be changed in this scenario, flood management is not possible for the given objective function due to impassability of using the irrigation outlets. In the WL3-C3-QH2-Lim3 scenario it is not possible to change 140 m<sup>3</sup>/s discharge by the powerhouse gates with 100 m<sup>3</sup>/s discharge ability, but instead it is possible to use irrigation gates. Thus, by using the irrigation outlets, it is possible to manage the flood for the given objective function.

## SUMMARY AND CONCLUSION

In this study, a user-friendly, Web-based DSS was developed using ASP.NET software based on the C# programming language. The system is linked to the user through graphical interfaces and tools such as textboxes, checkboxes, checklists, and charts. It takes the necessary information and scenarios from the user, and according to the user choosing one of the algorithms of GA, PSO, or SA, and using the multistage simulation in the opening spillway gates, determines the decision parameters that are the same as the opening values in each critical level, so that the objective function is satisfied. In this system, a reliable approximate method is used to estimate the reservoir inflow flood hydrograph. The objective optimization function can identify the release hydrograph from the reservoir with a specific peak ratio compared to the peak discharge of the inflow flood hydrograph ( $C$ ) or to reach the water level of the reservoir to the desired water level so that the type of objective function and the accuracy of the answer for it can be verified by the operator of the system. In this system, the possibility of engaging the powerhouse and irrigation gates has been considered by dedicating priorities and related constraints on

use in flood management. In addition, if a pre-release is required to reach the intended target, the system calculates the required pre-release volume, and if the pre-release process is not feasible, the system alerts the user and provides a timetable for preventive actions. Conversely, in this system, it is possible to apply different scenarios according to the changing conditions of the reservoir, so that the user can decide on their scenario with greater accuracy and confidence. This WRDFM system is capable of executing automatically at certain times and also has the ability to develop and deploy other reservoirs.

In order to evaluate the efficiency of the WRDFM system, various scenarios were defined for the type of objective function, the initial water level of the reservoir, the initial outflow discharge, and the limitation of the use of irrigation gates and powerhouse gates. Then, according to each scenario, the flood management on April 14, 2016 was simulated by the system. The difference in results for different scenarios showed that the user and the system administrator are able to make different choices for each of the flood conditions. It is also able to see the result of applying a decision to manage a flood and, if necessary, make any decision at any time to modify its decision. The comparison of the WL3-C3-QH1-Lim1 scenario similar to that of the reservoir during April 14 was indicative of the daily peak inflow of 5,841.75 m<sup>3</sup>/s, the spillway peak discharge reached 2,437.24 m<sup>3</sup>/s while the powerhouse discharge during the whole duration of the flood reached only a maximum of 191.8 m<sup>3</sup>/s in the 6-hour period and remained unchanged at other discharge periods at the powerhouse staying at 171.8 m<sup>3</sup>/s. No irrigation gate was used. Eventually, the peak discharge of the outflow hydrograph from the reservoir reached 2,548.04 m<sup>3</sup>/s. Nevertheless, management by dam operators had led to the release hydrograph with a daily peak discharge of 3,545 m<sup>3</sup>/s, which is 997 m<sup>3</sup>/s more than the peak discharge of the outflow hydrograph from the dam that it is proposed by the system. By comparing these two values, according to the study of Malekmohammadi *et al.* (2010), the damage was reduced only on the basis of the peak discharge outflow from the dam, showing a reduction, namely, from 299.55 billion rials (\$2.5 million) to about 215.65 billion rials (\$1.8 million). In order to increase the efficiency and accuracy of the system in management of the flood, the development of the system in the

following cases is highly recommended: the use of more precise methods for river routing; considering the runoff in the middle basin; improving optimization methods to form the best solution in the shortest time; linking the system to software such as GIS to determine flood plains and flood damage; linking the system with real-time flood forecasting systems instead of using an estimated flood; auto-determining of the *C* ratio in the objective function in terms of peak flood inflow during flood control.

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## SUPPLEMENTARY MATERIAL

The Supplementary Material for this paper is available online at <https://dx.doi.org/10.2166/hydro.2020.185>.

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