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Forensic engineering analysis applied to flood control

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ABSTRACT

Floods have various impacts, including loss of life and damage to property. Flood- management reservoirs can help mitigate floods, but their operation can also worsen flood impacts. This paper presents a novel forensic engineering approach to assess the role of reservoir operation on flood control. Fourteen criteria are employed for assessing forecast-based prereleases of water from reservoir storage to reduce the impact of flooding. The proposed approach is applied for forensic assessment of the system performance of reservoirs during the large flood of 2019 in southwestern Iran (the Great Karun Basin). The two main study areas are in the sub-basins of Karun and Dez. Results concerning two key performance criteria (the peak discharge reduction (PDR) and flood volume reduction (FVR)) show the PDR criterion in the Karun sub-basin multi-reservoir system reached about 79% (where 100% is the theoretically best performance) under historic operations (actual operating conditions in 2019), and improved from 8 to 19% if various prerelease operations were made. The FVR achieved about 33% in the historical situation and improved from 20 to 59% under prerelease operations scenarios, respectively. The PDR criterion achieved 26% under the historical scenario, but with better operation could exceed 55% in the Dez sub-basin multi-reservoir system, whereas FVR was as low as 11% in 2019 but could be raised to between 15 and 25% under prerelease operations. This forensic work's assessments establish that improved reservoir operation could be achieved by applying specialized operation approaches.

1. Introduction

River waters have played a major role in the development of civilizations (Delli Priscoli, 2000; Macklin and Lewin, 2015; Karami et al., 2020). Human reliance on water have led to the formation of human settlements along rivers (Yevjevich, 1992; Acharya et al., 2020). Urbanization, the uncontrolled extraction of sand and gravel from riverbeds, and development within floodplains have disrupted riverine flow regimes. These types of mismanagements have led to decreasing river capacity for conveying waters especially during floods, which has led to significant damages all over the world (Grunewald, 1998; Wang, 2000; Plate, 2002; Konrad, 2003; Zhao et al., 2020).

Floods inflict recurring damages the world over with far-reaching consequences in terms of loss of property and life (Pham, 2011). Floods cause environmental damage (such as harm to wildlife, pollution of rivers and habitats by contaminated flood waters.) and economic damage (such as damage to buildings, transportation infrastructure, and utilities) (Gardiner, 1994; Chen et al., 2019a, 2019b; Adeel et al., 2020;

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Diakakis et al., 2020). Flood control approaches are therefore indispensable to reduce flood risk, and various flood control methods have been proposed for flood assessment, such optimization, hydraulic simulation, and uncertainty analysis (e.g. Qiu et al., 2010; Wang et al., 2012: Woodward et al., 2014; Shao et al., 2017; Volpi et al., 2018; Kundzewicz et al., 2019; Leandro et al., 2020). There are also, structural flood-control methods, such as the construction and operation of reservoirs (Gomez-Ullate et al., 2010, 2011; Zhao et al., 2014; Chen et al., 2015, 2020). Reservoirs play an important role in the planning and management of water resources, especially in arid and semi-arid regions. Real-time operation of multi-reservoir is central to flood control and management (e.g., Kuo et al., 1990; Mesbah et al., 2009; Liu et al., 2011, 2017; Wu and Chen, 2013; Ming et al., 2017; Huang et al., 2018).

Flood control by means of reservoir operation is affected by many factors. Therefore, the judicious operation of reservoirs is necessary but challenging during a flood event. The operation of a flood control reservoir is normally accomplished using specific operating rules and policies, which involves guidelines for water-release decision making under various conditions (Liu et al., 2015a, 2015b; Zhou et al., 2015a, 2015b). Flood control has two main simultaneous objectives: to prevent flood damage downstream of reservoirs, and to ensure dam safety. Accordingly, releases are limited by the maximum allowable safe discharge to downstream channels and rivers. Moreover, flood forecasts provide information about future streamflow and are vital in operating a flood control reservoir (e.g., Windsor, 1973; Reddy and Kumar, 2006; Wei and Hsu, 2008; Zhu et al., 2017a, 2017b; Wallington and Cai, 2020).

Reducing flood peak discharge by reservoirs has a significant impact on preventing flood damages in the downstream. In this regard, Qi et al. (2017) developed a preference-based multi-objective optimization model for reservoir flood control operation. Their model took water demand into consideration while optimizing two conflicting flood control objectives, namely, minimizing the highest upstream water level (to protect against damages in the upstream reaches) and minimizing the largest water release volume (to protect the downstream reaches). The schedules obtained by their model could significantly reduce the flood peak and guarantee reservoir safety. Liu et al. (2017) developed a multi-objective flood control and hydropower generation operation model for Three Gorges Reservoirs (TGR) in China. Results showed that the flood control infrastructure such as spillways would have a significant impact on reservoir operation in flood conditions. Therefore, the number and operation of spillways must be considered in the forensic assessment of reservoir operation. The latter authors concluded that the application of the Smooth Support Vector Machine (SSVM) model could have twofold benefits by reducing flood risk and increasing hydropower generation during the flood season. Several researchers have developed flood forecasting models. For example, Huang et al. (2018) proposed a stochastic copula-based simulation method accounting for flood forecasting uncertainty in the TGR, China. Results demonstrated that the entropy method was effective for evaluating flood risk due to different uncertainties.

Flood forecasting is beset by uncertainties. Zhang et al. (2019) evaluated these uncertainties in their study. They developed a two-stage flood risk analysis model in multi-reservoir systems to evaluate uncertainty in flood forecast by dividing the operation horizon into beyond-forecast time period and forecast lead-time. They concluded that hydropower generation could increase during the summer flood season without increasing the flood risk in the multi-reservoir system.

Despite advances in flood management there are systematic and human errors (e.g., faults in the operation of gates and spillways, inaccurate streamflow predictions) in the operation of reservoirs. Also, it is key for flood control that the reservoir operators make optimal decisions under emergency flood conditions. Forensic engineering has made substantial contributions in recent decades to the identification and study of failure causes, their mechanisms and progression in buildings, complex facilities, etc. (e.g., Carper, 2000; Noon, 2001). Forensic hydrology has emerged in recent years to discern the causes and processes of hydrologic events causing economic and life losses (Loáiciga, 2001; Hurst, 2007; Lischeid et al., 2017). Generally, forensic hydrology studies extremes such as floods and droughts and their impacts, water-quality degradation, and the causes of adverse groundwater phenomena. Forensic hydrology is a part of Forensic Disaster Analyses (FDA) (Keating et al., 2016).

For example, Loáiciga (2001) demonstrated that flood damages caused in San Luis Obispo County near Avila Beach, California, in 1995, were not due to extreme rainfall, but, rather, to progressive changes made to streams and flood plains over many years. Such changes required higher water levels to pass the design floods than those predicted before the changes, thus leading to the submergence and collapse of buildings. Bronstert et al. (2018) provided forensic hydrologic analysis of the hydrological consequences of the Braunsbach flash flood in 2016. The results showed that the flood event was due to a very rare rainfall intensity, which, in combination with catchment properties, led to extreme runoff coupled with severe geomorphological hazard. Bronstert et al. (2018) determined that due to the complex and interacting processes no, single flood could be identified for the severe damage that occurred, while the interaction and cascading characteristics led to such an event.

Many published studies have dealt with several aspects of flood control by reservoirs (e.g. Mariën, 1984; Tung et al., 2006; Zhou, 2010; Li et al., 2010; Yan et al., 2014; Chen et al., 2019a, 2019b; Jing et al., 2020). However, studies considering how forensic engineering can be used to improve the operation of flood reservoirs and how best to conduct these forensic investigations are rare. This study's contributions are (1) developing applicable criteria to guide forensic engineering assessments of reservoirs' flood control performance during flood events under diverse managing scenarios, and (2) developing pre-release prediction-based scenarios for the severe 2019 flood event in southwestern Iran, which is this work's case study. Heavy and continuous rains in 2019 led to severe floods in large parts of Iran, which was associated with many financial and human losses and affected the southwestern regions of the country. According to the Crisis Management Organization of Iran, the 2019 flood affected 25 provinces of Iran, including 200 cities and 4304 villages. Among them, more than 135,000 urban and rural homes and properties were damaged and destroyed and also, 76 people lost their lives. The 2019 flood event raised the question of whether the reservoirs in the flood region were operated properly. This work evaluates the reservoir operators' performance by means of forensic engineering based on novel forensic criteria.

2. Methods

The operation of multi-reservoir systems is a complex task, especially during flood events. In the case of reservoirs in series, the downstream reservoirs are directly affected by water releases from upstream reservoirs. The releases of water from reservoirs in parallel may converge downstream in which case they may cause serious damages. The complexities of multi-reservoir configurations require that forensic engineering analyses be performed for the reservoirs individually and as a system to evaluate the sub-basin and basin storage-release performance. Both quantitative and qualitative criteria are required to evaluate single- and multi-reservoir systems operation performance under flood conditions. A criterion must be defined for each managerial aspect or reservoir function to evaluate the reservoir or multi-reservoir system performance concerning the defined functions. The flowchart of this paper's methodology is shown in Fig. 1.

2.1. Flood control policy (FCP)

Each basin may be divided into several sub-basins. The sub-basins may or may not have reservoir(s) in them. The operation of each reservoir affects the operation of downstream reservoirs, and may also affect the performance of reservoirs in other sub-basin(s). These

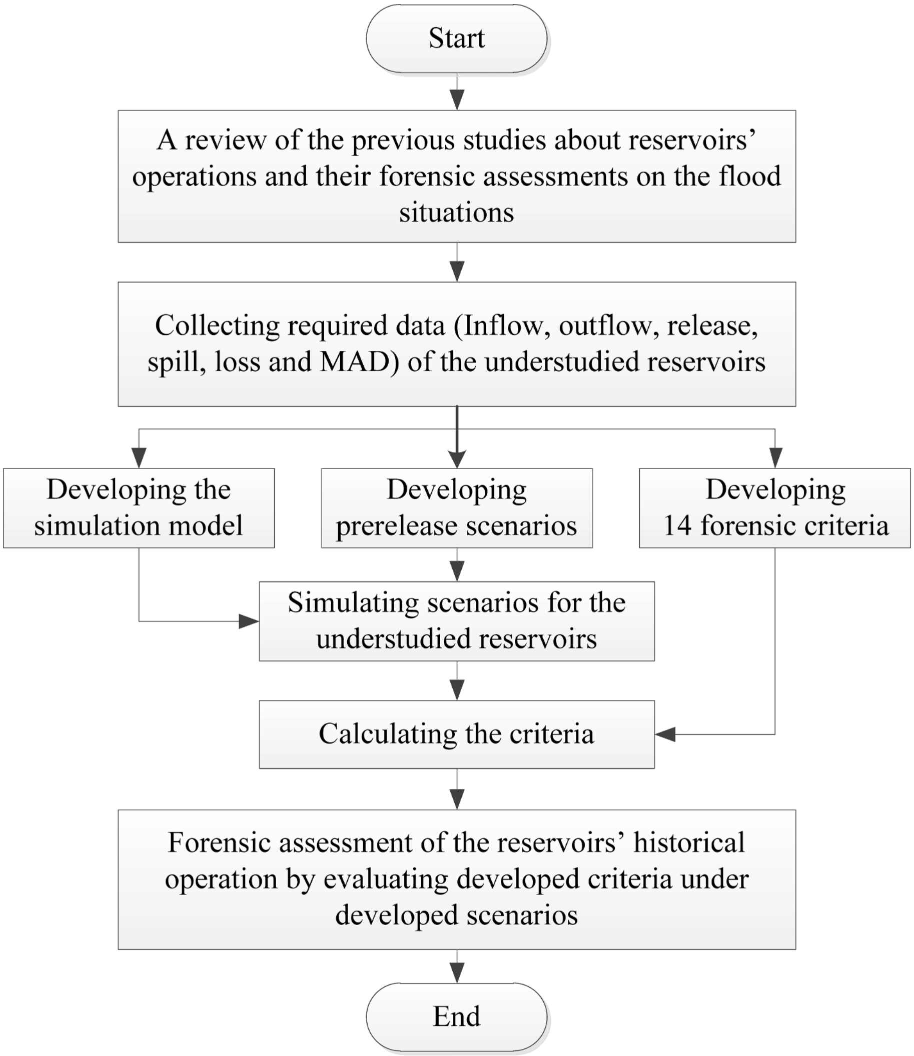


Fig. 1. Methodology's flowchart.

interrelated impacts may have positive or negative effects on the areas downstream from reservoirs. For example, in a flood situation each reservoir can prevent damages by means of prereleases of water, whereas it can also cause otherwise preventable damages via its operation (Hossain et al., 2019). This highlights the importance of forensic engineering investigations in assessing reservoir operation during historical flood situations.

Reservoir inflows and outflows generally change over time and space. Inflows, which either originate from the associate watershed or are combined with the releases from upstream reservoirs, are regulated by reservoirs to reduce downstream flood damages. Water is often released from reservoirs before a flood event to create additional storage capacity for flood control. This is called a prerelease. During flood periods reservoir releases are managed so that excess water is stored to help meet water demands during subsequent low-inflow periods, and to prevent downstream flooding. The flood volume may become so large that reservoir releases may reach their maximum magnitudes thus endangering the spillway and dam integrity.

Reservoir flood simulation may be expressed in terms of a series of water balance equations. Eq. (1) represents the change of storage in reservoir *i* during period $t (S_{i,t})$:

$$\Delta S_{i,\,t} = S_{i,\,t+1} - S_{i,\,t} \qquad i = 1, 2, \ldots, N \ and \ t = 1, 2, \ldots, T \tag{1}$$

where N denotes the total number of reservoirs in a multi-reservoir system; t = operation day index; T = total days in the operation period; S = reservoir storage. When reservoir releases are controlled through several gates the water balance equation takes the following form:

$$S_{i,t+1} = S_{i,t} + Q_{i,t} + Q'_{i,t} - L_{i,t} - \sum_{j=1}^{m} R_{i,j,t} - SP_{i,t} \tag{2}$$

$$L_{i,t} = \left[\frac{A_{i,t} + A_{i,t+1}}{2}\right] Ev_{i,t} \tag{3}$$

$$A_{i,t} = f_i(S_{i,t}) \tag{4}$$

$$A_{i,t+1} = f_i(S_{i,t+1}) \tag{5}$$

$$0 \leqslant S_i^{Min} \leqslant S_{i,t} \leqslant S_i^{Max} \tag{6}$$

$$0 \leqslant R_{i,j}^{Min} \leqslant R_{i,j,t} \leqslant R_{i,j}^{Max} \tag{7}$$

$$0 \leqslant Sp_i^{Min} \leqslant Sp_{i,t} \leqslant Sp_i^{Max} \tag{8}$$

where $j = 1, 2, \ldots, m$ denotes the number of gates; L = the volume of water loss or gain due to the difference between reservoir evaporation and precipitation; A = the reservoir water surface area; R = the released volume of water from the reservoir except the spill; Q and Q' denote respectively natural reservoir inflow and releases from upstream reservoir and return flows which indicates upstream non-regulated flows (such as middle basin runoff); Sp = the volume of spilled water from the reservoir; S^{Min} = the minimum operating volume; S^{Max} = the maximum operating volume; R^{Min} = is the minimum allowable release volume; R^{max} = is the maximum allowable release volume; Sp^{Min} = is the minimum allowable spill volume; Sp^{Max} = is the maximum allowable spill volume; Ev = the difference between the evaporation and precipitation rates.

The integrated operation of a multi-reservoir system is essential for successful flood control during floods. Reservoirs built along a river's main reach constitute a system of cascade lakes, or reservoirs in series. In this case, their operation must be carried out jointly because of the effect of upstream reservoirs' releases on downstream reservoirs. The total inflow into the downstream reservoir is a combination of releases and spills from an upstream reservoir and the natural inflows generated downstream of reservoirs. The downstream reservoirs must be operated based on the total inflow. Reservoirs built on different branches of a river network are said to be in parallel. The operation of parallel-reservoir subsystems may or may not have to be carried out jointly with respect to flood control depending on the locations of vulnerable areas. Fig. 2 shows a schematic of reservoirs. Reservoir 1 and 2 are in series above the point of confluence, and so are reservoirs 3, 4. The subsystems (1,2) and (3,4) are in parallel. Reservoir 5 is affected by the operation of all reservoirs. Reservoir 5 is in series with respect to subsystems (1,2) and (3,4). Area A is impacted by the operation of reservoir 3 and 4. Area B is influenced by the operation of all reservoirs.

2.2. Criteria development

This paper's purpose is to perform a forensic analysis of the performance of reservoir operations under severe flood conditions. It is, therefore, necessary to develop quantitative criteria to evaluate performance at the local or single-reservoir level and the global or multi-reservoir-system level. The performance evaluation of a single reservoir is conducted assuming that downstream reservoirs receive inflows that are not regulated. In other words, the effects of the upstream reservoirs are not considered in the single-reservoir performance evaluation.

The criteria development accounts for the main characteristics of floods, such as inflow and outflow flood volumes, the inflow and outflow peak discharges, and the safe downstream discharge, which defines the Maximum Allowable Discharge (MAD) from a reservoir (Stedinger and Cohn, 1986; Koutsoyiannis et al., 2007; Shamir et al., 2013; Bozorg-Haddad, 2018). The following criteria were developed to simplify the forensic-engineering assessments in evaluating the performance of reservoirs' operators under flood conditions:

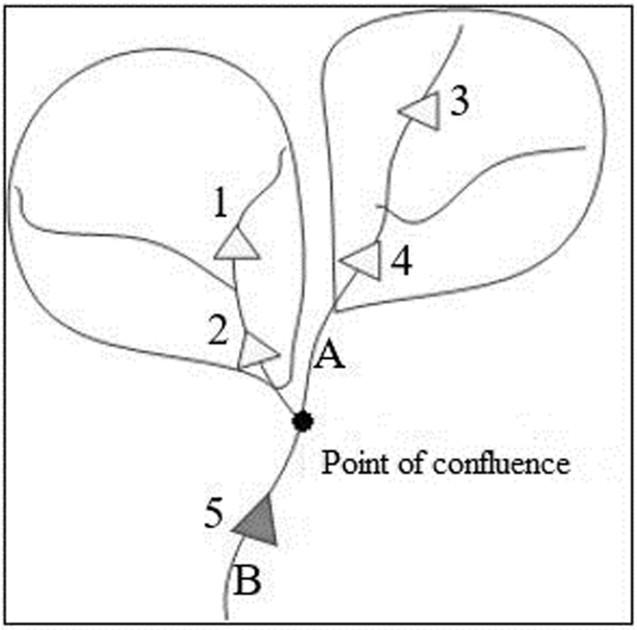


Fig. 2. Schematic of parallel and series reservoirs systems.

1- Peak Discharge Reduction (PDR) of a single reservoir:

$$I1_i = \left[1 - \frac{Max({Q_{i,t}^{Out}}_{t=1}^{T})}{Max({Q_{i,t}^{In}}_{t=1}^{T})} \right] \times 100 \qquad i = 1, 2, \ldots, N \tag{9}$$

$$Q_{i,t}^{Out} = R_{i,j,t} + SP_{i,t} \tag{10}$$

in which $I1_i$ = PDR criterion for reservoir i; $Q_{i,t}^{In}$ and $Q_{i,t}^{Out}$ denote the reservoir inflow and outflow in day t, respectively.

2- Peak Discharge Reduction (PDR) of multi-reservoir systems:

$$I2 = \left[1 - \frac{Max({Q_{t}^{Out}}_{t=1}^{T})}{Max({QB_{t}^{In}}_{t=1}^{T})} \right] \times 100 \tag{11}$$

$$QB = \begin{cases} For\ i = 1 & QB_1 = Q_1 \\ For\ i = 2 & QB_2 = Q_2 + QB_1 \\ For\ i = 3 & QB_3 = Q_3 + QB_2 \\ \vdots & \vdots \\ For\ i = N & QB_N = Q_N + QB_{N-1} \end{cases} \tag{12}$$

in which $I2$ = PDR of multi-reservoirs system criterion; QB_t^{In} is the non-regulated inflow of the flooded basin (the downstream reservoir of the basin) in day t, respectively.

3- Flood Volume Reduction (FVR) of a single reservoir:

$$I3_i = \left[1 - \frac{\sum_{t=1}^{T} Q_{it}^{Out}}{\sum_{t=1}^{T} Q_{it}^{In}} \right] 100 \quad i = 1, 2, \ldots, N \tag{13}$$

in which $I3_i$ = FVR of reservoir i.

4- Flood Volume Reduction (FVR) of multi-reservoir systems:

$$I4 = \left[1 - \frac{\sum_{t=1}^{T} Q_{t}^{Out}}{\sum_{t=1}^{T} QB_{t}^{In}} \right] 100 \tag{14}$$

in which $I4$ = FVR of multi-reservoir system.

5- Peak Flow Delay (PFD) of a single reservoir:

$$I5_i = D\left(\underset{t=1}{\overset{T}{Max}}(Q_{i,t}^{Out}) \right) - D\left(\underset{t=1}{\overset{T}{Max}}(Q_{i,t}^{In}) \right) \qquad i = 1, 2, \ldots, N \tag{15}$$

in which $I5_i$ = PFD criterion in reservoir i; $D\left(Max({Q_{i,t}^{Out}}_{t=1}^{T}) \right)$ and $D\left(Max({Q_{i,t}^{In}}_{t=1}^{T}) \right)$ are the peak discharge occurrence time of the inflow and outflow of reservoir i , respectively.

6- Peak Flow Delay (PFD) of multi-reservoir systems:

$$I6 = D\left(\underset{t=1}{\overset{T}{Max}}(Q_t^{Out})\right) - D\left(\underset{t=1}{\overset{T}{Max}}(QB_t^{In})\right) \tag{16}$$

in which $I6 =$ PFD criterion of the multi-reservoirs system; $D\left(Max(Q_t^{Out}{}_{t=1}^{T})\right)$ and $D\left(Max(QB_t^{In}{}_{t=1}^{T})\right)$ are the peak discharge occurrence time of the inflow and outflow of the flooded basin (the downstream reservoir of the basin), respectively.

7- Flood Control Readiness (FCR) of a single reservoir:

$$I7_i = \left[\frac{S_{i,0}^{Empty}}{\Delta T \sum_{t=1}^{T} Q_{i,t}^{In}}\right] \times 100 \qquad i = 1, 2, ..., N \tag{17}$$

in which $I7_i =$ FCR criterion of the reservoir *i*; $S_{i,0}^{Empty} =$ the empty volume of reservoir *i*, in day 0 (the day preceding the flood occurrence).

8- Flood Control Readiness (FCR) of multi-reservoir systems:

$$I8 = \left[\frac{SB_0^{Empty}}{\Delta T \sum_{t=1}^{T} QB_t^{In}}\right] \times 100 \tag{18}$$

in which $I8 =$ FCR criterion of the multi-reservoirs system; $SB_0^{Empty} =$ the total empty volume of the multi-reservoir system in the day preceding the flood occurrence.

Reservoir operation must be planned in such a way that reservoir safety is assured and water-supply targets (such as meeting water demands and non-violation of the MAD) are met. Just as reservoir safety is important for operators, so are the outflow volume, flood peak, and the timing of the flood peak for stakeholders and downstream residents and property owners. This study selects the MAD as the main target because the violation of this parameter could result in reservoir and downstream destruction and damages. MAD-based criteria are also herein developed to analyze the performance of reservoir operators in terms of the number of MAD violations, their severity, and the time to return to desirable operation following violations.

The reliability of the system indicates the level of the system's ability to meet acceptable targets and is calculated for any time period including the flood duration and also longer periods extend to the entire operation period of a reservoir system. The reliability criterion does not provide any information about the rate of return to a satisfactory state in the event of a failure. Also, reliability does not measure the severity of a failure. Criteria such as vulnerability and resiliency are used to quantify the severity of failures and the system's ability to return to a satisfactory state following a system failure to perform adequately, respectively (Bozorg-Haddad, 2018). Any operational period in which reservoir releases exceed the MAD is considered as a failure period in this work. Otherwise, it is considered as a normal period. Therefore, reservoir operation as envisioned in this work aims to ensure that all outflows do not exceed the MAD to prevent flood damages.

9- Reliability of avoiding downstream damage of single reservoirs:

$$I9_i = 1 - f_i/_T \qquad i = 1, 2, ..., N \tag{19}$$

in which $I9_i =$ reliability of no downstream damage criterion of reservoir *i* $f_i =$ the number of failure days which is calculated as follows:

$$f_i = \sum_{t=1}^{T} a_{i,t} \ , \ \ a_{i,t} = \begin{cases} 1 & \sum_{j=1}^{m} R_{i,j,t} + Sp_{i,t} > MAD_i \\ 0 & \sum_{j=1}^{m} R_{i,j,t} + Sp_{i,t} \leqslant MAD_i \end{cases} \qquad i = 1, 2, ..., N \tag{20}$$

in which $MAD_i =$ maximum allowable discharge to river downstream of reservoir *i.*

10- Reliability of no downstream damage in multi-reservoir systems:

This is calculated as follows:

$$I10 = 1 - f_B/_T \ , \ \ f_B = \begin{cases} 1 & \sum_{i=1}^{N} f_i \geqslant 1 \\ 0 & \sum_{i=1}^{N} f_i < 1 \end{cases} \tag{21}$$

in which means that the multi-reservoir system would incur a failure whenever one or more of its components incur failure. Failure occurs whenever the system does not have sufficient capacity to meet the desired goals.

11- Resiliency to downstream damage of a single-reservoir system

$$I11_i = \frac{1}{\left(\frac{f_i}{fs_i}\right)} \qquad i = 1, 2, ..., N \tag{22}$$

in which $I11_i =$ resiliency to downstream damage criterion of reservoir *i* and $fs_i =$ number of continuous failure days.

The system resiliency criterion is the probability that a reservoir system returns to a normal state after a failure state. The higher the resiliency of a system, the greater its capacity to cope with changes in the factors affecting that system.

12- Resiliency to downstream damage of multi-reservoir systems:

$$I12 = \frac{1}{\left(\frac{f_B}{fs_B}\right)} \tag{23}$$

in which $I12 =$ resiliency to downstream damage criterion of multi-reservoirs systems and $fs_B =$ number of continuous failure days of the multi-reservoir system. The definition of failure in the context of the resiliency of a multi-reservoir system is such that failure by one or more reservoirs means system failure, also.

13- Vulnerability to downstream damage of single reservoirs:

$$I13_i = \frac{Max_{t=1}^{T}\left(\left(\sum_{j=1}^{m} R_{i,j,t} + Sp_{i,t} - MAD_i\right), 0\right)}{MAD_i} \tag{24}$$

in which $I13_i =$ vulnerability to downstream damage criterion of reservoir *i.* Vulnerability measures the difference between the normal and the failure states of reservoirs; therefore, it is a probabilistic criterion which measure of the severity of the failure. The lower the vulnerability, the greater is the capacity to maintain satisfactory operating conditions.

14- Vulnerability to downstream damage of a multi-reservoir system:

$$I14 = \frac{Max_{t=1}^{T}\left(\sum_{i=1}^{N} Max\left(\sum_{j=1}^{m} R_{i,j,t} + Sp_{i,t} - MAD_i, 0\right)\right)}{\sum_{i=1}^{N} MAD_i} \tag{25}$$

in which $I14 =$ vulnerability to downstream damage criterion of multi-reservoir systems.

2.3. Prerelease scenarios

Operation of a single-reservoir or multi-reservoir systems during floods is beset by multiple complexities. Evaluating the operation of multi-reservoir systems requires simulating system operation with observed data and under new scenarios (i.e., "unseen" or projected reservoir inflow data). These scenarios are intended to demonstrate if a system's operation could have been improved by prerelease of water in a timely manner. Therefore, this work analyses various prerelease scenarios to assess the performance of reservoir system' operation.

- Using short-term forecasting models in reservoir operation

Technology and models have been developed to forecast runoff during flood events (Bozorg-Haddad, 2018). This relies on scenarios developed based on one-week and two-week flood predictions (these time periods will give enough time for operators to make decisions about timing and magnitude of releases from reservoirs), which is one of the forensic engineering methods applied to assess the possibility of improved operation relying on this type of predictions.

- Ideal Reservoir Operation

Forensic engineering approach involves the evaluation of the historical operation of reservoirs by comparing it with a defined ideal practical operation. The ideal operation is simulated based on having perfect foresight. Reservoir inflows (one and two months before the flood) can be forecasted using regression methods or other data mining methods (such as neural networks) based on monthly long-time discharge series. The model's accuracy generally increases with the length and quality of the time series. The reservoir inflow predictions lead time is herein considered as an ideal forecasting lead time, but it could be changed in other studies depending on the reservoir capacity

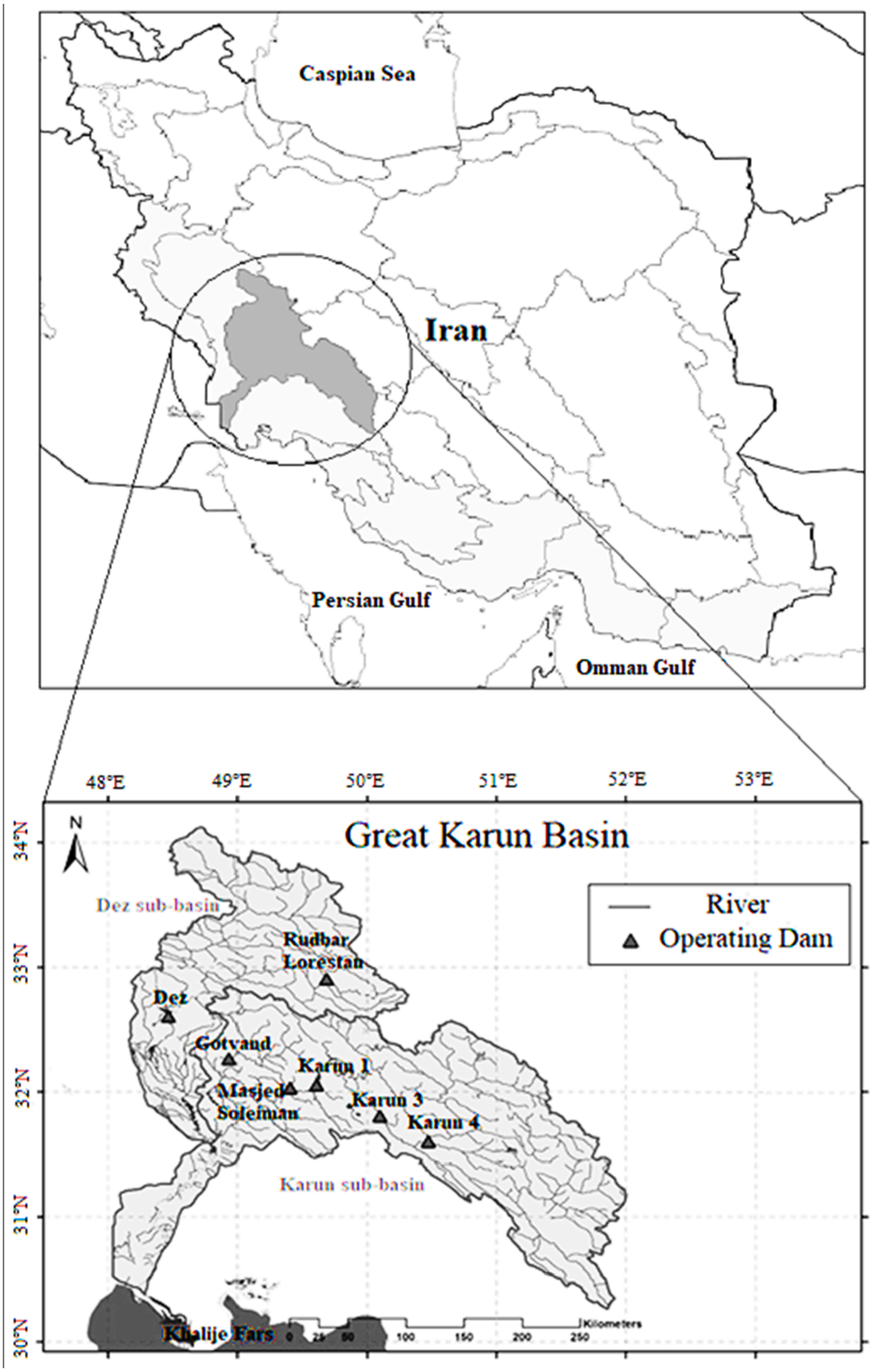


Fig. 3. Map of the Great Karun Basin and its operating reservoirs.

and its downstream MAD. Ideal reservoir operation must be such that reservoir storage does not exceed the maximum allowable storage (this ensures dam safety) and the reservoir outflow (release plus spill) does not cause downstream damage during flood events.

3. Case study

The Great Karun basin was chosen as a case study to illustrate this paper's methodology. The basin is located in southwestern Iran and covers about 4.2% of the Iran's total area. Great Karun consists of two sub-basins, which are (1) the Karun sub-basin, and (2) the Dez sub-basin. The Karun River (Iran's largest) drains the basin and it is a key element of Iran' water resources. Many regions of southwestern Iran meet their agricultural, industrial, domestic, and environmental demands from reservoirs built on the Karun River. Droughts and floods have a significant impact on the Great Karun basin water use. Floods constitute a hazard to life and property in the basin. Fig. 3 shows five reservoirs in the Karun sub-basin which from upstream to downstream are: (1) Karun 4, (2) Karun 3, (3) Karun 1, (4) Masjed-Soleiman, and (5) Gotvand. The Dez sub-basin features two reservoirs, which are: (1) Rudbar-Lorestan (upstream), and (2) Dez (downstream). Outflows from the Gotvand and Dez reservoirs converge at Bande-Ghir and flow to Ahwaz City. The operation of the two downstream reservoirs must be coordinated to provide flood protection to Ahwaz City. The reservoirs' characteristics are listed in Table 1.

This work assesses the 2019 flood event in southwestern Iran (Great Karun Basin) using the forensic engineering approach herein developed. The 2019 flood is one of three major floods in the past 70 years in the Great Karun basin. The flood began on March 23rd and ended on April 3rd. It caused severe economic and human loses. The forensic assessment of the 2019 flood evaluates the performance of reservoir operation in the study area and analyses the periods immediately before, during, and immediately after the flood. The "before flood" period starts on September 23, 2018, and ends on March 22, 2019 (180 days); The "during flood" period starts on March 23, 2019, and ends on April 3, 2019 (13 days), and the "post-flood' period starts on April 4, 2019, and ends on April 19, 2019 (16 days).

4. Results and discussion

The 2019 flood caused losses of life and properties in the Great Karun basin, for this reason this paper's forensic analysis of reservoirs operations takes heightened relevance to avoid future losses. This paper evaluates 14 quantitative criteria (Eqs. (9)–(25)) to assess operation performance of an individual reservoir and a multi-reservoir system under several prerelease scenarios. The pre-release scenarios cover one-week and two-week prereleases. The ideal scenario was developed based on runoff prediction with a lead time of one and two months.

4.1. Scenario 1

This scenario was developed using short-term streamflow prediction models for reservoir operation. This means that the forensic analysis assumes that reservoir operators use the inflow predictions up to two weeks in advance of the flood event. Thus, all reservoirs were allowed to pre-empty and release the maximum allowable water without endangering the dams or downstream areas. Under Scenario 1 the prerelease of all reservoirs in the two sub-basins would begin two weeks before the flood (March 11, 2019). The specification of the prerelease flows and other details are listed in Tables 2 and 3 for the Karun and Dez sub-basins, respectively. It is noteworthy that the Masjed-Soleiman reservoir was built for power generation; therefore, due to its low capacity it does not play any role in flood control. Therefore, the release rate of this reservoir equals its inflow rate. The prereleases of the Karun 4, Karun 3, and Karun 1 reservoirs were chosen to achieve the following: (1) providing storage for flood control, and (2) providing adequate operational water level at the end of the flood period to fulfill their other functions (e.g., agricultural, municipal and industrial water supply, power generation). Therefore, during the prerelease period a reservoir release would equal half of its power plant's design flow; during the flood, the release would equal the power plant's design flow; after the flood period the release would equal half of the power plant's design flow seeking to increase the reservoir's water level.

4.1.1. The Karun Sub-basin

Concerning the Karun 4 reservoir, by following this scenario, this reservoir was 8% more prepared for floods according to FCR criterion. Also, the maximum inflow during the flood, was 2,546 m^3/s, while the peak outflow discharge was 595 m^3/s. Under this scenario the Karun 4 reservoir attenuates the flood peak by about 77% (Table 4). However, this performance criterion, achieved 66% of flood attenuation under the historical scenario, i.e., the actual performance during the flood event. Which means, by two weeks flood forecasting and earlier prerelease, this reservoir could have reduced about 11% more of flood peak discharge. Also, under Scenario 1, Karun 4 Reservoir stores 47% of the flood volume, which is about 20% higher under the historical scenario (see Fig. 4). This means that of the 1,777 × 10^6 m^3 of water that enters the reservoir, about 940 × 10^6 m^3 are released to the downstream. Therefore, by following this scenario, in the beginning of the summer, this reservoir's water level is on the normal level which is full capacity and ideal for water demand meeting in the summer. Also, by two weeks earlier prerelease, it could be possible to delay the occurrence of outflow peak discharge about 24 days. The reliability of no downstream damage, resiliency and vulnerability criteria are equal 100%, 100% and 0%, respectively, under this scenario, which means that the outflow of this reservoir would not exceed the MAD during operations.

Under scenario 1 the Karun 3 reservoir had more than 870 × 10^6 m^3 of free storage space for flood control at the beginning of the flood event, which is equivalent to 36% of its capacity and about 20% more than historical scenario. Therefore, this reservoir manages to store 30% of the 2,445 × 10^6 m^3 of reservoir inflow and releases about 1,718 × 10^6 m^3, which is far better than the 13% achieved under the historical scenario. The Karun 3 reservoir reduces the flood peak discharge by 71%, which results in the inflow peak of 2,393 m^3/s being reduced to 686 m^3/s. However, under the historical scenario, this reduction was only about 3% (see Fig. 4). Also, the reliability, resiliency, and vulnerability criteria are equal to 100%, 100% and 0%, respectively, under this scenario, which means the outflow of this reservoir would not exceed the MAD. Also, it should be noted that, the occurrence of the inflow and outflow peak discharge was in a same day and PFD criterion equals to zero.

Concerning the Karun 1 reservoir the calculated PDR criterion is about 30%, while under the historical scenario it achieved only 1% (Table 4). This means that the peak discharge decreases from 1,412 to 995 m^3/s under scenario 1. As expected, the PDR value for Karun 1 is

Table 1
Reservoir characteristics.

Reservoir Specification	Karun 4	Karun 3	Karun 1	Masjed-Soleiman	Gotvand	Rudbar-Lorestan	Dez
Normal operating volume (10^6 m^3)	2280	2719	2438	261.6	4671	215	2698.5
Minimum operating volume (10^6 m^3)	1446	1094	824	201	1621	97.5	726.5
Power plant's design discharge (m^3/s)	684	1371	1471	1605	843	116	357

Table 2
Developed scenarios' specifications for the Karun sub-basin reservoirs.

Name of Reservoir	Karun 4		Karun 3		Karun 1		Masjed-Soleiman		Gotvand	
Power plant's design discharge (m^3/s)	684		1371		1471		1605		843	
Downstream Safe Discharge (m^3/s)	3000		3000		3000		3000		1500	
Ahwaz Safe Discharge (m^3/s)	3000–3200									
N. Scenario	Prerelease starting date	Releasing discharge (m^3/s)	Prerelease starting date	Releasing discharge (m^3/s)	Prerelease starting date	Releasing discharge (m^3/s)	Prerelease starting date	Releasing discharge (m^3/s)	Prerelease starting date	Releasing discharge (m^3/s)
1	3/11/2019	342	3/11/2019	685.5	3/11/2019	735.5	3/11/2019	Inflow	3/11/2019	843
	3/18/2019	684	3/18/2019	1371	3/18/2019	1471	3/18/2019	Inflow	3/18/2019	843
	3/23/2019	342	3/23/2019	685.5	3/23/2019	735.5	3/23/2019	Inflow	3/23/2019	843
2	3/18/2019	684	3/18/2019	1371	3/18/2019	1471	3/18/2019	Inflow	3/18/2019	843
	3/23/2019	342	3/23/2019	685.5	3/23/2019	735.5	3/23/2019	Inflow	3/23/2019	843
3	3/20/2019	684	3/10/2019	1371	3/2/2019	1471	3/18/2019	1605	1/22/2019	843
	3/23/2019	9.8	3/23/2019	228.5	3/23/2019	245.2	3/23/2019	267.5	3/23/2019	140.5

Table 3
Developed scenarios' specifications for the Dez sub-basin reservoirs.

Name of Reservoir	Rudbar-Lorestan		Dez	
Power plant's design discharge (m^3/s)	116		357	
Downstream Safe Discharge (m^3/s)	460		1100	
N. Scenario	Prerelease starting date	Releasing discharge (m^3/s)	Prerelease starting date	Releasing discharge (m^3/s)
1	3/11/2019	58	3/11/2019	1100
	4/4/2019	Historical outflow	4/4/2019	Historical outflow
2	3/18/2019	58	3/18/2019	1100
	4/4/2019	Historical outflow	4/4/2019	Historical outflow
3	3/23/2019	19.3	2/28/2019	1100

lower compared to its upstream reservoirs, and the reason for this is that this reservoir stores the release discharge of upstream reservoirs (see Fig. 4). Also, this reservoir stores about 13% of the flood volume, which is about 3% higher than the historical volume. Also, the reliability, resiliency, and vulnerability criteria are equal to 100%, 100% and 0%, respectively, under this scenario, which means the outflow of this reservoir would not exceed the MAD. Also, it should be noted that, the occurrence of the outflow peak discharge was delayed 13 days from inflow peak discharge occurrence. This means that, by following this scenario, the outflow peak discharge could have reduced and delayed significantly compared to historical scenario which could significantly prevent downstream damages of this reservoir. Also, this reservoir had capacity of 13% for controlling the total flood volume.

The main purpose of the Masjed-Soleiman reservoir is hydropower generation. Scenario 1 assumes that its outflow equals its inflow, and, therefore, did not play any considerable role in reducing the flood volume or the discharge (see Table 4).

The Gotvand reservoir is the largest in the Karun basin which could have 22% readiness for flood control aim at the beginning of the flood by following this scenario. This reservoir attenuates the peak inflow by 73% (the inflow discharge decreases from 3,119 to 843 m^3/s), compared with 47% under the historical scenario. The achieved FVR criterion value is 22%, which is about 12% higher than its historical counterpart (Table 4). This means a reduction from 2,699 × 10^6 m^3 of inflow to 2,112 × 10^6 m^3. According to Scenario 1, the Gotvand reservoir had about 600 × 10^6 m^3 of free capacity for flood control just before the flood event (see Fig. 4). It released an outflow larger than the safe discharge under the historical scenario despite the presence of upstream reservoirs. This is a clearly an undesirable situation that did not occur under the developed scenarios herein considered. Also, the criteria of reliability, resiliency and vulnerability are equal 100%, 100% and 0% under this scenario, which are equal to 21%, 77% and 10%, respectively, better than the relative value in the historical scenario. This means the outflow from this reservoir would not exceed the MAD under this scenario, in contrast to the actual violation of the MAD that occurred during historic operation. Also, it should be noted that, the occurrence of the inflow and outflow peak discharge was in a same day and PFD criterion equals to zero.

Concerning the evaluation of the multi-reservoir system (the basin-wide criterion) it was determined that the peak inflow discharge to the Karun sub-basin is 7,706 m^3/s, which is reduced to 843 m^3/s by the upstream reservoirs. This means an 89% attenuation of the peak discharge in the Karun basin, which is 10% more than the corresponding historical value. During the flood 4,579 × 10^6 m^3 of water enters the Karun basin. Under Scenario 1, 2,112 × 10^6 m^3 is released, and the rest is stored in the reservoir system. Therefore, 54% of the volume that enters the Karun Basin is stored in the reservoir system, which compares with 33% in the historical scenario. It is worth noting that under Scenario 1 the reservoir system attenuates the flood peak discharge during a single day (Fig. 5).

4.1.2. *The Dez sub-basin*

The Dez sub-basin includes Rudbar-Lorestan and Dez as its two main reservoirs in the upstream and downstream sections of the basin, respectively. The flood readiness criterion for Rudbar-Lorestan reservoir is 31%, which is slightly higher than the historical value of 28% (see Table 5). Judging by the storage in the Rudbar-Lorestan reservoir compared with the Dez reservoir the prerelease of the former reservoir during the pre-flood period does not make much difference with respect to flood control readiness in this reservoir. However, during the flood event the power plant was operating at half of its capacity with a steady discharge being released during 10 days. In this case the FVR criterion for the Rudbar-Lorestan reservoir reaches 21%, which exceeds the historical state criterion of 14%. Under Scenario 1 the Rudbar-Lorestan reservoir does not have any significant releases in excess of the safe discharge and does not spill during the flood period. The reason for this

Table 4
Calculated criteria for Karun sub-basin reservoirs.

			Reservoir				
Criterion	Scenario	Unit	Karun 4	Karun 3	Karun 1	Masjed-Soleiman	Gotvand
PDR	Historical	%	66	2.6	1	1	47
	1		77	71	30	0	73
	2		77	71	30	0	67
	3		66	56	58	0	91
FVR	Historical	%	28	13	10	1	9
	1		47	30	13	0	22
	2		47	30	14	0	20
	3		46	58	62	0	72
PFD	Historical	Day	13	8	0	0	20
	1		24	0	13	0	0
	2		24	0	14	0	24
	3		13	24	7	0	25
FCR	Historical	%	39	16	12	1	23
	1		47	36	13	7	22
	2		47	30	14	2	19
	3		46	58	62	3	71
Reliability of no downstream damage	Historical	%	100	100	100	100	79
	1		100	100	100	100	100
	2		100	100	100	100	100
	3		100	100	100	100	100
Resiliency to downstream damage	Historical	%	100	100	100	100	33
	1		100	100	100	100	100
	2		100	100	100	100	100
	3		100	100	100	100	100
Vulnerability to downstream damage	Historical	%	0	0	0	0	10
	1		0	0	0	0	0
	2		0	0	0	0	0
	3		0	0	0	0	0

is the effect of the prerelease policy (see Fig. 6). This reservoir performed the best in terms of reliability, resiliency and vulnerability to downstream damage criteria, which are 100%, 100%, and 0%, respectively. This means the outflow from this reservoir would not exceed the MAD under this scenario.

According to the FVR criterion the Dez reservoir stores 15% of the flood flow in the Dez Reservoir under Scenario 1, which is equal to 10% under the historical scenario. The FCR criterion corresponding to the developed and historical scenarios for the Dez reservoir equal 21% and 16%, respectively (Table 5). The peak outflow discharge under Scenario 1 is 1,956 m^3/s, which is about 39% less than under the historical scenario. The vulnerability to the downstream damage criterion is about 78%, which is about half of the value during historic operation (see Fig. 6). Therefore, it can be concluded that due to the high volume of water entering to the reservoir, even by using accurate forecasting of discharge from two weeks before the flood and proper discharge about MAD and providing more empty volume, there were only possible to store about 200 × 10^6 m^3 more compared to the historical scenario. However, the peak flood discharge has significantly decreased compared to the MAD and the rate of violation of the safe discharge has decreased from 193% historical to 78% of the proposed scenario.

The results for the multi-reservoir system show that there is a similar trend for all developed criteria, whereby the PDR criterion by the reservoirs is equal to 55%. Thus, there is a significant effect of the prereleases in reducing the peak discharge. Also, the occurrence of the peak outflow discharge from the reservoir system is delayed by three days. The FVR criterion in the multi-reservoir system is 17%, with most of the relief volume stored in the Dez reservoir and the rest in the Rudbar-Lorestan reservoir (Fig. 7).

4.2. Scenario 2

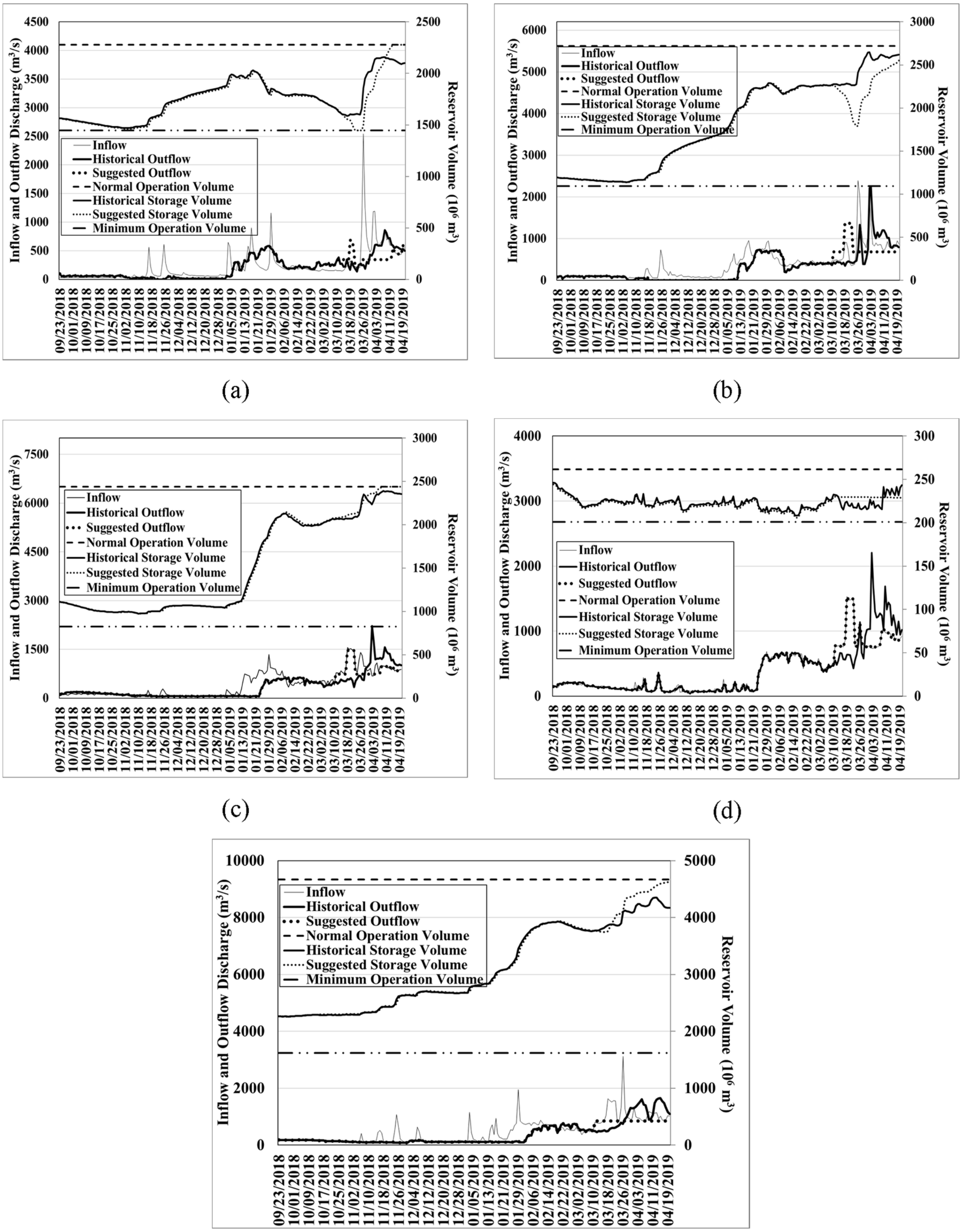
Under scenario the runoff predictions are made one week before the flood. Therefore, the prerelease from all reservoirs of the Karun and Dez sub-basins begins one week before the flood (March 18, 2019). The scenario's specifications are listed in Tables 2 and 3.

4.2.1. The Karun sub-basin

Under scenario 2, this reservoir was 8% more prepared for floods according to FCR criterion. The Karun 4 reservoir reduces the inflow discharge from 2,546 m^3/s to 595 m^3/s in the outflow, which is equivalent to 77% of the PDR (Table 4). Also, this reservoir releases only 53% of the inflow flood volume. At the time beginning of the flood the reservoir has ample storage capacity as its total active capacity of 834 × 10^6 m^3 provides an FCR of 47%, and uses the available storage to store the flood (Fig. 8). The criteria of reliability, resiliency, and vulnerability are equal to 100%, 100% and 0%, respectively, under this scenario which means, the outflow of this reservoir would not exceed the MAD during operations. Also, it should be noted that, at the beginning of the flood, the reservoir had 834 × 10^6 m^3 of free capacity, which used all this volume to control and store the flood.

Concerning the evaluation of Karun 3 the results of Table 4 indicate the maximum inflow discharge of the Karun 3 during the flood equals 2,393 m^3/s, while the peak outflow discharge is reduced to 686 m^3/s. In other words, this reservoir reduces the flood peak by about 71%. This means that of the 2,444 × 10^6 m^3 of water entering the reservoir, about 30% are stored and 1,718 × 10^6 m^3 are released. The Karun 3 reservoir operation under Scenario 2 has a readiness criterion of about 30% of the reservoir volume at the beginning of the flood (see Fig. 8). The results of three criteria of reliability, resiliency and vulnerability (which are 100%, 100% and 0%, respectively) shows that the outflow of this reservoir would not exceed MAD during operations. Also, it should be noted that, the inflow and outflow peak discharge has happened in the same day and so the PFD criterion of this reservoirs is zero under this scenario.

The calculated criteria establish that at the beginning of the flood the Karun 1 has more than 330 × 10^6 m^3 of empty volume for flood control, which is equivalent to 14% of its active capacity (Table 4). Due to the empty volume in the reservoir Karun 1 releases about 2,026 × 10^6 m^3 of the 2,366 × 10^6 m^3 of water entering the reservoir and stores the rest. The reservoir reduces the peak inflow discharge by 30% which means that it reduces the peak inflow discharge from 1,412 m^3/s to 987 m^3/s in the outflow (see Fig. 8). The results of the reliability, resiliency and



(a) (b)

(c) (d)

(e)

Fig. 4. Daily changes in the water volume and discharges of (a) Karun 4 (b) Karun 3 (c) Karun 1 (d) Masjed-Soleiman and (e) Gotvand reservoirs under Scenario 1.

vulnerability criteria (which are 100%, 100% and 0%, respectively) shows that the outflow of this reservoir would not exceed the MAD during operations. Also, it should be noted that, the occurrence of the outflow peak discharge was delayed 14 days from inflow peak discharge occurrence. This means that, by following this scenario, the outflow peak discharge could have reduced and delayed significantly compared to historical scenario which could prevent serious downstream damages of this reservoir

It is seen in Fig. 8 that the Masjed-Soleiman reservoir exhibits similar results as those of Scenario 1, which means that it does not play any role in reducing the flood volume or discharge (Table 4).

The Gotvand reservoir, could have 19% readiness for flood control aim at the beginning of the flood by following this scenario. The PDR in this reservoir is about 67% (Table 4), which means the peak of discharge decreases from 3,119 to 1,027 m^3/s (see Fig. 8). Accordingly, the reservoir stores about 20% of the inflow flood volume and releases the rest of the inflow downstream. The total spill volume from Gotvand during this period is about 41×10^6 m^3. In addition, the criteria of

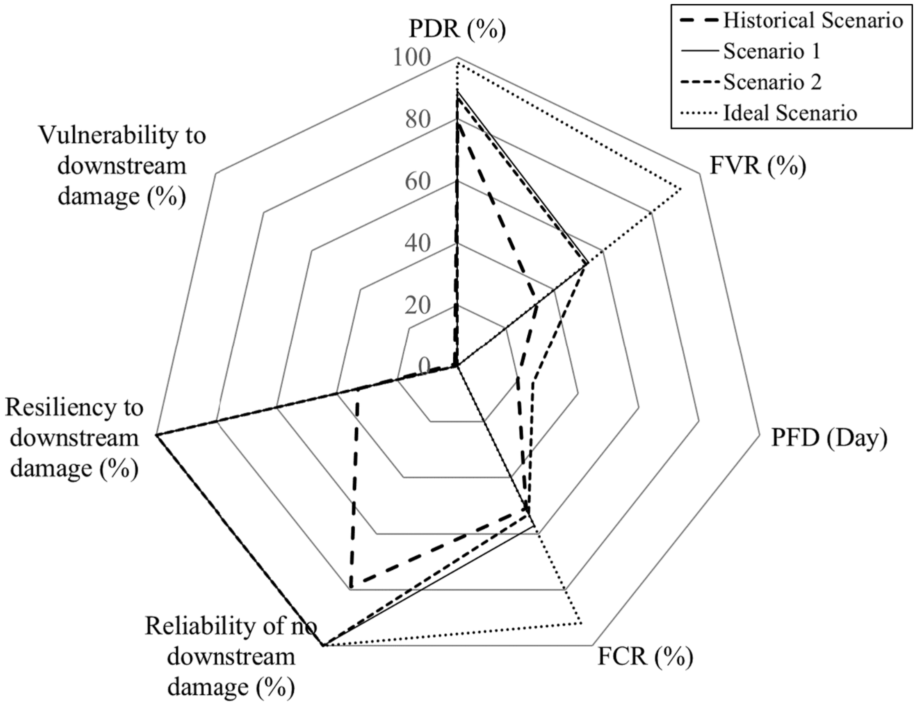


Fig. 5. Comparison radar graph of the developed basin criteria for historical and developed prerelease scenarios of the Karun sub-basin.

Table 5
Calculated developed criteria in Dez sub-basin reservoirs.

Criterion	Scenario	Unit	Reservoir	
			Rudbar-Lorestan	Dez
PDR	Historical	%	33	22
	1		33	53
	2		33	53
	3		64	52
FVR	Historical	%	14	10
	1		21	15
	2		21	14
	3		79	23
PFD	Historical	Day	7	8
	1		7	9
	2		7	10
	3		6	7
FCR	Historical	%	28	16
	1		31	21
	2		31	19
	3		79	22
Reliability of no downstream damage	Historical	%	100	21
	1		100	14
	2		100	14
	3		100	28
Resiliency to downstream damage	Historical	%	100	4
	1		100	4
	2		100	4
	3		100	10
Vulnerability to downstream damage	Historical	%	0	193
	1		0	78
	2		0	78
	3		0	77

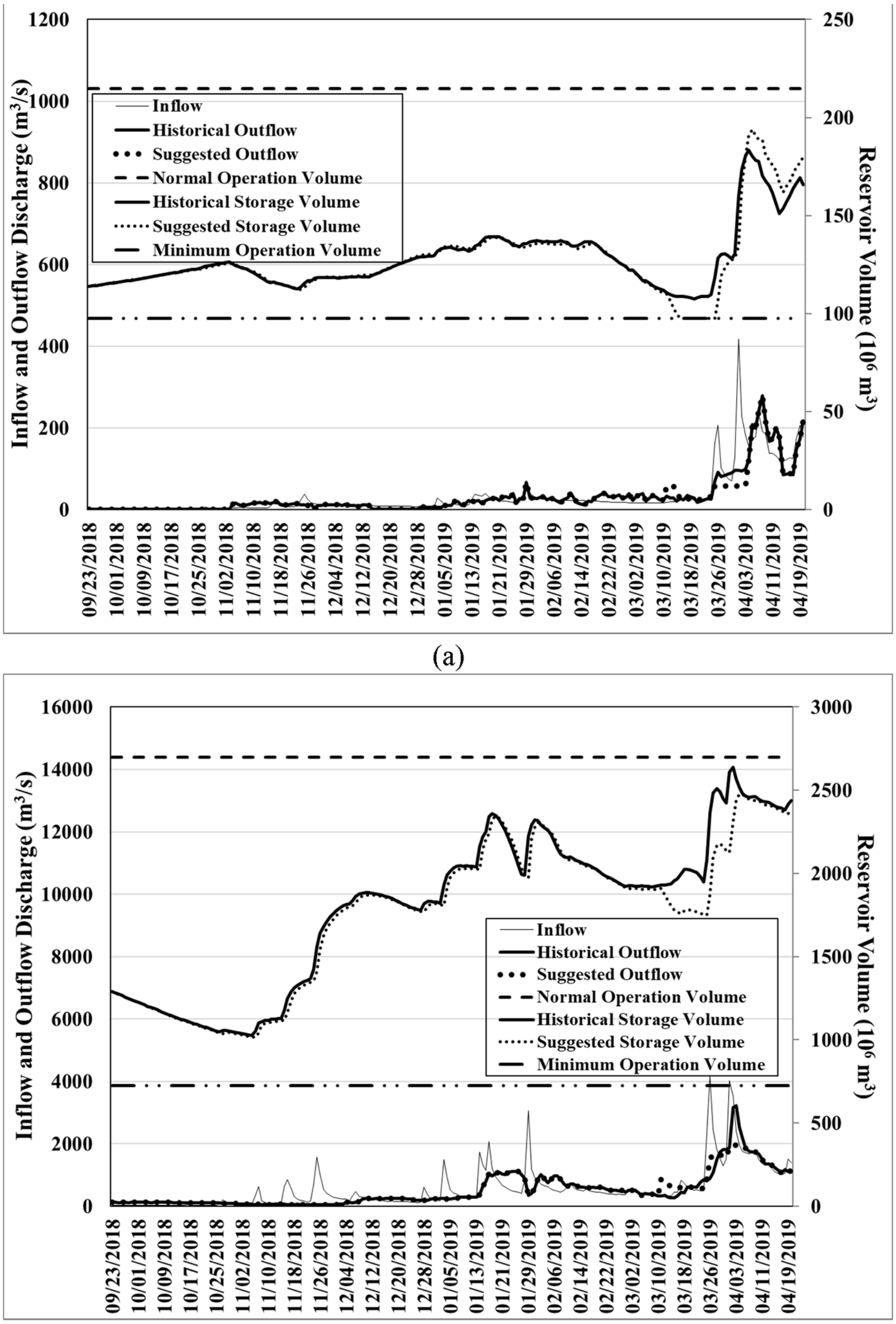
reliability, resiliency, and vulnerability are equal to 100%, 100% and 0% under this scenario, which are 21%, 77% and 10%, respectively, better than their values under historical operations. This means the outflow of this reservoir would exceed the MAD under operations, in contrast to the violation that occurred during historic operations. Also, according to PFD criterion, the outflow peak discharge of this reservoir could have delayed 24 days from the inflow peak discharge occurrence.

With respect to the evaluation of the reservoir system it was calculated that the peak outflow discharge under this scenario is 1,027 m^3/s, while the inflow peak is 7,706 m^3/s. Therefore, the operation of the reservoir system under Scenario 2 reduces the peak discharge by 87%. During and after the flood, 4,577 × 10^6 m^3 of water enters the Karun basin and 2,135 × 10^6 m^3 is released. The rest of the water is stored in the reservoirs, which amounts to about 53% of the total flood volume. It is worth noting that under Scenario 2 the reservoir system delays the peak flood discharge by 24 days (Fig. 5).

4.2.2. *The Dez sub-basin*

The Rudbar Lorestan reservoir could have 31% readiness for flood control aim at the beginning of the flood by following this scenario. This reservoir attenuates the peak inflow by 33% (the inflow discharge decreases from 418 to 279 m^3/s), which is the same compared to the historical scenario. The achieved FVR criterion value is 21%, which is about 7% higher than its historical counterpart (Table 5). This means a reduction from 382 × 10^6 m^3 of inflow to 303 × 10^6 m^3. According to this scenario, the Rudbar Lorestan reservoir had about 117 × 10^6 m^3 of free capacity for flood control just before the flood event (see Fig. 9). Also, the criteria of reliability, resiliency and vulnerability are equal 100%, 100% and 0% under this scenario, which are equal historical scenario. This means the outflow from this reservoir would not exceed the MAD under this scenario. Also, it should be noted that, the outflow peak discharge could have delayed 7 days from inflow peak discharge occurrence. It is seen in Fig. 9 that low inflow and the adequate volume of available storage compared to the flood volume in Rudbar-Lorestan lead to similar results under Scenarios 1 and 2 in terms of pre-flood performance. However, larger outflow under Scenario 2 causes the volume of Rudbar-Lorestan to be equal to the minimum operational volume. During the flood this reservoir stores more water by releasing less water than during historical operation.

Concerning the Dez reservoir, the calculated PDR criterion is about 53%, while under the historical scenario it achieved only 22% (Table 5). This means that the peak discharge decreases from 4127 to 1956 m^3/s under scenario 2. Also, this reservoir stores about 14% of the flood volume, which is about 4% higher than the historical volume. Also, the reliability, resiliency, and vulnerability criteria are equal to 14%, 4%



(a)

(b)

Fig. 6. Daily changes in the water volume and discharges of (a) Rudbar-Lorestan (b) Dez reservoirs under Scenario 1.

and 78%, respectively, under this scenario, which means the outflow of this reservoir would exceed the MAD, but the vulnerability have improved about 115% under this scenario. Also, it should be noted that, the occurrence of the outflow peak discharge was delayed 10 days from inflow peak discharge occurrence. This means that, by following this scenario, the outflow peak discharge could have reduced and delayed significantly compared to historical scenario which could prevent serious downstream damages of this reservoir. Also, this reservoir had readiness of 19% for controlling the total flood volume. It is worthy of notice that under Scenario 2 the peak outflow discharge is about 1,956 m^3/s, but the value of this variable under historical operation was about 3,226 m^3/s, which means a reduction of flood damage (see Fig. 9). This reduction demonstrates the positive effect of prereleases.

Overall, the Dez sub-basin under Scenario 2 exhibits similar results to those obtained under Scenario 1. This means that reservoir operators could reduce the flood peak by changing the release pattern and by keeping sufficient storage capacity to store floods in the reservoir system (see Fig. 7).

4.3. Scenario 3 (Ideal Operation)

This scenario was developed based on March and April reservoir inflow prediction using long-term inflow series and the data mining method Artificial Neural Network (ANN). The specification of the ANN model and prediction results are listed in Table 6. This scenario specifies that the reservoirs' initial volume must be at its minimum level if the

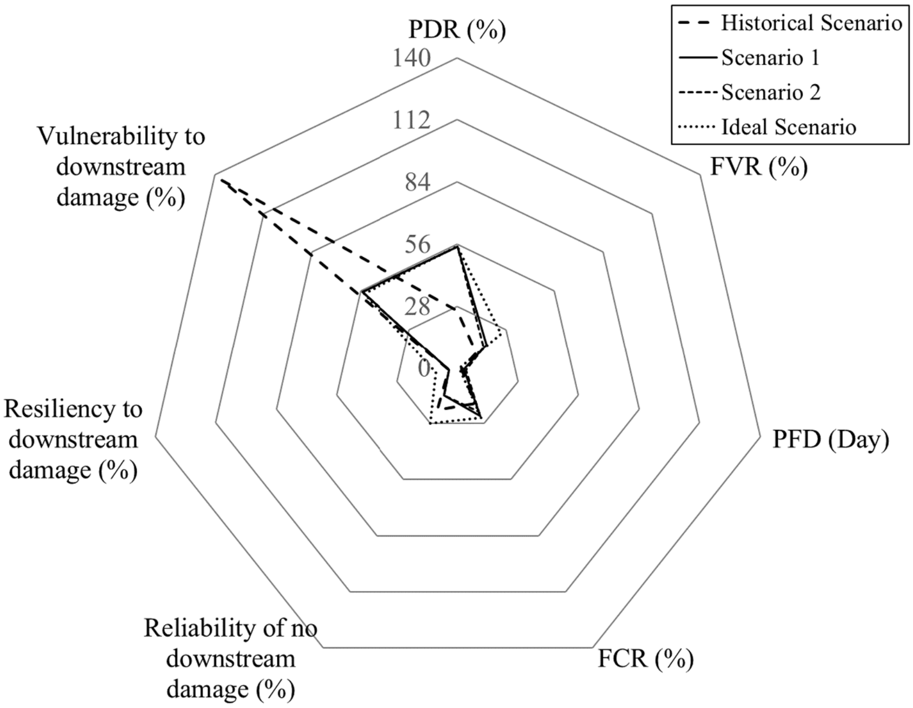


Fig. 7. Comparison radar graph of the developed basin criteria for historical and developed prerelease scenarios of the Dez sub-basin.

volume of reservoir inflow in March and April is larger than reservoir capacity; otherwise, the reservoirs must have available storage capacity equal to the predicted volume of inflow. As a result, the reservoirs would be at their maximum operational level at the end of April.

4.3.1. The Karun sub-basin

The rate of release from the reservoir reaches the maximum capacity of the power plant's tunnels (684 m^3/s). With this volume of release the Karun 4 reservoir, the most upstream reservoir in the Karun basin, would be empty at the beginning of the flood, and, therefore, would store a large flood volume. According to the calculated criteria for this reservoir the peak flow and volume reduction criteria of this reservoir are 66% and 46%, respectively (see Table 4). The reservoir also delays the peak discharge by 13 days. Due to the low storage volume of the reservoir on the day before the start of the flood (816 million cubic meters) the readiness for flood control for this reservoir is 46% (see Fig. 10). The results of three criteria of reliability, resiliency and vulnerability (which are 100%, 100% and 0%, respectively) shows that the outflow of this reservoir would not exceed MAD during operations.

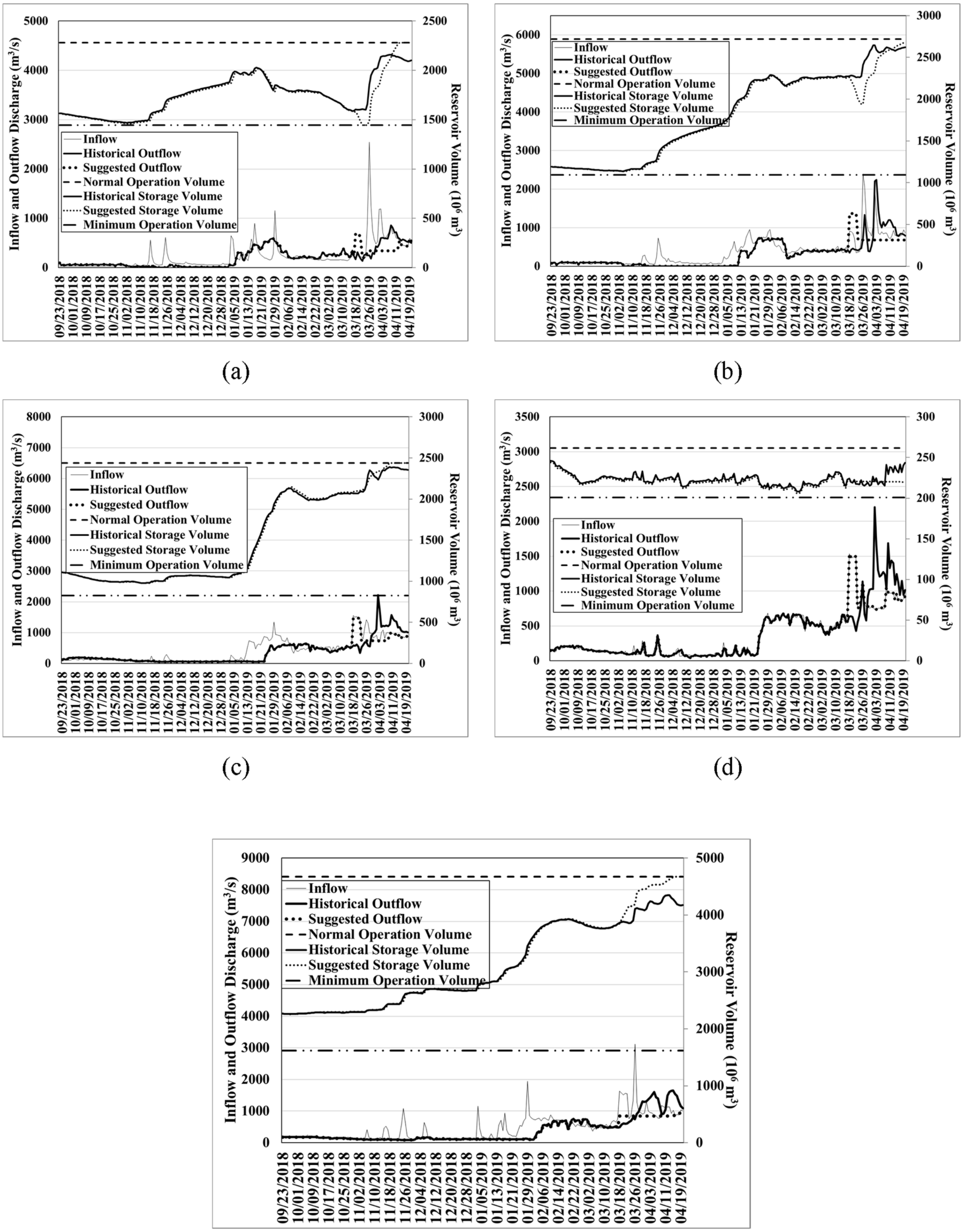
The Karun 3 reservoir reduced the inflow peak discharge of 2,165 m^3/s to 947 m^3/s in the outflow, which is 56% of the PDR criterion (see Fig. 10). The Karun 3 reservoir releases 42% of the total flood volume (see Table 4). At the time of the start of the flood the reservoir has 1,433 $\times 10^6$ m^3 of available storage to control the flood, which is used to store the flood waters. The reservoir also delays the peak discharge by 24 days. Also, it has readiness of 58% for controlling flood volume at the beginning of the flood which improved about 42% compared to historical scenario. The results of three criteria of reliability, resiliency and vulnerability (which are 100%, 100% and 0%, respectively) shows that the outflow of this reservoir would not exceed MAD during operations.

The maximum inflow discharge into the Karun 1 reservoir during the flood is 1,220 m^3/s, while the peak outflow discharge is reduced to 512 m^3/s. In other words, the Karun 1 reservoir reduces the flood peak by about 58% (see Table 4). This means that of the 1,674 $\times 10^6$ m^3 of water entering the reservoir about 62% is stored, and 637 $\times 10^6$ m^3 is released. As expected, this reservoir's performance is far better than the upstream reservoirs' performance with respect to flood control (see Fig. 10). Also, the reliability, resiliency, and vulnerability criteria are equal to 100%, 100% and 0%, respectively, under this scenario, which means the outflow of this reservoir would not exceed the MAD. It is seen in Fig. 10 that the Masjed-Soleiman reservoir does not have any significant role in flood control under this scenario (see Table 4).

The calculated criteria calculated for evaluating the Gotvand reservoir (Table 4) establish that at the beginning of the flood the reservoir has an empty volume of about 900 $\times 10^6$ m^3 (about 71% readiness) to control the flood, which is about 30% of its active volume. Therefore, this reservoir releases about 358 $\times 10^6$ m^3) of the inflow volume of 1286 $\times 10^6$ m^3 and stores the rest. The reservoir also reduces the peak food discharge by 91%, which means that it reduces the inflow peak discharge from 2,628 m^3/s to 224 m^3/s in the outflow (see Fig. 10). In addition, the criteria of reliability, resiliency, and vulnerability are equal to 100%, 100% and 0% under this scenario, which are 21%, 77% and 10%, respectively, better than their values under historical operations. This means the outflow of this reservoir would exceed the MAD under operations, in contrast to the violation that occurred during historic operations. Also, according to PFD criterion, the outflow peak discharge of this reservoir could have delayed 25 days from the inflow peak discharge occurrence.

The outflow peak discharge of the reservoir system under Scenario 3 is 224 m^3/s, while the inflow peak discharge of the system is 7,706 m^3/s. Therefore, reservoir system operation under Scenario 3 reduces the peak inflow discharge by 97% (Fig. 5). During and after the flood 4,579 $\times 10^6$ m^3 of water entered the Karun sub-basin, about 359 $\times 10^6$ m^3 is under ideal operation, and the rest, or 92%, is stored in the reservoir system (Fig. 5).

Fig. 5 compares the operation of the Karun sub-basin in each scenario. It is seen in Fig. 5 that the PDR criterion in this sub-basin in the historical scenario was about 80%, but ideally it could have improved up to 98%. Based on the FCR and FVR criteria the difference between the ideal and historical values increases, which means that it is possible to improve these criteria by about 50 and 60%, respectively. Therefore, it can be concluded that in this sub-basin it is possible to improve the criteria to a large extent with specialized operation.



(a)

(b)

(c)

(d)

(e)

Fig. 8. Daily changes in the water volume and discharges of (a) Karun 4 (b) Karun 3 (c) Karun 1 (d) Masjed-Soleiman and (e) Gotvand reservoirs under Scenario 2.

4.3.2. The Dez sub-basin

The Rudbar-Lorestan reservoir could have 79% readiness for flood control aim at the beginning of the flood by following this scenario which is 51% higher than the historical scenario. This reservoir attenuates the peak inflow by 64% (the inflow discharge decreases from 418 to 237 m^3/s), which is the same compared to the historical scenario. The achieved FVR criterion value is 79%, which is about 65% better than its historical counterpart (Table 5). This means a reduction from 382 × 10^6 m^3 of inflow to 264 × 10^6 m^3. According to this scenario, the Rudbar Lorestan reservoir had about 117 × 10^6 m^3 of free capacity for flood control just before the flood event (see Fig. 9). Also, the criteria of reliability, resiliency and vulnerability are equal 100%, 100% and 0% under this scenario, which are equal historical scenario. This means the outflow from this reservoir would not exceed the MAD under this scenario. Also, it should be noted that, the outflow peak discharge could have delayed 6 days from inflow peak discharge occurrence.

Concerning the Dez reservoir, the calculated PDR criterion is about 52%, while under the historical scenario it achieved only 22% (Table 5).

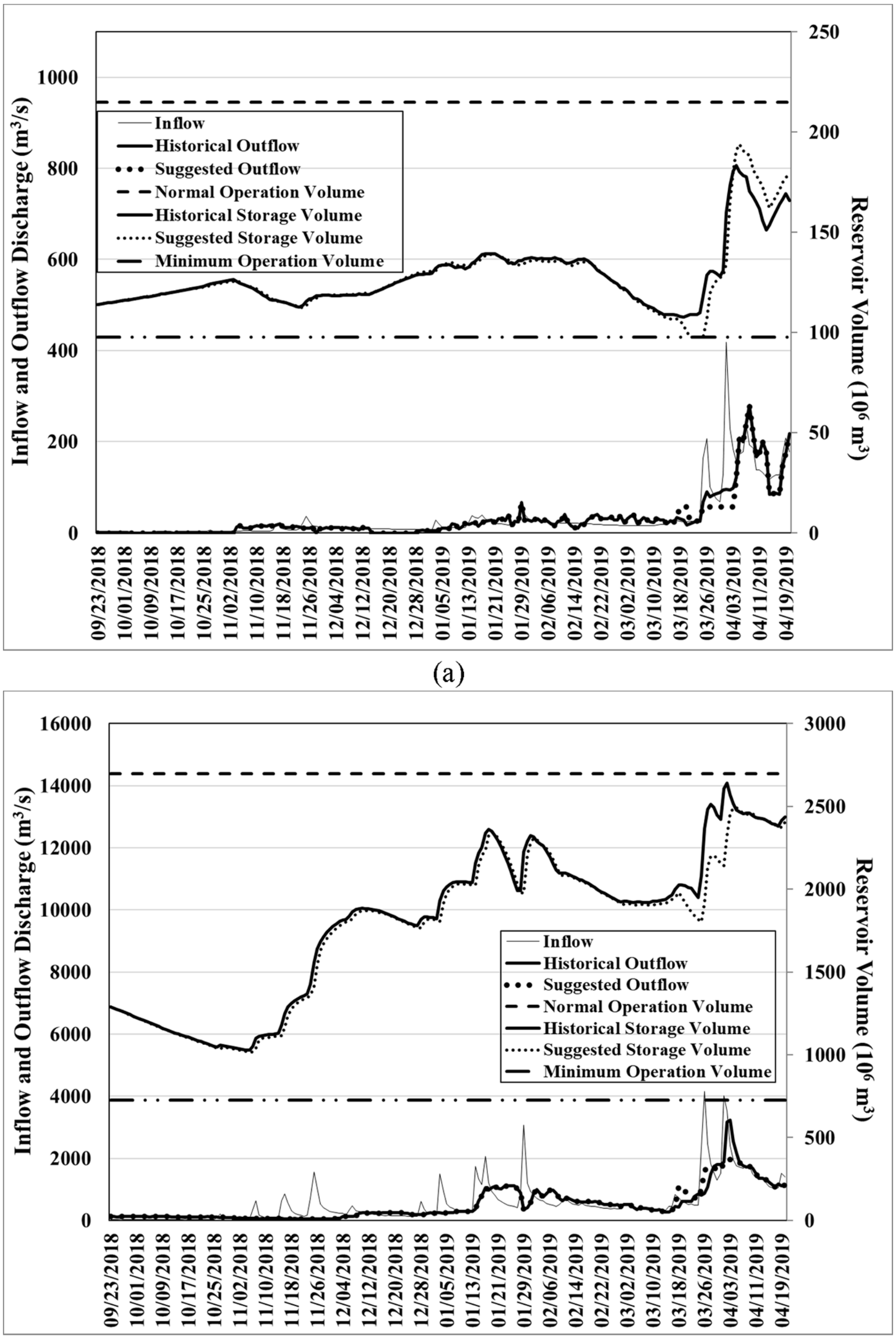


Fig. 9. Daily changes in the water volume and discharges of (a) Rudbar-Lorestan (b) Dez reservoirs under Scenario 2.

Table 6
Predicted values of Inflow using artificial neural network and its specifications.

Sub-Basin	Predictive months	Predicted month	Number of years in model training	Historical cumulative inflow (10^6 m^3)	Predictive cumulative Inflow (10^6 m^3)	Error (%)	RMSE (10^6 m^3)	Number of layers	Number of first layer neurons	Number of second layer neurons	Epoch	Transfer function
Karun	January and February	March	58	7440.3	8585.4	15.4	1145.1	2	3	1	1000	Logsig
		April		12080.7	14981.3	24	2900.5	2	3	1	1000	Tansig
Dez	January and February	March	54	5787	7639.6	32	1852.5	2	3	1	1000	Logsig
		April		10296.3	7992.8	22	2303.5	2	3	1	1000	Tansig

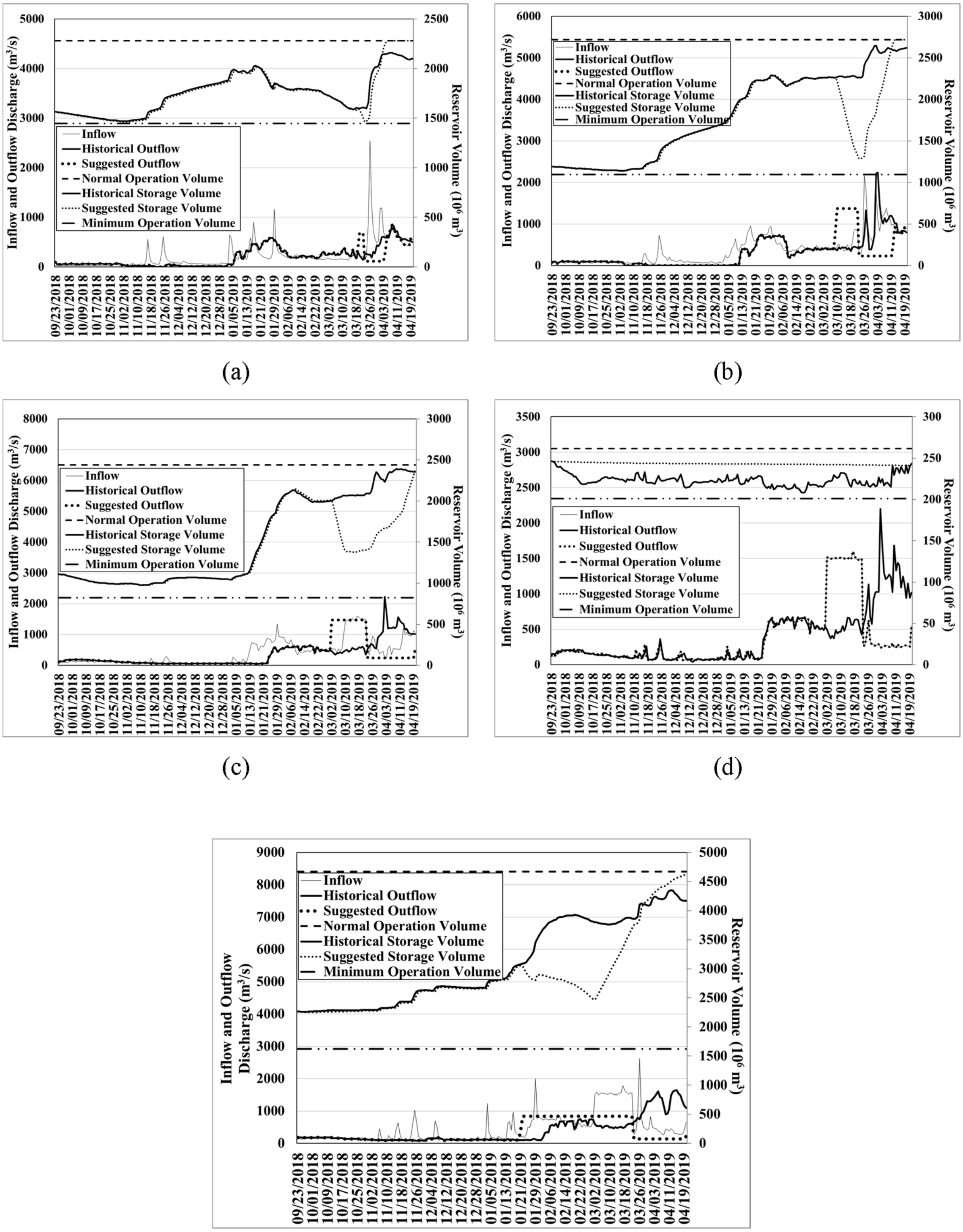
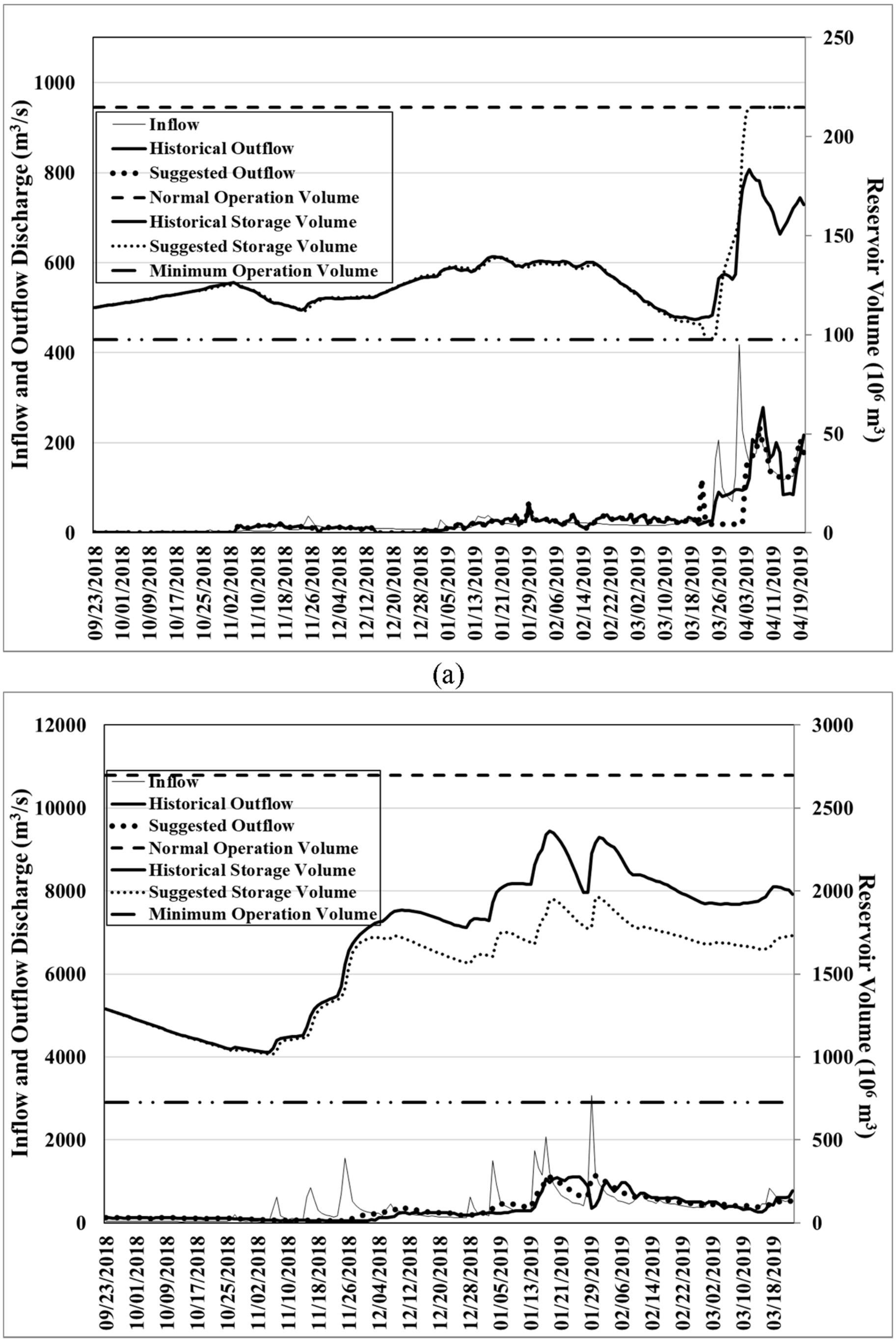


Fig. 10. Daily changes in the water volume and discharges of (a) Karun 4 (b) Karun 3 (c) Karun 1 (d) Masjed-Soleiman and (e) Gotvand reservoirs under Scenario 3.

This means that the peak discharge decreases from 4088 to 1947 m^3/s under scenario 2. Also, this reservoir stores about 23% of the flood volume, which is about 13% higher than the historical volume. Also, the reliability, resiliency, and vulnerability criteria are equal to 28%, 10% and 77%, respectively, under this scenario, which means the outflow of this reservoir would exceed the MAD, but the vulnerability have improved about 116% under this scenario. Also, it should be noted that, the occurrence of the outflow peak discharge was delayed 7 days from inflow peak discharge occurrence. This means that, by following this scenario, the outflow peak discharge could have reduced and delayed significantly compared to historical scenario which could prevent serious downstream damages of this reservoir. Also, this reservoir had readiness of 22% for controlling the total flood volume. As a result, according to Fig. 11, the Dez reservoir cannot release as much as it does under the other scenarios due to its high inflows before the flood because its release is near the safe discharge. Under this scenario and starting prerelease on February 28, 2019, the PDR and the FVR criteria yields better values in comparison to other scenarios (see Table 5).



(a)

(b)

Fig. 11. Daily changes in the water volume and discharges of (a) Rudbar-Lorestan (b) Dez reservoirs under Scenario 3.

Fig. 7 compares the operation of the Dez sub-basin in each scenario, where it is seen that the PDR criterion in this sub-basin in the historical scenario was about 28%, but ideally it could have been improved by up to 56%. Based on the FCR and FVR criteria the difference between the ideal and historical values increased, which means that it is possible to improve these criteria by about 10 and 12%, respectively. Therefore, it can be concluded that in this sub-basin it is possible to reduce the floods effects with specialized operation.

As a result, with considering one and two-week flood forecasting (scenarios 1 and 2), about 89% attenuation of the peak discharge in the Karun basin could be happen which is about 10% more than the corresponding historical value. Also, this value in Dez sub-basin, was at least 55% of PDR which was 20% more than historical scenario. But with increasing the lead-time of flood forecasting to one and two-month (ideal scenario), the PDR criterion of Karun and Dez sub-basins will increased to 98% and 56% respectively. In addition, insufficient storage capacity increases the vulnerabilities of water and hydroelectric systems (Ehsani et al., 2017) which with earlier prediction of inflow to reservoirs, could decrease significantly. In Gotvand and Dez reservoirs, this criterion, have improved about 10 and 115%. Therefore, improving the accuracy of the forecasting models with the lead time of one and two months would achieve successful operation that would prevent flood damages (Liu, 2016; Lee and Kim, 2018; Hu et al., 2019).

5. Concluding remarks

Floods affect many parts of the world inflicting loss of property and life. Many approaches have been devised for flood control, and reservoirs represent one of the key structural measures for that purpose. Historic reservoir operation for flood control can be assessed by forensic engineering and studied for making improvements to flood control operation planning.

This work developed 14 criteria and three prerelease scenarios to perform forensic engineering assessment of the 2019 flood. The main flood characteristics were considered in developing these criteria, including inflow and outflow flood volumes, inflow and outflow peak discharges, MAD, etc. These criteria quantify reservoir operation performance before, during, and after the flood event. Also, prerelease scenarios were based on realistic runoff predictions with a lead time of one and two weeks. Furthermore, an ideal scenario was considered with the lead times equal to one and two months depending on the both flood and reservoir capacity volumes. These scenarios assist forensic engineers in assessing reservoir operation and in comparing their performance with a defined ideal operation.

This work's results show that reservoirs in the Karun Sub-Basin could reduce inflow peak discharge by 79%. The outflow flood volume could be reduced by about 33% compared to the inflow flood volume in the reservoir system observed during the floods of April 2019. An evaluation of historical data concerning the operation of the Karun Sub-Basin reservoirs shows that the reservoirs played a vital role in attenuating the flood hydrographs. Without the reservoir system the maximum daily inflow to Gotvand City would have been 7,706 m^3/s, but with the reservoirs the discharge peak was reduced to about 1,650 m^3/s. The flood control readiness (FCR) criterion ranges between 53 and 57% under prelease scenarios, and under historic operations it was 51%. The reliability of no downstream damage criterion under the prerelease scenarios equals 100%, and under historic operations it was 79%. The vulnerability to downstream damage criterion under the prerelease scenarios is 0%, and under historical operation it equals 1%. The resiliency to downstream damage criterion is calculated as 100% under the prerelease scenarios, and 33% under historical operation. Overall reservoir operators in the Karun Sub-Basin performed well in 2019. This work demonstrates it would have been possible to perform better with a more specialized approach.

The Dez sub-basin reservoirs feature a FCR criterion between 22 and 24%, and it equaled 18% under the historical operation. The reliability of no downstream damage criterion is 14% under prerelease scenarios and 21% under historical operation. The vulnerability to downstream damage criterion was 55% under prerelease scenarios and 136% under historical operation. The criterion of resiliency to downstream damage is 4% under the prerelease scenarios. The Dez Sub-Basin has high reservoir inflows in the pre-flood period, which made violation of the safe discharge inevitable. However, ideal reservoir operation largely avoids this violation. This paper shows that with specialized reservoir operation as herein proposed reservoir operators could reduce flood damages. Therefore, by using this forensic engineering approach (which applies the developed criteria and prerelease scenarios) the performance of reservoirs' operators during floods would be fully and specifically assessed, which would improve future reservoir operation during floods.

This paper's results indicate that the improvement and use of flood forecasting models could potentially improve flood-control operations leading to optimal planning of water prerelease and successful flood control. In this regard, consideration of uncertainty and climate change impacts would improve reservoir operation studies of the type herein considered. Implementing the developed criteria in this work would lead to accurate evaluation of the performance of reservoir operation maximize the effectiveness of flood control by means of reservoir operation.

CRediT authorship contribution statement

Mohammad Delpasand: Software, Formal analysis, Writing - original draft. **Elahe Fallah-Mehdipour:** Validation, Methodology, Visualization. **Mohamad Azizipour:** Validation, Methodology, Visualization. **Mohammadreza Jalali:** Validation, Methodology, Visualization. **Hamid R. Safavi:** Validation, Methodology, Visualization. **Bahram Saghafian:** Validation, Data curation, Writing - review & editing. **Hugo A. Loáiciga:** Validation, Writing - review & editing. **Mukand Singh Babel:** Validation, Writing - review & editing. **Dragan Savic:** Validation, Writing - review & editing. **Omid Bozorg-Haddad:** Conceptualization, Supervision, Project administration.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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