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ORIGINAL PAPER

Scenario analysis of flood control structures using a multi-criteria decision-making technique in Northeast Iran

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Abstract Predicting the impacts of flood control measures to determine the best spatial distribution and specifications of check dams assists managers and engineers in planning flood control projects. The focus of this paper is on scenario analysis of check dam construction using a multi-criteria decision-making (MCDM) technique in the Jafar-Abad Watershed, Golestan Province, Iran. Based on spatial distribution, number and elevation of check dams, eight structural management scenarios were developed. For each scenario, flood hydrographs for different return periods were simulated using the HEC-HMS model. To predict the impacts of implementing the management scenarios, some hydrologic and hydroeconomic indices were quantified for each management scenario. To weight the indices, expert knowledge was elicited using the Delphi process. A MCDM approach was employed to choose the best management scenarios. The analysis shows that Scenario 7 (increasing the number of check dams from 58 to 69) is the best management scenario from the hydrologic perspective. In addition, best management scenarios from hydroeconomic perspective are Scenario 1 (current condition), and Scenario 5 (with only 15 check dams on an upstream sub-watershed), respectively. The approach implemented in this research is a useful way to allocate flood control measures efficiently and effectively.

Keywords Check dams · Flood control · MCDM · HEC-HMS model · Structural management scenarios · The Jafar-Abad Watershed

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1 Introduction

Flood events cause considerable losses and damages in many areas of Iran each year. Floods have historically killed more people than any other form of natural disaster and cause massive damage to economic activities (Yazdi and Neyshabouri 2012; Abdelkareem 2017). Humans have attempted to reduce floods using different methods with varying degrees of success (Sharifi et al. 2012; Banks et al. 2014). Addressing such a crucial environmental problem, at both large and small scales, requires an integrated watershed modelling approach, in which key biophysical and socio-economic drivers, processes and impacts are all considered (Zheng and Baetz 1999; Maidment and Djokic 2000; Sadoddin 2010).

Watershed management practices such as construction of check dams can be useful for soil and water conservation purposes. Check dams have been successfully implemented in watershed management practices to storm water settings in arid and semi-arid regions of Iran, as well as other regions (Zehtabiyan et al. 2011). Check dams are relatively easy to establish and low-cost measures which are effective in reducing erosion, and removing coarse and medium-sized sediments from run-off in small water courses (Agoramoorthy et al. 2008). Check dam is a permeable or non-permeable barrier to obstruct flow discharge and cause upstream pooling. Check dams are constructed in concentrated flow water ways which can either be permanent or temporary barrier from different materials that prevent erosion by slowing flow velocities (Polyakov et al. 2014). Check dams have upstream and downstream effects. They modify water and sediment transport by impounding storm flow, reducing its velocity and peak rate, decreasing channel slope, and allowing more time for infiltration and sediment settling (Mishra et al. 2007; Polyakov et al. 2014). Check dams tend to pond during low flow periods and then infiltrates through the check dam (Polyakov et al. 2014). This pooling of water increase infiltration of rainfall to groundwater and reduces the peak discharge of storm hydrograph while trapping transported sediments (Xu et al. 2007). These small dams are mainly constructed to catch sediment materials, while doing so, they affect the flood flow regime as well. The check dams catch the considerable amount of surface run-off in first flood events. The upstream volume of check dams will be filled by trapped sediments after few occurred floods depending the size of the dam and cross section of the water way (Boix-Fayos et al. 2007; Mishra et al. 2007). The water will store in the reservoir of the check dams in first years of the construction. Implemented check dams in series reduce the intensity of the hydrograph peak by lengthening the conveyed water through the waterway, as well as it reduces the water volume (Castillo et al. 2013). Check dams can recharge local aquifer providing temporary source of water for irrigation, reduce erosion and sediment transport, accumulate sediment, and provide a suitable environment for planting local plants (Wani et al. 2003; Hassanli, et al. 2009; Government of Gujarat 2012; Renganayaki and Elango 2013). Construction of check dams not only affects flow characteristics but, also alters river habitat (Shieh et al. 2007). A scenario analysis approach has been suggested by Harvey et al. (2009) in Taihu basin, China. According to their study results, the quantified modelling methodology presented can be used to test a more exhaustive set of scenarios and conduct a more objective flood risk driver and response ranking process. Construction of check dams in rural communities lead to the replenishment of water resources and restore moisture to the local ecosystem and benefit the environment (Khonkaen and Jie-Dar 2011). Construction of check dams is increasing in disturbed water courses to provide flow regulation and sediment control due to cost and ease of construction and availability of required construction materials (Krishna

2005). Check dams function by reducing the flow peak of water through a water course, causing accumulation of water immediately upstream (Roshani 2003). Mitigation of flood damages requires high-quality maintenance and modifications of flood control structures. Assessing various impacts of management activities in the watershed scale can improve decision-making (Gul et al. 2010). The explicit use of flood management scenarios provides an apparent method to recognise the potential impacts of management activities on watershed response (Mazzorana et al. 2013).

Multi-criteria decision-making (MCDM) techniques are gaining importance as potential tools for complex real-world problems because of their inherent ability to judge different alternative scenarios for possible selection of the best one which may be further analysed in depth for its final implementation (Raju et al. 2000). Environmental decisions are often complex and multifaceted and involve many different stakeholders with diverse priorities or purposes (Kiker et al. 2005). MCDM tools can be applied to assess value judgments of individual decision-makers or multiple stakeholders. Most multi-criteria approaches in the context of flood assessment focus on the evaluation of flood mitigation measures (Meyer et al. 2008). A scenario-based integration approach is capable of helping the decision-makers and users to understand and investigate the possible outcomes of different management interventions and the trade-offs associated with the outcomes (Heathcote 1998). Sadoddin et al. (2010) suggested MCDM as one capable approach for determining best vegetative management scenarios for flood and erosion control in the Ramian Watershed. They used SCS and EPM models to predict the physical impacts of implementing various vegetative management scenarios. The impact of afforestation, terracing, construction of check dams, and various combinations of these measures on flood peak and volume was evaluated by Al-Weshah and El-Khoury (1999) using calibrated WMS model in Jordan. Impacts of river training and retention measures on flood peaks along the Rhine were evaluated for return periods of 200, 500, 1000 and 1250 years. The results of a study conducted by Lammersen et al. (2002) showed that time to peak has been increased by river training and retention measures, and in contrast, peak volumes have been decreased. By analysis of the results of the HEC-HMS model and DEFINITE software, Roshani (2003) identified the best number of check dams from economic point of view for the Kan Watershed. Water management scenarios were evaluated by Srdjevic et al. (2004) in a Brazilian river basin using a multi objective decision-making technique. Martin et al. (2007) developed a multi-criteria decision aid approach for the best management practices in urban storm water drainage management and stated that the results obtained allow ranking the various alternatives from best to worst, taking into account the different strategies adopted by the decision-makers involved. The effect of gabion check dams on the suspended load of streams in the Marmeh watershed was investigated by Zehtabiyan et al. (2011). They found that the Gabion check dams did not achieve the objective of the implemented project in reducing the suspended sediment load. Also, according to their results based on statistical tests, it was found that there was no meaningful difference in erosion–sediment control efficiency at a validated level of 95% in the Marmeh watershed. Castillo et al. (2013) developed a conceptual model to classify flow regimes and a method of estimating efficiency in order to provide guidelines for optimal design. They identified the main classifications on the element and level of influence. Amini et al. (2014) evaluated the impacts of watershed management on run-off storage and peak flow in a small watershed, and found that the watershed management practices had significant impacts on the run-off storage and peak flow reduction. Most studies on the impacts of dams have focused on the influence of large dams and reservoirs, but less attention has been paid to the efficiency of small check dams (Castillo et al. 2007). Understanding the impacts of different flood management measures (small dams, delay structures, gabion and masonry structures) as well as vegetation management activities on watershed response is important. Flood control objective is to reduce the risk of flood events to the downstream communities. Development of the quantitative models in flood risk management is ongoing process and have some key progress including the development of climate change scenarios, hydrologic and hydraulic flood models, assembly of socio-economic data and the development of a model to assess flood damage, classification and assessment of the reliability of flood control measures, and setting up the GIS-based risk assessment system (Harvey et al. 2009). A flood control strategy determines and implements approaches to reduce the risk of the flooding (Wanielista 1997). Also, the cost and benefit analysis of management scenarios should be taken into account in overall reducing the risk (NRC 2013). Rainfall–run-off modelling has become a must for sustainable water resources development and for flood risk and drought management (Elfeki et al. 2017). The main aim of this paper is the evaluation of flood control measures and assessment of the hydrologic and economic impacts of different structural management scenarios using a MCDM technique. The results can be useful for decision-makers to trade-off various impacts of management options and to choose the best management option(s). Hence, this study aims to assess the impacts of structural management scenarios through hydrologic modelling. Also by conducting a scenario analysis and trade-off on the construction cost, consequently, aims at an appropriate watershed management.

2 Methodology

2.1 Study area

The Jafar-Abad Watershed is a forested watershed located in the southern part of the Golestan Province, northeast Iran. The watershed area is about 109 km^2 (Fig. 1). The Jafar-Abad watershed is characterised by its steep slopes (42% on average) and its elevation ranges from 80 to 2530 m above the Mean Sea Level. The geological formations in the study area consist of a sequence of conglomerate, armoured limestone, dolomite and some shale in the upper layers (known as Khosh-Yeilagh formation). The sandstone and dark-shale and basal layers also were identified within the lithology of study area as a part of Jirood geological formation (Nahrsazane-Rostagh Consultancy Inc 2001). Soil hydrologic groups B and C, based on the NRCS hydrologic soil group classification system (NRCS 2009), are the dominant soils in the watershed. The average annual precipitation is about 566 mm, and the average temperature is 15 °C. The rainfall data were extracted from the Fazel-Abad climatology station which is located close to the Jafar-Abad watershed to

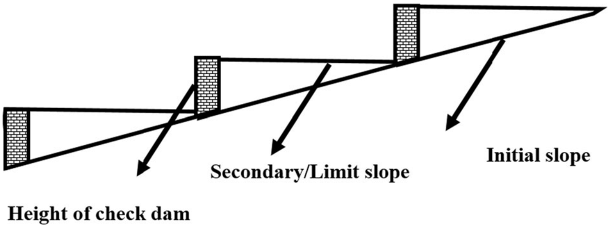

Fig. 1 Schematic representation of a series of check dams in a water course and slope reduction

the north. After filling the reservoir of the constructed check dams, a delay and attenuation will occur in the peak of the flood events. Also, the velocity and turbulence of the flood flow are greatly reduced due to increasing cross-section area and provided level pool in the upland area of structural measures (Amini et al. 2014). Figure 1 is a schematic representation of a series of check dams in a water course and slope reduction. The corresponding discharge data recorded at the Taghi-Abad river gauge station located in the outlet of the watershed was used for modelling purposes (see Fig. 2). Run-off regime (monthly variation of the river discharge) of the Jafar-Abad watershed is presented in Fig. 3.

Statistical summary of the observed monthly run-off data recorded at Jafar-Abad station is presented in Table 1.

During 2002 and 2003, the Golestan Watershed Management Office (GWMO) constructed 58 check dams (gabion and masonry) in the watershed in order to reduce flood damages and to warrant stream bed stabilisation (Fig. 4).

2.2 Data preparation

The digital elevation model (DEM) of the basin was created based on the 1:25,000 topographic maps. GIS technology was used as a supplementary tool for sub-watershed delineation, hydrologic parameter determination, and geographic information management. The Jafar-Abad Watershed divided into 11 main sub-watersheds denoted by SUB1 to SUB11 and nine intermediate sub-watersheds are also identified by IB1 to IB9 (see Fig. 4). The physiographic characteristics of all sub-watersheds were derived from the DEM. Also, the characteristics of river reaches were determined for flood routing purposes (the Muskingum–Cunge method). In addition, the position of the implemented check dams,

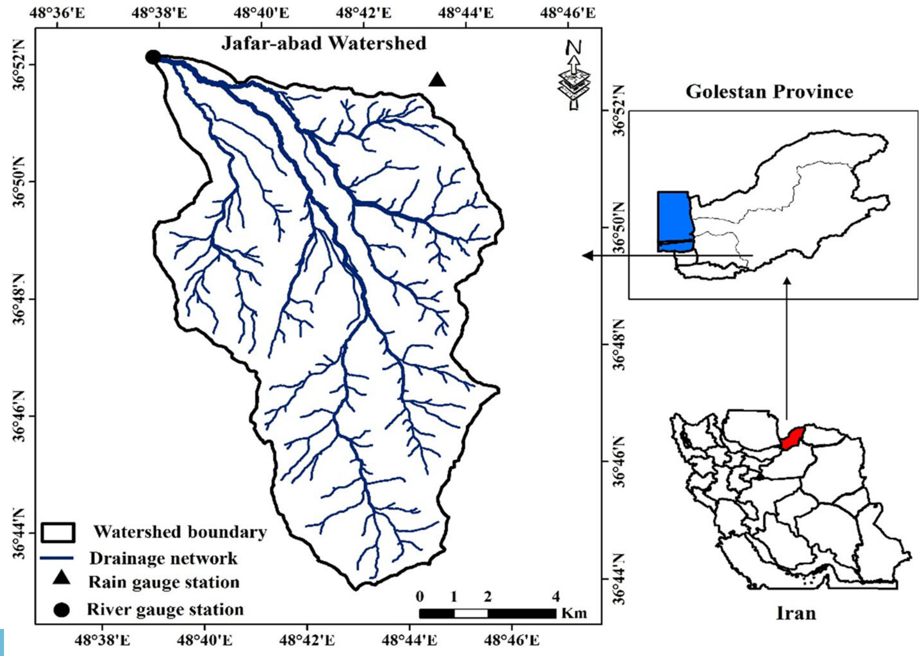

Fig. 2 Location of the Jafar-Abad Watershed

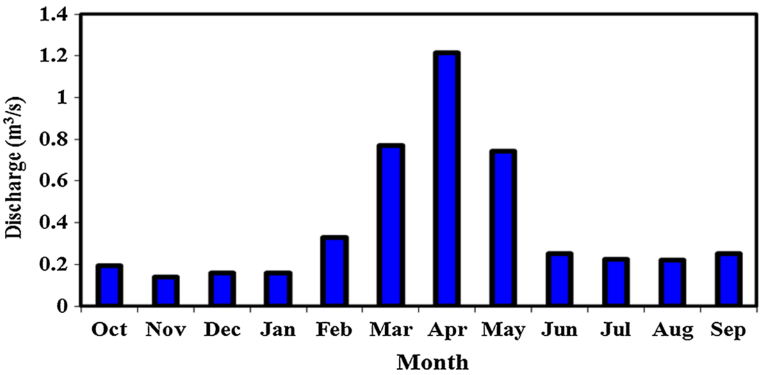

Fig. 3 Long-term average of monthly discharge in the Jafar-Abad river gauge station

their dimensions and effective height, as well as their weir dimensions were measured during field surveys. Paired *t* test was performed for hydrologic indices in the Taghi-Abad river gauge station for the periods before and after construction of the check dams.

2.3 Development of structural management scenarios for flood control

Management scenarios must be mutually exclusive. Taking into account the delay in transferring the run-off in streams is an important factor in choosing the location of check dams. It should be noted that the existing flood control project with 58 check dams (Scenario 2) have been implemented before in the watershed. The aim of this research was to evaluate the effectiveness of the project as well as to predict the effects of other possible scenarios. This shows to the planners and managers the usefulness of such simulating practices to achieve better results. Structural management scenarios were developed considering the changes on location, height and number of check dams constructed along the water courses of the watersheds. The condition before the construction of check dams was considered as a base-case scenario (no action) to compare the effects of the other structural management scenarios on flood control (Table 2). According to the spatial pattern of implemented check dams, the possible new locations for the construction of structures were identified through conducting a field surveys. Site selection was conducted based on stream characteristics such as stream slope and cross section and the appropriate distances among the check dams. Also, evaluating the effect of various spatial patterns of the check dams in two water courses of the main stream as well as upstream and downstream areas was considered in the scenario development process.

2.4 Modelling the hydrologic impacts of the structural management scenarios

"The type and complexity of a hydrologic model used in an integrated modelling framework depends on what management decisions are to be considered, the spatial and temporal scales considered in the integrated framework, and what outputs are required by other models within the framework" (Jakeman et al. 2005:111). The structure of the integrated framework dictates what the inputs and outputs of the hydrologic model should be. Ideally, the simplest model that fulfils these basic requirements should be employed, as more complex models will require more resources to develop, due to increased data requirements and difficulty in calibration and validation (Jakeman et al. 2005). In this

Table 1 Statistical characteristics of monthly stream discharge at Jafar-Abad river gauge station

Statistics	Months											
	October	November	December	January	February	March	April	May	June	July	August	September
Average	0.2	0.1	0.2	0.2	0.3	0.8	1.2	0.7	0.3	0.2	0.2	0.2
Maximum	1.7	0.6	0.5	0.9	0.8	1.7	2.5	3.3	1.4	1.5	2.3	1.9
Minimum	0.0	0.0	0.0	0.0	0.0	0.1	0.1	0.1	0.0	0.0	0.0	0.0
CV (%)	109.9	48.4	43.6	58.1	64.7	108.9	195.0	206.2	97.2	109.0	165.6	130.6

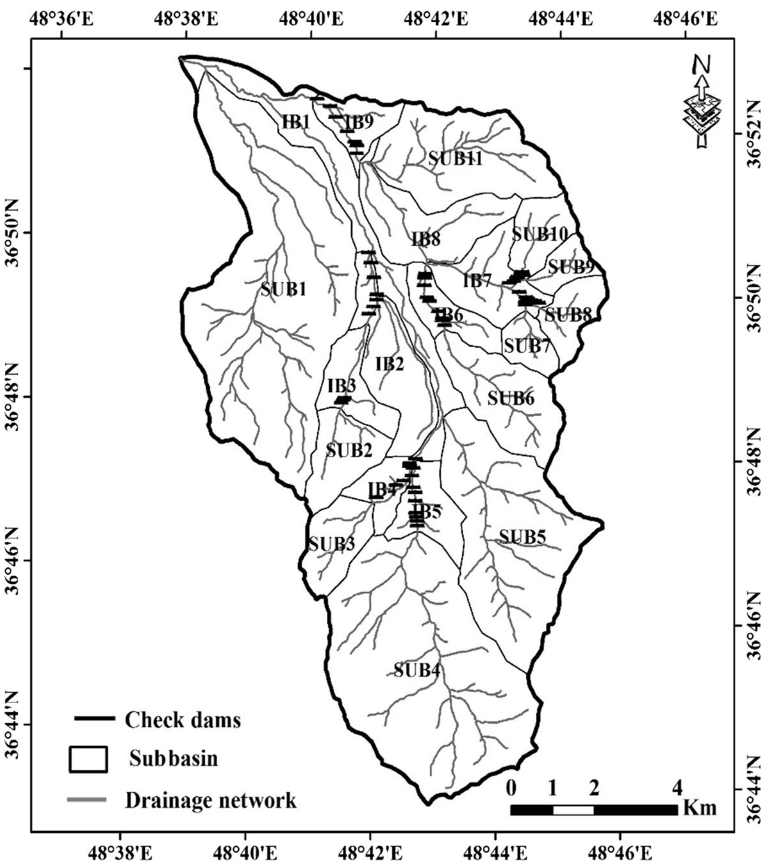

Fig. 4 Location of check dams constructed along water courses in the Jafar-Abad Watershed

study, the hydrologic response of the watershed was simulated by the HEC-HMS model. The Jafar-Abad watershed is divided into 20 hydrologic response units considering the location of check dams, and the drainage network pattern. For each sub-watershed, the data required for modelling, transformation method and other control specifications were inserted within the HEC-HMS model (USACE 2001). The weighted average curve number (CN) for each sub-watershed was estimated using land use, soil hydrologic groups, hydrologic conditions and antecedent moisture conditions.

The hourly rainfall–run-off data set (22 storm events) was divided into two groups, one for model calibration and the other for validation purposes. The spatial patterns of rainfall events were determined employing isohyetal maps and the Fazel-Abad hyetographs were used for derivation of rainfall temporal patterns (FAO 2001; Mostafazadeh et al. 2009). The SCS unit hydrograph method was used for rainfall–run-off transformation. The Muskingum–Cunge and Pul's methods were used for flow routing from the outlet of the sub-watersheds to the main outlet and through the reservoirs, respectively (USACE 2001). The hydrologic model was then calibrated using 12 storm events. The curve number and lag time were calibrated for each sub-watershed. Sum of absolute residuals and sum of squared residuals objective functions were selected for model calibration. These functions compare each ordinate of the computed hydrograph with the observed counterpart. These

Table 2 Structural management scenarios for flood control in the Jafar-Abad Watershed

Scenarios	Description	Justification
1	Before construction of the check dams	No-action-virgin flow
2	After construction of 58 check dams	Existing condition
3	Construction of 25 check dams at IB2 sub-watershed	To delay flow from western sub-watersheds
4	Construction of 33 check dams at IB6 and IB7 sub-watershed	To delay flow from eastern sub-watersheds
5	Construction of 15 check dams at IB5 sub-watershed	To delay flow from upstream sub-watersheds
6	Construction of 43 check dams at IB2, IB6 and IB7 sub-watershed	To delay flow in downstream
7	Increasing number of check dams from 58 to 69	To further increase the lag time of the watershed
8	Increasing the height of existing check dams	To further increase the lag time of the watershed

functions are implicitly measures of fit of the magnitude of the peaks, volumes, and time to peaks of the two hydrographs (USACE 2001). The HEC-HMS model after calibration was used to simulate the design flood hydrographs (Saghafian et al. 2008; Gul et al. 2010), for different return periods ranging from 2 to 100 years for the Taghi-Abad Station. The accuracy of the model to simulate the discharge is evaluated for validation data set using four evaluation criteria including, Nash–Sutcliffe (Eq. 1), model bias for water balance (Eq. 2), relative error in peak discharge (Eq. 3), simulation variance (Eq. 4) and model efficiency for high flows (Eq. 5) (ASCE 1993; Legates and McCabe 1999; Bahremand 2006; Moriasi et al. 2007)

$$C_{\mathrm{NS}} = 1 - \sum_{i=1}^{n} (Q_{\mathrm{Si}} - Q_{\mathrm{Oi}})^2 \Big/ \sum_{i=1}^{n} (Q_{\mathrm{Oi}} - \overline{Q_{\mathrm{O}}})^2 \tag{1}$$

$$\%\mathrm{RE}_{\mathrm{VF}} = \left(\sum_{i=1}^{n} Q_{\mathrm{Si}} \Big/ \sum_{i=1}^{n} Q_{\mathrm{Oi}} - 1 \right) \times 100 \tag{2}$$

$$\%\mathrm{RE}_{\mathrm{Qpeak}} = 100 \left| \frac{Q_{\mathrm{Si}}(\mathrm{peak}) - Q_{\mathrm{Oi}}(\mathrm{peak})}{Q_{\mathrm{Oi}}(\mathrm{peak})} \right| \tag{3}$$

$$\mathrm{SV} = \sum_{i=1}^{n} (Q_{\mathrm{Si}} - \overline{Q_{\mathrm{O}}})^2 \Big/ \sum_{i=1}^{n} (Q_{\mathrm{Oi}} - \overline{Q_{\mathrm{O}}})^2 \tag{4}$$

$$\mathrm{ME} = 1 - \sum_{i=1}^{n} (Q_{\mathrm{Oi}} - \overline{Q_{\mathrm{O}}})(Q_{\mathrm{Si}} - Q_{\mathrm{Oi}})^2 \Big/ \sum_{i=1}^{n} (Q_{\mathrm{Oi}} - \overline{Q_{\mathrm{O}}})(Q_{\mathrm{Oi}} - \overline{Q_{\mathrm{O}}})^2 \tag{5}$$

where Q_{Si} and Q_{Oi} are the simulated and observed discharges, respectively, $\overline{Q_{\mathrm{O}}}$ is the mean of observed discharges, and n is the number of data. For a perfect efficiency, C_{NS} and ME must be 1, and value of the other criteria should be close to zero (Liu et al. 2006; Bahremand et al. 2006).

Design flood hydrographs for 2 to 100 years recurrence intervals were also calculated for each scenario. Design rainfalls amounts for 2- to 100-year recurrence intervals equal with concentration time of the study watershed were calculated using the Vaziri Eqs. (6) and (7) as hydrologic model input. The Vaziri equations are developed for Iran conditions using data available in meteorology stations nation-wide (Vaziri 2000). The calibrated HEC-HMS model was applied for both rainfall–run-off modelling in sub-watersheds and routing through the check dams as cascade of reservoirs

$$P(10\,\text{years}, 1\,\text{h}) = (1.3352 - 0.1964 \times \text{Ln}(Pd\text{max})) \times Pd\text{max} \tag{6}$$

$$P = (0.4847 + 0.2251\text{Ln}(\text{Tr} - 0.4112)) \times \left(-0.0158 + 1.0197T^{0.3753}\right) \times P(10\,\text{years}, 1\,\text{h}) \tag{7}$$

where *Pd* max is the maximum 24-h rainfall, *P*(10 years, 1 h) is the 1-h rainfall over 10-year return period, and *P* refers to design rainfall (Vaziri 2000).

2.5 Modelling the economic impacts of structural management scenarios

Construction costs were used as an index to predict the economic impacts of structural management scenarios (Shokoohi 2007; Sadoddin et al. 2010). Therefore, different scenarios with respect to the number and dimensions of activities at each scenario were compared (see Table 7). For instance, construction costs were 0 and 685.43 million Iranian Rials for “without” and “with” check dam construction, respectively (Scenarios 1 and 2).

2.6 Identification of criteria

Assessment criteria are required to be quantifiable and capable of distinguishing the differences among various scenarios (Heathcote 1998). Two groups of indices were identified to assess the impacts of different structural management scenarios as given below.

1. Physical indices including peak flow (Qp), time to peak (Tp) and base time of hydrographs (Tb).
2. Economic index including construction and maintenance costs (cost).

The physical indices were quantified for each structural management scenario at different return periods (Tables 4, 5, 6). Also, economic analysis was conducted to calculate the economic criterion. In this research the criteria are of different nature, therefore they must be standardised. The maximum standardisation method was used to convert indices to a range between 0 and 1 (Heathcote 1998; Sharifi et al. 2004). The weights assigned to the standardised indices were determined using the Delphi process. Delphi is an expert opinion survey with three special features: anonymous response, iteration and controlled feedback, and statistical group response. Another advantage of this method is that it is possible to cover a wide geographic area and a large heterogeneous group that can participate on an equal basis (Turoff 1970; Akter and Simonovic 2002). In this study, expert opinion about the possible impacts of different management scenarios on flood characteristics was elicited from a panel of eight experts.

In this study, weights were assigned to the indices on the basis of two different perspectives: (1) the hydrologic perspective (including Qp, Tp, and Tb) and (2) the hydroeconomic perspective (including Qp, Tp, Tb, and cost). Standardised values were multiplied by their corresponding weights. The summation of the weighted indices represents the final preference of alternatives when all decision criteria are considered. In the maximum standardisation technique, the indices are categorised into two groups: benefit and cost. Equations 8 and 9 are used for standardisation of benefit and cost groups of indices, respectively (Sharifi et al. 2004)

$$\mathrm{Score_s} = \frac{\mathrm{score}}{\mathrm{highest\ score}} \tag{8}$$

$$\mathrm{Score_s} = 1 - \frac{\mathrm{score} - \mathrm{lowest\ score}}{\mathrm{highest\ score}}. \tag{9}$$

In the present study, a MCDM technique was employed to choose the best scenario(s) as used by Srdjevic et al. (2004) and Costa et al. (2004). The MCDM was used as the method of selection for integrating management scenarios influencing the occurrence and consequence of flood hydrographs, standardised against a common scale. Sensitivity analysis is a fundamental concept in the effective use and implementation of quantitative decision models, whose purpose is to assess the stability of an optimal solution under changes in the preference values of alternatives (Triantaphyllou and Sachez 1997). The sensitivity analysis examines the impact of changes in the weights of importance of the decision criteria on the measures of performance of the alternatives and therefore on the final ranking of the alternatives. Sensitivity analysis of the indices was conducted based on generation of different weights assigned to each index in order to examine the robustness of the MCDM outcomes (Tables 9, 10).

3 Results

3.1 Statistical comparison

The hydrologic indices “before” and “after” check dam construction were compared statistically using *t* test to determine the level of the impacts of the flood project. The results of statistical *t* test reveal that existing flood control project does not have a significant impact on the hydrologic indices ($\alpha < 0.05$).

3.2 Hydrologic simulation

Model evaluation criteria for the calibration and validation periods are given in Table 3 for the Taghi Abad station. Model performance is satisfactory for both calibration and validation periods. In addition, scatter plots of the observed versus simulated flows for the rising limb of the hydrographs that is more useful for flood analysis are illustrated in Figs. 5 and 6, respectively.

Table 3 Performance criteria of HEC-HMS model for the Taghi-Abad river gauge station

Criteria	Calibration	Validation
Nash–Sutcliffe efficiency	0.674	0.789
Model bias for water balance	−0.31	−0.206
Relative error in peak discharge (%)	20.6	15
Simulation variance	1.11	1.108

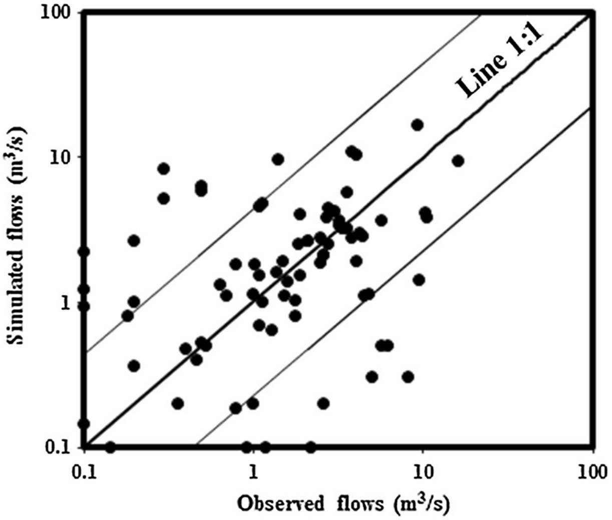

Fig. 5 Observed versus simulated flows for the rising limbs of the hydrographs at the Taghi-Abad river gauge station for the calibration period with the 95% confidence limits

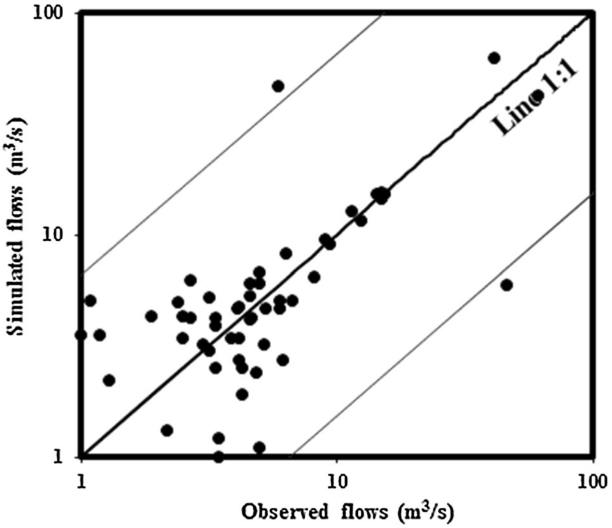

Fig. 6 Observed versus simulated flows for the rising limbs of the hydrographs at the Taghi-Abad river gauge station for the validations period with the 95% confidence limits

The results of flood hydrograph simulation for different structural management scenarios are presented in Fig. 7. Simulated hydrographs represent a time-lagged ensemble across different management scenarios.

The values of hydrologic indices calculated for different structural management scenarios and various return periods are given in Tables 4, 5, and 6.

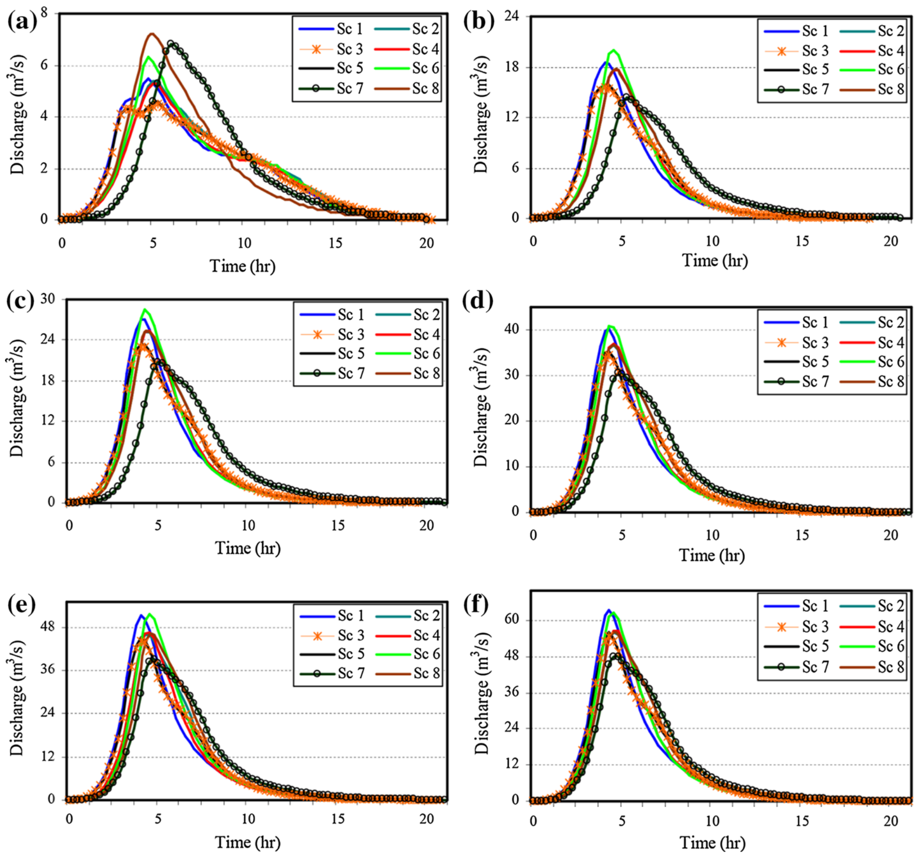

Fig. 7 Flood hydrograph simulated for eight flood control scenarios with different return periods (**a** 2 year, **b** 5 year, **c** 10 year, **d** 25 year, **e** 50 year, **f** 100 year)

Table 4 Peak discharge (m³/s) for eight flood control scenarios with different return periods simulated for the Taghi-Abad river gauge station

Return period (year)	2	5	10	25	50	100
Scenario						
1	5.5	18.5	27.1	40.2	51.3	63.7
2	5.4	17.7	25.2	36.6	45.8	56.2
3	4.5	15.5	22.9	34.4	44.3	55.0
4	5.3	17.7	25.3	37.0	46.5	56.7
5	4.6	15.8	23.4	35.2	45.10	56.0
6	6.3	20	28.5	40.9	51.5	62.6
7	6.8	14.3	20.8	30.6	39.0	48.0
8	7.3	17.7	25.2	36.6	45.8	56.1

3.3 Economic analysis

The amounts of construction costs for each structural management scenarios presented in Table 7.

Table 5 Time to peak (h) of hydrographs for eight flood control scenarios with different return periods simulated for the Taghi-Abad river gauge station

Return period (year)	2	5	10	25	50	100
Scenario						
1	4.75	4	4	4.25	4	4.25
2	5	4.5	4.5	4.5	4.5	4.5
3	4.25	4	4	4.25	4	4.25
4	5	4.5	4.5	4.5	4.5	4.5
5	5	4	5	4.25	4	4.25
6	4.75	4.5	4.25	4.25	4.5	4.5
7	6	4.25	5	4.75	4.75	4.5
8	5	4.5	4.5	4.5	4.75	4.5

Table 6 Base time of hydrograph (h) for eight flood control scenarios with different return periods simulated for the Taghi-Abad river gauge station

Return period (year)	2	5	10	25	50	100
Scenario						
1	20.25	19.0	19.75	20.75	21.0	21.5
2	20.5	19.0	19.5	20.5	20.75	21.25
3	20.5	19.0	19.75	20.75	21.0	21.5
4	20.5	19.0	19.5	20.5	20.75	21.25
5	20.5	19.0	19.75	20.75	21.0	21.5
6	20.25	19	19.5	20.5	21.0	21.25
7	20.25	20.75	21.25	20.75	21.0	22.25
8	19.0	19.0	19.5	20.5	21.0	21.25

Table 7 Construction volume and costs of eight flood control scenarios for the Jafar-Abad Watershed

Scenario	1	2	3	4	5	6	7	8
Construction volume (m^3)	0	3705.8	1136.3	2569.5	605.0	3100.8	4240.4	4054.5
Construction costs (million Ir. Rials)	0	685.4	215.5	469.8	114.7	570.6	786.8	750.2

3.4 Trade-off analysis using a multi-criteria decision-making technique

As mentioned earlier, the indices corresponding to each structural management scenario were standardised. Different weights assigned to the indices using the Delphi process were presented in Table 8. The standardised values of indices were multiplied by their corresponding weights and the summation of the products was used to choose the best scenario(s). Scenario ranking at various return periods by two different weighing perspectives based on the Delphi process have been shown in Tables 9 and 10.

The reliability of all scenarios is approved in terms of implementation in the study watershed. As shown in Table 2, all of scenarios are different and a subset of Scenario 2 (the current implemented status, with 58 structures). Based on the priorities that are presented in Tables 9 and 10 different approaches were used to weighting criteria and ranks of possible scenarios are provided. There are also managers or organizations that are willing to consider all potential alternatives and choose the one most likely to result in

Table 8 Weights assigned to the indices from both hydrologic and hydroeconomic perspectives based on the Delphi process

Perspective	Description	Peak discharge (Qp) (%)	Time to peak (Tp) (%)	Base time of hydrograph (Tb) (%)	Construction costs (cost)
1	Hydrologic	45.37	28.87	25.75	–
2	Hydroeconomic	32.29	18.57	16.86	32.29%

Table 9 Ranking of eight structural flood control scenarios with a MCDM technique considering hydrologic perspective and based on the Delphi process

Return period (year)	2	5	10	25	50	100
Scenario						
1	3	7	7	7	7	7
2	5	3	3	3	8	8
3	4	5	5	5	2	2
4	2	4	2	8	4	4
5	1	2	8	2	3	3
6	7	8	4	4	5	5
7	6	1	1	1	6	6
8	8	6	6	6	1	1

Table 10 Ranking of eight structural flood control scenarios with a MCDM technique considering hydroeconomic perspective and based on the Delphi process

Return period (year)	2	5	10	25	50	100
Scenario						
1	5	1	1	1	1	1
2	1	5	5	5	5	5
3	3	3	3	3	3	3
4	4	4	4	4	4	4
5	2	7	7	7	7	6
6	6	6	6	6	6	7
7	6	2	2	2	6	6
8	8	6	6	6	2	2

acceptable hydrologic indices while also providing an acceptable amount of implementation costs. However, considering only the hydrologic criteria, the Scenario 7 would be more appropriate, whereas taking into account the cost criterion along with hydrologic criteria, the Scenario 1 would be more realistic scenario. However, the flood return period can also be considered in selecting the best scenario or scenarios. As mentioned in the "study area" section, the Scenario 2 in the study watershed has already been implemented. In other words, the present study aims to evaluate the project and the effects of different structural scenarios in line with the Jafar-Abad flood control plan. However, the effectiveness of the project in modification of flood hydrograph component had not evaluated as satisfactory. Certainly the approach can be applied to model and test the impacts of different management scenarios before the spending huge costs. From the practical feasibility aspect, cost allocation, prioritisation of different regions according to flood severity and vulnerability to flood damage will be barriers to project implementation.

In order to examine the robustness of the MCDM results, a part of the results achieved by the Delphi process, different weights were arbitrarily assigned to the indices on the basis of the two different hydrologic and economic perspectives (see Tables 11, 12). Scenarios were also ranked based on the new sets of weights accordingly. The results show that weights assigned by the Delphi method is satisfactorily robust to evaluate the scenarios, and the priority weights considered in the sensitivity analysis do not alter notably the final ranking of the scenarios.

4 Discussion and conclusions

Impacts assessment of various management scenarios require models to predict the outcomes arising from implementing management scenarios (Heathcote 1998). A MCDM framework was implemented for evaluation of flood control impacts in a watershed scale. In this study, the Jafar-Abad structural flood control project and the hydrologic performance of the check dams constructed in the watershed were evaluated. In addition, the hydrologic and economic impacts of six potential structural management scenarios were predicted in order to inform and assist the local watershed managers to design flood control structures. The results of model evaluation indicate that the HEC-HMS model can simulate the flood hydrographs with reasonable performance. It should be mentioned that, the same calibrated model was employed to simulate the impacts of different alternatives. Thus a relative comparison between the alternatives was achieved that is considered to be helpful for decision-making purposes. In order to obtain more accurate absolute values, it is suggested to use physically based models as well as more comprehensive and accurate field data.

As expected from earlier publications (e.g. Costa et al. 2004; Akter and Simonovic 2002; Yilmaz and Harmancioglu 2010), such a multi-criteria decision-making system must be based on appropriate modelling tools. Flood control measures cannot usually be evaluated from a single point of view. In the last three decades, considerable progress has been made in MCDM for the area of environmental management (e.g. Hobbs and Meier 2000; Kiker et al. 2005; Yilmaz and Harmancioglu 2010; Hao and Chen 2010; Colton 2011). The

Table 11 Weights assigned to the indices from hydrologic perspective for sensitivity analysis

Weighting scheme	Description	Peak discharge (Qp) (%)	Time to peak (Tp) (%)	Base time of hydrograph (Tb) (%)
1	Equal emphasis on all indices	33.3	33.3	33.3
2	Emphasis on peak flow attenuation	50	25	25
3	Emphasis on time to peak flow reduction	25	50	25
4	Emphasis on stretching out base time of hydrograph	25	25	50

Table 12 Weights assigned to the indices from both hydrologic and hydroeconomic perspectives for sensitivity analysis

Weighting perspective	Description	Peak discharge (Qp) (%)	Time to peak (Tp) (%)	Base time of hydrograph (Tb) (%)	Construction costs (cost) (%)
1	Equal emphasis on all indices	25	25	25	25
2	Emphasis on peak flow attenuation	40	20	20	20
3	Emphasis on time to peak flow reduction	20	40	20	20
4	Emphasis on stretching out base time of hydrograph	20	20	40	20
5	Emphasis on economic index	20	20	20	40

performance of flood control measures, in terms of hydrologic impacts, has to be compensated by economic values. Construction of check dams along water courses has significant impacts on hydrologic characteristics of the watershed (Shokoohi 2007). The approach used in this study allows decision-makers and/or stakeholders to understand the responses of the watershed system to the scenarios and to reach their own decision for the best flood control scenario at each return period based on the scenario outcomes and their preferences. Scenario testing was used to create the corresponding map of location of check dams along the water courses across the watershed. The information presented in Fig. 7 can be used to support decision-making in the subsequent way. Selection of appropriate management scenarios requires involvement with local managers and, if possible, the local rural community at risk. The results of ranking the scenarios by MCDM considering hydrologic outcomes indicate that Scenario 7 (increasing number of check dams) is considered as the best scenario (Table 9). Trade-off analysis of the results show that when an economic index is considered along with the other indices, for most return periods, Scenario 1 (no-action) gets the highest score followed by Scenario 5 (construction of 15 check dams in IB5 sub-watershed), and Scenario 3 (construction of 25 check dams in IB2 sub-watershed), consequently (Table 10). As Stated by Roshani (2003), the construction costs associated with the structural flood control projects can significantly reduce the overall performance of scenarios. The results of the MCDM analysis show that by assigning equal weights to the cost of the project and hydrologic indices, Scenario 7 will be the best alternative, which cause more reduction on flood peak than the other scenarios do. With respect to Scenario 2 (existing condition), the results of this research indicate that the current flood control project for the Jafar-Abad watershed, does not properly warrant the objectives of the project. Regarding the scenarios, based on high-, mid-, and low-cost management strategies, the decision-maker has a range of costs and performance to assess to arrive at a best management approach considering the available financial plan. To allocate weights to the criteria, the Delphi method is proposed, which explicates the ranking of management scenarios preferences, as suggested by Akter and Simonovic (2002). The sensitivity analysis agrees with the results of ranking of the scenarios given the weights assigned to the indices based on the outcomes of the Delphi process. The model results can be used in decision-making process for the Jafar-Abad watershed and the methodology is applicable for other watersheds. The present study shows that scenario analysis can take into account the spatial allocation of flood control measures, as well as the construction costs of flood control structures, and significantly assist the assessment and ranking of management scenarios for flood control projects. One of the most effective ways to prevent stream bank erosion and bed scouring in Iran is to construct check dam systems. It can slow down the movement of the water and sediment during flood events. The guiding principal of site selection of check dams can improve the efficiency of future watershed management plans in the country and elsewhere. The methodology employed in this research, is an appropriate tool to assist the decision-makers for prioritising and making decisions and choosing the proper strategies. The approach implemented in this research can be further developed by adding additional indices from ecological and social discipline. In addition, the results of the hydrologic modelling can be used to assessing the vegetation management impacts and the outcomes can be used with the design of watershed management plan for water quantity and quality control projects. Further studies are required to achieve a better understanding for designing and constructing check dams in watersheds with different conditions. The results presented show that the MCDM approach is inclusive and confident in concept and relatively simple in computation.

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