4th International Conference on Water Resources and Arid Environments (ICWRAE 4): 29-36
5-8 December 2010, Riyadh, Saudi Arabia

Assessment of Flood Control Structures by Scenario Analysis in the Jafar-Abad Watershed, Golestan Province - Iran

Amir Sadoddin[1], Abdolreza Bahremand[1], Raoof Mostafazadeh[2] and Vahedberdi Sheikh[1]

[1]Department of Watershed Management,
Gorgan University of Agricultural Sciences and Natural Resources
[2]M.Sc Student of Watershed Management,
Gorgan University of Agricultural Sciences and Natural Resources

Abstract: Flood events cause considerable losses and damages in many areas of Iran each year. Evaluation of flood control projects to improve the future design of the projects is an efficient and effective way to reduce the consequences of flood events. The focus of this study is on the evaluation of the Jafar-Abad structural flood control project to examine the hydrologic performance of the check dams constructed in the watershed. Also the hydrologic and economic effects of six potential structural management scenarios were predicted in order to inform and assist watershed managers in the design of flood control projects. The Jafar-Abad Watershed (109 Km^2) is located in the Golestan Province, north of Iran. The six structural management scenarios were developed considering the changes in location, height and numbers of check dams constructed along the water courses in the watershed. The calibrated HEC-HMS model was used to simulate rainfall-runoff relationships in sub-watersheds. Using the flow data recorded at a river gauge station located on the outlet of the watershed, paired t-test was performed to compare hydrologic conditions before and after the construction of 58 check dams already constructed in the watershed. For each scenario, flood hydrographs for 2 to 100 year return periods were calculated. To predict the potential impacts of implementing the management scenarios on flood characteristics, indices such as peak flow, time to peak and base time of hydrographs and construction costs were chosen and quantified for each management scenario at the different return periods. The indices then were standardised using the maximum standardisation method. To weight the indices, expert knowledge was elicitated using the Delphi process. The most appropriate management scenarios from both hydrologic and hydro-economic perspectives were assigned using a Multi Criteria Decision Making (MCDM) approach for the various return periods. Sensitivity analysis with regard to different weights of the indices was conducted. The statistical t-test indicates that the existing check dams in the watershed had no significant hydrologic impacts. The MCDM results show that scenario 7 (increasing the number of check dams, from 58 to 69) would be the most appropriate management scenario from the hydrological perspective. However, most appropriate management scenarios from both hydrologic and hydro-economic perspectives are scenario 1 (no action) and scenario 5 (with only 15 check dams constructed on an upstream sub-watershed), respectively. This kind of evaluation and prediction assists the designers of flood control projects to choose the most preferred management option/s considering the hydrologic as well as economic considerations.

Key words: Structural management scenarios • Flood control • Check dams • MCDM • HEC-HMS Model • The Jafar-Abad Watershed

INTRODUCTION

Flooding in many parts of Iran causes considerable destructions annually. Addressing such a crucial environmental problem, at both large and small scales, requires an integrated watershed modelling approach, in which key biophysical and socioeconomic drivers, processes and impacts are all considered [1]. Watershed management practices such as construction of check dams can be useful for soil and water conservation

---

Corresponding Author: Amir Sadoddin, Department of Watershed Management,
Gorgan University of Agricultural Sciences and Natural Resources

purposes. Check dams may have short-term benefits for soil and water conservation, but also have long-term negative consequences [2]. Mitigation of flood damages requires high-quality maintenance and modifications of flood-control structures [3]. Assessing various impacts of management activities in watershed scale can improve decision making. 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 which may be further analysed in depth for its final implementation [4]. 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 [5, 6] suggested MCDM as one of the capable approaches for determining the 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 [7] 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 showed that time to peak has been increased by river training and retention measures and in contrast, peak volumes have been decreased [8]. By analysis of the results of the HEC-HMS model and DEFINITE software, [9] identified the best number of check dams from economic point of view for the Kan Watershed. Construction of check dams not only affects flow characteristics but also alters river habitat [10]. Most researches on the impacts of dams have focused on the influence of large dams and reservoirs, but less attention has been paid to the effects and efficiency of small check dams [11].

The main objective of this paper is the evaluation of flood control measures and assessment the hydrologic and economic effects 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 before any action and therefore before any expenditure.

MATERIALS AND MEHODS

Study Area: The Jafar-Abad Watershed is a forested watershed located in the southern part of the Golestan Province, Iran. The watershed area is approximately 109 km^2 (Figure 1). This watershed is characterised by its steep slopes (42% on average) and its elevation ranges from 80 to 2530 m above the sea level. The lithology of the watershed consists mainly from Khosh-Yeilagh, Jirood and loess geology formations. Soil hydrologic groups B and C are the dominant soils in the watershed. Average annual precipitation is about 566 mm and average temperature is 15°C. The meteorological and observed discharge data were taken from the Fazel-Abad and Taghi-Abad stations that are located adjacent to the watershed and at the outlet of the study area, respectively (Figure 1).

During 2002 and 2003, the Golestan Watershed Management Office constructed 58 gabion and masonry check dams in the watershed in order to reduce flood damages and to warrant stream bed stabilisation (Figure 2).

Data Preparation: The digital elevation model (DEM) of the basin was prepared in GIS based on the 1:25000 topographic maps. The Jafar-Abad Watershed divided into 11 main sub-watersheds denoted by SUB 1 to SUB 11 and nine intermediate sub-watersheds are also identified by IB 1 to IB 9 (see Figure 2). The physiographic characteristics of all sub-watersheds were derived from the DEM. Also the characteristics of river reaches were determined for flood routing by the Muskingum-Cunge method. Also, the position of the implemented check dams, their dimensions, effective height and their weir dimensions were measured during field surveys. Paired t-tests were performed for hydrologic indices in the Taghi-Abad gauging station for the periods before and after construction of the check dams.

Development of Structural Management Scenarios for Flood Control: Management scenarios must be mutually exclusive. Structural management scenarios were developed considering the changes on location, height and number of check dams constructed along the water courses in the suggested sub-watersheds. The period before the construction of check dams was considered as a base case scenario (no-action) to compare the performance of the other scenarios in flood control (Table 1).

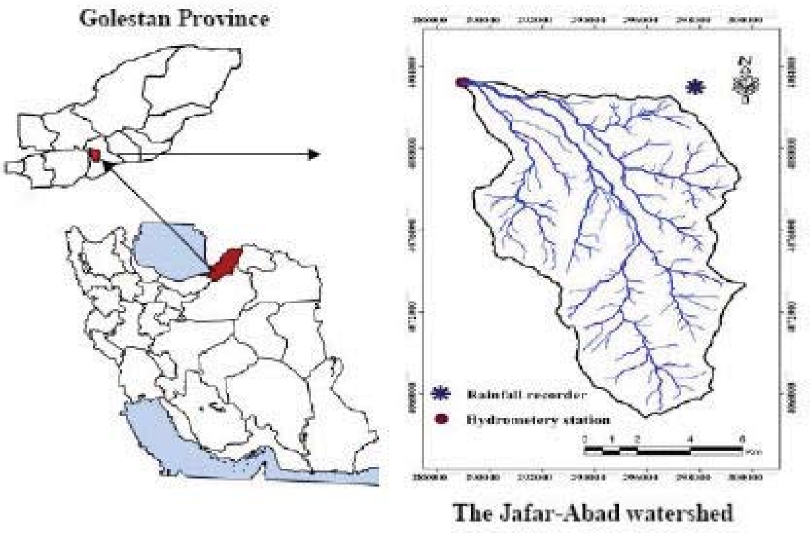

Fig. 1: Location of the Jafar-Abad Watershed

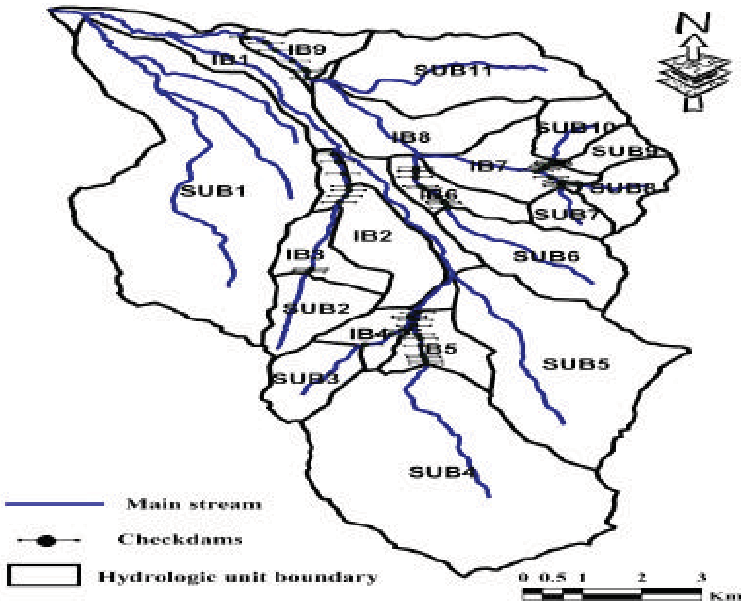

Fig. 2: Location of the check dams constructed across the Jafar-Abad Watershed

Table 1: Structural management scenarios for flood control in the Jafar-Abad Watershed

Scenario	Description	Justification
1	Before construction of the check dams	No-action
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

Modelling the Hydrological Impacts of the Structural Management Scenarios: In this 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, data required for modeling, transformation method and other control specifications were inserted within the HEC-HMS model [12]. 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 measured daily discharge dataset (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). The SCS unit hydrograph method was used for rainfall–runoff 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 [12].

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. Thess functions are implicitly measures of fit of the magnitude of the peaks, volumes and time to peaks of the two hydrographs [12]. The HEC-HMS model after calibration was used to simulate the design flood hydrographs 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 dataset 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).

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

$$\%RE_{VF} = \sum_{i=1}^{n} Q_{Si} \Big/ \sum_{i=1}^{n} Q_{Oi} - 1 \tag{2}$$

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

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

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

Where Q_{si} and Q_{Oi} are the simulated and observed discharges, respectively, $\overline{Q_O}$ 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 [13].

Design flood hydrographs for 2 to 100 year recurrence intervals were also calculated for each scenario. Design rainfalls for 2 – 100 recurrence intervals were calculated using the Vaziri equations. The Vaziri equations have been developed for Iran conditions using data available in meteorology stations nation-wide [14]. The calibrated HEC-HMS model was applied for both rainfall–runoff modelling in sub-watersheds and routing through the check dams as cascade of reservoirs.

Modelling the Economic Impacts of Structural Management Scenarios: Construction costs were used as an index to predict the economic impacts of structural management scenarios. Therefore, different scenarios with respect to the number and dimensions of activities at each scenario were compared (see Table 6). For instance, construction costs were 0 and 685.43 million Rials for without and with check dam construction, respectively (Scenarios 1 and 2).

Identification of Criteria: Evaluation criteria must be quantifiable and also they should be able to distinguish the differences among various scenarios [5]. Two groups of indices were identified to assess the impacts of different scenarios as given below.

- Physical indices including peak flow (C1), time to peak (C2) and base time of hydrographs (C3).
- Economic index including construction and maintenance costs (C4).

The physical indices were quantified for each management scenario at the different return periods (Tables 3 to 5). 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 [5, 15]. The weights assigned to the standardised indices were determined using the Delphi process [16], consulting eight experts. In this study, the indices were weighted in two different perspectives: 1) by the hydrologic indices (C1, C2 and C3), 2) by the hydro-economic indices (C1, C2, C3 and C4). Standardised value were multiplied by their respective weights. The sum of the weighted indices were used to determine the best scenario(s). In the maximum standardisation technique, the indices are categorised into two groups: benefit and cost. Equations 6 and 7 are used for standardisation of benefit and cost groups of indices, respectively [16].

$$Score_{s\tan dardised} = \frac{Score}{highest \quad score} \tag{6}$$

$$Score_{s\tan dardised} = 1 - \frac{Score - lowest \quad score}{highest \quad score} \tag{7}$$

In the present study, a MCDM technique was employed to choose the best scenario(s). Sensitivity analysis of the indices was conducted by different weights assigned to each index in order to examine the robustness of the MCDM outcomes [17,18].

RESULTS

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 revealed that existing flood control project had no significant impacts on the hydrologic indices ($\alpha < 0.05$).

Hydrologic Simulation: Graphical comparison between observed and simulated hourly flow shows that the model generally overestimated the peak discharges. Scatter plot of observed versus simulated flows for the calibration and validation periods at the Taghi-Abad station are illustrated in Figures 3 and 4, respectively. Model evaluation criteria for the calibration and validation periods are given in Table 2.

Model performance is satisfactory for both calibration and validation periods.

Table 2: Hydrologic model performance criteria in the Taghi-Abad station

Criteria	*Calibration*	*Validation*
Nash–Sutcliffe efficiency	0.674	0.789
Model bias for water balance	-0.310	-0.206
Relative error in peak discharge	20.631	14.935
Simulation variance	1.110	1.108
Model efficiency for high flows	0.550	0.795

Table 3: Simulated peak discharge (m^3/s) for structural flood control scenarios across different return periods

	Return period (year)					
Scenario	2	5	10	25	50	100
1	5.5	18.5	27.1	40.2	51.30	63.7
2	5.4	17.7	25.2	36.6	45.80	56.2
3	4.5	15.5	22.9	34.4	44.30	55.0
4	5.3	17.7	25.3	37.0	46.50	56.7
5	4.6	15.8	23.4	35.2	45.10	56.0
6	6.3	20.0	28.5	40.9	51.50	62.6
7	6.8	14.3	20.8	30.6	39.00	48.0
8	7.3	17.7	25.2	36.6	45.80	56.1

Table 4: Simulated time to peak (hr) for structural flood control scenarios across different return period

	Return period (year)					
Scenario	2	5	10	25	50	100
1	4.75	4.00	4.00	4.25	4.00	4.25
2	5.00	4.50	4.50	4.50	4.50	4.50
3	4.25	4.00	4.00	4.25	4.00	4.25
4	5.00	4.50	4.50	4.50	4.50	4.50
5	5.00	4.00	5.00	4.25	4.00	4.25
6	4.75	4.50	4.25	4.25	4.50	4.50
7	6.00	4.25	5.00	4.75	4.75	4.50
8	5.00	4.50	4.50	4.50	4.75	4.50

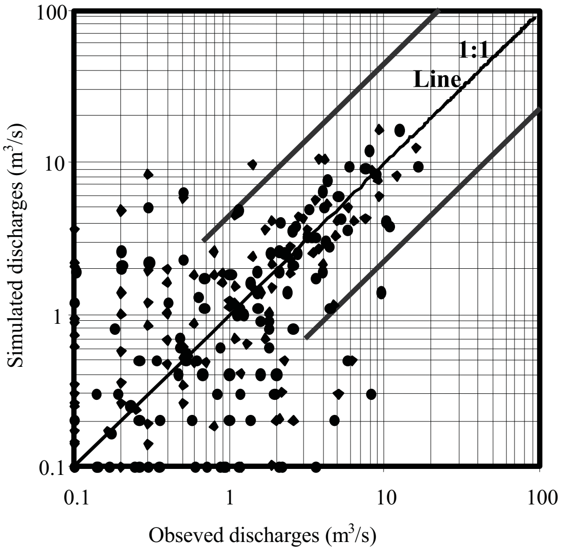

Fig. 3: Observed flows versus simulated flows at the Taghi-Abad station for the calibration period at 95% confidence level

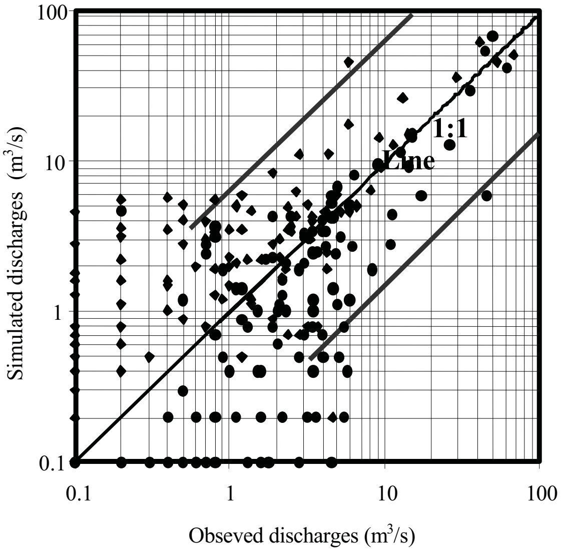

Fig. 4: Observed flows versus simulated flows at the Taghi-Abad station for the validations period at 95% confidence level.

Table 5: Simulated base time of hydrographs (hr) with return periods across flood control scenarios

	Return period (year)					
Scenario	2	5	10	25	50	100
1	20.25	19.00	19.75	20.75	21.00	21.50
2	20.50	19.00	19.50	20.50	20.75	21.25
3	20.50	19.00	19.75	20.75	21.00	21.50
4	20.50	19.00	19.50	20.50	20.75	21.25
5	20.50	19.00	19.75	20.75	21.00	21.50
6	20.25	19.00	19.50	20.50	21.00	21.25
7	20.25	20.75	21.25	20.75	21.00	22.25
8	19.00	19.00	19.50	20.50	21.00	21.25

Table 6: Construction volume and costs for different scenarios

	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 Rials)	0	685.4	215.5	469.8	114.7	570.6	786.8	750.2

Table 7: Weights assigned to the indices from hydrologic and hydro-economic perspectives

Perspective	Description	Peak discharge	Time to peak	Base time of hydrograph	Construction costs
1	hydrologic	45.37%	28.87%	25.75%	-
2	hydro-economic	32.29%	18.57%	16.86%	32.29%

Table 8: Ranking of structural flood control scenarios using MCDM from hydrologic perspective

	Return period (year)					
Scenario	2	5	10	25	50	100
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 9: Ranking of structural flood control scenarios using MCDM from hydro-economic perspective

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

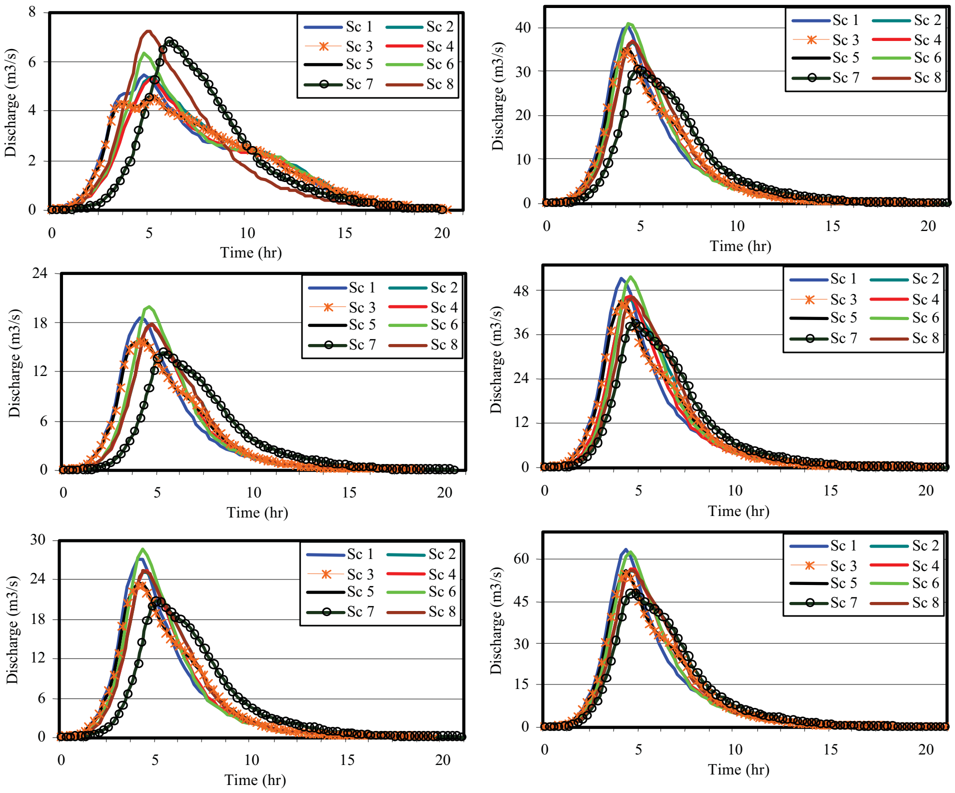

Fig. 5: Simulated flood hydrographs for different scenarios and return periods (a=2 y, b=5 y, c=10 y, d=25 y, e=50, f=100 y)

The results of flood hydrograph simulation for different scenarios are presented in Figure 5.

The values of hydrologic indices calculated for different scenarios and return periods are given in Tables 3, 4 and 5.

Economic Analysis: The amounts of construction costs for each scenario presented in Table 6.

Trade off Analysis Using a Multi- Criteria Decision Making Technique: As mentioned earlier, the indices corresponding to each management scenario were standardised. Different weights were assigned to the indices based on two different perspectives (Table 7). The standardised values of indices were multiplied by their 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 has been shown in Tables 8 and 9.

DISCUSSION AND CONCLUSIONS

Impacts assessment and social indices. Further detailed studies are needed to obtain a better picture of designing and constructing of check dams at watersheds with different conditions.

REFERENCES

1. Sadoddin A., R. Mostafazadeh, V. Sheikh and M.Gh. Halili, 2010. Analysis of vegetation-based management scenarios using MCDM in the Ramian watershed, Golestan, Iran. International J. Plant Production, Volume 4. Issue1.
2. Boix-Fayos, C., G.G. Barberá, F. López-Bermúdez and V.M. Castillo, 2007. Effects of check dams, reforestation and land-use changes on river channel morphology: Case study of the Rogativa watershed (Murcia, Spain). J. Geomorphology, 11: 1-20.
3. Wanielista, M.P., 1997. Hydrology and water quantity control. University of Central Florida.
4. Raju, K.S., L. Duckstein and C. Arondel, 2000. Multicriterion analysis for sustainable water resources planning: A case study in Spain. J. Water Resources Management, 14: 435-456.
5. Heathcote, I.W., 1998. Integrated watershed management. John Wiley and Sons.
6. Sadoddin, A., 2006. Bayesian network models for integrated-scale management of salinity. Ph.D thesis, Australian National University.
7. Al-Weshah, R.A. and F. El-Khoury, 1999. Flood analysis and mitigation for Petra area in Jordan. J. Water Resources Planning and Management, pp: 170-177.
8. Lammersen, R., H. Engel, W.V.D. Langemheen and H. Buiteveld, 2002. Impact of river training and retention measures on flood peaks along the Rhine. J. Hydrology, 267: 115-124.
9. Roshani, R., 2003. Evaluating the effect of check dams on flood peaks to optimise the flood control measures (Kan case study in Iran), M.Sc thesis, International Institute for Geo Information Science and Earth Observation Enschede, The Netherlands.
10. Shieh, Ch.L., Y.R. Guh and S.O. Wang, 2007. The application of range of variability approach to the assessment of a check dam on riverine habitat alteration. J. Environmental Geology, 52: 427-435.
11. Castillo, V.M., W.M. Mosch, C. ConesaGarcia G.G. Barbera, J.A. NavarroCano and F. Lopez-Bermudez, 2007. Effectiveness and geomorphological impacts of check dams for soil erosion control in a semiarid Mediterranean watershed: El Carcavo (Murcia, Spain). Catena, 16: 57-69.
12. US Army Corps of Engineers, 2001. Hydrologic Engineering Center Hydrologic Modeling System (HEC-HMS) User Manual.
13. Bahremand, A., 2006. Simulation the effects of reforestation on floods using spatially distributed hydrologic modeling and GIS. Ph.D thesis, Vrije Universiteit Brussel, Belgium.
14. Vaziri, F., 2000. Applied hydrology in Iran, First Book, Tehran (In Persian).
15. Sharifi, A., M.V. Hervijnen and W.V.D. Toorn, 2004. Spatial decision support systems. International Institute for Geo-Information Science and Earth Observation (ITC).
16. Ludwig, L. and S. Starr, 2005. Library as place: Results of a Delphi study. J. the Medical Library Association, 93(3): 315-327.
17. Costa, C.A.B., P.A.D. Silva and F.N. Correia, 2004. Multi-criteria evaluation of flood control measures: the Case of Ribeira Do Livramento. Water Resources Management, 18: 263-283.
18. F.A.O., 2001. Small dams and weirs in earth and gabion materials. Food and Agriculture Organization of the United Nations. Land And Water Development Division.