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OPTIMAL FLOOD MANAGEMENT OPTIONS WITH PROBABILISTIC OPTIMIZATION: A CASE STUDY[*]

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Abstract– In this paper a probabilistic optimization model for determining flood management options is presented. The proposed model minimizes flood damages and costs based on optimal flood management options such as structural, non-structural, emergency and permanent actions in a probabilistic framework to consider risk in decision making. In the optimization model different discharge-elevation-damage-probability curves are used as the inputs which are developed based on routing floods with different return periods. The proposed methodology is applied to the Sefidrud river in the northern part of Iran. In this study, the HEC-RAS model is used for hydraulic routing of floods with different return periods along the river considering different types of flood management options. The estimated flood damage is the basis for comparing different options and determining appropriate actions. The results demonstrate the integration of various options in flood damage reduction and show the high potential of this approach in floodplain planning and management. The results also show the significant value of using the probabilistic approach in flood management and its applications in decision making.

Keywords– River basin, probabilistic optimization, floodplain management, flood routing

1. INTRODUCTION

Flooding causes significant damage to local populations and infrastructure which are mostly due to structural, agricultural and industrial activities near the river, especially within the 25 year return period floodplain. Therefore, an integrated approach for the management of floodplain could significantly reduce the damage. The risk of flood occurrences can increase the accuracy of the estimation of expected flood damage. Further, integration of permanent and emergency flood control options is a long-standing challenge in water resources planning and management. These issues are addressed in this paper.

Needham et al. [1] applied a mixed integer linear programming model for evaluating the value of coordinated reservoir operations in the Iowa and Des Moines rivers. Michele and Rosso [2] developed a simplified approach to the uncertainty assessment of regionalized flood frequency estimation using generalized extreme value distribution. Lund [3] proposed a two-stage linear programming formulation which provides an explicit economic basis for developing integrated floodplain management plans. Akter and Simonovic [4] have proposed a methodology to attract multiple stakeholders using fuzzy set theory and fuzzy logic. Hossain and Anagnostou [5] developed a probabilistic discharge prediction scheme based on an uncertainty framework called generalized likelihood uncertainty estimation (GLUE). Pingel and Ford [6] described how used standard-of-practice models within a coincident-frequency analysis framework to evaluate existing flood damage potential and flood damage potential with a variety of proposed damage-reduction measures. Zhang and Singh [7] obtained the probability distribution of

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damage using the total probability theorem in conjunction with other distributions, order statistics, a kinematic diffusion model, and the Box-Cox transformation. Roughani et al. [8] presented an innovative methodology for spatial optimization of flood control measures based on the location of sub-catchments with the aim of flood damage reduction. Chen et al. [9] provided a new method of discharge calculation for debris flow induced by moraine-dam failure. In their study, two main parameters are required to predict debris flow peak discharges which are debris flow density and the shape of the channel.

In this paper, a probabilistic optimization model is developed to obtain an effective mix of flood management options along a river. This model minimizes different flood control construction costs and the expected value of flood damages with different return periods. In order to calculate the flood damage, the discharge-elevation-damage-probability curve for different types of flood management options are developed based on the hydraulic routing results.

In the following section, methodologies of the study and model formulations are given. Then the development of damage probability curves is presented by analyzing the existing and estimated damage data. A case study in the Sefidrud watershed, located in the northern part of Iran, is described with the details of an hydraulic simulation model of floods as well as flood control options results. Finally, a summary and conclusion are presented.

2. METHODOLOGY

In this study, an optimization model considering the probability of flood damage has been proposed. The proposed model provides the optimal structural and non-structural flood control alternatives along the river considering the expected value of flood events with different return periods. The probability of flood events with different return periods has been considered by the expected value of flood damage and the cost of implementing flood control options.

In the formulation, the objective function is the costs of different flood control alternatives and the expected value of flood damage with different return periods. The variation of the flood plain extent with different return periods of flood can be obtained using an hydraulic flood routing model. Variation of flood damage is a function of flood volume related to the flood return period and floodplain land use in each river reach. In this paper, the HEC-RAS software is used for flood routing along the river and estimating the discharge-elevation-damage-probability curves for different reaches of the river. These curves are used as the optimization model constraints for the damages calculation. Figure 1 shows the proposed model flowchart. As shown in this figure, in Step 1, the flow data needed for the simulation model is collected. This data consists of river cross sections, land use, hydrological characteristics of the river and the topography of the river basin. In Step 2, the collected data must be analyzed and processed. This processing includes fitting a statistical distribution to annual maximum flood peaks. The probabilities of different flood events are used to obtain flood discharge with different return periods. These probabilities are obtained through the Probability Distribution Function (PDF) of flood peaks and are used in the HEC-RAS model. HEC-RAS simulates the flood routing in the main channel and determines the extent of floodplains. The floods are routed in Step 3 for different reaches of the river. According to the result of the simulation model, damages can be estimated considering the elevation of water in the floodplain. The results of the simulation model are coupled in four curves representing discharge-elevation-damage-probability distribution. These curves provide the needed input data of the optimization model in Step 4. These curves are discharge-elevation, discharge-probability, elevation-damage and damage-probability, which are obtained in Step 3. Selecting the best options for flood control in the river and the floodplain is the most important task in Step 4. These options are the decision variables in the optimization model. In Step 5, the value of the damages is estimated based on the level of water in the floodplains considering the simulation results of Step 3 and the decision variables of Step 4. Also the construction costs of flood control options are estimated to calculate the total cost of different alternatives along the river which are estimated in this step. These estimated damages and costs are entered into the optimization model in the final step (Step 6) to select the best alternatives. In the end, an economic analysis is done on the results of the optimization model to help decision makers. Model formulation is presented in the following parts.

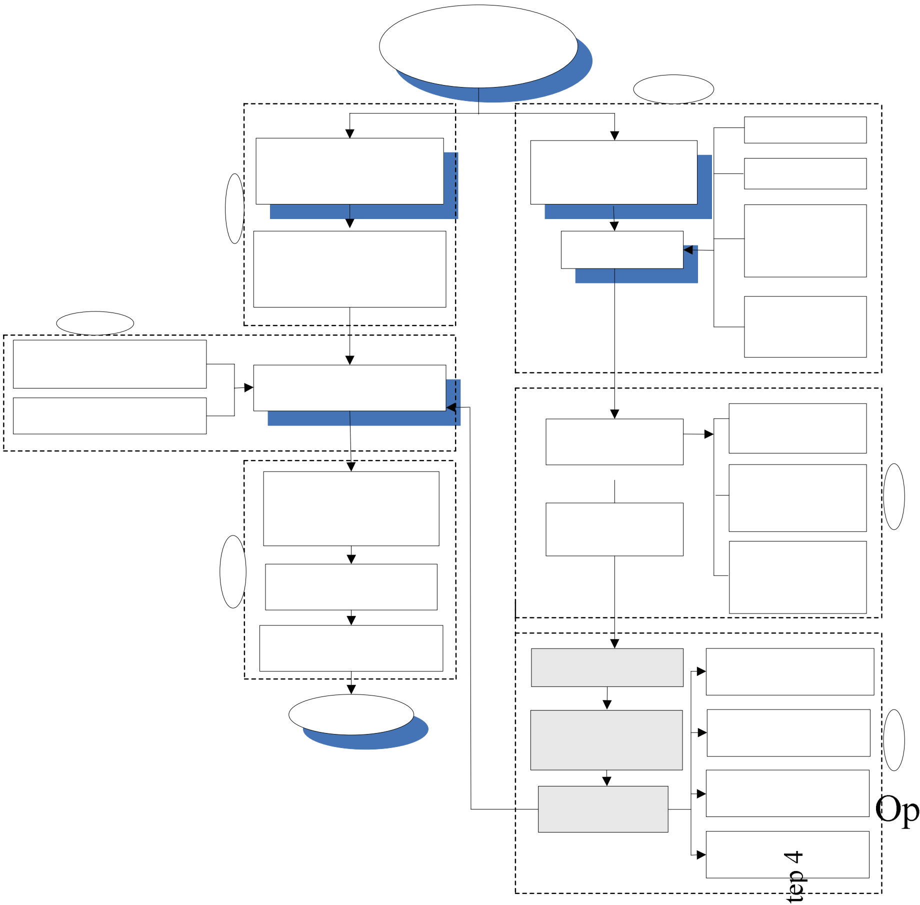

Fig. 1. The flowchart of the proposed algorithm

a) Model formulation

The proposed objective function provides the optimal structural and non-structural flood control options along the river considering the expected value of damages due to the return periods of flood events. The probabilities of flood events with different return periods are considered by the expected value of flood damages and the expenses of flood management options.

$$\text{Minimize} \quad Z = \int_{0}^{\infty} P(i)(D_{T_i}) + \sum_{s=1}^{S} X_s Cost_s = \sum_{i=1}^{m} \left(P_i \times D_{T_i}\right) + \sum_{s=1}^{S} X_s Cost_s \tag{1}$$

$$Cost_s = f(CD, CL, CF) = X_d CD + X_L CL + X_f CF \tag{2}$$

$$H_{ij} = f(Q_i) = \frac{\sum_{t=1}^{T} x_{tj} d_{ijt}}{\sum_{t=1}^{T} x_{tj}} \tag{3}$$

$$D_{ik} = \frac{C_{bf} - C_{af}}{C_{bf}} \tag{4}$$

$$A_{D_{ijk}} = \left(D_{ik} \times A_{ijk}\right) \tag{5}$$

$$D_{F_{ij}} = A_{D_{ijk}} \times C_k \tag{6}$$

$$D_{h_{ij}} = \left(Death_{ij} \times pop_j \times d\right) \tag{7}$$

$$D_{T_i} = f(D_{F_{ij}}, D_{h_{ij}}) = E(D) = \sum_{i=1}^{m} p_i \times \left(\sum_{j=1}^{n} \left(D_{F_{ij}} + D_{h_{ij}}\right)\right) \tag{8}$$

$$CD = f(H_D, T, b_1, b_2, C_c) = V_1 \times C_c \tag{9}$$

$$RC = f(Q_{peak-output}, Q_{peak-input}) = \frac{Q_{peak-output}}{Q_{peak-input}} \tag{10}$$

$$CL = f(L_j, H_L, C_e) = V_2 \times C_e \tag{11}$$

where:
i: flood event probability index ($i = 1......m$), j: reach index ($j = 1......n$), k : land use index ($k = 1......l$), t : number of cross sections in reach j ($t = 1......T$), s : number of flood control options (s=1 detention dam, s=2 levee, s=3 flood warning system)
P_i: probability of flood event i, D_{T_i} : total flood damage of flood event i, X_s : decision variable related to flood control option s ($\{0,1\}$), X_d : decision variable related to detention dam option ($\{0,1\}$), X_L : decision variable related to levee option ($\{0,1\}$), X_f : decision variable related to flood warning system option ($\{0,1\}$), CD: construction cost of a detention dam, CL: construction cost of levee in a reach, CF : installation cost of flood warning system, $Cost_s$: construction cost of flood control options, Q_i : peak of flood discharge with return period i, x_{kj} : effective length of cross-section t in reach j, d_{ijk} : hydraulic depth of flood event i in cross-section t in reach j, H_{ij} : weighting mean of hydraulic depth in reach j with probability i, D_{ik} : damage coefficient for land use k in flood event i, C_{bf} : value of properties before flood event i, C_{af} : value of properties after flood event i, $D_{F_{ij}}$: financial damages for flood event i in reach j, $A_{D_{ijk}}$: real damaged area of flood event i in reach j for land use k , D_{ik} : damage coefficient of land use k in flood event i, A_{ijk} : total flooding area of land use k in reach j for flood event i, $D_{h_{ij}}$: loss of life for flood event i in reach j, $Death_{ij}$: percentage of death for flood event i in reach j, pop_j : population of the reach j, d : death insurance rate (dieh), C_k : value of land use k , $D_{h_{ij}}$: loss of life in flood event i for reach j, V_1 : volume of needed concrete for detention dam construction, V_2 : volume of concrete for levee, C_c : cost of one cubic meter of reinforced concrete, b_1 : crest width of the detention dam, b_2 : foundation width of detention dam, H_D : height of detention dam, T : thickness of detention dam, RC : reduction coefficient of flood event i after routing, $Q_{peak-output}$: peak of output flood event i in detention dam, $Q_{peak-input}$: peak of input flood event i in detention dam, L_j : length of reach j, H_L : height of levee, C_e : cost of earth filling.

This objective function minimizes the expected value of damages (loss of life and properties) and the costs of construction of flood control options using the stage-probability distribution P_i. This function is shown in Eq. (1), presented as a discrete probability function. Equation (2) demonstrates the costs of flood control options if implemented. The flood control options are used in the model as binary values. All the stages of the simulation model are expressed in Eqs. (3) to (11). In Eq. (3), the weighted average of the water level in each reach of the river is calculated. Equation (4) shows the damage coefficients which are used to obtain the actual damaged areas as utilized in Eq. (5). Equation (6) demonstrates the financial damages as expressed in section 2.c.1. Equation (7) shows damages associated with the loss of life and property and the total damages are obtained in Eq. (8) for each reach of the river as discussed in section 2.c.2. Equation (9) shows the construction costs of detention dams which are discussed in section 4. Equation (10) shows the reduction coefficient of flood events as described in Section 4. Finally Eq. (11) shows the construction costs of levees, as explained in Section 4.

b) Estimation of discharge-elevation-damage-probability curves

As mentioned before, the HEC-RAS software is used for hydraulic simulation of the river and routing floods along the river. The discharge-elevation curve (rating curve) is an output of this model which shows the stage of water in the floodplain as shown in Fig. 2a. These curves are estimated for all cross sections along the river. All cross sections must be classified into groups with respect to the number of reaches in the river. A total discharge-elevation curve is needed for each reach of the river, and therefore the weighted average is used to determine the hydraulic depth or flooding area in each reach as shown in Eq. (3).

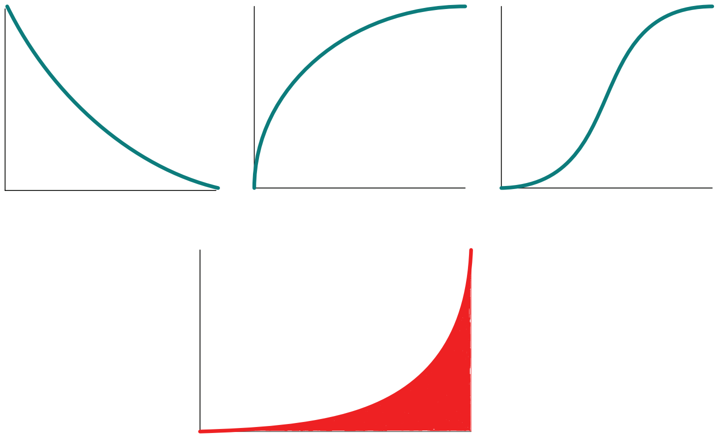

Fig. 2. The schematic of discharge-stage-damage-probability curves

The records of past floods and their peaks are processed and a Flow Duration Curve (FDC) is developed for different return periods considering Weibull distribution. The discharge-probability curve is generated by the FDC and is shown in Fig. 2b.

There are two types of damages associated with an increase of the water level in the floodplain. The values of these damages are different for different types of land use and they are estimated according to the flooding area. These damages are estimated separately for all reaches along the river. Hence, the damage-elevation curves are obtained for each reach of the river on the basis of the flooding area and the water level for different land use as shown in Fig. 2c.

The probability-damage curve is calculated based on flood frequency using estimated damages in the past for all reaches separately. These curves are used as input for the optimization model which will be discussed in the next section. Figure 2 shows a schematic of these four curves.

c) Estimation of damages

There are two types of damages in flood occurrence: 1) financial damages and 2) loss of life. Estimating the value of these damages plays an important role in the planning and management of floodplains. These damages are estimated in the following sections.

1. Financial damages: The type and area of different land use should be determined separately to evaluate the financial damage caused by floods. Also, the portion of each land use must be estimated discretely for all reaches. These damages are related to the level of water in the floodplain and the values of these damages are not similar for different land use. In order to study this issue for different land use, a typical house with two floors and its common household equipment have been considered [10]. The prices of all belongings are estimated in this house before the flood. This sample house is considered to be in the floodplain and the value of household equipments is calculated for different water levels. Equation (4) and Table 1 express the figures needed for damage estimation of different land use.

Table 1. Percentage of financial damages for different land use

Water elevation (m)	Industrial damage - ($D_C - \%$)	Agricultural damage (D_a-%)	Residential damage ($D_r - \%$)
0-0.5	28	0	14
0.5-1.0	50	50	25.9
1.0-1.5	75	75	34.2
1.5-2.0	80	87	35.5
>2	100	100	100

There is limited data on the value of different industrial land use and insurance companies have done little or made no effort to set realistic figures. In this study the damages associated with industrial land use is assumed to be double the residential land use as shown in Table 1. Agricultural land use damage estimation is also needed with thorough investigations using engineering judgment. It is assumed that if the depth of water is less than 0.5 meters, there is no damage and for depth more than 1.5 meters, 100% of the investment will be lost. The third column of Table 1 shows the percentage of damages for this type of land use.

In order to determine the actual damaged area in each land use, the percentages of damages in Table 1 must be multiplied by the flooding area. It is estimated for each reach of the river separately as shown in Eq. (5). Table 1 shows the percentages of damages in each land use in different flood depths. The financial cost of flood damage is estimated by multiplying the damaged area of each land use to its associated cost as presented in Eq. (6).

2. Loss of life: Loss of life is of no monitory equivalence. But even airline industries put a value when estimating the risk of a plane crash. The estimation of this loss is a highly sensitive matter with different social reactions. By determining the density of population and the compensation value according to insurance criterion, the damage associated with the loss of life can be evaluated. Table 2 shows the estimated percentage of human loss of life that could be expected in different water depths in the floodplain.

This table shows that human losses do not occur in depths less than 1 meter, but the probability of its occurrence increases when the flood depth rises in the floodplain. In order to calculate the loss of life financially, the death insurance rate (called "dieh" in Arabic/Persian) is used for every loss. By multiplying the percentage of human loss by the density of people in each zone of the study area, the rate of human loss is estimated. The loss value of death in each reach is calculated using Eq. (7). In this equation, the value of each life is evaluated according to the established national figures (in Iran, the dieh for each person is estimated as 200 million rials about 200,000 Dollars).

Table 2. Loss of life

Water elevation (m)	Human losses (%)
<1.2	0
1.2-2.0	5
>2	10

To estimate the total damage caused by flooding, the financial damages and human losses must be added. The expected value is used to consider the risk of flood occurrence in Eq. (8). As this equation shows, C_k is the value of the land use that must be estimated and should be multiplied by the damaged area of each land use and for all reaches along the river.

3. Model assumptions: The objective function is limited by several types of constraints.

- Budget limitations are considered for constructing the flood control options.
- There are limits on each decision variable (the Xs), representing the limits of construction of one flood control structural option in each reach. $X_s \leq 1 \quad \forall s$

The optimization model is a complex problem because of the interaction among the performance of different management options. Applying optimization techniques for the problem developed here is unavoidable because of a large number of feasible solutions which will be introduced in the case study. One suitable method for dealing with this problem is the Genetic Algorithm (GA).

One of the most important constraints that control the construction of flood control options is the budget limitation for implementing the structural and non-structural options. They are considered as a penalty function in the GA optimization model and indicate the effect of the available budget on the optimal solution. The other constraint demonstrates limits for the construction of flood control options in every reach of the river. In the proposed model, different structural and non-structural flood control options are determined based on budget limits which are determined by the decision maker.

3. CASE STUDY

Sefidrud watershed is located in the northwestern part of Iran and is the largest watershed in the central and northern part of Iran. The Sefidrud dam, which has been operating since 1962, is located at the intersection of the Ghezelozan and Shahrood rivers. Downstream of the dam, the Sefidrud river continues north and discharges into the Caspian Sea in the northern part of Iran (Fig. 3). Rudbar and Astaneh are the two hydrometrical stations in the study area. The recorded data from these two stations are used for model calibration.

a) Hydraulic simulation of Sefidrud river

An HEC-RAS model is used to simulate the level of water with 2, 5, 10, 25, 50, 100 return periods in the river. Furthermore, it is necessary to subdivide the river into reaches on the basis of the mentioned parameters. In this study nine reaches are considered between the Sefidrud dam to the Caspian Sea. The considered flood control options for the Sefidrud river are detention dams and levees as the structural options, and a flood warning system as the non-structural option.

The Sefidrud floods are routed and the level of water and the rating curves are obtained. As mentioned, the outputs of the river simulating section are discharge-elevation-damage-probability curves which are shown in Fig. 4 for reach 7 of the river. The discharge–elevation curves are obtained by the steady state simulation. The discharge-probability curve is obtained by the flood duration curve, the damage-elevation curves are obtained by the first through third steps of the flowchart in Fig. 1 and finally, the damage-probability curve is obtained using these three curves as shown in Fig. 2. These curves are then entered into the optimization model to obtain the best combination of flood control options.

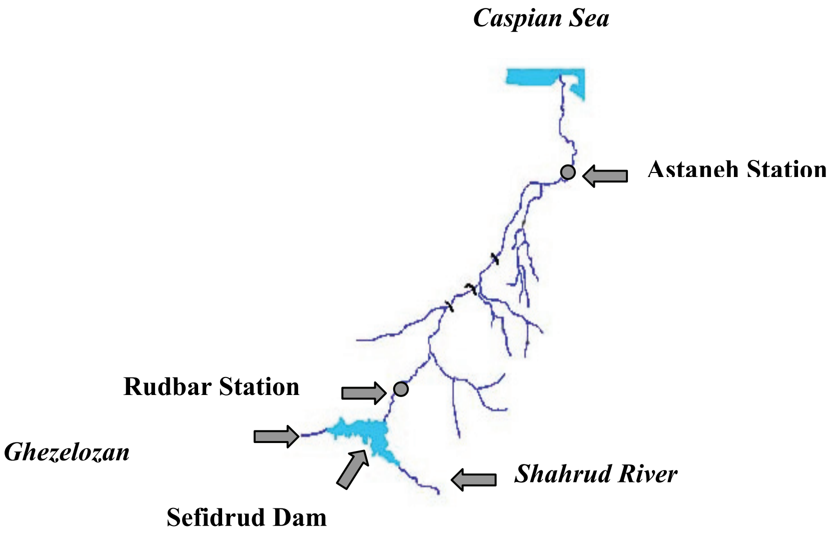

Fig. 3. The schematic of the study area

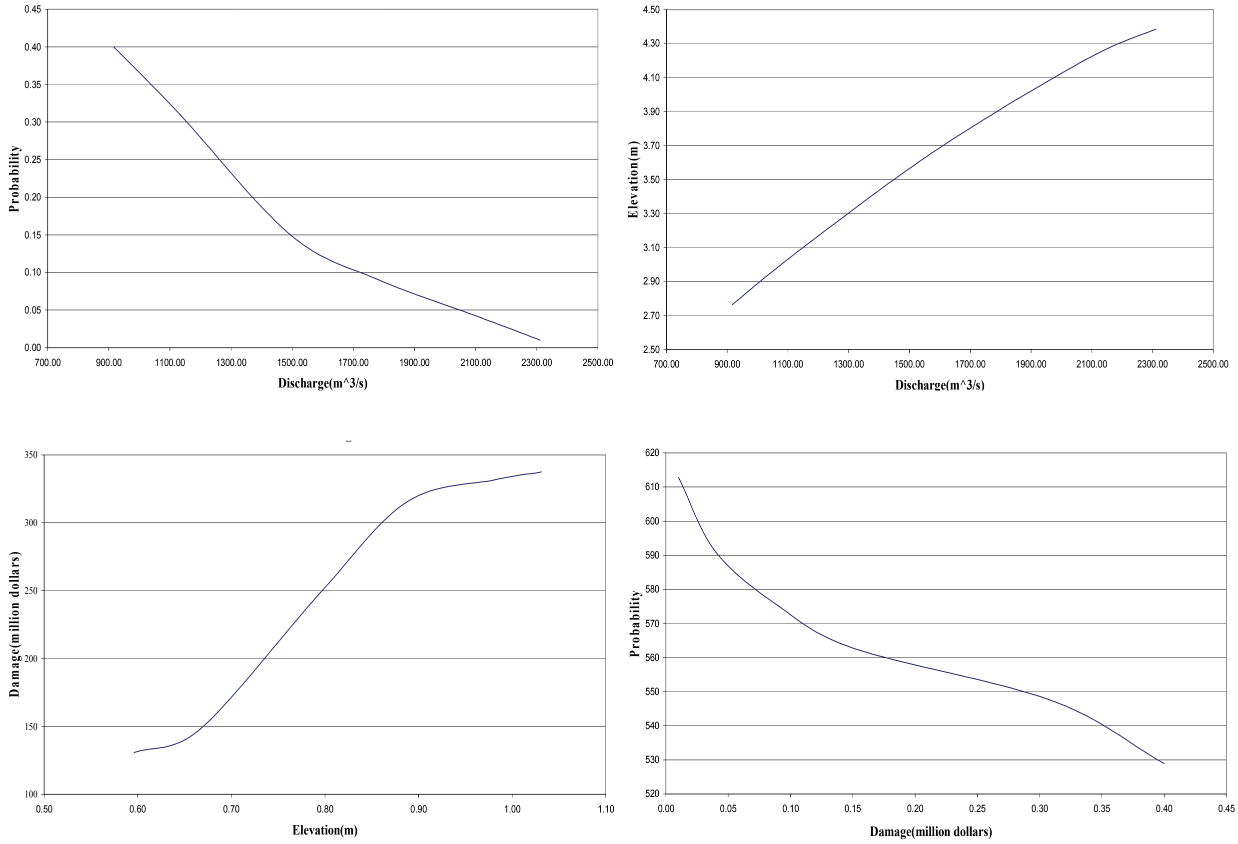

Fig. 4. The discharge-elevation-damage-probability curves for reach 7

In this study, the return period of different floods are considered as the probability of flood occurrence in calculation of the expected value of damages. In order to reduce the flood damage, two structural options and one non-structural option are considered. The impacts of these three options in flood damage control are considered in the objective function.

b) Calibration of the simulation model

In this paper, the river is simulated using the HEC-RAS software in both steady and unsteady states. To increase the confidence coefficient of this routing, it is necessary to calibrate the model. The historical record at the Rudbar station shows that a flood has occurred in the year 1996 with a 100 year return period. The peak discharge of that flood was about 1300 m^3/s. This flood and its hydrograph are used for the calibration of the model in steady and unsteady states. Figure 5 shows the results of the observed and the simulated flood hydrographs at the Rudbar station. This figure shows that the observed hydrograph and simulated hydrograph closely match.

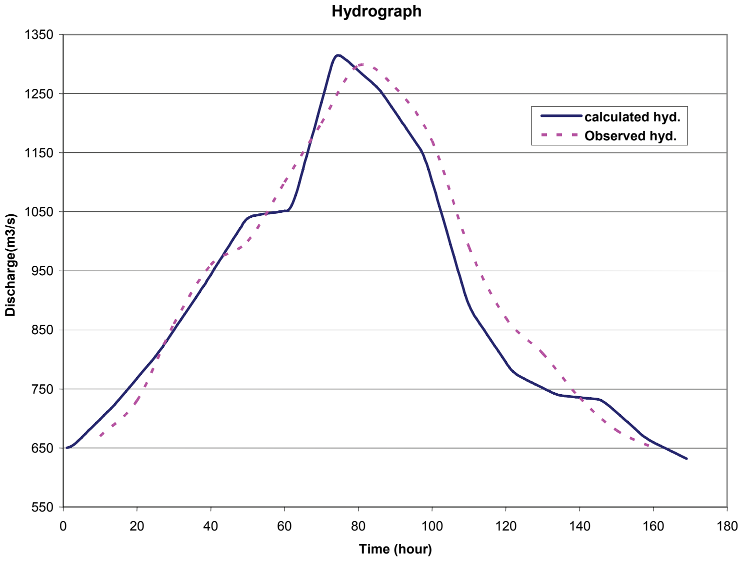

Fig. 5. The result of calibration at Rudbar station for a 100 year flood return period

4. OPTIMIZATION MODEL

In order to extend the optimization model, its input data should be prepared. The input data are the decision variables which are the heights of detention dams and the levees, as well as the utilizing flood warning system. These options have different effects on flood control and reducing damage. Detention dam is made of reinforced concrete and its cost is calculated based on the cost of one cubic meter of concrete. This option is used to reduce flood peaks and delay traveling time. A detention dams are usually implemented as a trapezoidal section. The size of the dam depends on the width of the river. The impact of this option in reducing the flood peak has been determined by the reservoir hydrological flood routing model. The outflow hydrograph of this unsteady state routing (as shown in Table 3 and Fig. 5) shows the rate of reduction in the flood peak with different return periods as shown in Eq. (10). These results show that the proposed detention dams could decrease the peak of the flood significantly.

Levee is another option used to limit the spreading of water in the floodplain. To calculate the construction cost of the levee in each reach, a trapezoidal embankment is considered and the volume of this cross section is multiplied by the length of the reach. Construction costs of a levee are calculated based on one cubic meter of soil and its embankment in the study area. The cost of this option varies in different reaches of the river due to its length. The levee construction cost is calculated based on Eq. (11). In this equation the cost of earth filling for one cubic meter is considered equal to 35 dollars according to the Iran Standard Inventory.

Table 3. The reduction coefficients of detention Dam

Detention dam height (m)	T=100	T=50	T=25	T=10	T=5	T=2
2	14%	11%	10%	9%	8%	5%
4	18%	14%	13%	10%	9%	6%
6	21%	18%	16%	13%	11%	7%
8	22%	19%	17%	14%	12%	8%
10	30%	26%	23%	21%	19%	15%
mean	21%	18%	16%	13%	12%	8%

Flood warning system is a non-structural option which reduces flood damages, especially loss of life. This system is used widely in many regions such as Japan and Australia. This system is usually implemented upstream of the river and the U.S Army Corps of Engineers (1996) has determined different components of an ordinary flood warning system including the software and hardware needed. They also estimated the installation costs of this type of system to be about $120,000. The goal of this option is to eliminate loss of human life and also reduce flood damages through early warning of the public. In this study, it is assumed that this system eliminates the loss of human life completely. It is also assumed that the installation costs are used as the installation and maintenance cost of this system. In actual settings, this option can be supplemented by temporary measures such as the placement of sandbags in the floodplain.

- Structure of decision variables: In the GA setting, the structure of decision variables as genes of a chromosome in each reach of the Sefidrud river is shown in Fig. 6. These gene values are considered for all 9 reaches of the Sefidrud river. The first gene belongs to a flood warning system which is usually constructed upstream of the river and works with the reservoir operation for decreasing the flood peak. The second gene is a binary gene and shows the construction of the detention dam. The third gene is the height of the detention dam (2, 4, 6, 8, 10 meters in height). The fourth gene is a binary gene and shows the levee construction in each reach. The fifth gene belongs to the height of the levee (1, 2, 3, 4, 5 meters in height).

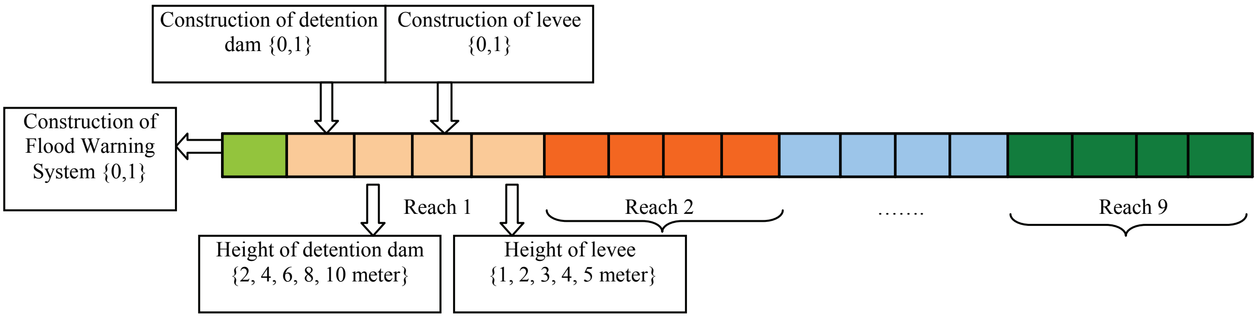

Fig. 6. Structure of a chromosome

5. RESULTS

The interaction among different flood control options with the goal of reducing flood damages has been considered in the proposed optimization model. The optimization and simulation models should be linked together and damages should be analyzed considering the interactions among the flood control options along the river. The results of the optimization model are presented in Table 4.

Table 4. Proposed flood control options based on budget limitation

Investment thousand dollars	Expected damage in million dollars	Flood warning system	Reach 1	Reach 2	Reach 3	Reach 4	Reach 5	Reach 6	Reach 7	Reach 8	Reach 9
0	257	-	-	-	-	-	-	-	-	-	-
99	244	-	D-2	-	-	-	-	-	-	-	-
549	199	-	L-1	L-1	-	-	-	-	-	-	-
1099	157	-	L-1	L-1	L-1	D-2	D-2	D-2	-	-	-
2198	139	√	L-1	L-1	L-2	D-2	L-1	D-2	D-2	-	-
4945	119	√	L-1	L-1	L-2	L-2	L-2	D-2	D-2	D-2	D-2
10879	93	-	L-1	L-1	L-2	D-4	L-2	D-2	D-2	D-2	L-3
21538	67	√	L-1	L-1	L-2	L-2	L-2	L-3	L-4	D-4	L-4
*32527	39	√	L-1	L-1	L-2	L-2	L-2	L-3	D-6	L-4	L-4

D-□: D is the detention dam and □ is the height of detention dam (2, 4, 6, 8, 10 meters)
L-□: L is the levee and □ is the height of levee (1, 2, 3, 4, 5 meters)
*: the solution without the budget limit
√: means that there is a flood warning system in this solution

The first two rows of Table 4 show the value of the optimal objective function. They present the trade-off between the reduction of the expected value of damages and the investment expenses. The following results have been obtained:

- The second row of Table 4 shows the state in which no structural and non-structural options are constructed along the river. This means no reduction in the expected value of damages has occurred. The total expected value of damages with no protection option is about 257 million dollars.
- The last row of Table 4 presents the maximum investment needed when there is no limitation on the budget. The expected value of damages and costs are about \$ 39 million, which implies that the reduction in the expected value of damages is about \$ 248 million. This shows that \$ 32.5 million is required to prevent the most probable damages caused by the flood events. The flood warning system is an option when there is no limitation on the budget.
- There is no specific rule for the existence of a flood warning system but if enough budget is available, it could be considered.
- In most states, levee construction is proposed by the optimization model rather than the construction of a detention dam. In particular, for reaches located upstream of the river, the levee with a lower height has been selected in comparison to the other options. Better cost-effective performance of this structure is shown compared to the other options.
- The detention dam has been selected for reaches 4 through 9 with the maximum height of 4 meters considering the tributary branches of the river. This shows that detention dams higher than 4 meters have less efficiency compared to the other structures which are not cost-effective structures in this case. According to the results, downstream reaches have greater potential for exercising this option.

The tradeoff between the model objective function and the available budget is shown in Fig. 7, which is dimensionless. In this curve, the horizontal axis displays different alternatives of investment which increase from left to right. The vertical axis displays the value of the objective function and also the construction cost of the options. The dashed curve (C1) shows the objective function for the investment alternatives. This curve shows that as the investment value increases, the expected value of damages decreases. The other curve (C2) shows that by increasing the investment value, the construction cost of the flood control options increase. As demonstrated by these curves, the ideal point is the intersection point of curves C1 and C2.

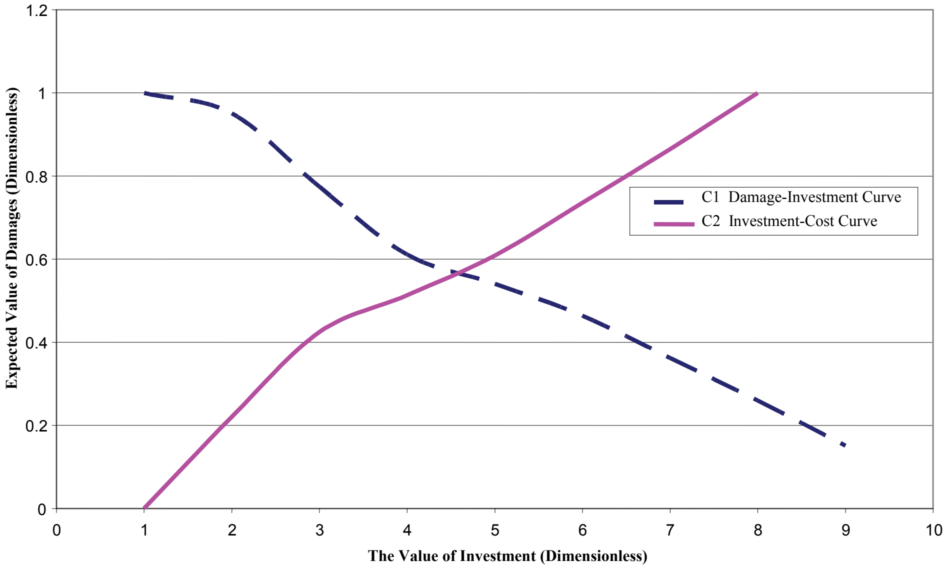

Fig. 7. The tradeoff between the available budget and the model objective function

The objective function considers the variations of investment costs as shown in Fig. 8. This figure is divided into two sections, A and B. In section A, an increase in budget causes a small decrease in the objective function. In section B, a small increase in the investment cost and budget causes a high decrease in the objective function. Therefore, it seems economical to increase the budget as much as possible in this region. Based on the results, the preferred value of investment is obtained from the intersection of A & B in the horizontal axis which is about 1.2 million dollars because the rate of increase in the damage reduction relative to the budget limitation is too high.

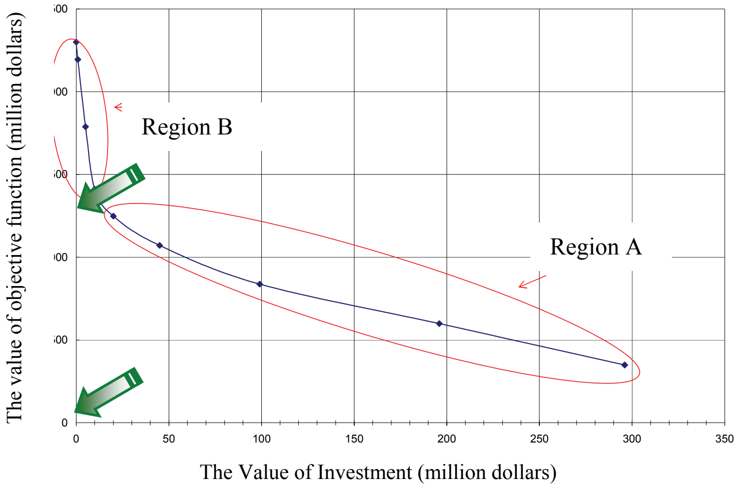

Fig. 8. The tradeoff between investment costs and objective function value

The desirable point of the optimization and economic model shown in Fig. 8 is equivalent to the ideal point in Fig. 7 and is equal to a \$ 1.2 million budget. All of the discussed results are based on the cost-effective economical criterion of different flood control options. These results help decision makers take the most economical and proper management decisions.

6. SUMMARY AND CONCLUSION

In this paper, a probabilistic optimization model is used to select structural and non-structural flood control options in the Sefidrud River in the northern part of Iran. An HEC-RAS model is used for the hydraulic routing of floods along the river and the Discharge-Elevation-Damage-Probability curves are derived based on the results of a hydraulic simulation model. The expected value of annual damages and costs are calculated based on these curves. The proposed optimization model utilizes a Genetic Algorithm model in order to select the best flood control alternatives along the river. The innovative aspect of this study is the application of HEC-RAS modeling with the Genetic Algorithm optimization model utilizing DEDP (Discharge-Elevation-Damage-Probability) curves. According to the results, by investing about \$ 2.4 million for the construction of flood control and warning measures along the river, the expected value of damages are reduced to \$ 118 million. This considerable gain shows the significant value of utilizing the proposed approach.

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