Risk assessment of earth dam overtopping using system dynamics and monte carlo simulation (case study: hajilarchay dam)

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Abstract

Risk assessment of the hydraulic structures is one of the serious concerns of researchers especially in earth dams. Using uncertainty and risk analysis, it is possible to use uncertain parameters in mathematical equations for designing. This paper considers the different uncertainties related to flood and wind with various return periods and uses system dynamics to evaluate overtopping risk on earth dams in order to mitigate this risk and then increase the earth dam's operational life. In order to evaluate risk in proposed model, we use Monte-Carlo simulation (MCS) method with different iterations. In this research, system dynamics is used as a simulation OF overtopping risk in the Hajilarchay dam, Northwestern Iran. The results show the effectiveness of system dynamics in earth dams overtopping risk assessment with different parameters effecting the overtopping risk. Moreover, opening the bottom outlet of the Hajilarchay dam could cause 12 percent reduction in overtopping risk. Also overtopping risk obtained from the Monte-Carlo simulation is one to two percent greater than Latin hypercube sampling and with less simulation running time. It can be concluded that system dynamic is very effective tool for evaluation and calculation of overtopping risk of dams and is easier and faster than other common numerical methods like Programming.

Keywords: Earth dam, Overtopping risk, System dynamics, Uncertainty, Return period.

1. INTRODUCTION

Although dams have a lot of benefits, their failure can create many dangers and problems for life and property of human beings. Among all the factors that cause the failure of dams, overtopping is considered as one of the most important factors. In designing and performance of engineering systems there are always uncertainties. Calculating the risk of failure with these uncertainties will be necessary. With the help of reliability and risk theory, all uncertainties of random nature of parameters can be formed as mathematical equations, and safety and performance considerations are quantitatively enter the process of designing (Mays, 2000).

Because of the importance of dam in terms of economic, efficiency, failure and destruction, safety and risk of dams' destruction have always been of interest to researchers and engineers. Hsu et al. (2011) examined uncertainty parameters caused by two effective phenomenons that is wind and flood on dam overtopping. They compared the probability of overtopping based on two models of maximum monthly and annual data. Goodarzi et al. (2012) examined dam overtopping risk by univariate and bivariate flood frequency analyses and stated that in assessing the dangers of dam two mathematical analyzes of uncertainty and risk are taken into consideration. In their studies, five univariate and bivariate flood frequencies by applying Gumbel logistic distribution for Doroudzan dam has been evaluated. Mansouri and Kabiri (2012) examined the risk of Vanak dam overtopping using the Monte Carlo method. The results of their research indicated that the initial water level of reservoir does not have much effect on the overtopping risk of this dam and the important factor in this regard is water flow entering dam reservoir. Gebregiorgis and Hossain (2012) evaluated hydrological risk of the old Wilson dam. These researchers reassessed dam risk analysis by flow data, in which old peak-flow data is considered instead of distribution of values. They also used L-moment method for maximum annual volume of reservoir. Mollahosseini et al. (2012) evaluated the effect of creating reservoir capacity in reducing flood damage using a simulation – optimization model based on the systems dynamics. In the aforementioned study, PSO-Vensim simulation – optimization model has been developed to optimize exploitation from reservoir during the flood and allocation of optimal initial control volume of reservoirs. The results showed that improving the conditions of exploitation in terms of flood peak reduction optimal criterion and distribution of initial control volume between the reservoirs of river basin are advantage of constructing Garsha dam. Goodarzi et al. (2012) investigated the possible dam overtopping risksin the case of Mijran dam and stated that hydrological risk assessment and uncertainty analysis by mathematical and statistical methods provides useful information for decision makers. Sharafati and

Zahabiyoun (2014) analyzed dam overtopping analysis by using Monte Carlo simulation. The results of this research show that the average changes of Jamishan dam failure per unit, spillway width variation, normal level and dam crown level is 0.03, 3.1 and 1.56 percent respectively. Goodarzi et al. (2014) in another study examined overtopping risk of Doroudzan dam with Monte Carlo and latin hypercube methods and indicated that increasing the initial level of reservoir water of dam increases the risk of overtopping. Vali Samani et al. (2015) examined uncertainties and evaluation of Maroon dam overtopping risk. In their research, they used Monte Carlo and latin hypercube methods in analyzing overtopping risks and by comparing these two methods they showed that an increase in the input flow is more effective compared to the return period in overtopping risk changes of this dam. In another research, Sharafati (2015) examined overtopping risk of Jamishan dam. In this research by using precipitation threshold theory and combining it with the conditional Monte Carlo method, he reduced the simulation time.

Risk management of earth dams due to various failure modes is one of great importance. Dam overtopping risk contains large number of uncertainty factors, parameters and effective modes. Since these modes have feedback and system dynamics perspective can serve as a simulation tool for managers in risk management. By using system dynamics perspective and modelling the interactions and feedbacks inside the system along with imposing different scenarios to the system, an approximation of what actually happens will be presented which will enable stakeholders to make proper decisions in relation to safety and economic issues.

In this paper by using system dynamics simulation and using Monte Carlo simulation method, we tried to examine and calculate Hajilarchay earth dam and in order to calculate overtopping risk, in addition to flood and wind return period as effective parameters on overtopping of dam and considering their integrative effect, initial height of water in dam reservoir and also dam height itself are considered as uncertainty parameters. The risk by using above methods is calculated and the obtain results are compared with each other. These cases can be stated as innovation in this research.

2. MATERIALS AND METHODS

2.1. MONTE CARLO SIMULATION METHOD (MCS)

Monte Carlo analysis is one of the strongest engineering tools that is able to statistically analyze uncertainties in engineering issues. This method is useful especially in complex issues in which many random variables are connected by nonlinear equations. The basis of this method is producing a set of random numbers that are mechanically or electronically generated. First n random numbers are generated for each of the available random parameters. After that, with regard to an appropriate probability distribution, n random number with certain probability density is obtained and finally we will have n value for performance function (Z), and by using statistical information and frequency histogram for obtained results, the probability of failure and reliability of system can be evaluated (Ghias, 2014).

2.2. THE EFFECT OF FLOOD ON OVERTOPPING PHENOMENON

In this paper flood hydrograph with different return periods is taken into consideration and then overtopping risk is calculated after flood routing in reservoir using Vensim software and calculation of water height in reservoir.

2.3. THE EFFECT OF WIN ON OVERTOPPING PHENOMENON

The speed of wind and the length of river that is exposed to severe wind blows are among the most important factors affecting the occurrence of the overtopping phenomenon. Overtopping phenomenon of wind is defined as the following equation in which overtopping happens when increase in the height of lake water due to wind blow exceeds dam height (Khakbaz et al, 2001).

$$P_f = P(h_w > H_{dam} - H_0) \quad (1)$$

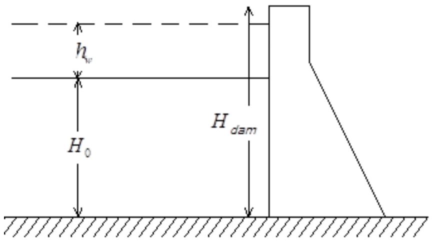


Figure 1. A view of dam height, initial height of water in dam reservoir and increasing water height due to the wind

In figure 1, H_{dam} is dam height, H_0 is initial level of water and $h_w$is increased water level due to the wind. Increased water level due to the wind h_w is normally divided into the following factors:

a. Wave height due to wind in reservoir level (h_s)

The height of biggest waves due to prevailing winds of the area is called wave height. To calculate wave height due to the wind, USBR (1992) presented the following equation:

$$h_s = 0.00237V^{1.23}F^{0.5} \quad (2)$$

In which h_s is wave height (m), F is flux wavelength (km) and V is the velocity of wind blow (km/hr).

b. Wave flux height due to the wind (h_t)

Because of continuous wind blowing to the surface of dam lake water, water level rises. The amount of this rise is a function of wavelength, wind speed and average depth of water along with the flux wavelength and is calculated based on equation USBR (1992) as follows:

$$h_t = \frac{V^2F}{62772D} \quad (3)$$

In which h_t is flux height due to wind (m), F is flux wavelength (km), V is the speed of wind (km/hr) and D is the average depth of water in flux wavelength (m).

c. The height of wave flux on the upper roof of dam

When a wave collides with the body of dam, part of energy is wasted due to porosity and roughness of dam roof and the remainder of the energy causes the wave to rise on the upper roof of dam. Hugh presented the following equation to calculate this parameter (Hugh, 2004).

$$\frac{h_r}{h} = 3.84 \times tan\,\theta \, (\frac{M_F}{\rho g h^2})^{\frac{1}{2}} \quad (4)$$

In which h_r is the height of wave rise on the roof (m), h is the depth of water (m), ρ is density of water and M_F is instantaneous movement of wave in width unit which can be calculated from the following equation:

$$(\frac{M_F}{\rho g h^2})_{Max} = A_0(\frac{h}{gT^2})^{-A_2} \quad (5)$$

Where

$$A_0 = 0.6392 \times (\frac{h_s}{h})^{2.0256} \quad (6)$$

And

$$A_1 = 0.1804 \times (\frac{h_s}{h})^{-0.391} \quad (7)$$

And h_s is the height of dam wave (m) (Wang and Bowles, 2005). Finally the height of water rise due to the wind is calculated as follows:

$$h_w = h_s + h_t + h_r \quad (8)$$

2.4. ANALYSIS OF OVERTOPPING RISK AND DAM FAILURE

The failure of a system occurs when the system does not have an acceptable performance against the loads. In other words, failure of a system occurs when the load on the system (L_F) exceeds system capacity (R). In analyzing overtopping phenomenon and water spillway of dam, water height in dam reservoir (H_{max}) and dam height (H_{dam}) are considered as load and resistance of system.
Overtopping risk of input flood to the dam reservoir and wind speed can be explained by the following functions:

$$Z_{Flood} = ln\frac{H_{dam}}{H_{max}} \quad (9)$$

$$Z_{Flood\&Wind} = ln\frac{H_{dam}}{H_{max}+h_w} \quad (10)$$

In the above equations, Z is performance function and h_w is the height of water rise due to the wind. Finally, dam overtopping risk is calculated as follows:

$$Risk = 1 - \varphi\left(\frac{\mu_Z}{\sigma_Z}\right) = 1 - \varphi(\beta) \quad (11)$$

In which μ_Z and σ_Z are the average and variation coefficient Z. $\beta = \frac{\mu_Z}{\sigma_Z}$ is reliability index and $\varphi(\beta)$ is normal cumulative probability of β (Kwon and Moon, 2005).

3. SYSTEM DYNAMICS MODEL

System Dynamics is able to make long term decisions by setting feedback relationship between phenomena and simulation of these relationships. This methodology in first time was used by Forster in 1961 and it was modified over the past decades. it was originally used for business and resource management. Dynamics simulation allows us to observe the behavior of modeled system and its response while interacting with external factors and changes over time. In system dynamics analysis four tools of storage, flow, interfaces, and converters are used to transform system characteristics into flow and chart. Storages represent accumulation and they are considered as the source. Flow is a component of storages that one does not exist without another (Sterman, 2000). If something accumulates (like water in reservoir), this accumulation must lead to an activity (input flow to reservoir). Storages and flows form the minimum structure for defining a dynamics. Converters convert inputs to outputs. They can be the representative of values or information. Connection connects storages to converters, storages to regulator flows and converters to other converters. They do not take numerical values but they transfer information (Simonovic and Ahmad, 2000).

Generally, storages accumulate input and output differences and we have the following formula:

$$Stock\ (t) = \int_{t_0}^{t_n}[Inflow\ (t) - Outflow\ (t)].dt + Stock\ (t_0) \quad (12)$$

In which Stock (t)، $Inflow\ (t)$ and $Outflow\ (t)$ are value storage, input and output value respectively. In this research Vensim DSS software has been used for systems dynamics simulation by Monte Carlo method in earth dam overtopping issue.

4. THE DAM UNDER STUDY

The Hajilar River basin is one of the tributaries of Aras river basin and is located in eastern Azarbaijan, Iran. The Hajilarchay dam is located two kilometers north of Garagayeh village, 50 km south-east of Varzaghan and 135 km south of Tabriz (Figure 2). Hajilarchay dam is planned for irrigating nearly 2000 hectares of current low efficiency farmlands and about 40 million cubic meters of water for domestic and industrial use and totally it will prevent 65 million cubic meters water loss of river (Bandab, 2013).

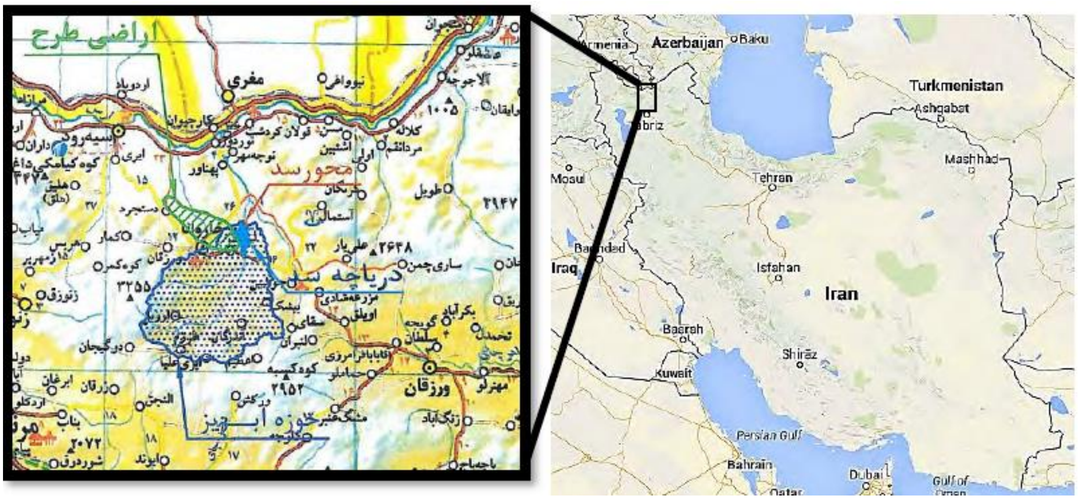


Figure 2. The scope of location of Hajilarchay dam. (Bandab, 2013)

The characteristics of Hajilarchay reservoir dam is presented in table 1.

Table 1. Hajilarchay dam information and dependent structures

Type of spillway	Useful volume (MCM)	Reservoir volume in normal level (MCM)	Height from bed (m)	Height from foundation (m)	Crest width (m)	Crest length (m)	Dam type
Morning glory spillway	47.30	48.90	71	95	10	265	Earth dam with clay core

Figures 3 and 4 shows the Vensim model of Hajilarchay reservoir to simulate water level changes and evaluates dam overtopping risk.

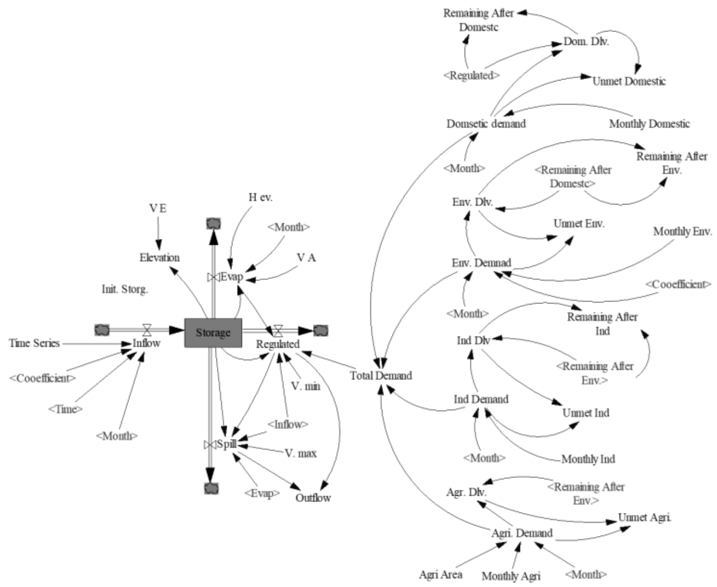


Figure 3. A view of system dynamics model made for simulating water changes in reservoir

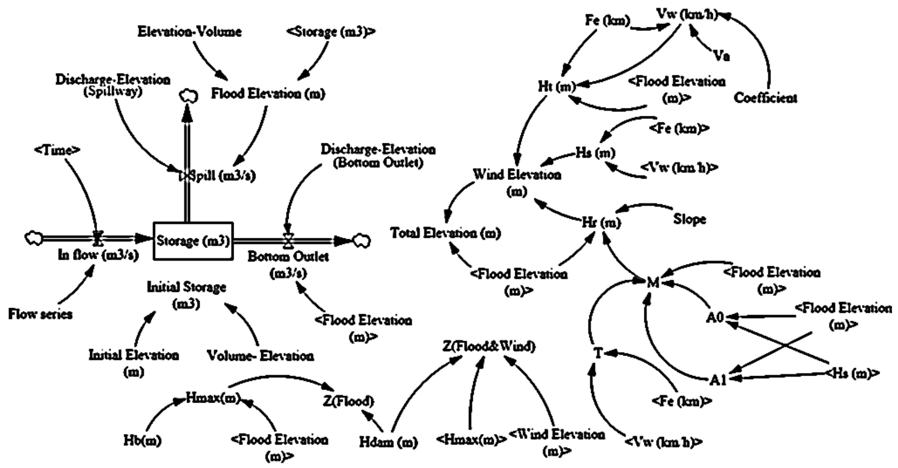


Figure 4. A view of system dynamics model made for simulation of water level and calculating performance function (Z) in Vensim environment.

5. RESULTS AND DISCUSSION

In this study parameters of initial level of water and dam height were considered as uncertainty factors along with the speed of wind with different return periods. and flood with different return periods with maximum probability. Also we assumed that dam bottom outlet is closed within the occurrence of the flood and probable overtopping. Regarding the model of the reservoir, the minimum and maximum initial water level of dam before the flood is 1005 and 1047 meters respectively. Also according to dam characteristicsreported by Bandab consulting Engineers Company, dam height was 71.00 meters and the maximum long-term settlement of dam in 50 years is 1.48 meters. Therefore the minimum and maximum dam height is 69.52 meters and 71.00 meters.

5.1. THE EFFECT OF WIND AND FLOOD RETURN PERIOD ON OVERTOPPING RISK

In this part of study, effects of wind and flood return period on overtopping risk are investigated and in the first mode, the uncertainty of initial level changes of water reservoir is from 1005 to 1047 meters and in the second mode in addition to initial level changes of the reservoir, the uncertainty of dam height changes is from 69.52 and 71.00 m. simulation numbers in Monte Carlo method for these modes is 200000 and by considering these change, the overtopping risk of wind and flood effect was calculated simultaneously. The results show that maximum value of overtopping risk was for probable maximum flood (PMF) and wind with 100-year return period and its value is 0.101702 for uncertainty of initial height changes of dam reservoir water and it is 0.115223 for uncertainty of initial height changes of dam reservoir water and dam height itself. Also the results show that by considering uncertainty of dam height changes in addition to initial level changes of dam reservoir water, the amount of overtopping risk will increase averagely about 8.8 percent. The results are presented in figures 5 and 6.

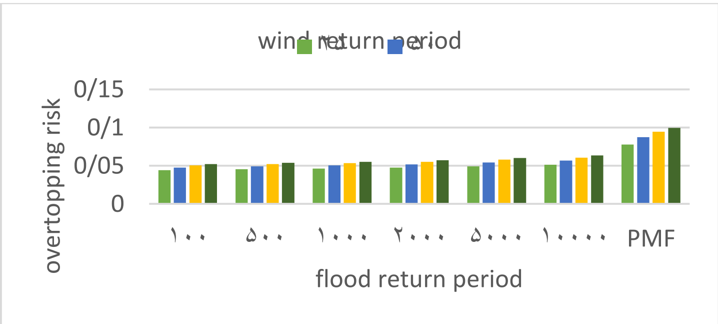


Figure 5. The effect of wind and flood return period changed on overtopping risk by considering uncertainty of water initial level

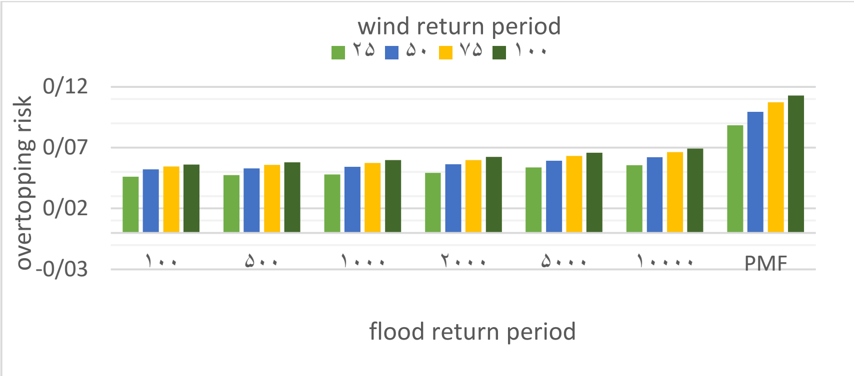


Figure 6. The effect of wind and flood return period changes on overtopping risk by considering uncertainty of water initial level and dam height

5.2. THE EFFECT OF THE NUMBER OF SIMULATION WITH MONTE CARLO METHOD ON OVERTOPPING RISK VALUE

In this part of study effect of the number of simulation repetitions on overtopping risk due to flood and wind is investigated. In this part to calculate overtopping risk calculations, probable maximum flood (PMF) and also wind with 100-year return period has been used. The obtained results of these calculations are presented in figure 7.

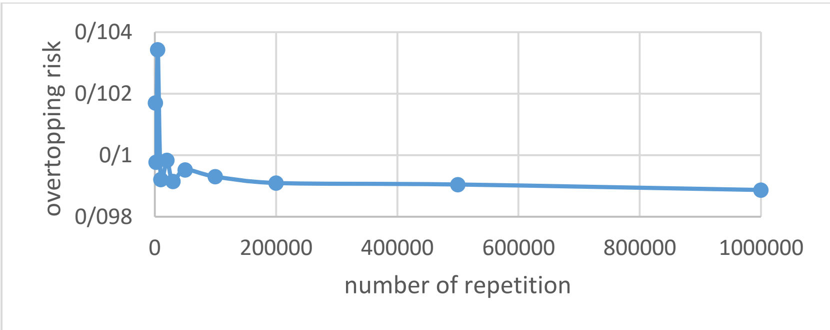
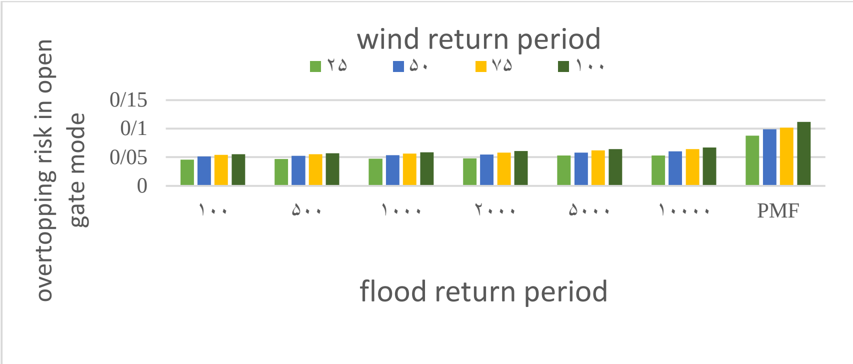


Figure 7. The effect of simulation repetitions of dam reservoir on overtopping risk due to simultaneous effect of wind and flood

With regard to the above graphs, it is clear that in both cases after 200000 simulation repetition, overtopping risk will have the same value.

5.3. THE EFFECT OF OPENING BOTTOM OUTLET GATE ON OVERTOPPING RISK AMOUNT

In order to examine the effect of opening bottom outlet on overtopping risk amount, in first time dam reservoir l was simulated in close bottom outlet gate and overtopping risk amount was calculated and another time in addition to simulating dam reservoir in open bottom outlet gate, the overtopping risk amount was calculated and the results are presented in figure 8. It should be noted that in both modes initial level of dam reservoir water was considered with the minimum and maximum amount of 1005 and 1047 meters respectively and also dam height with the minimum and maximum amount of 69.52 and 71 meters respectively as uncertainty parameters and in both modes Monte Carlo simulation with 200000 repetitions was performed.



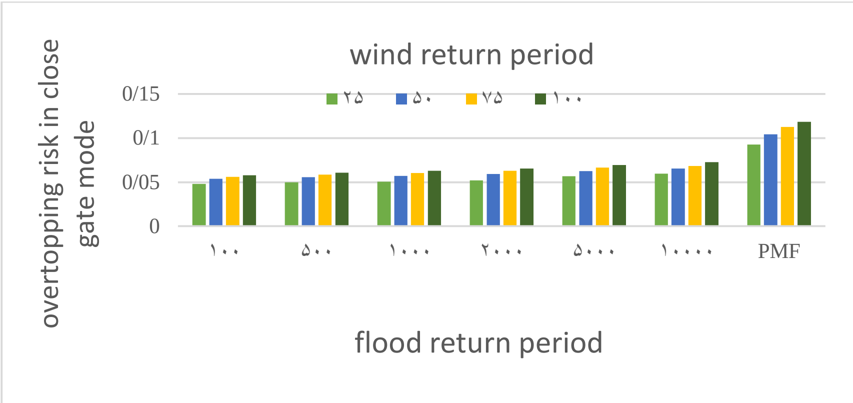


Figure 8. The comparison of overtopping risk due to flood and wind for close and open bottom outlet mode

With regard to figure 8 in which overtopping risk which is under the influence of wind and flood for a condition that bottom outlet gate is closed it is compared to open mode of gate, we can see that in this mode by opening bottom outlet gate the overtopping risk value reduces averagely 7.2 percent.

6. CONCLUSIONS

In this paper Hajilarchay overtopping risk was calculated for different return periods of flood and wind using dam reservoir modeling through system dynamics method in uncertainty condition. For this purpose, by considering initial level uncertainties of dam reservoir water and dam height and using Monte Carlo simulation methods in system dynamics model made for dam reservoir, the overtopping risk value in the mode of flood and wind combination was calculated. The obtained results of simulation show that adding the effect of wind considerably increases overtopping risk value compared to the effect of flood alone. Furthermore, considering both the effect of dam height along with initial water level uncertainty, causes a considerable increase in the amount of calculated overtopping risk compared to the condition in which the only uncertainty is initial water level of dam reservoir is. Also the obtained results of reservoir simulation indicate that when bottom outlet gate is open the overtopping risk reduces 12 percent due to flood and 7.2 percent due to flood and wind respectively. With regard to the obtained result, systems dynamics method with Monte Carlo can be considered as a useful tool to evaluate and calculate dam overtopping risk.

7. ACKNOWLEDGMENTS

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