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Concept Note

Simulation of the water behaviour at the Karaj dam break using numerical methods in GIS environment

Authors:
Gudarz Rashno[1], Mostafa Ghiyasvand[1], Ali Akbar Matkan[2], Babak Mirbagheri[2] and Hamid Salehi Shahrabi[1]

Institution:
1. M.Sc of RS & GIS, RS and GIS Department, Shahid Beheshti University, Tehran, Iran.

2. Faculty Member of RS and GIS Department, Shahid Beheshti University, Tehran, Iran.

Corresponding author:
Gudarz Rashno

ABSTRACT:

Dam failure, estimating water velocity and height of wave caused as well as damage caused by the possible failure of dams, have long been of interest to researchers. In order to estimate these parameters, simulation of the failure of the dam is to be studied. The simulation is done by solving the shallow water equations using numerical methods. The method used in this research is HLL, which is written for the first time in. NET programming environment with software components of Arc Objects and its output is analyzed in a GIS environment. Spatial data used in this research includes DEM of Karaj dam reservoir and downstream areas, and also descriptive data on the Manning roughness coefficient, and water level. In this study, a failure of Karaj dam is simulated and downstream areas are zoned in terms of risk of flooding in two scenarios at the same level with the dry and wet bed. The results showed that in the wet downstream bed scenario with a 1770 meter level, the villages Khouzankala and Adrian have been flooded for 11 minutes and 39 seconds. Whereas, in the dry downstream bed scenario with the water level of 1770 m this time reaches 12 minutes and 30 seconds; and it represents more rapid flood for wet bed.

Keywords:

GIS, Dam failure, Numerical modeling, Finite Volume Method, Approximate Riemann Solver, Karaj dam.

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INTRODUCTION

Although the construction of large dams have improved the welfare and prosperity for the human, but their break have caused huge costs to life and property. So, in terms of space time, we must have the information about the behaviour of water after the dam break to provide the necessary procedures for emergency response in dam failure case. Without dam break simulation no data can be achieved about the behaviour of water at the dam during the incident. Therefore, we cannot respond appropriately when the dam is broken. Prediction is important about how and when the flood occurs due to dam break, in order to prepare the necessary arrangements, as well as when associated with the risk of dam failure and this has led to the development of mathematical models for simulation of dam failure since 1980. Researchers have proposed a variety of different methods to model dam break phenomenon. Most of these models are based on the equations of Saint-Venant with the help of finite difference methods. It should be noted that most of the models have been prepared to assume rigid and non-erosive floodplain; of these methods, methods of Riemann, Lak-Friedrich methods and Gadano method.

The governing equations of shallow waters are the best methods to show the wave motion caused by a dam failure. Due to the lack of precise mathematical methods for solving these equations in general, researchers have suggested various numerical methods. In this study, using the finite volume numerical model, and HLL numerical method, we tried to solve these equations. Then, using a numerical model, the behaviour of water when the Karaj dam broke is simulated (Alcrudo and Mulet, 2007).

In Iran, less studies have been done in the field of modeling of the behaviour of water when the dam break directly in GIS using a programming language. The majority of investigations have used written models or integration of GIS and hydraulic applications. Also, few of these studies have the ability to simulate the behaviour of water when the dam break with the dry downstream bed. But this study is able to simulate the behaviour of water after the failure of the dam with both dry and wet the downstream bed (Nadim, 2015).

MATERIALS AND METHODS

Position

Karaj dam and downstream areas of the dam are

Figure 1. The dam

built between 1957 to 1962 located geographically at northeast of the Karaj city, at 35º, 46 min, and 42 sec to 36º, 00 min, and 29 sec of North; 51º, 00 min, and 17 sec, to 51º, 14 min, 45 sec of East. The dam is located in Chalus road, Khouzankala area in the Strait of Varian (Figure 1). The dam with a crest length of 390 m and height of 180 m has formed a lake with an area of about four square kilometers. Also, the dam is 25 km far from the provincial capital, the city of Karaj. Several villages are in the flow direction of the dam, in which there is a possibility to flood villages on occurrence of dam failure.

In this study, because the gardens have formed much of Karaj dam downstream on the river flow line, manning coefficient of 0.03 is considered. Manning roughness coefficient is more important because less coefficient results in more speed (Table 2).

The data used in research

In order to provide high-risk areas' map, location and non-location data are needed. Location data provides information related to the form and structure of the region, and non-location data give us information such as water level of the reservoir at dam failure, manning roughness coefficient of riverbed of dam area, as well as control parameters of the model such as the overall simulation time, and time difference of the output files. In this section, location data used in the simulation of dam failure are discussed.

Location Data

This data includes the topography of the reservoir, where Digital Elevation Model (DEM) of the reservoir is good. DEM is used to find the thalweg and also to create cross sections of the flow line.

- The topography of the reservoir is taken from the Tehran Water Resources
- DEM is prepared by mapping organizations
- ETM Satellite images from Landsat-2006 are used

Topographic data

The most important data needed for the hydraulic simulation, which initially examined, is land topography. In general, accurate bed topography is necessary for two ranges of reservoir and river axis.

The topography of the reservoir, on the one hand, affects the volume of the tank, and on the other hand, hydrograph affects flood caused by the tank severely. In the present simulation, the output of the dam hydrograph is among the information that has been prepared and ready to use in the simulation. Topography accuracy around the river axis, in practice, is effective on the slope of the river, and as a result, on the quality of flood wave propagation.

HLL numerical method

HLL method is provided by three researchers, namely Lax, Van leer and Harten in 1983. The main idea in this method is ignoring the medium wave and the assumption of two waves in the structure of the Riemann problem, that this assumption is true only in the shallow water equations in one dimension. In this study, this method is used which is explained below (Viseu and Almeida, 2009).

As mentioned in the previous sections, the procedures used to simulate flows due to dam failure must be able to simulate flows with shock in a way free of oscillation and with high accuracy and at the same time simulate the flow on the dry ground. So, given the importance of the above, HLL is selected to solve the equations in this model. This method, which is one of the approximate methods for solving the problem of Riemann, is one of the ways to simulate flows due to a dam break. In this simulation method, flood wave propagation in dry and wet beds are computed using the equations of each of these modes. HLL method suggests a simple way deal with dry fronts. In calculating the transitional flasks of the approximate method of solving the Riemann problem, the approximate values for wave propagation speed of the left and right are used shown as SL and SR. In the dry side, an approximation for wave propagation is considered to be equal to the exact amount of dry front propagation velocity.

$$S_L = \begin{cases} u_R - 2a_R & if \quad h_L = 0 \\ usual\ estimate & if \quad h_L > 0 \end{cases} \quad 1$$

$$S_R = \begin{cases} u_L + 2a_L & if \quad h_R = 0 \\ usual\ estimate & if \quad h_R > 0 \end{cases} \quad 2$$

where, 'U_R' and 'U_L': are the particle velocity to right and left, respectively; 'a_R' and 'a_L': are $\sqrt{g.h_R}$ and $\sqrt{g.h_L}$ 'h_R' and 'h_L': are the depth on both sides. In addition, using this method we can simulate flows with shock accurately (ESRI, 2000). An overview of how to solve equations using this method can be expressed as follows:

To solve the equation, at first, integration is performed on equations (2-3) and (2-4) on a control volume.

$$\int_v \frac{\partial \vec{U}}{\partial t} dv + \int_v \nabla F dv = \int_v S dv \quad 3$$

The second term on the right side of the equation above may be converted from a volume integral to a surface integral as "(2), (3)".

$$\int_v \frac{\partial \vec{U}}{\partial t} dv + \oint_s (\vec{F}.\vec{n}) ds = \int_v S dv \quad 4$$

In the equation above, the equals with flux across control volume in the perpendicular direction. In equation "(2)", "(4)", the integral above is turned into a series for a control volume with 'k' edges (Cameron *et al*., 1999).

$$\oint_s (\vec{F}.\vec{n}) ds = \sum_{r=1}^{k} (\vec{F}_r.\vec{n}_r) ds_r \quad 5$$

Calculating the $\vec{F}_r$ amount is one of the factors that lead to the development of numerical methods, with different accuracy levels. To calculate the $\vec{F}$ amount, or in other words, the magnetic flux through the borders of HLL, the "(2)", "(6)" is used.

$$\vec{F}.\vec{n} = \begin{cases} F_L & S_L \geq 0 \\ F_{HL} = \dfrac{S_R F_L - S_L F_R + S_R S_L (U_R - U_L)}{S_R - S_L} & S_L \leq 0 \leq S_R \\ F_R & S_R \leq 0 \end{cases} \quad 6$$

In the above equation, indices L and R represents the left and right of each computing element, F_L and F_R represent the value of the parameter in question of the left and right of each computing element, SR and SL, respectively the wave propagation speed in the computational nodes on the left and right of each element, that there are different ways to calculate them, and at the same time, the amount the pioneer flood wave in dry and wet beds are different. In the model, the relationship between "(2)" and "(7)" are used to calculate these values (Namin *et al*., 2004).

$$S_L = U_L - \sqrt{g h_L} q_L$$
$$S_R = U_R - \sqrt{g h_R} q_R \quad 7$$

How to calculate q_L and q_R following equations are derived:

$$q_K = \begin{cases} \sqrt{\dfrac{(h^* + h_K) \times h^*}{2h_K^2}}, & h^* > h_K \\ 1, & h^* \leq h_K \end{cases} \quad 8$$

In the equation above, the index 'K' can be selected 'L' or 'R' also the amount 'h^*' can be calculated from "(2)" and "(9)".

$$h^* = \frac{1}{g}\left[\frac{\sqrt{gh_L} + \sqrt{gh_R}}{2} + \frac{U_L - U_R}{4}\right] \quad 9$$

Since the method used in the equations is an explicit method, stability control is necessary. For this reason, if the conditions provided by the Courant criterion are satisfied, HLL method will be stable (Mata *et al*., 2014). With this condition for the one-dimensional flow, the time step is considered as following:

$$\Delta t = CFL.\frac{\Delta x}{\left|{}^{q_x}/_{h}\right| + \sqrt{gh}} \quad 10$$

Scenarios

In this study, there are three basic parameters are considered

1. The water level
2. The dam break
3 Beds downstream (dry or wet)

Based on the parameters above several, scenarios have been considered.

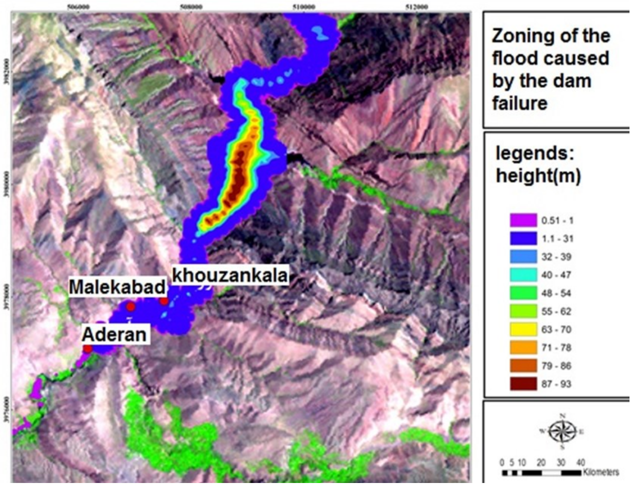

Figure 2. Flood spread after 12 min

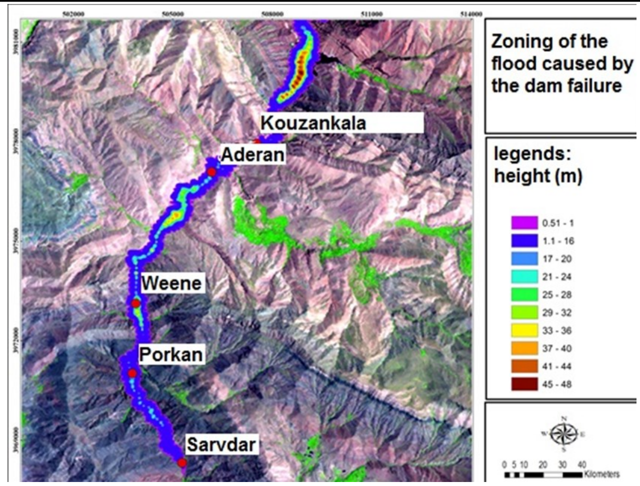

Figure 3. Flood spread after 110 min

Table 1. Downstream areas of the dam, and the distance from the stream thalweg

S. No	The area	Land use	Distance to the dam (m)	Distance to the thalweg
1	Kouzankala	Residential	1950	0
2	Malekabad	Residential	2700	167
3	Aderan	Residential	3900	64
4	Winne	Residential	9330	60
5	Porkan	Residential	11700	53
6	Sarv Dar	Residential	14560	10
7	Karaj	Residential	20500	200
8	Karaj highway	Road	23250	240

Water level and maximum gap (dry bed)

In this scenario, the reservoir has the maximum water height, at the water level of 1770 meters above the sea level is considered. Also, the gap is considered to be maximum; i.e., in a moment, the dam could be broken and the water could begins to move towards the downstream. In this scenario, the bed downstream is considered dry.

Water level and the opening up (more downstream bed)

In this scenario, the reservoir has the maximum water height, at the water level 1770 meters above the sea level; also, the maximum gap is at max, i.e. the dam could be broken at a moment, and the water could

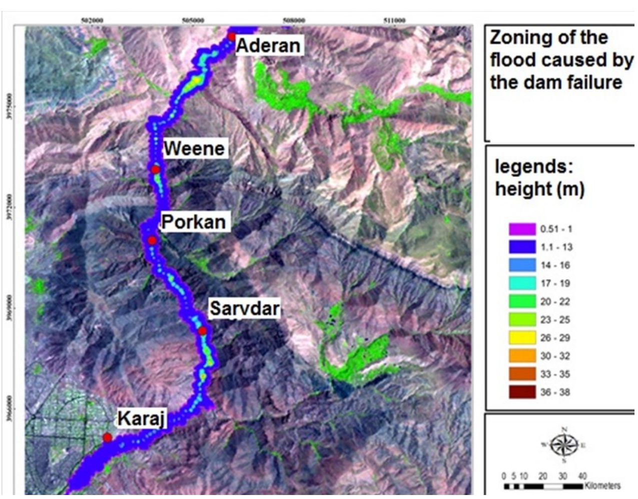

Figure 4. Flood spread after 189 min

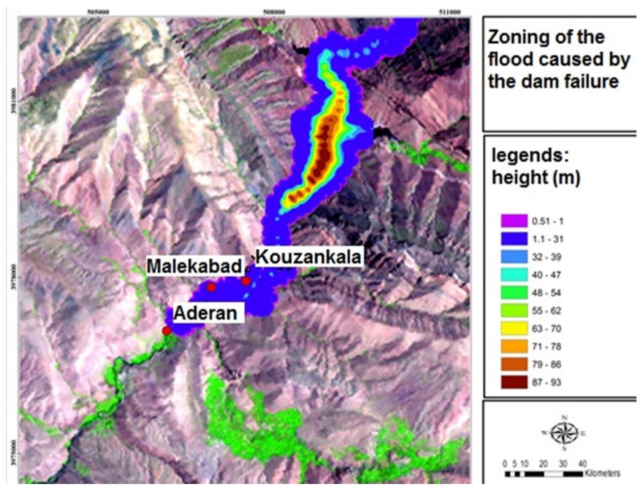

Figure 5. The flood spread after 12.5 min

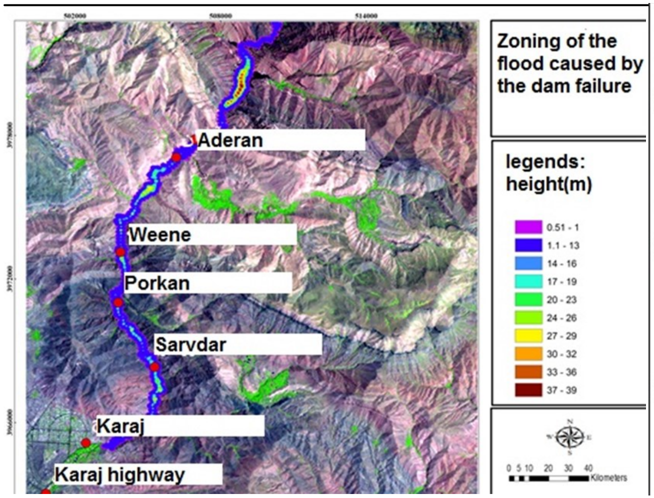

Figure 6. The flood spread after 180 min

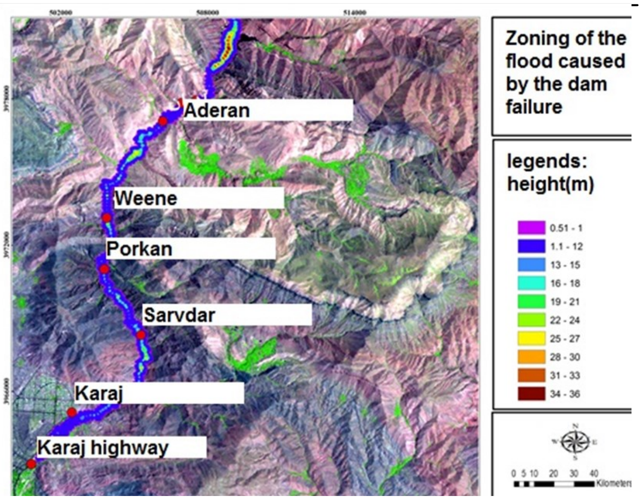

Figure 7. The flood spread after 206min

begins to move toward the downstream. In this scenario, the downstream bed of the dam is considered to be wet; so, the water level is 1m on the downstream.

RESULTS

Scenario results in more bed

In this simulation, the gap is at max and the water level is 1770 meters. Bed downstream considered to be wet, i.e., the downstream water level is 1 m. In the following maps, zoning of the flood caused by the dam failures are given at different times (Table 1).

As shown in Figure 2, in the first 12 minutes, after the dam was broken, the flood has engulfed Aderan village and is advancing towards the gardens bottom of this village. Water velocity at this point is 5.5 meters per second. Also at this time, the flood zone has covered an area of about 181 hectares of the earth. This area includes 9.3 hectares of villages of Aderan, Malekabad, Khouzankala, as well as 82 hectares of gardens. At this time, the population at risk in these villages is 946 people.

Table 2. Estimated manning coefficient for the soil with various covers

S. No	Soil	Manning coefficient
1	River bed	0.025-0.045
2	River bed with the covers	0.014-0.017
3	Orange crops	0.05-0.1
4	Rice paddy	0.02-0.025
5	Vegetable gardens	0.025-0.04

As shown in Figure 3, the flood has engulfed the village of Sarvdar as well as regions before it and has begun to advance toward the downstream. Water has the speed of 2.21 meters per second at the moment. Flood zone, at this time, has covered an area of about 690 hectares of the Earth's surface. This area includes approximately 21.6 hectares of villages of Khouzankala, Aderan, Weene, and Porkan, as well as an area of about 356 hectares of orchards under the risk of flood hazard. At this time, the population of these villages is 1754 (Table 3).

As shown in Figure 4, the flood has reached the highway. At this moment it has the speed of 2.03 meters per second. Population and area of the villages are the same as the previous time step. The garden area engulfed by flood zone is about 621 hectares.

Results of dry bed scenario

In this simulation, the water level of 1770 meters has been considered, and in an instant, the dam is totally destroyed. The water begins to flow to the dry downstream area. Table 4 shows the arrival time of flood to different downstream areas. Also, in the figure below, zoning of flooding due to dam break is given at different times.

As shown in Figure 5, in the first 12.5 min after

Table 3. Time taken for the flood to reach the downstream

S. No	Area	Distance to the dam (m)	Time during for the water to reach
1	Kouzankala	5	5'
2	Malekabad	2700	8'19 "
3	Aderan	3900	11'39 "
4	Winne	9330	53'45 "
5	Porkan	11700	77'53 "
6	Sarvdar	14560	109'8 "
7	Karaj	20500	165'
8	Karaj highway	23250	189'30 "

Table 4. Arrival times in dry scenario

S. No	Area	Distance to the dam (m)	Time during for the water to reach
1	Kouzankala	5	5'12 "
2	Malekabad	2700	9'10 "
3	Aderan	3900	12'30 "
4	Winne	9330	57'54 "
5	Porkan	11700	83'45 "
6	Sarvdar	14560	117'53 "
7	Karaj	20500	180'
8	Karaj highway	23250	206'

dam failure, flood zones has reached Aderan village, and villages before it are covered. This shows that the maximum time to evacuate the village is 12.5 minutes. Water speed, at the moment of arrival to the village Aderan is 5.2 meters per second. Also at this time, a flood zone has covered an area of about 176 hectares. The area includes 5.7 hectares of villages Malekabad and Khouzankala, as well as 80 hectares of the gardens. At this time, the population at risk in these villages is 365. Because the flood flows in a valley, therefore, the width of this zone does not exceed a certain limit. Where the height of the surface of the water level is

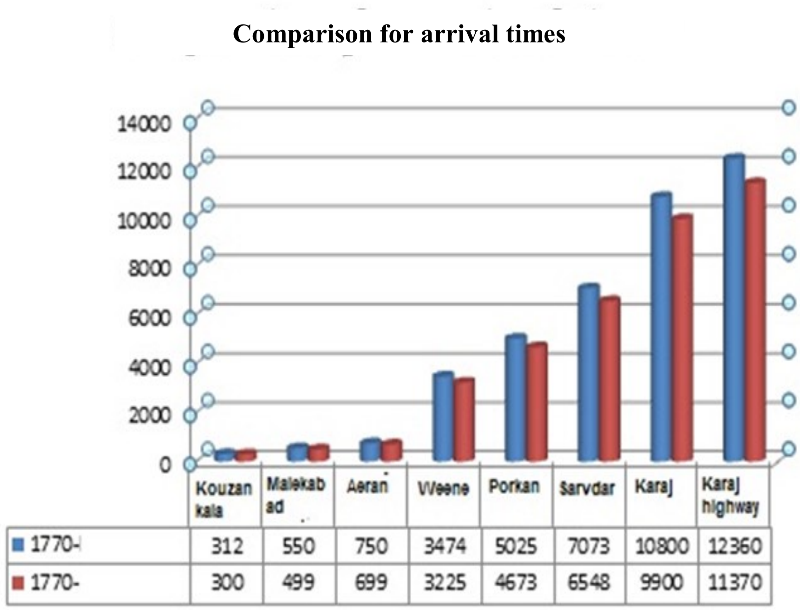

Figure 8. Comparison for arrival times

lower is engulfed by flood zone.

As shown in Figure 6, the flood has reached the vicinity of city of Karaj, so it has engulfed the whole villages on the way. At this moment, the speed is 1.9 meters per second. Because the slope has decreased, so the speed is lower at the end of the path. At this time, the flood has engulfed an area of 885.8 hectares of the ground. This area includes 21.6 hectares of the villages, and about 670 hectares of gardens. In this time, the population of these villages at risk is 1754 people.

As shown in Figure 7, the flood zone has reached the highway. At this moment, the speed is 1.88 meters per second. Also, flood zone has covered an area of approximately 1011.4 of the Earth's surface. Population and area of villages are like the previous time step. The garden area is about 742 hectares engulfed by flood zone.

Comparison of the results for dry bed and the wet bed

In this section, the results are compared to wet and dry beds; because these two scenarios are similar, and differ only in terms of water depth in the bed downstream of the dam. Water depth in the wet downstream is considered 1m. As can be seen in Figure 8, the arrival of water to downstream areas, in the fifth scenario is less than the first scenario. This is because the depth of the water on downstream of the dam in the fifth scenario is 1m, which makes less friction, and thus increases water velocity.

CONCLUSION

In this study, the finite volume numerical model was used for zoning the flooding caused by Karaj dam break. This model is able to simulate dam break with HLL. Due to the positive aspects of HLL, including taking into account, the conditions of dry fronts, this method is used in this simulation. Before using the model for Karaj dam break, the model accuracy was measured with existing analytical solutions. After making sure of its capability, the model was used for flood zoning of Karaj dam break. Water level, the gap, and manning are the most important parameters essential in the current model. In general, an increase in manning reduces the flood speed, and delays in the process of engulfment. Flood zone caused by dam break is mapped, and the arrivals of floods to downstream areas are obtained. Also, these areas have been studied in terms of being at the risk of the flood (Chen, 2015).

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