Risk assessment for hypothetical dam break
A method for the rapid and consistent evaluation

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Abstract

This paper details the technical contribution to the theme of flood risk analysis as consequence of a dam failure. According to the numerical problem proposed for the workshop, the analysis consists of the evaluation of the dam break and its consequences. The simulation includes two scenarios of dam breach: the scenario 1 that represents the case of an easy erodible dam and the scenario 2 the case of an erosion resistant dam. For each scenario, a dam failure discharge hydrograph was calculated and the subsequent flood wave and consequences have been evaluated.
The methodology adopted involves, for a first part, the use of standard models for the hydraulic modelling of the dam breach and flood wave propagation. For the second part, a set of GIS scripts was written, tested and developed using the python scripting language to obtain a rapid appraisal of consequences for the population and to assess the direct economic damages for residential, commercial, and industrial buildings.
Since the latter elaboration depends greatly on the type and the level of detail of available data, in this study we have been used data as generic as possible and GIS scripts that allow, for a great variety of cases, a rapid initial assessment.

Introduction

Modern society considers it essential to increase the safety of the infrastructure. Risk analysis is a helpful tool for the evaluation and management of risks which can affect people, environment and human development. The purpose of this paper was to demonstrate the application of an example of quantitative risk assessment technique that consists of estimating the consequences of failure of a dam near populated areas with complex demographics, infrastructure and economic activity.
The first chapter concerns the hydraulic modelling and simulation of the dam breach, the second the subsequent flood wave propagation and the last focuses on consequence estimation.

Dam failure

This section includes the description of modelling of the breaching process and the subsequent discharge hydrograph for the hypothetical overtopping of the dam.
Two methods have been adopted and the results are named respectively scenario 1 and 2.

Scenario 1

In this case were used, a statistical method available in the literature for the dam failure peak-discharge estimation of and a physically based mathematical model for calculating the total discharge hydrograph.

P. Molinaro [1] utilised 31 data sets (predominantly earthfill and some rockfill) extracted from the report of J. E. Costa [2] to develop a relationship from the peak-discharge, the height of dam and the reservoir volume at time of failure.

$$\frac{Q_{\max}}{\sqrt{g}H^{5/2}} = 0.116\left(\frac{V}{H^3}\right)^{0.221} \tag{1}$$

Where: Qmax = peak-discharge (m^3/s)
g = gravity of Earth that has an approximate value of 9.81 m/s^2
H = height of the dam (m)
V = volume of water at breach time (m^3)

Applying the formula (1) for this case (H=61 m and V=30.3*10^6 m^3) we obtain:

$$Q_{max} = 32800 \text{ m}^3/\text{s}$$

The latter value was used to calibrate parameters of the mathematical model.

The mathematical model was developed by Molinaro [3] and simulates the breach development process through an earthen dam due to overtopping.

The model is developed by coupling the conservation of mass of the reservoir inflow, spillway outflow, and breach outflow with the sediment transport capacity of the quasi-steady uniform flow along an erosion-formed breach channel. The rate at which the breach is eroded is evaluated using the Engelund and Hansen [4] sediment transport relation.

The dam is modeled as an isosceles triangle formed by a noncohesive material of uniform diameter D. The storage characteristics of the reservoir are described by specifying a table of volume vs. water elevation.

The overtopping failure simulation starts by assigning a small initial breach whose bottom elevation must be below the reservoir water level. The first stages of erosion are along the downstream face of the dam while the breach bottom erodes vertically downward. An erosion triangular channel is gradually cut into the downstream face of the dam. The sides of the breach channel has a constant angle (α) with the vertical which is a function of the internal friction (φ) of dam's material. The flow into the channel is determined by the broad-crested triangular weir relationship.

The breach bottom is allowed to progress downward until it reaches the bottom elevation of the dam, subsequently the channel becomes trapezoidal with the sides that maintain the same slope α of the previous triangle.

The following figure Figure 1 shows the sequence of the simulation of the breach formation.

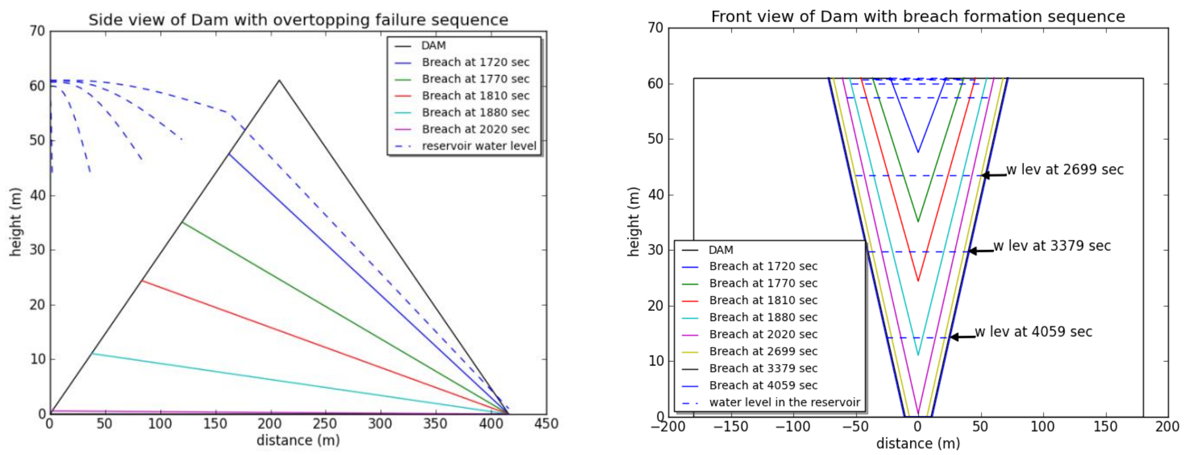

Figure 1: Breach formation sequence

The most important parameter for model calibration is the characteristic diameter D. In this case, taking into account the result of the equation 1, we have adopted the value D = 0.01 m. The discharge hydrograph obtained is shown in the Figure 3.
This hydrograph was used for the first propagation of a flood wave referred to the next chapter. It is characterized by Q_{max} =28936 m^3/s and a breach formation time of 2040 sec (0.57 hrs).

Scenario 2
In addition to the above, a second method was applied for the evaluation of failure discharge hydrograph. Even in this case a regression equations was used for the estimation of dam breach parameters, and then a mathematical model was applied.
Table 1 summarizes the resulting breach parameters (*Wb*: bottom width of the breach and *tf*: breach formation time) computed by several approaches available in the literature.

Table 1: Breach Parameters

Method	Wb (m)	tf (hrs)
MacDonald and Langridge - Monopolis (1984)	167	1.99
Floehlich (1995a)	147	0.66
Floehlich (2008)	110	0.57
Von Thun and Gillette (1990)	207	1.47

In the last column you can see that the breach formation time ranges from 0.57 to 2 hours. As in scenario 1 the resulting time corresponds with the minimum, then for this scenario the case of the maximum value of tf=2 hours was investigated.
For performing the dam breach outflow hydrograph computation, HEC-RAS model was adopted. The implementation of these breach parameters in the HEC-RAS modelling system is depicted on Figure 2. The resulting discharge hydrograph compared to the previous scenario is depicted in Figure 3. As can be seen in the latter figure, the second hydrograph, having the same volume, is characterized by a peak value cut in half compared to the first, but a duration in time approximately double.
For further analysis, we can consider the two hydrographs: the first as representing of a easy erodible dam and the second an erosion resistant dam.

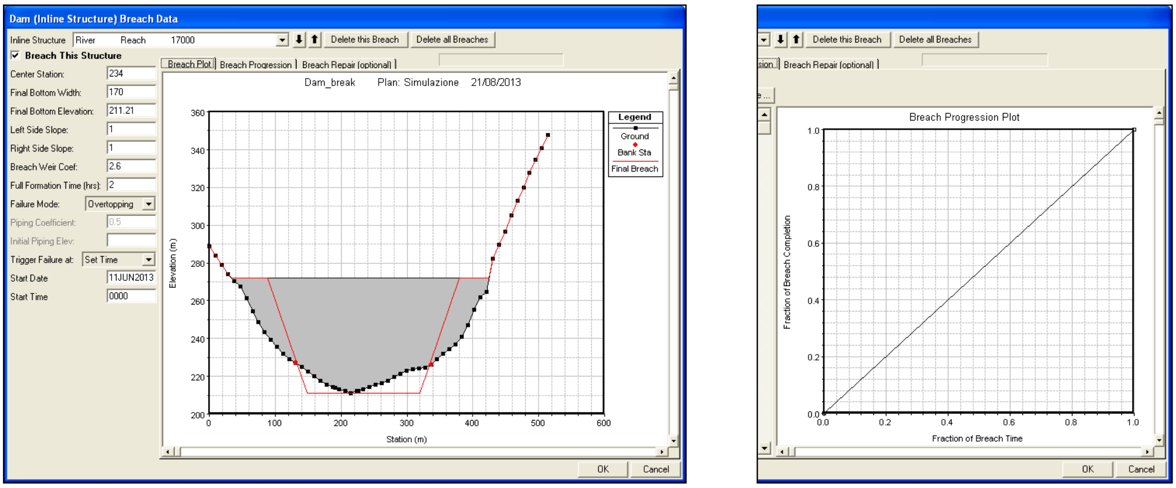

Figure 2: HEC-RAS Dam Breach Model of scenario 2

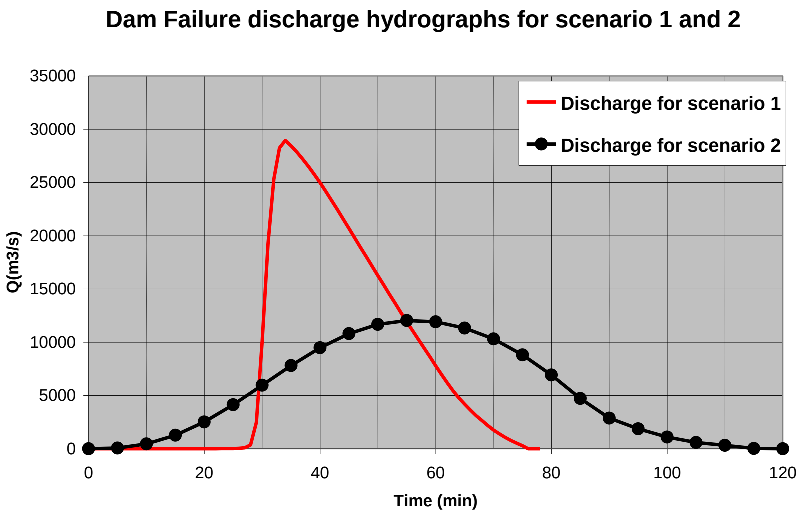

Figure 3: Discharge hydrograph of scenario 2 compared with scenario 1

Flood simulation

Hydraulic modelling has carried out using the MIKE 21 software by the DHI Water Environment Health to simulate flood wave propagation in the river and to describe the inundation on the floodplain. This software solves the shallow water equations by means of a finite difference scheme. For each scenario, the simulation has been constructed using, as upstream boundary condition, the corresponding discharge hydrograph for the hypothetical overtopping of the dam.
According to Bunya et al. [5], the Manning *n* coefficient is spatially assigned associating the value of *n* with the land cover definition of 2001 from the USGS National Land Cover Data (NLCD) (Table 2), These values are selected or interpolated from standard hydraulic literature.

Table 2: Manning *n* value for 2001 NLCD classification

Lu Code	Description	n Mann. ($s/m^{1/3}$)
11	Open Water	0.020
12	Perennial Ice/Snow	0.022
21	Developed-Open Space	0.050
22	Developed-Low Intensity	0.120
23	Developed-Med Intensity	0.120
24	Developed-Hight Intensity	0.121
31	Barren Land	0.040
41	Deciduous Forest	0.160

Lu Code	Description	n Mann. ($s/m^{1/3}$)
42	Evergreen Forest	0.180
43	Mixed Forest	0.170
52	Shrub/Scrub	0.070
71	Grassland/Herbaceous	0.035
81	Pasture/Hay	0.033
82	Cultivated Cropland	0.040
90	Woody Wetlands	0.140
95	Herbaceous Wetlands	0.035

The results of flood modelling consist of values, for each grid cell in the study area, depth (m) and the two components of the vector unit flow rate (m^2/s) for 15 minute intervals and the envelope of their maximum. Using a GIS scripts, hydrographs flow at different cross sections were extracted. Some of these are shown in Figure 4.

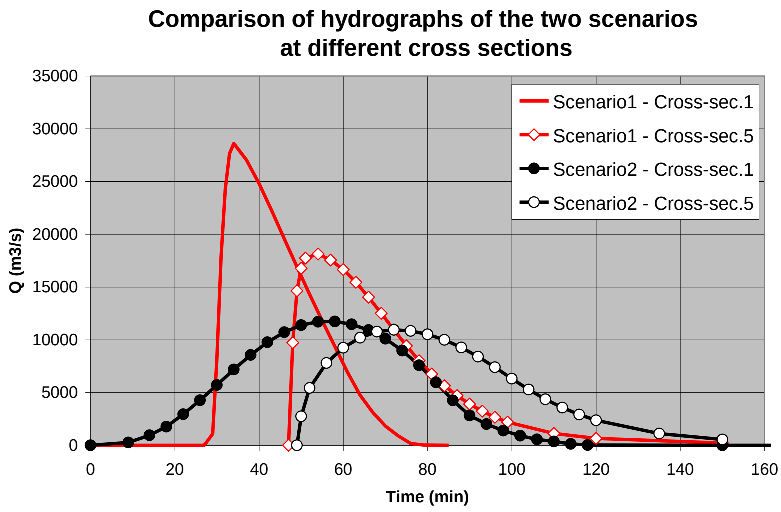

Figure 4: Discharge hydrographs of the two scenarios at different cross sections

Comparing the hydrographs of two scenarios in different cross sections we may note that: while having at the initial cross-section a large difference in peak flow rate, however, during the process of propagation downstream, an attenuation of the difference occurs.

Impacts assessment

The potential risks associated with the failure or disruption of dams could be considerable and potentially result in significant destruction, including loss of life, massive property damage, and severe long-term consequences. The following sections contain the analysis of two categories: public safety and direct economic impact.

Population at Risk and Loss of Life estimation

The analyzes described in this section have been carried out by adopting the published guidelines of the report [6] that provides guidelines and recommendations for estimating loss of life resulting from dam failure or disruption.

The results of flood modelling and the data from the population census are used. Geographic analyzes were carried out using Map Algebra techniques implemented in a set of scripts written, tested and developed using the python scripting language and the Open Sources GDAL libraries and NumPy Python module. To combine multiple maps in Map Algebra all data have been converted into grid format.

The outputs of the hydrodynamic model have been processed to derive the information required for the analysis. Using a GIS scripts, a **Flood Wave Arrival Time** grid was obtained, in addition the two components of the vector unit flow rate are combined to obtain the maximum **Peak Unit Flow Rate** values (m^2/s). These values, called parameter DV, are representative of the general level of destructiveness that would be caused by the flooding. The DV values are then categorized, as suggested in the Figure 5 extracted from guidelines, into ranges of values which define low, medium, and high severity zones.

Table 8. Flood Severity Rating Criteria for Use with 2D Modeling Output (Source: LSM Users Guide)

Flood Severity Rating	Rating Criteria
Low	DV less than 50 ft^2/s
Medium	DV equal to or greater than 50 ft^2/s and less than 160 ft^2/s
High	DV equal to or greater than 160 ft^2/s combined with rate of rise of at least 10 feet in 5 minutes

Figure 5: Flood severity rating criteria reported in the guidelines

The vector polygons of the population census block were converted into grid format: the hypothesis assumed for the different values of the fields is that their distribution within the polygon is homogeneous.
By overlaying grid maps of flood with the grid of the population is achieved as a result the map of Population at Risk (PAR).
The estimate of loss of life is finally obtained by multiplying the PAR with the Fatality Rate (Fraction of people at risk projected to die).
The latter was obtained by using the values of the Table 3 (from tab. 4 of guidelines) as a function of warning time and flood severity.
Table 4 shows the results for the two scenarios for the hypothesis of event occurred at night (understanding=vague). In the case of the first scenario, there is a population at risk greater than 11 percent, while the estimate of the largest loss of life is almost 30 percent. The last result is mainly caused by the shorter warning time of the first scenario.
It should be noted that in each case that the differences in terms of the consequences are less than the differences of the peak discharge of the two scenarios at the breach of the dam, . This result is due to the fact that the volume released from the dam is still the same.

Table 3: Recommended Fatality Rates for Estimating Loss of Life as reported in the guidelines

Flood Severity	**Warning Time (min)**	**Understanding**	**Fatality Rate**
HIGHT	Not applicable	Not applicable	0.75
MEDIUM	No warning	Not applicable	0.15
	15 to 60	Vague	0.04
		Precise	0.02
	More then 60	Vague	0.03
		Precise	0.01
LOW	No warning	Not applicable	0.01
	15 to 60	Vague	0.007
		Precise	0.002
	More then 60	Vague	0.0003
		Precise	0.0002

Table 4: Population at Risk and Loss of Life estimation

Time Interval (min)	Total Population At Risk		14-yr and Under Population at Risk		65-yr and Over Population at Risk		Loss of Life	
	Scen. 1	Scen. 2	Scen. 1	Scen. 2	Scen. 1	Scen. 2	Scen. 1	Scen. 2
0-15	0	3	0	0	0	0	0	2
15-30	2	4	0	0	0	1	2	2
30-60	4 529	2 794	1 169	732	308	196	1 783	1 262
60-90	5 111	641	721	110	1 057	105	2	0
90-120	10 411	8 529	1 491	1 084	2 163	1 996	0	0
120-180	8 935	12 346	1 350	1 899	1 662	2 290	0	0
>180	688	1 911	85	265	121	360	0	0
Total	**29 676**	**26 228**	**4 816**	**4 090**	**5 311**	**4 948**	**1 787**	**1 266**

Peak Flood Depth Range (m)	Flooded Area (m^2)		Total Population At Risk		14-yr and Under Population at Risk		65-yr and Over Population at Risk	
	Scen. 1	Scen. 2	Scen. 1	Scen. 2	Scen. 1	Scen. 2	Scen. 1	Scen. 2
0.0-0.5	8 308 132	4 088 784	5 854	4 825	915	706	1 017	937
0.5-1.0	6 025 869	7 190 976	5 683	6 770	895	1 021	987	1 237
1.0-1.5	7 854 660	7 858 701	8 937	7 769	1 373	1 164	1 664	1 453
1.5-2.0	5 612 806	5 141 466	3 768	2 879	543	391	781	676
2.0-2.5	3 711 550	2 970 641	1 562	1 038	197	118	404	304
2.5-3.0	2 547 251	1 901 885	510	380	72	60	137	98
3.0-3.5	1 746 448	1 453 532	274	292	43	49	68	70
3.5-4.0	1 279 417	711 995	209	220	37	53	49	28
4.0-4.5	546 680	392 859	125	228	35	62	8	17
4.5-5.0	391 332	310 246	153	237	43	65	11	17

5.0-5.5	380 736	209 944	211	216	57	54	15	13
5.5-6.0	242 630	250 352	190	271	51	67	15	16
6.0-6.5	201 323	294 532	194	346	53	90	14	25
6.5-7.0	192 882	221 527	162	337	44	83	9	30
7.0-7.5	176 180	128 947	176	154	44	37	11	11
7.5-8.0	186 417	101 919	254	84	61	18	16	7
>8	1 880 693	850 640	1 414	182	353	52	104	9
Total	**41 285 006**	**34 078 946**	**29 676**	**26 228**	**4 816**	**4 090**	**5 311**	**4 948**

Direct Economic Impact estimation

Methods and values of the parameters used in this section are drawn mostly from the report [7]. They concern the assessment of the direct economic damages for residential, commercial, and industrial buildings. The input data consist of map of land use and parcel zone map of the study area. As in the previous paragraph, for the analysis, all the data are preliminarily converted into grid format.

The following assessments do not take into account Agricultural, Roads, Infrastructure and Vehicles damages. The assessment however allows the estimation of the damage to buildings and their contents, and when applied to different scenarios allows an effective comparison of the impact.

The extent of damage to the buildings and its contents is estimated from the depth of flooding by the application of a depth-damage curve associated with each occupancy type.

Depth damage curves demonstrate the relationship between the depth of the flood relative to the first finished floor level of buildings and the damage caused to the structures and contents. Damages are typically expressed as a percentage of depreciated building replacement value. Adopting a non-traditional approach, the adopted method models directly the content damage as a percentage of structure value rather than using a content-to structure value ratio.

Not having a map of buildings, the area covered by the buildings has been derived from the land use map according to the hypothesis of Building Coverage shown in the following table.

Table 5: Relationship between Land Use and Building Coverage

Lu Code	Description	Building Cover. %
11	Open Water	0%
12	Perennial Ice/Snow	0%
21	Developed-Open Space	**10%**
22	Developed-Low Intensity	**20%**
23	Developed-Med Intensity	**35%**
24	Developed-Hight Intensity	**50%**
31	Barren Land	0%
41	Deciduous Forest	0%

Lu Code	Description	Building Cover. %
42	Evergreen Forest	0%
43	Mixed Forest	0%
52	Shrub/Scrub	0%
71	Grassland/Herbaceous	0%
81	Pasture/Hay	0%
82	Cultivated Cropland	0%
90	Woody Wetlands	0%
95	Herbaceous Wetlands	0%

To calculate damages, each structure must be assigned to a structure occupancy type. For each structure occupancy type an estimated replacement value and a structure depth-damage and a content depth-damage relationship must be defined.

In our case, replacement values were extracted from the "*Table C-3 Estimated Replacement Value*", depth-damage relationship from "*Table C-1 Depth Damage Curves, Defining Damages as a Percentage of Depreciated Building Value for Depth of Flooding Above Floor*

Height” and the height of the floor of buildings from the ground level was taken from "*Table C-2 Foundation Heights*" of report [7]. The following table contains the list of occupancy type categories adopted.

Table 6: Occupancy types

Occup. Type	Description	Unit Cost ($US/sqm)	Origin data of Depth Damage Curve
RES1	Residential One Story, No Basement	1711	USACE Generic Depth Damage Curves for residential buildings
RES2	Residential Two or more Stories, No Basement	3336	"
COM	Commercial buildings	1528	USACE depth damage, as used in Ford (2005) [8]
IND	Industrial buildings	1528	"
PUB	Public buildings	1711	"
FAR	Homestreads	1711	"

The Figure 6 below shows the graph of the depth-damage curves.

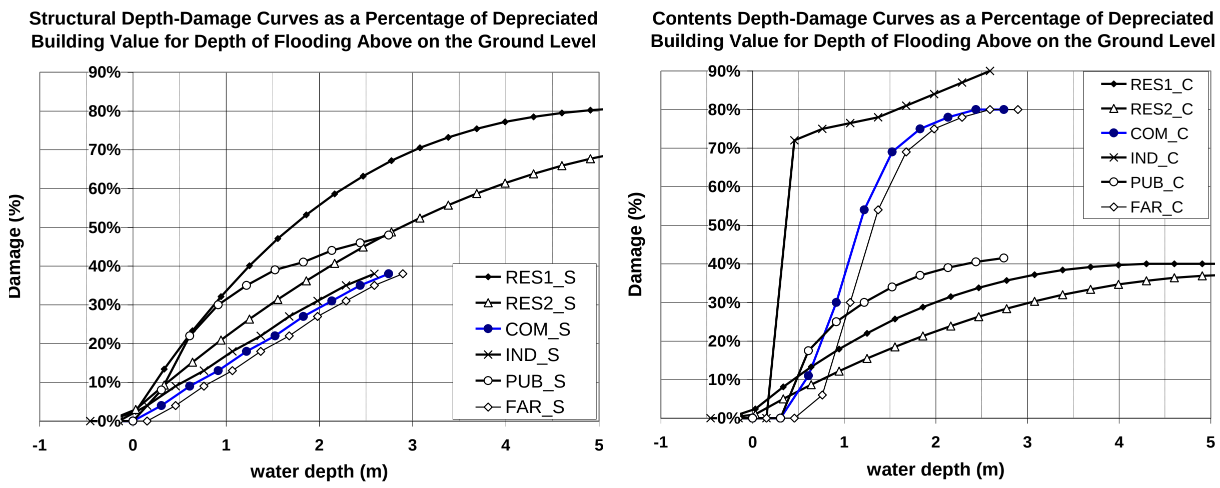

Figure 6: Depth damage curves

To assign at each parcel the occupancy type we chosen the values according to the Table 7.

Table 7: Reclassify table: from parcel ZONINGCATE to occupancy type

ZONINGCATE	Stories	Occupancy Type
COMMERCIAL	any	COM
INDUSTRIAL / WHOLESALE / MANUFACTURING	any	IND
INSTITUTIONAL / GOVERNMENT	any	PUB
OFFICE	1	RES1
OFFICE	2	RES2
OFFICE	3	RES2
OPEN SPACE / RECREATION / AGRICULTURAL	any	FAR
RESIDENTIAL	1	RES1
RESIDENTIAL	2	RES2
RESIDENTIAL	3	RES2

RESIDENTIAL / AGRICULTURAL	any	FAR
UTILITIES / TRANSPORTATION	any	RES1

The results of applying the method for the two scenarios are listed in the following table.

Table 8: Direct Economic Impact

Time Interval (min)	**Direct Economic Impact ($US)**	
	Scenario 1	Scenario 2
0-15	0	0
15-30	0	0
30-60	499 417 507	333 141 773
60-90	671 323 845	151 037 801
90-120	839 403 518	854 746 410
120-180	577 769 953	822 621 093
>180	12 807 947	64 207 745
Total	**2 600 722 770**	**2 225 754 822**

The results show that the total damage, in the case of the first scenario, are greater than 14% and that difference occurs in the first 120 minutes. Also in terms of economic loss the difference between the two scenarios are less than the differences of the peak discharge in the breach of the dam.

Conclusion

In this paper we present the results of the analysis of a possible dam failure. The development of a dam break is a complex process involving numerous uncertainties: the methodology adopted in this work is a medium-scale approach type and can be used for the rapid and consistent evaluation of consequences for the population and to assess the direct economic damages for residential, commercial, and industrial buildings. Rapidity is allowed by using aggregate data: maps of land-use, population census and parcel zone. Consistency is required to ensure comparability between evaluations. For that reason the method can be used to prioritize corrective actions to achieve the greatest and quickest possible risk reduction or for identification of the most effective and better-justified measures of risk mitigation.
The comparison carried out for the two scenarios is an example of use of the methodology to estimate the sensitivity of results with respect to an uncertain parameter which is the breach formation time.

Acknowledgements

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