Loss of life estimation and risk level classification due to a dam break

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A B S T R A C T
This report estimated the loss of life and the variation of risk level to people and properties from the city of São José do Jacuípe, at Bahia State, in Brazil, through a simulation of the dam break near the city. The simulations employ the HEC-RAS program with the HEC-GeoRAS plugin, both made available by the U.S. Army Corps of Engineers. The program is a hydrological model for the hydraulic flow propagation arising from the complete resolution of the Saint-Venant equation, while the plugin was used for vector editing by creating a geomorphological model from the river basin. The results from the research demonstrated that the city is exposed to a risk that is time dependent. In addition, the lack of a warning system about a possible break could cause the death of almost all residents. Otherwise, with a warning system operating, the estimation of destruction would be dramatically reduced.

1. Introduction

Great hydraulic constructions such as Dams for water resource utilization have been implanted for more than 7,500 years, as occurred with Sumerian people in Mesopotamia who had around 200 km of irrigation channels. Dams are especially necessary for water scarcity regions, such as the city of São José do Jacuípe, which has a semiarid climate. However, their construction entails environmental risk, which implies the need for an emergency action plan. Otherwise, they could represent a potential risk for local people living at dam's downstream.

The simulation of a flood wave due to a dam break, presented in a graphical preview, is not a recent procedure. Craya (1946) and Ré (1946) were pioneers in the use of graphic methods to calculate the variable unsteady flow caused by dam break, which enabled the spatial and temporal distribution of water depth, velocity, and discharge downstream the breach. In recent years, the Hydrologic Engineering Center's River Analysis System has become one of the most widely used models in the analysis of a chaotic flow arising from dam-breaks (Redon et al., 2012), due to its satisfactory precision (Rao and Hromadka, 2016) and to the software's free availability. HEC-RAS is a software program developed by the U.S. Army Corps of Engineers and offers many tools such as one-dimensional (1D) calculation of steady flow, one-dimensional and two-dimensional (2D) calculation of sediment transport flow; moving beds and temperature modeling, and water quality. The program is very common in research and the management of flooded areas and flood insurances (Andrei and Robert, 2017).

In recent years, the modeling of floods has been improved substantially with the arrival of geoprocessing tools (Khalfallah and Saidi, 2018). The use of HEC-RAS tools alongside the Geographic Information System (GIS) was used to outline flow velocity and discharging depth. With this information applied to the model of Hydrologic Risk (Rh), it is possible to quantify the estimation of loss of life over time. That was adopted in the case analysis of a dam break in São José do Jacuípe. Therefore, this report studied the damage of a flood wave caused by the hypothetical break of a dam and the expected number of fatal victims. The break wave was simulated based on hydrologic models attached to HEC-RAS software.
With the demographic data, hydrologic models, and equation to estimate the loss of life, we can represent dams’ potential risk: both for the human factor as there are people living downstream the barrier, and for non-human factors, like plantation, animal husbandry, and properties. It was also possible to estimate the number of lives that could be lost because of the warning time. Considering that São José do Jacuípe does not have a system of warning, it was estimated that the city is at a high-risk level. In addition, it was identified the classification of risk levels about local population and properties, according to Viseu (2008).

2. Methods

2.1. Description of research’s area

São José do Jacuípe city (Figure 1) had a population estimated at 10,180 people according to the 2010 Census. 68% of them are situated in the urban zone, corresponding to a total of 6,991 residents. The city has a total area of 37,081 square kilometers and a demographic density of 27.54 inhabitants per square kilometer (IBGE, 2010). On a scale from 0 to 1, the Human Development Index - HDI is 0.552. The average per capita income is 47 dollars (August of 2020). About the adult population, only 6% finished elementary school, 10% finished high school, and 36% is uneducated (2020).

São José do Jacuípe is located in the semiarid climatic field region of Bahia state in Brazil. The average annual rainfall varies from 500 to 800 mm, with 60%–85% of precipitation occurring from February to May. Since it is located in a low latitude, the city has high annual indexes of insolation, evapotranspiration, and temperature. Nevertheless, there is a significant temperature range determined by the continentality, with the annual absolute minimum of 12°C Celsius, maximum of 38°C Celsius, temperature range of 28°C Celsius, and an annual average of 24°C Celsius (Nimer, 1989).

The landform of the region is known as sertaneja depression, with low altitude varying from 20 to 500 m in the dissected depressions that correspond to the largest part from the geomorphological domain. In upper zones, the altitude can reach 800 m. The landform has a very flat structure with slight curvatures characterized by residual elevation along the landscape (Velloso et al., 2002). Regarding hydrography, it has small streams and intermittent rivers. There is a large river, the Jacuípe River, where the São José do Jacuípe's dam is situated.

2.2. Research procedures

Boundary conditions and initial conditions that the HEC-RAS 4.1 software requires are used to generate the rupture wave, the program’s mathematical model is the Saint-Venant system of equations (Eqs. 2, 3, and 4 will be presented in section 2.2.3). To obtain the solution of the one-dimensional Saint-Venant equations it is necessary to specify the upstream and downstream boundary conditions. The upstream conditions can be specified either by the hydrograph or by the inlet elevation. There are four downstream boundary conditions in the HEC-RAS model, which can be specified as follows (USACE, 2016):

I - Time series of water level rise; II - Time series of flows (when the recorded data are available and the model is calibrated for a specific flood event); III - Key curve of permanent flow; IV - Key curve of permanent flow obtained using the Manning equation, where the value of
variable $S$ (see 2.2.3 below: Eqs. (2), (3), and (4)) is specified as the slope in the vicinity of the cross section of wave $N$. Variables $Q$ and $h$ are water flow and free surface level. For USACE (2016) the initial conditions for the variables $Q$ and $h$ must be known for time $t = 0$, in all cross sections ($i = 1, 2, 3, \ldots, N$).

The model's solutions represent flood waves caused by dam burst, impacting the urban environment.

To simulate that phenomenon some calibration of the model was performed. In that calibration it's necessary to procedure we use the topology of the elements that constitute this diverse space, such as blocks, bridges, culverts, i.e., every structure caused by urbanization that may interfere with the flow regime (Schmitt et al., 2004).

HEC-RAS, in integration with Geographic Information Systems, especially ArcMap 10.3, has all the necessary characteristics for the construction of the flood model resulting from dam failure. This is due to the algorithms integrated into HEC-RAS that simulate permanent and transient 1D (one-dimensional) flows. In addition, urban streets should be accurately included through the MDT in the model, as these urban features act as drains for surface floods (Mark et al., 2004).

The city of São José do Jacuípe is a small inland city and does not have large urban structures such as large buildings, sewage or drainage defined in the streets as well as asphalt in the floodplain area of the Jacuípe River. Therefore, in the dam studied, the inclusion model downstream of the dam considered streets as well as asphalt in the urban area, the inclusion model downstream of the dam considered streets as well as asphalt in the urban area, features act as drains for surface floods (Mark et al., 2004).

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The layout of elements from river geomorphology (mainstem, riverbanks) as well as the cross-sectional areas was made based on TIN, with 10632 nodes, and 2111440 triangles with the bathymetric value of 310 m in the lower values and 590 m in the values where it is higher. Those levels are altitude ones, meaning the sea level.

Table 1. Soil's classes found in São José do Jacuípe’s region. Manning’s coefficient values were adopted according to De Jong et al. (2003) and Campos (2011).

| Soil Coverage                          | Value |
|---------------------------------------|-------|
| Riverbank and aquatic’s vegetation: edges | 0.05  |
| Water                                 | 0.03  |
| Urban: House Construction             | 0.20  |
| Asphalt/urban area’s pavement         | 0.05  |
| Ground vegetation/pasture             | 0.259 |
| Soil exposed/wastelands (it was adopted the value to the extended riverbank with low vegetation and excellent condition) | 0.05  |
| Cloud                                 | 0.0   |
| Cloud shadow                          | 0.0   |

The system of cartographic projection World Geodetic System – WGS 84 spindle 24 South. As of the images (SRTM), curvatures of level with ranges of 10 m were created. The Triangular Irregular Network – TIN (Figure 2 A) was generated according to the Delaunay triangulation method, with 10632 nodes, and 2111440 triangles with the bathymetric value of 310 m in the lower values and 590 m in the values where it is higher. Those levels are altitude ones, meaning the sea level.

Figure 2. It presents the cross-sectional areas generated by vector edition in GIS and GeoRAS (A), subsequently exported to the HEC-RAS (B) model which is essential for the 2D model's construction.

2.2.2. Flow modeling and channel

For the construction of the cross-sectional area, it was necessary to build a numerical modelling of the field, generated from SRTM – Shuttle Radar Topography Mission – image. The images used on the report are Tagged Image File Format – TIFF files with 30 m of spatial resolution, on the system of cartographic projection World Geodetic System – WGS 84 spindle 24 South. As of the images (SRTM), curvatures of level with ranges of 10 m were created. The Triangular Irregular Network – TIN (Figure 2 A) was generated according to the Delaunay triangulation method, with 10632 nodes, and 2111440 triangles with the bathymetric value of 310 m in the lower values and 590 m in the values where it is higher. Those levels are altitude ones, meaning the sea level.

The layout of elements from river geomorphology (mainstem, riverbanks) as well as the cross-sectional areas was made based on TIN, originating the following elements: Banks, Flowpaths, River, XSCutLine, River 3D and XSCutLine 3D, that were later exported to the HEC-RAS model (Figure 2 A and B).

89 of the XSCutLine (cross-sectional areas) were generated: the smallest XSCutLine had an extension of 998 m, while the biggest extension had 4524 m, which implies a variation of 3526 m. It occurs due to the phenomenon of variation where some parts from the fluvial channel are narrow and others are large, but with a low altimetry variation.

Cross-sectional areas are essential to the analysis of wave propagation since it is a 2D model. In the cross-sectional area, Manning's coefficients are inserted and used to describe the flow resistance to the roughness of the fluvial channel. This coefficient can be specific to each cross-sectional area, subdivided as the function of riverbanks – as used for this research –, or to each fluvial stretch. The process of Manning's class determination.
was obtained according to Table 1, as proposed by De Jong et al. (2003) and Campos (2011).

To each cross-sectional area, the friction value regarding Manning, according to soil use, is added, depicting how soil’s characteristics and cross-sectional area affects the type of usage.

2.2.2. Rupture’s hydrograph and hydraulic parameters

The total and immediate removal of an earth and rockfill’s dam type is physically unlikely since it always leaves residues from the barrage. Therefore, they must adopt a generic hydrograph of gradual rupture. The use of a hydrograph is justified because it treats the break almost immediately, presenting a critical catastrophic scenery, but still near to the reality of the physical parameters of a dam (Vérol et al., 2013).

Aiming to adjust the model, it was used the hydrograph (Figure 3) that demonstrates the formation of the first breach that quickly expands up to the moment of the total dam break.

To calculate the flood peak, Eq. (1) of Saint-Venant apud USACE (2016) was used. The choice for the equation is the fact that it represents the most catastrophic scenery. The decision-making was the most conservative model for planning. It was adopted 1 h for the formation time of the breach, as proposed by Gee and Brunner (2007):

\[
Q_b = \frac{8}{27}B_y \sqrt{gY^2}
\]

where \(Q_b\) is the maximum discharge of the dam at breach (\(\text{m}^3/\text{s}\)); \(B_y\) dam width (\(\text{m}\)); \(g\) acceleration of gravity, equivalent to 9.81 \(\text{m/s}^2\) and \(Y\) is the average depth (\(\text{m}\)) in the reservoir at the instant of breakage.

2.2.3. Mathematical modelling for dam break

The hydraulic features of the dam as well as the discharging’s physical parameters are briefly described in Table 2.

The mathematical modelling of dam break was calculated by the complete resolution of the 2D Saint-Venant’s model, applied to simulate flows according to Hromadka, III et al. (1987); Khosravi et al. (2019) and (USACE 2016).

\[
\frac{\partial Q_x}{\partial t} + \frac{\partial Q_x}{\partial x} + \frac{\partial H}{\partial x} = 0
\]

\[
\frac{\partial Q_x}{\partial t} + \frac{\partial Q_x}{\partial x} + \frac{\partial Q_y}{\partial y} = 0
\]

\[
\frac{\partial Q_x}{\partial t} + \frac{\partial Q_y}{\partial x} + \frac{\partial Q_y}{\partial y} + gA_y \left( s_y + \frac{\partial H}{\partial y} \right) = 0
\]

Considering \(x\) direction as the longitudinal one, aligned with water flow, and \(y\) direction as the transversal one in relation to \(x\) direction; we have: \(Q_x\) and \(Q_y\) are discharges in the planar \(x\) and \(y\) directions; \(A_x, A_y\) are directional cross-sectional areas; \(S_{fx}, S_{fy}\) are directional friction slopes. So, \(x, y, \text{and} t\) are the spatial and temporal coordinates; \(g\) is the acceleration due to gravity; \(H\) is the water surface elevation. This model is attached to HEC-RAS, a potent and largely computational tool used in one-dimensional and two-dimensional hydraulic calculation to a network of natural or artificial channels, areas over flood plains, protected zones, among others (Khalifallah and Saidi, 2018).

The hydraulic data are calculated to each cross-sectional area, generating many results as flood zone, shearing force, rise gradient of water column, flow velocity and discharging power. This report concentrates on studying only a cross-sectional profile regarding São José do Jacuípe downtown, to calculate the Hydrological Risk in a possible dam break.

2.2.4. Estimation of loss of life by hydrodynamic model of risk level

Considering the dam break model, it is possible to infer the risk level (danger zone) and the areas susceptible to flood. The areas could be affected in different ways, as the value of \(h\) (water height) and the time of wave coming (\(t_{\text{chord}}\)) are variable. However, there is a factor to be considered, the discharging velocity (\(V\) – corresponding to its destructive force) that corresponds to the average velocity of water level rise (discharging height) (\(\Delta h/\Delta t\)) and the submersion’s time (\(d\) - allowing to study the material costs) (Viseu, 2008; Norkhahiri et al., 2018; Milanesi, 2015).

The result of the relation between discharging velocity (\(V\)) and water height (\(h\)) is the most illustrative to estimate human life threat, characterized by Hydrological Risk (USBR, 1989). It is estimated that an “average” human being could not overcome the water impact when the values of \(Rh\) (Risk hydrodynamic) are higher than 1.0 \(\text{m}^2/\text{s}\). This parameter was calculated considering the study establishing that to people with less than 41 kg, the value that separates “danger” and “non-danger” is about 0.7 \(\text{m}^2/\text{s}\); to a person that weighs 91 kg, the value goes to 2.0 \(\text{m}^2/\text{s}\) (Viseu, 2008).

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Table 2. Data presentation of São José do Jacuípe’s dam. It is observed that the average declivity is very small. It is a marked feature of the region’s morphology.

| Dam’s data          |               |
|---------------------|---------------|
| Depth               | 50 m          |
| River’s average declivity | 0.00142 m/m   |
| Distance between cross-sectional areas | 80 m         |
| Propagation time    | 48 h          |
| Interval time       | 10 min        |
| Dam height          | 41 m          |
| Reservoir volume    | 357 \(\times\) 10^7 \(\text{m}^3\) |
| Dam type            | Earth and rockfill |
| Length of the main reservoir | 1.560 m |
| Initial flow        | 7391.703 \(\text{m}^3/\text{s}\) |
| Peak flow           | 44350 \(\text{m}^3/\text{s}\) |

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Figure 3. Triangular hydrograph simplified to the hypothetical progressive dam break, according to Vérol et al. (2010).
The parameter $R_h$, equivalent to ($V_h$), is also used to calculate the level of property damage, such as cars and buildings. Based on historic floods, Clausen and Clark (1990), Pilotti et al. (2020) and Milanesi et al. (2018) proposed the relation between damage limit and submersion, and the partial devastation, $V_h = 3.0 \text{ m}^2/\text{s}$, and the limit between the partial and the total destruction, $V_h = 7.0 \text{ m}^2/\text{s}$. According to laboratory experiments, the danger curve was proposed by USBR (1989) (Figure 4).

The estimation of loss of life was proposed according to Viseu (2008) that points out that the number of victims in a dam break depends on three factors:

I- people that are resident in the area of risk; II- danger level of flood-induced; III- warning time to people in risk. The equations of loss of life estimation were proposed according to USBR (1998) and Graham (1998).

3. Results and discussion

3.1. Simulation of flood wave in 2D

The HEC-RAS is not a 3D (three-dimensional) model; therefore, the fluvial channel was transversally divided into several segments. There are proper distances to the channel’s representation that, due to its irregular sinuosity, must not be overlaid. To measure the flood wave with destructive potential to the city of São José do Jacuípe, the cross-sectional data was used as reference, with random effects covering downtown.

The early pattern from the average hydric flow is presented in Figure 5. In the illustration, it is possible to verify that the early level adopted to the mainstem corresponds to 7 m of depth. To a usual pattern, it is a high volume. However, as a simulation, this value is representative, since it is the average value of water flow, which means the ratio between maximum and minimum values regarding the regular flow. The usual hydric flow corresponds to a maximum of 1 m of depth because of dam restraint, and, also considering that this river stretch is in a semiarid region. Due to the climatic seasonality that concentrates a large volume of rain during some days in the year, a big portion from the fluvial channel (wide semi-riverbed and small semi-riverbed) do not submerge, which promotes the disordered construction in riverbanks.

The city is located on the left riverbank, just a few meters from the fluvial channel of the Jacuípe River. In the early moments, the water already reaches some houses of people that live by the riverside. It does the initial damage, but it is not sufficient to cause death or destruction by the flow force or hydric volume, with a main velocity of 1.6 m/s of maximum and 0.8 m/s in the left riverbank (Figure 6).

After ten minutes from the break, it is already possible to verify the variation of water volume as well as its velocity. According to (Figure 7), water depth rises approximately 0.4 m, which represents a risk for children and physically disabled people, that can be carried when $R_h$ is 0.2 $\text{m}^2/\text{s}$. However, the class of danger is still considered reduced (green), as well as for properties, according to Viseu (2008).

According to (Figure 8), it is possible to verify that the maximum velocity reached is 2.0 m/s in the central region, 0.5 m/s in the right riverbank, and 1.0 m/s in the left one, which creates a maximum acceleration in the core of 0.0065 m/s² and a force by water kilogram of approximately 0.0065 N. Concerning the initial stretch, there is a force 27.7% higher than the resulting force by water kilogram.

Nevertheless, there is a great increase in the maximum volume of water mass, since the initial water line volume goes from 7 m to 16.2 m, which results in an increase of 231.4 % over the initial volume (Figure 9). The value is high considering the region. A water column of this proportion could destroy the city completely, even if after four hours and forty minutes (time necessary for the break wave to reach its maximum volume) the area was evacuated. In addition, the city is in the countryside, whose feature of urban vertical profile is the low elevation, with few buildings, which could imply the flood of almost all the houses (Figure 9).
The Hydrodynamic Risk, $R_h$, is $18.4 \text{ m}^2/\text{s}$, enough to collapse buildings and carry people. The risk level here is classified as very important (red), according to Viseu (2008).

Dam breakage carries worrying factors, such as the increase of water column, and the velocity distribution (Figure 10) that reaches $3.0 \text{ m/s}$ in the central region and varies from $0.5 \text{ m/s}$ to $2.0 \text{ m/s}$ in the riverbanks of the mainstem. It creates an acceleration of approximately $0.000083 \text{ m/s}^2$, which implies a force by water kilogram of $0.000083 \text{ N}$. During the initial ten minutes, there is a decrease of force by water kilogram, which does not mean a decrease of the total force, since water volume at this point is $231\%$ higher than the initial volume. It must be noted that these values only correspond to a cross-sectional area. The urban zone of the city is composed of 10 cross-sectional areas, approximating 1 L to 1 kg of water. It's observed that the initial volume (after ten minutes from break) corresponds to approximately $200000 \text{ L}$ ($1000 \text{ m}$ of width by $1000 \text{ m}$ of length, and $0.4 \text{ m}$ of depth), creating a force of approximately $2520 \text{ N}$. In total volume, this force jumps to approximately $5312 \text{ N}$ ($2000 \text{ m}$ of width by $2000 \text{ m}$ of length, and $16 \text{ m}$ of depth). It must be observed that they are estimated values and, since the thalweg gets far, the value is reduced, just as the average velocity and the depth.

Figure 6. Water velocity in the cross-sectional area situated in the urban perimeter. It is observed that the higher velocity is in the main riverbed, while in the riverbanks the value is reduced. This effect happens due to the steeper value of Manning's coefficient that is more incisive to the urban perimeter. Source: Alarcon Matos.

Figure 7. Profile of water line after ten minutes from dam break in the vertical section of the urban zone. It can be observed a slight increase in water volume. Source: Alarcon Matos.
3.2. Variation according to time and flood peak

The variation of water volume in the first hour since the break and the maximum volume reached, as well as the velocity distribution on the cross-sectional area of the representative urban zone, can be seen in Figure 11. A marked discrepancy can be noticed between the initial and the maximum volume since it is necessary a time of four hours and forty minutes to water's peak. The pattern of the flood wave is described in a 10 min rate of change, starting with a slow increase in the first 30 min, with the water column varying only 2 m, and reaching 5.5 m in the first hour (Table 3).

In a graphical comparison between the two variations (Figures 11 A and B), it is possible to describe water rise through time. It shows the slow process initiated, which could allow the creation of a warning system to save people with safety since more than four hours are necessary to reach the water's peak. The risk levels that vary proportionally to the hydric volume are subsequently described.

The time of four hours up to the peak is assigned to the dam's distance up to the urban perimeter, the landform's low declivity – which implies a decrease of flood wave's average velocity – the time for the dam's breach until its total break and the land's roughness. It is possible to observe the variation of velocity through time in the first hour after the break.
with a high correlation of 0.97 between the discharge velocity and propagation time. The correlation reduces to 0.28, which shows the velocity decrease after the first hour. Regarding the water column’s height through time, the correlation is 0.99 in the first hour. Until the wave’s peak, the correlation is 0.90, which implies that, even with the velocity decrease, the risk rises due to the water column’s height.

3.3. Variation of risk level through time

It is assumed that Hydrodynamic Risk ($R_h$) varies according to the water column’s height and discharging velocity, with derivation’s rate because of time. It was noticed that during the first ten minutes, with average velocity $V_m = 1$ m/s and water column height of 0.2 m, the hydrodynamic risk corresponds to 0.2 m$^2$/s, enough to carry children and physically disabled people according to the scale of Synaven et al. (2000), Viseu (2008), Cestari Jr (2014) and Vieira (2018). After one hour of a dam break, $R_h$ goes from 0.2 m$^2$/s to 13.75 m$^2$/s, which represents an addition of more than 600%. On this background, there would be no condition to save people’s lives, and some buildings could even collapse. The peak is reached at the maximum volume where $R_h$ is 18.4 m$^2$/s, varying 133.82% concerning the first hour and 9200% about the first ten minutes. In this situation, there would be a building’s collapse and no chance to save people’s lives (Table 4).

Table 3. Rate of change of water column through time. A slow increase is observed in the first minutes due to the time of breach formation in the dam, beyond the city’s distance to the dam.

| Height (m) | Time (h) |
|-----------|----------|
| 0.2       | 00:10    |
| 1.0       | 00:20    |
| 2.0       | 00:30    |
| 3.0       | 00:40    |
| 4.0       | 00:50    |
| 5.5       | 01:00    |
| 9.2       | 04:40    |

(Figure 12) with a high correlation of 0.97 between the discharge velocity and propagation time. The correlation reduces to 0.28, which shows the velocity decrease after the first hour. Regarding the water column’s height through time, the correlation is 0.99 in the first hour. Until the wave’s peak, the correlation is 0.90, which implies that, even with the velocity decrease, the risk rises due to the water column’s height.
variation of risk level based on time. Also, according to Table 4, the first notifications, such as warning signs and text messages, must be reported before the break's first ten minutes to save more people.

The graphic representation of Hydrodynamic Risk is verified in Figure 13 A and B, where the pattern in the first hour is similar to a first-degree equation. For the peak wave, the function resembles the logarithmic equation. It must be noticed that in graphic B, there is no data about the period between the second and the fourth hour after the break because it appears only to compare the peak's wave to the break's first hour.

Figure 14 adjusts the data to the danger classification proposed by Viseu (2008), with a division into two non-excluding categories, human and material risk, based on the height of water column, flow velocity, and hydrodynamic risk ($R_h$).
The analysis of danger levels for human beings according to Viseu (2008) shows that in the first ten minutes, it has reduced risk, green. In this context, it is possible to send out warning signs to save many lives. However, in the next thirty minutes, the risk class is yellow, classified as medium risk. Ten minutes after that, the risk is classified as important, in orange. In the break's first hour, the risk is classified as very important, in red, and it lasts for the next four hours and forty minutes at least, up to the point when the water column starts to decrease.

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Risk variation for buildings, according to Viseu (2008) is analyzed in (Figure 15). In the first twenty minutes, the risk level is low, therefore, it is classified as green. Between thirty and forty minutes, the risk is yellow, which means medium risk. In fifty minutes after the break, the risk is important, in orange. After the first hour up to flood peak, the risk is very important and its color is red, which proves the high risk to the city in case of a dam break in São José do Jacuípe. It must be emphasized that the city of São José do Jacuípe has a small urban tissue, where the buildings have a small architectural dimension, without tall buildings. Therefore, the hypothetical water column would cover almost 100% of the houses in the municipal area (Figure 16).

According to Viseu (2008), the number of victims of a dam break is directly related to the warning time to downstream people. USBR (1998) and Graham (1998) suggest the following equations (equation 5) to relate the warning time of flood waves coming with the expected number of victims (NEV). Since (PAR) refers to the population at potential risk:

\[ t_{avw} < 15 \text{ min}; \quad NEV = 0.5 \times PAR \]
\[ 15 \text{ min} < t_{avw} < 90 \text{ min}; \quad NEV = PAR^{0.6} \]
\[ t_{avw} > 90 \text{ min}; \quad NEV = 0.0002 \times PAR \]

Assuming that São José do Jacuípe concentrates an urban population (PAR) of 6991 inhabitants, and, according to the time variation of flood wave to the urban zone which downtown is completely submerged, and considering the lack of a warning system, it is estimated that the entire urban population could lose their lives. However, because of the technology of mobile phones, the loss of life is calculated at 3495 human lives, considering a warning time of fifteen minutes. By adjusting the data to break's first hour where the risk class is red and the time is longer than fifteen minutes and shorter than ninety minutes, a loss of 203 human lives is estimated. To a time longer than ninety minutes, the estimation is of 1.39 victims.

### Table 4. Risk variation according to Synaven et al. (2000); Viseu (2008); Cestari Jr (2014); Vieira (2018). It is observed the progressive increase of \( R_h \), which emphasizes the high destructive power in case of a dam break.

| T (min) | H (m) | \( V_m \) (m/s) | \( R_h \) (m²/s) | Variation in (%) | Consequences |
|---------|-------|----------------|-----------------|-----------------|-------------|
| 00 h 10 min | 0.2 | 1.0 | 0.2 | 0.0 | Children and disabled people are carried |
| 00 h 20 min | 1.0 | 1.5 | 1.5 | 750 | Submersion damage in buildings and houses' poor structure |
| 00 h 30 min | 2.0 | 1.5 | 3.0 | 200 | Submersion damage in buildings and houses' poor structure |
| 00 h 40 min | 3.0 | 2.0 | 6.0 | 200 | Structural damage in buildings and possible collapse |
| 00 h 50 min | 4.0 | 2.5 | 10.0 | 166.7 | The collapse in some buildings |
| 01 h 00 min | 5.5 | 2.5 | 13.75 | 137.5 | The collapse in some buildings |
| 04 h 40 min | 9.2 | 2.0 | 18.4 | 133.82 | The collapse in some buildings |

### Figure 13. Comparative graphics of Hydrodynamic Risk between the water column’s first hour and its peak. It is notorious for the rising risk level in the first hour and its ascending constancy up to the moment of flood peak.

### Figure 14. Variation of danger levels: from the green, less important, to the red, very important. The greater the importance is, the higher the risk.
4. Conclusion

It is notorious that, in the absence of an alarm system, there is a threat posed by the dam to the population living downstream. In fact, according to the worldwide literature, dams are considered a potential risk. Many accidents have already occurred because of dams causing social, economic, and environmental damage, including the loss of people's lives.

The simulation of dam break in São José do Jacuípe has interesting results. The variation of the water column in cross-sectional areas through time was observed, based on the hydrograph rupture. During the first hour, there is a significant increase of water mass in the transversal profiles regarding the city's urban zone. The flood's maximum peak occurs after four hours and forty minutes since the breach formation up to the dam's total removal. The delay between the dam break and the city's flood peak is explained by the landform being relatively flat, which creates a small declivity and reduces the velocity of wave propagation. However, it promotes a longer stay of water mass in the areas it reaches. It must be emphasized that the worst scenario was considered for the catastrophe. About the initial volume, there is an increase of 231.4 %, going from 7 to 16.2 m of the water column, which would imply a 100 % flood in the urban zone of São José do Jacuípe.

The model of Hydrodynamic Risk Rh establishes the relation between the depth of flood, or in other words the water column's height, in meters, and the flow velocity in meters per second. In that way, the first ten minutes of dam break already imply a high danger level to human lives, while to the buildings, the risk can be considered low. However, at the moment of a peak, there is hardly any rescue to human lives; the material constructions have their structure considerably threatened.

The lack of a warning system in São José do Jacuípe's dam and the fact that the city would be completely covered by the water lead to the conclusion that the number of victims would be almost total. However, considering the communication technologies, like mobile phones, and the time until the wave's coming, it can be inferred that the shorter the warning time is, the higher is the chance of saving people's lives.

![Danger levels for human lives](https://example.com/danger_levels.png)

**Figure 15.** Danger levels to the buildings in the city of São José do Jacuípe in case of a dam break. It takes almost two hours for the city to be classified in a very important risk level, varying from 13 m²/s to 18 m²/s.

![Mosaic images](https://example.com/mosaic.png)

**Figure 16.** Mosaic with images of the city of São José do Jacuípe, which demonstrates the small architectural dimension, with no tall buildings.
Declarations

Author contribution statement

Alarcón Matos de Oliveira: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.
José Bueno Conti: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.
Rosangela Leal Santos: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.
Lusânia Nogueira Araújo de Oliveira: Performed the experiments; Analyzed and interpreted the data.
Carlos Alberto Oliveira Brito, Erivelton Nonato de Santana: Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

Flavio Pietrobon Costa: Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

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No data was used for the research described in the article.

Declaration of interests statement

The authors declare no conflict of interest.

Additional information

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