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INFLUENCE OF THE NATURAL GUTTER ON HYDRAULIC PARAMETERS RESULTING FROM A HYPOTHETICAL DAM RUPTURE

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Abstract: Resolution number 95 of the National Mining Agency (ANM) requires a Dam Break, being one of the bases of the Emergency Action Plan for Mining Dams (PAEBM), which aims to safeguard the population downstream. Such a study requires models that simulate rupture wave propagation. One commonly used to be HEC-RAS. Among the HEC-RAS input data is the Digital Terrain Model (MDT), which represents the geomorphology of the natural valley. The MDT, obtained from aerial surveys, does not properly characterize the natural bed. For this characterization, topobathymetric sections are used to allow an approximation of this. The study compared two hypothetical simulations of dam failure, one considering the natural valley and the other not. For this purpose, a hypothetical dam, resistance parameters, rupture gap parameters, regional hydrology and representative sections were defined. The results indicated that, for the scenario without a natural bed, there is a greater reduction in hydrographs along the stretch, which can be explained by the resulting higher Manning roughness coefficient. Furthermore, for this scenario, there is a lower propagation speed, translated into a longer arrival time for the same river section, in addition to a greater flood envelope. For the scenario with a natural bed, a higher propagation speed and shorter arrival time were noted, however, a lower flood envelope than the other simulated scenario.
Keywords – Hydraulic Modeling; Dam Break; HEC-RAS

INTRODUCTION

Law number 12,334, of September 20, 2010, established the National Dam Safety Policy (PNSB). According to Article 2 of ANM Resolution Number 95 of 2022, the Dam Safety Plan (PSB) is an instrument of the National Dam Safety Policy (PNSB), which is a document to be prepared and implemented by the entrepreneur. According to Article 9 of ANM Resolution Number 95 of 2022, the PSB must be composed – ordinarily – of 6 (six) volumes: General Information (Volume I), Plans and Procedures (Volume II), Records and Controls (Volume III), Periodic Dam Safety Review (RPSB) (Volume IV), Emergency Action Plan for Mining Dams (PAEBM) (Volume V) and Risk Management Process (PGRBM) (Volume VI).

According to Art. 33 of ANM Resolution Number 95 of 2022, the PAEBM must be prepared for all mining dams included in the PNSB, those that, according to Art. 1 of the same resolution, present – at least – one of the characteristics follow: Height of the massif, measured from where the foot of the downstream slope meets the ground level to the dam's crowning crest, less than or equal to 15 (fifteen) meters; Total reservoir capacity greater than or equal to 3,000,000 m^3 (three million cubic meters); Reservoir that contains hazardous waste in accordance with applicable technical standards; Associated Potential Damage Category (DPA) medium or high and Risk Category (CR) High.

In accordance with Article 2 of ANM Resolution Number 95 of 2022, the Flood Study aims to precisely identify the possible impacts arising from a flood caused by the rupture or malfunction of a Mining Dam. This study must be carried out by a legally qualified professional in this area. Its description and justification must be included in the PAEBM. Typically, such studies use mathematical models capable of reproducing flow in a two-dimensional environment. One of the programs commonly used in such simulations is HEC-RAS (Hydrologic Engineering Center's River Analysis System).

HEC-RAS solves, through the use of numerical methods, the Saint-Venant equations, capable of representing the behavior of non-permanent and gradually varied water flow, respecting the principles of conservation of mass and movement (Brunner, 2010).

A topographic base, consisting of a Digital Terrain Model (MDT), is used as input data in this model and, in some cases, topobathymetric sections (coming from field measurements) of the downstream watercourse. Such sections are used with the intention of characterizing the features of the bed of the main watercourse, through which the rupture wave will propagate, and incorporating them into the MDT, since this, obtained from aerial survey, does not properly characterize the geomorphology of the natural bed.

However, the process of obtaining and incorporating topobathymetric sections into the MDT is a thorough, laborious and costly process in terms of human and economic capital. It is relevant to understand and quantify the difference between this insertion of topobathymetric sections in hydraulic parameters resulting from a dam rupture. To this end, the present work aims to evaluate the interference of the bed insertion of the main watercourse downstream on hydraulic parameters of the breaking wave: speed, depth, wave arrival time (2 feet), flood envelope and hydrographs.

The insertion of the natural bed in the MDT is not required by law, it is simply a good Brazilian engineering practice. It is important to know the interference of such practice in the results of a simulation, as well as understanding how these affect the PAEBM and, therefore, the safety of the affected population during a rupture event.

MATERIAL AND METHODS

The methodology of this work consists of developing two two-dimensional (2D) hydraulic modeling of a hypothetical dam rupture event, using the HEC-RAS program, one with the insertion of the natural channel (with the aid of real topobathymetric sections) and the other without channel insertion. Next, the breach parameters and rupture hydrograph are defined to simulate the propagation of the flood wave along the downstream channel. Finally, it will be compared, through sections of interest along the modeled section, how the hydraulic parameters interesting to the Dam Break studies (depth, speed, flood envelope, arrival time and hydrographs) behaved in the hydraulic modeling with the insertion of natural canal and without natural canal insertion.

HYDRAULIC MODEL

The Hydraulic Model used was HEC-RAS (version 6.0), developed by USACE (United States Army Corps of Engineers). This model is free and widely used in hydraulic modeling around the world. It is capable of performing hydraulic simulations in a one- and two-dimensional environment.

To carry out this work, HEC-RAS was used in a two-dimensional environment and in a gradually varied non-permanent regime.

The computational mesh used was defined in such a way as to satisfactorily represent the main channel and floodplain of the simulated section. In the main thalweg region, where greater detail was sought, a 5m x 5m mesh was adopted, while in the floodplain region, a 15m x 15m mesh was adopted. It is noteworthy that the geometry created is the same for models with and without gutter. Singularities (bridges and culverts) were not considered due to the lack of geometric information.

REPRESENTATION OF THE NATURAL VALLEY

To represent the natural valley, data provided by the mining company Vale S.A. were used, namely:

- Digital Terrain Model (MDT) with a

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resolution of 3m x 3m, carried out from an aerial laser survey (LiDAR), of a stretch of thalweg on the Piracicaba River measuring approximately 58.4 km in length, in the region of the municipalities from Nova Era, Jaguaraçu and Antônio Dias - MG; It is

- 11 topobathymetric sections along the modeled section, this one located on the Piracicaba River, belonging to the large Doce River basin, in the state of Minas Gerais.

HEC-RAS allows the insertion of topobathymetric sections in the MDT in order to try to model the natural channel of the thalweg section. As soon as the sections were inserted and the natural gutter was incorporated into the model, as can be seen in Figure 1, as well as the location of the sections inserted in the model and the MDT used.

REGIONAL HYDROLOGY

The modeling represented a natural stretch of the Piracicaba River, belonging to the large Doce River basin, in the state of Minas Gerais, Brazil.

According to Dalrymple (1960), the average annual flow of a natural watercourse is defined by the recurrence time (TR) of approximately 2 years. In order to estimate this hydrological variable, regionalized models already produced by HIDROTEC were used. Such information is public and is available through the Águas de Minas Digital Atlas.

According to Euclydes et. al. (2005) the equation that defines the maximum specific annual daily flow associated with 2 years of return time

(q2years), in the study region is defined by:

$$q2years= 4{,}76^{-11} * A^{-0{,}1354}\ P\ sem^{3{,}1923} \qquad (1)$$

On what:

- "q2years" denotes the maximum specific annual daily flow with 2 years of return time (m3/s.km2);
- "A" denotes the drainage area of the basin (km2); It is
- "Psem" denotes the precipitation of the wettest semester (mm).

The value of (A) – referring to the starting point of the simulation – was calculated at 4,033.23 km2. (Psem) was obtained from HIDROTEC data, being weighted in relation to the basin considered. Its value was calculated at 1,277 mm. Applying the values found in Eq. 1, we have the value of q2years = 0.11 m3/s.km2. Multiplying its value by (A), the value of the natural flow for 2 years from the initial point of study is equal to 452.90 m3/s. Incremental downstream flows were not considered.

RESISTANCE PARAMETERS

In order to characterize flow resistance, Manning roughness coefficients (n) were used associated with the typologies of land use and occupation downstream, which were determined from Google Earth. The values of (n) were determined based on Chow (1959). These are shown in Table 1. Figure 2 shows an excerpt of the delimitation of the typologies of land use and occupation downstream.

BRECCIA PARAMETERS AND RUPTURE HYDROGRAPH

In order to make the study more representative and, considering that the MDT used has approximately 60 km of thalweg stretch, it does not make sense to define a structure whose rupture will result in changes only in the vicinity of the dam. As soon as possible, a large hypothetical structure was adopted. Thus, the characteristics of the structure to be broken were defined, which are shown in Table 2. Such characteristics imply a structure with a high DPA.

A hypothetical quota-volume curve was

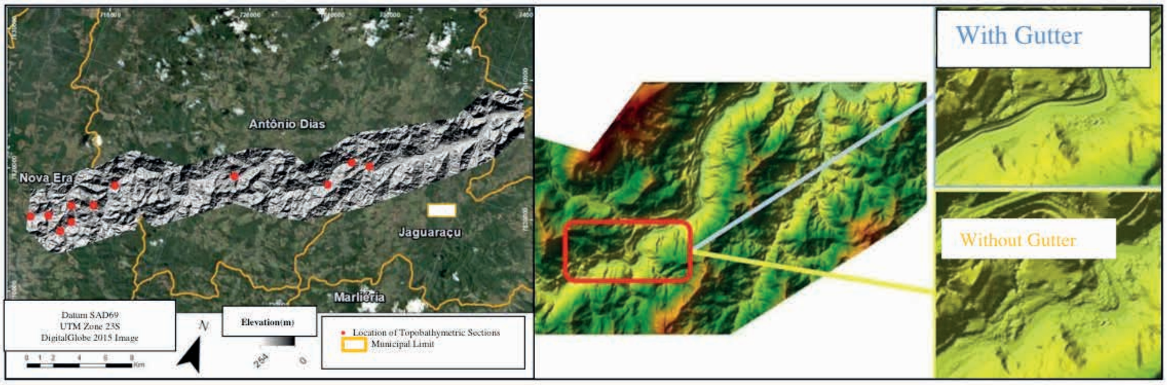

Figure 1 – Location of the topobathymetric sections used in the insertion of the natural gutter and MDT used (on the left) and comparison of a specific section of the model with gutter and without gutter inserted (on the right)

Typology of land use and occupation	Manning roughness coefficient
Water mirror	0,040
Exposed soil	0,045
Low Vegetation	0,050
Medium Size Vegetation	0,065
Large Vegetation	0,080
Anthropized Area	0,100

Table 1- Manning roughness coefficients considered in hydraulic modeling

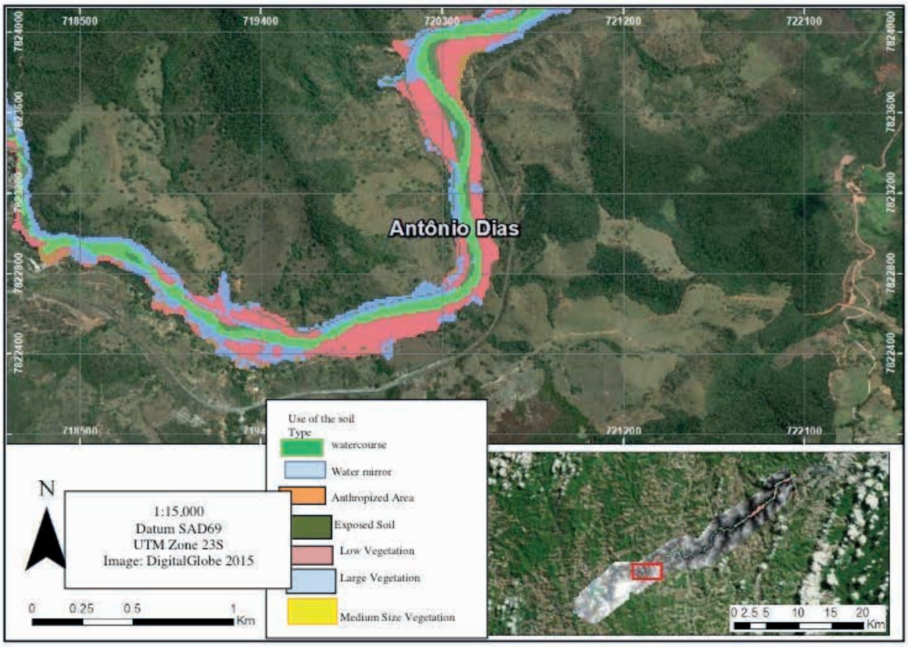

Figure 2 - Types of land use and occupation in the floodplain downstream of the hypothetical dam – detail in a specific section

defined to represent the dam's reservoir. The elevation-volume curve of this reservoir and the volume propagated downstream are shown in Table 3. The breach parameters were defined based on the equations of Froehlich (2008), and are presented in Table 4. The erosion failure mode was adopted internal (Piping). The initial elevation of Piping was judged to be equal to half the height of the massif.

Using HEC-HMS, and inserting the information provided in Table 2 to Table 4, the hydrograph of the hypothetical dam considered in the modeling was arrived at (Figure 3). The peak flow was 5.410 m^3/s.

DATA EXTRACTION

The hydraulic parameters resulting from the modeling with and without gutter were obtained from the representative sections shown in Figure 4.

The sections were inserted every 2 km, starting from the hypothetical bus, with the addition of one at the end point of the model. The modeled section is approximately 58.4 km long, resulting in 30 representative sections.

RESULTS AND DISCUSSION

The figure 5 graphically displays the results obtained in terms of maximum depth (top left), maximum speed (top right), burst wave arrival time (2 feet) (bottom left) and flood envelope area (bottom right corner). Wave arrival time (2 feet) is relative to the time required to raise the flow depth by 2 feet (0.61 m) relative to the preceding natural condition in a given river section.

There is a greater depth of the natural bed scenario, explained by the insertion of the latter, which makes the channel deeper. Considering that the model without gutter will have greater laterality, its shallower depth in the thalweg sections is understandable.

For speeds, it can be seen that the scenario with a natural bed has, in general, higher speed throughout the modeled section compared to the scenario without a channel. In the scenario with a trough, there will be less laterality compared to the other scenario. Considering that plains have a higher value of (n), the lower their interference, the lower the resistance to flow and, consequently, the higher the propagation speed.

In relation to wave arrival times (2 feet), shorter times are noted for the natural bed scenario for the same representative study sections. This assertion can be explained in terms of the propagation speed, which is higher in this scenario.

One of the main and most basic results of a Dam Break study is the Flood Envelope, it defines the polygonal area that will be flooded. Still in Figure 5, it is possible to observe the cumulative flood areas (in km2) reached in the representative sections in the model with and without gutter inserted, in addition to the difference between the areas covered by the two models. It is noted that the flood areas in the scenario without a gutter are higher, this is explained by the smaller wetted perimeter between the banks of the natural watercourse, which – for the same flow – results in a greater flood envelope.

Figure 6 shows the propagations of the hydrographs along the simulated section with and without a gutter. In order to make the presentation of the graphics more understandable, they are divided into three sections, comprising the sections ST-01 to ST-10, ST-11 to ST-20 and ST-21 to ST-30, respectively.

It is observed, through the hydrographs shown in Figure 6, a greater attenuation of the hydrographs of the hydraulic model without a natural bed inserted. Such attenuation possibly occurs due to the resulting higher value of (n), caused by the greater laterality reached by the spot without a gutter and resulting in greater

Crest Quota (m)	40,00
Dimension of the threshold – N.A. normal (m)	38,00
Foundation Quota (m)	0,00
Reservoir Volume at the Time of Rupture (m³)	6.000.000
Fail mode	Internal erosion (*Piping*)

Table 2 - Characteristics of the hypothetical structure

Elevation (m)	Accumulated volume (m³)	Propagated Volume (m³)
0,00	0,00	0,00
38,00	5.500.000	5.500.000
40,00	6.000.000	6.000.000

Table 3 - Volume quota curve of the hypothetical bus

Gap bottom width (m)	18,2
Left slope slope (xH:1V)	0,70
Right slope slope ()	0,70
Elevation of *Piping* (m)	20,0
Coefficient of *Piping*	0,61
Time of formation (hrs.)	0,34

Table 4 - Geometric and temporal parameters used in calculating the hypothetical dam rupture hydrograph – determined by the Froehlich equations (2008)

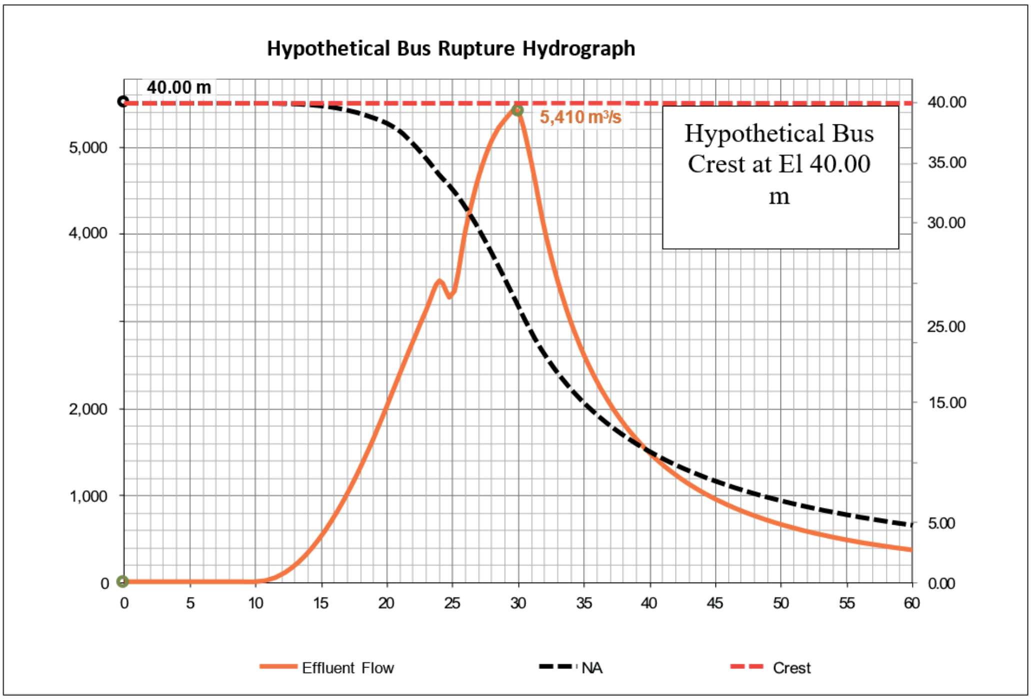

Figure 3 - Hypothetical bus rupture hydrograph

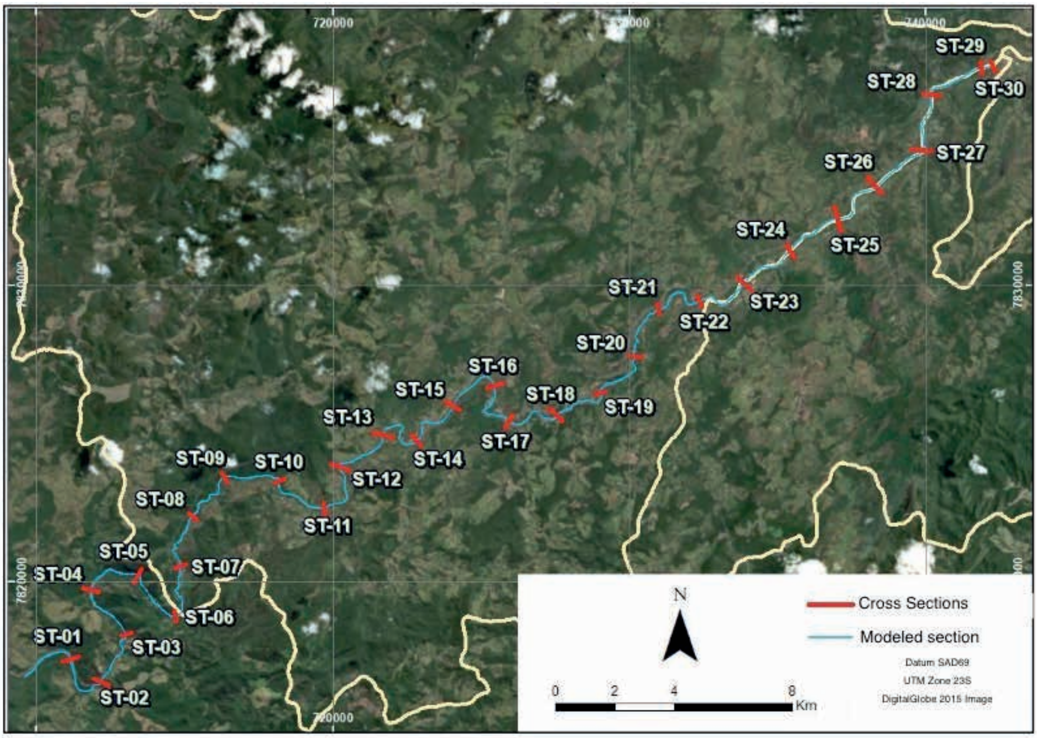

Figure 4 - Representative sections used to extract results from the hydraulic model

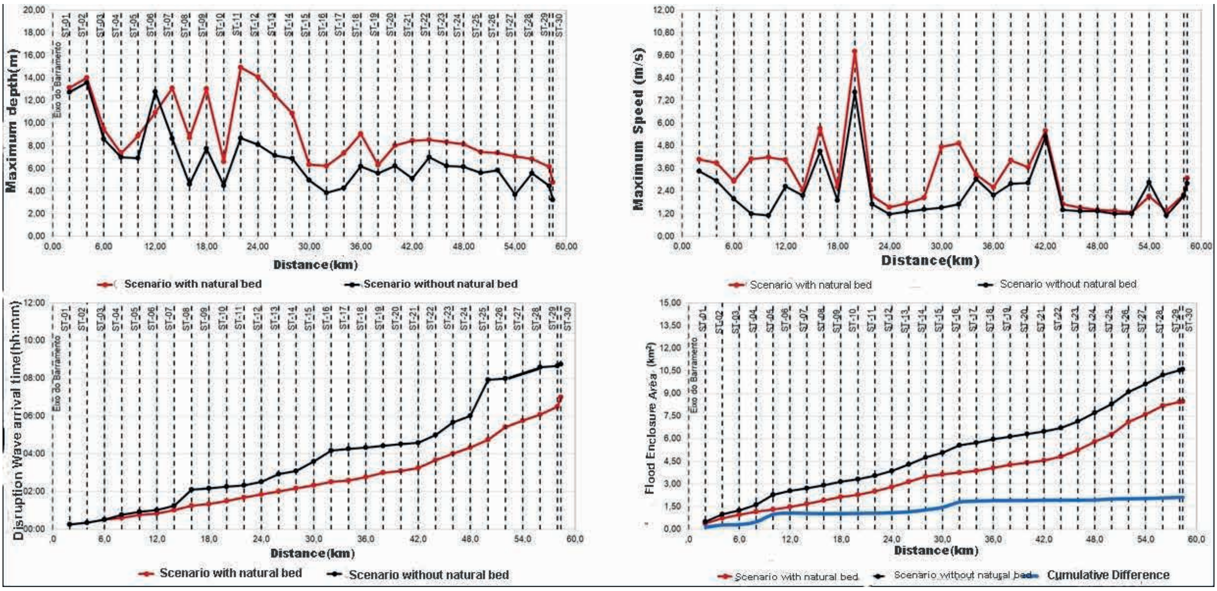

Figure 5 – Results of maximum depths, maximum velocities, wave arrival time (2 feet) and flood envelope area obtained through the reference sections in the two simulated models – with and without gutter

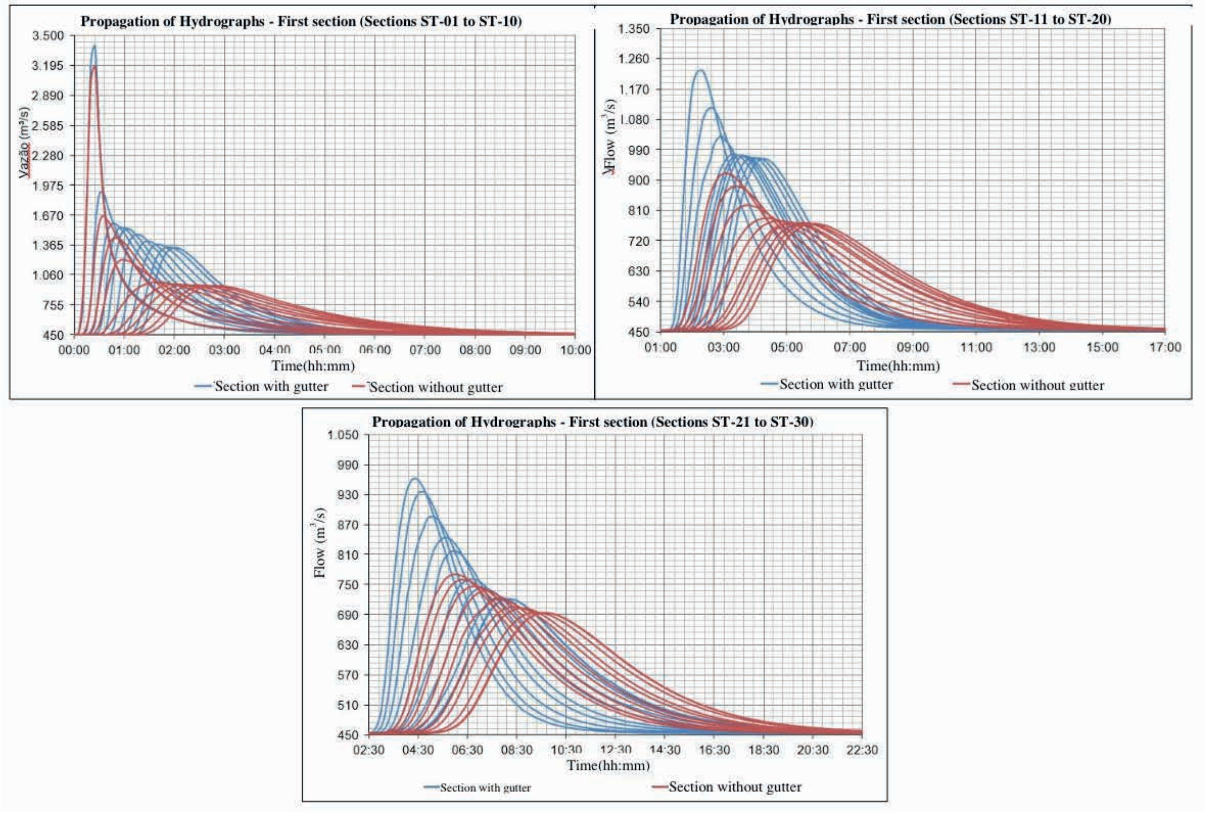

Figure 6 – Propagation of hydrographs in representative sections with and without gutter inserted

resistance to runoff (bearing in mind that the values of n in the floodplain are considerably higher). The hydraulic model with inserted gutter is considered more conservative. since the flows resulting from it are higher compared to the model without a channel, for the same river section.

CONCLUSIONS

It was noted the high interference of the Manning roughness coefficient in the results of hydraulic modeling with and without gutter. As in the model without gutter there is greater laterality of the spot and greater resistance to flow, there was greater attenuation of the hydrographs along the representative sections.

Furthermore, in relation to the arrival times of the rupture wave, it is noted that the models with trough are more conservative. This assertion can be explained, again, by the lower overall resistance to flow, which increases the propagation speed and – consequently – decreases the wave arrival time (2 feet) for the same river section.

In relation to flood envelopes, translated by their area (Figure 5), modeling without gutter brings a more conservative approach. The model without gutter has, within the banks of the natural watercourse, a smaller wetted perimeter, which – for the same flow in transit – can be translated into a greater flood envelope. The modeled gutter is just a rough approximation of reality, which aims to make the hydraulic model more feasible, its obtaining, insertion and reliability make all the difference. Furthermore, between sections, there is an interpolation of the points obtained, depending on the survey distances and the shape of the watercourse, this may be far from reality.

When a dam breaks, the natural section - downstream - can be significantly altered through erosion and deposition processes, modifying its geomorphology, which implies changes in geometry and resistance to flow.

When preparing a PAEBM, the wave arrival time and the flood envelope are taken into consideration – mainly. These are used to design meeting points and escape routes, which aim to allow the self-rescue of the population within the first kilometers of the rupture.

The present study showed that, within the numerical framework used by HEC-RAS, only the insertion of the approximate geomorphology of the natural valley (translated by the topobathymetric sections) resulted in distinct envelope and arrival time behaviors. For the model with a natural bed inserted, both the arrival time and the envelope were lower; the opposite is not true for the model without a natural bed, which presented opposite results. Therefore, this assertion corroborates that such studies must always be evolving, not only in relation to the mathematical models used, but also in relation to the input data, such as the adequate representation of the geomorphology of the valley and natural bed.

It is up to the entrepreneur and the person responsible for hydraulic modeling to understand how the model and its results behave according to simplifications and/or refinements, defining the objectives of the study, always working in accordance with the safety and reliability of the results.

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