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CLASSIFICATION OF DAMS BY ITS HAZARD POTENTIAL: THE EXPERIENCE OF THE BRAZILIAN NATIONAL WATER AGENCY

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Abstract. *With the issue of Law No. 12.334/2010, which created the National Dam Safety Policy, the National Water Agency (ANA for its acronym in Portuguese) became the enforcement body of the safety of multiple-uses dams in federal rivers. After consolidating the dams record under its jurisdiction, ANA came to understand the great challenge it was to classify these structures, mainly as to the Hazard Potential (DPA for its acronym in Portuguese), due to the precariousness of the relief data and other data from these dams. To establish the classification procedures, ANA was supported by the World Bank, with the participation of the National Laboratory of Civil Engineering (LNEC for its acronym in Portuguese) from Portugal. One of the products developed was a simplified method for determining the flood area due to dam break, based only on data such as height, volume and location and using the Shuttle Radar Topography Mission (SRTM) as the digital elevation model. The resultant polygon is suitable only for classification purposes and does not replace the dam break study to be carried out by the responsible for the dam. ANA adapted the methodology developed, both for the generation of the simplified flood polygon and for the criteria described in the classification matrix of the National Water Resources Council (CNRH for its acronym in Portuguese). Following the classification of 136 dams by DPA, the conclusions are that the method for generating the simplified flood polygon is a cheap and easy-to-use tool, recommended mainly for the classification of dams, or even for an initial estimation of flooded area, ideal for enforcement bodies with little information and lack of qualified personnel to perform more complex simulations. The greater challenge observed relates to very small dams, where the resulting simplified polygon is too conservative, often leading to the suspicion that the obtained DPA is overestimated.*

1 INTRODUCTION

In 2010, Law No. 12,334[1] was promulgated, which established the National Dam Safety Policy and created the National Dam Safety Information System (SNISB, for its acronym in Portuguese). This law defines that ANA became in charge of the supervision of the dams licensed by it, i.e. multiple-use dams with water accumulation, located in rivers of Federal

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Domain (those which cross more than one state or country), except those ones with hydropower generation as the main use.

In this law were also defined the instruments for its application, e.g. the classification systems by Risk Category (CRI, for its acronym in Portuguese) and Hazard Potential (DPA, for its acronym in Portuguese). In this system, the dams are classified by the enforcement bodies according to general criteria established by the National Water Resources Council. The classification by CRI is done according to the technical characteristics, the state of conservation of the structure and compliance to the dam's Safety Plan, while the classification by DPA is done according to the potential of loss of human lives and economic, social and environmental impacts arising from the possible dam failure.

To fulfill its role, ANA at first sought to refine its dam's database, checking from satellite imagery all the water bodies located in federal rivers. Then a search for the respective authorization was performed in ANA administrative files. If no document was found, it was conducted an in loco verification to check if it was really a dam. If positive, the technical information was collected and, if the entrepreneur was identified, he was demanded to formulate the licensing request to rectify the situation. Once licensed, the dams would become part of SNISB's database.

After the consolidation of the database, ANA sought to classify the dams by DPA, because Law No. 12,334 does not apply for those with low DPA, height under 15 meters, volume less than 3 million cubic meters and reservoir without dangerous residues. In doing so, ANA realized the size of the challenge ahead, because when trying to start the classification procedure two major problems existing in most of the Brazilian dams arose: absence of design data, and precarious relief data available. Without good quality data, both of relief and design, it was not possible to perform reliable dam break simulations, thus preventing the verification of the area potentially affected, and consequently the classification by DPA.

Due to its inexperience in this area, ANA sought for the technical support of the World Bank[2]. Specifically relating to the classification of dams, ANA requested a simplified method to be developed, correlating the flooded area downstream with known parameters such as the volume and height of the dam. This simplification was necessary, because regardless the lack of data, ANA could not postpone the DPA classification.

In addition, the method to be developed should be easily replicable since other enforcement bodies had the same problems with their data and this tool could be used in their dam's classification procedures.

2 THE SIMPLIFIED METHOD OF GENERATING FLOOD POLYGONS

With the assistance of the National Laboratory of Civil Engineering of Portugal (LNEC) a simplified method was developed for generating flood polygons due to the failure of a dam, based only on data such as height, volume and location and using the *Shuttle Radar Topography Mission* (SRTM) as a digital elevation model. It was accomplished resorting to a database of 145 dam break studies compiled by *United States Army Corps of Engineers (USACE)*. Regardless of all simplifications this method has proven to be useful to classify dams by DPA and has been adopted by ANA.

2.1 The original method developed by LNEC

The simplified methodology developed by LNEC aims to outline areas that would be flooded in case of the failure or malfunction of a dam. It was developed exclusively for the purposes of classification by the DPA.

The model is not dynamic. The equations do not consider explicitly the time. Hence, the flood areas produced by it should not be used in Emergency Action Plans (PAE for its acronym in Portuguese), when such a plan is required. For the preparation of the PAE, the entrepreneur should obtain a detailed survey of the relief and a simulation with a hydrodynamic model to obtain a more precise flood area, including the time spread of the rupture wave.

The simplified methodology was developed considering: (1) the information available on the location of dams, watercourses and altimetry, and (2) the possibility to resort to empirical formulas for calculating the extension to be modeled, the maximum flow rate of the wave spreading throughout the valley and flow damping as the wave propagates downstream. Synthetically the simplified methodology contains the following steps:

a) Empirical calculation of the downstream extension of the river to be modeled.
b) Calculation of the maximum flow rate associated with the rupture at the dam section.
c) Verification of the adequacy of the downstream zone given by the empirical estimation in face of the occupation of the valley and possible extension of this limit to cover occupied areas which might be affected.
d) Empirical calculation of the damped flow rate at the various cross-sections established along the valley for hydraulic analysis.
e) Extraction of the altimetry of points in the cross-sections.
f) Simplified hydraulic calculation of the maximum level of flood wave at each section.
g) Creation of a surface representing the top of the flood wave at each section using ESRI ArcGIS.
h) Estimation of the flooded area using ESRI ArcGIS.
i) Assessment of correction factors to cover the uncertainties associated with the flood area.
j) Establishment of the affected area to be considered for the classification by DPA.

One of the main simplifications applied to the model was that the maximum stored volume in the reservoir was considered the factor of major relevance to determine the downstream extension to be modeled. Analyzing actual cases of dam breaks a table was created relating the volumes stored to the maximum downstream distance where significant effects of the rupture would be felt. To make it seamless, thus enabling the automation of the procedure, a regression curve was determined resulting in the following polynomial expression.

$$D_{max} = 8.870 \times 10^{-8} V_{max}^{3} - 2.602 \times 10^{-4} V_{max}^{2} + 2.648 \times 10^{-1} V_{max} + 6.737 \quad (1)$$

For practical purposes, two values in the curve were imposed: minimum of 6.737 km and a maximum of 100 km, both considered suitable for the classification by the developers.

For the calculation of the rupture and damped flow rates along the valley the method also resorts to empirical equations available in the literature.

For maximum rupture flow at the dam were adopted the equations from Froehlich (1995) or Mapping, Modeling, and Consequences Production Center (MMC) of USACE (both *apud* The World Bank, 2014), depending on the ratio between the height and the volume of the dam.

For higher volumes relative to height, the method uses the MMC equation:

$$Q_{max} = 0.0039(V_{max}^{0.8122}) \quad (2)$$

Otherwise, the Froehlich equation (1995) is used:

$$Q_{max} = 0.607\ (V_{max}^{0.295} .\ H_{max}^{1.24}) \quad (3)$$

Damped flow rates along the channel also required de use of two equations. In case of dams with volume greater than 6.2 hm³ were adopted the recommendations proposed by *United States Bureau of Reclamation - USBR* (1989), *apud* The World Bank, 2014, where damping depends only on the distance x from the section to the dam.

$$Q_x = Q_{max}10^{-0.01243x} \quad (4)$$

In case of dams with volumes lower than 6.2 hm³ was adopted the equation proposed in *Dams Sector* (2011) apud The World Bank, 2014, where damping depends on the distance x and the total volume of the reservoir V_{max}. In the latter case an expression was also created to ease the automation of the procedures.

$$\frac{Q_x}{Q_{max}} = a.e^{b.x} \quad (5)$$

$a = 0.002 \ln (V_{max}) + 0.9626$
$b = -0.20047 (V_{max} + 25000)^{-0.5979}$

Being:

x - Distance to the dam (m);
V_{max} - Reservoir volume (m³)
Q_x - Maximum flow rate at distance x of the dam section (m³/s);
Q_{max} - Maximum flow rate at the dam section (m³/s);
a and b - Parameters obtained by multiparametric regression based on the five curves represented in the Figure 11.

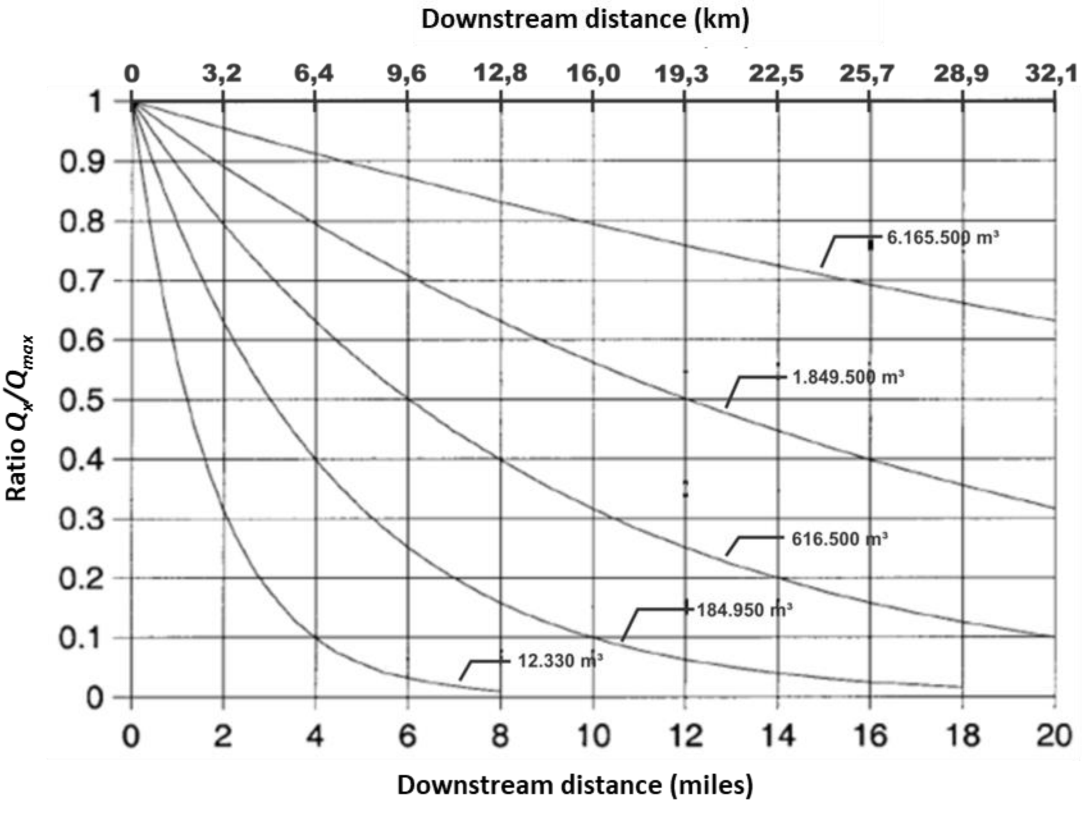

Figure 1 -Maximum flow attenuation with distance downstream from Dam (Dam Sector, 2011 *apud* The World Bank, 2014)

For the characterization of the altimetry of the cross-sections the first step is outlining the talweg of the river and smoothing its tracing to allow the determination of the cross-sections minimizing the angles between each other. At this point, using automated procedures on the software ESRI ArcGIS, the cross-sections are drawn and recorded in format Geodatabase. Subsequently the cross-sections are split in 80 points each and the altitude of the points is determined by the intersection with the digital elevation model, the SRTM.

To determine the maximum level of the rupture wave in each section a worksheet was developed in Microsoft Excel that calculates the transport capacity of each cross-section based on the *Manning-Strickler* formula.

$$\frac{Q_x}{\sqrt{j}} = K_s . A . R^{2/3} \quad (6)$$

where:

Q_x- The maximum flow rate distance *x* of the dam section (m^3/s);

j - The slope of the energy line based on the scheme of the Figure 2;

K_s- The roughness coefficient of Manning-Strickler. Admitted value of K_s= 15 $m^{1/3}s^{-1}$;

A - The area of the drainage section (m^2);

R - The hydraulic radius of the drainage section (m).

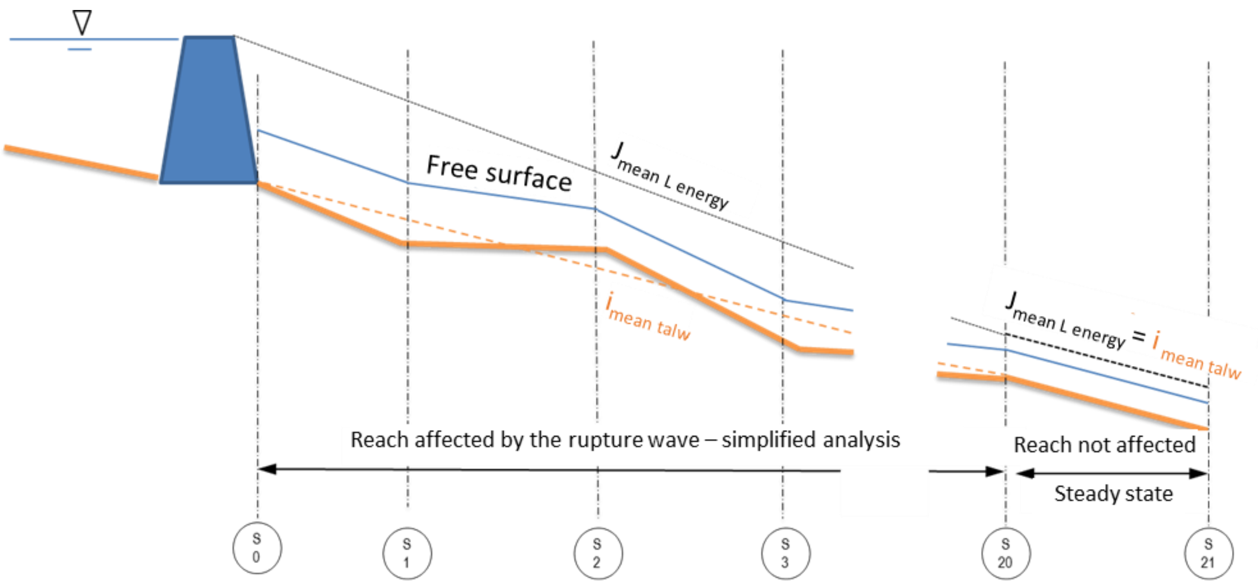

Figure 2: Scheme translating simplified hydraulic operation based on the calculation of the transport capacity of each cross-section

So, by means of the simplified hydraulic calculation method, it is possible to estimate the maximum levels reached by the flood wave in a predefined number of cross-sections, based on easily obtainable data.

Maximum heights thus calculated are then loaded into the ArcMap and associated with the respective cross-sections, leaving each section line with a maximum wave level. Using those lines, a surface representing the maximum flood levels is generated by performing an interpolation between the lines of the sections. The product is a surface in Triangular Irregular Network (TIN) format.

Last, relief is subtracted from this surface, so that the areas in which the relief is higher result in negative values and are discarded, leaving only the areas close to the River, where the flood surface is higher than the SRTM.

Because of the quality of the basic data, mainly of the digital elevation model and the position of the dam, shapefiles of the hydrography and satellite imagery, the developers of the method established some correction factors, to consider the errors arising from the uncertainty of the data. Thus, the following adjustments were inserted into the simplified model:

- Increase of 3.0 m into the heights of the flood surface, since the absolute altimetry errors of the SRTM for South America were reported as being around 6.2 m;
- Creation of a buffer of 250 m from the river talweg, since it was verified in the literature that this is the geopositioning error verified between the satellite images of Google Earth and reference values.

Altogether, it can be said that the methodology developed, yet simplified, is technically well-founded, being grounded on multiple empirical formulas obtained from real case studies of ruptures and mathematical modeling of dam breaks.

The simplified methodology allows the mapping of the flood zone with some degree of automation of procedures, not dismissing the analysis of intermediate results, nor even some manual adjustments, these dictated by the singularities of each case. Sometimes the inundated zone obtained is discontinuous, or some “isles” appear due to the presence of high trees canopy. These are situations where the analyst must intervene manually to correct.

2.2 The method modified by ANA

In implementing the procedures advocated by LNEC at ANA, it was verified that some improvements had occurred on the data, for instance, the digital elevation model SRTM available for Brazil at the time of development had a pixel of 90m, however, at the end of 2015 it was released a new version with a 30m pixel. Additionally, the relative positioning between the SRTM and the images available in both Google Earth and the ESRI ArcGIS basemap has been improved. Thus, the following increments were applied to the methodology:

- The digital model of elevation SRTM with a pixel of 30m was adopted. ANA created a mosaic covering the entire Brazilian territory. This would mean a great increase in processing time, so a routine was introduced to cut the mosaic to the region of interest of each dam processed;
- The river outlining was to be made according to the SRTM, eliminating the main difference between the input information, which was the mispositioning between the hydrography and the digital elevation model. In addition, there was an improvement in positioning between SRTM and Google Earth images. With these two new factors it became possible to discard the 250m buffer around the river, resulting in more realistic flood areas, especially for the smaller dams;
- Considering that: 1) the relative errors between any SRTM pixel and its neighbors is much smaller than the absolute error of 6,2m collected by LNEC; 2) the maximum elevation of the rupture wave is calculated by adding the wave height to the elevation value of the talweg obtained from the SRTM; 3) the overall accuracy of the method increased with the reduction of the pixel to 30m; and 4) the experience of the North American USGS that uses the pure values of its models of elevation in their dam break studies; It was decided to eliminate the addition of the 3m factor, because it introduced an excessive “correction”, increasing the error of the process, rather than reducing it.
- Another measure was opening the possibility of using the value obtained from the SRTM for the crest height of the dam (in the case of dams that already existed and are registered in this model). Sometimes differences were found between the dam project values and the SRTM elevation that caused processing errors. In each case, the analyst must decide what is the best value to use. The use of local values eliminates discrepancies in comparison with absolute values.

In addition to these changes, ANA developed programs in the Python language to increase the degree of automation of the process, by standardizing the necessary configurations and speeding up the various stages of the process. As a result, the generation of flood area became a fast and easy-to-use process, preserving the essence of the method originally proposed.

2.3 The complementary criteria for classification by DPA adopted by ANA

Based on these criteria, ANA made an initial classification of the 113 dams that had reliable data (this represented about 88% of the dam's database). From this set, 92 dams (81%) received high DPA, causing trouble for enforcement purposes due to excessive rigor. Once the classification places almost all the dams in the same class, the instrument loses its quality of serving as a prioritization tool, that is, loses the focus on those dams that represent a greater risk to society.

Analyzing the criteria, the items Environmental Impacts and Socioeconomic Impacts seemed to have received scores very rigorous, resulting in an excessive weight in the final score of the dam. There were few classes to choose from, not allowing a correct association with the reality verified on the field. For instance, in the Environmental Impact item, the only options were "Significant" or "Very Significant". In many small dams the environmental impact is not necessarily significant, so the introduction of a class with a lower score would better reflect reality.

Thus, ANA introduced for the classification of its dams by the DPA additional classes into the criteria related to Environmental Impacts and Socioeconomic Impacts, seeking a complementation and detailing of the CNRH classification criteria. the CNRH. Should be noticed that these complementary criteria are only applicable to the dams overseen by ANA. The other enforcement bodies must follow the criteria set out by the CNRH unless they create their own complementary criteria.

By introducing these complementary criteria, ANA achieved an improvement on the distribution of DPA between high, medium and low classes, which led to a more precise representation of reality and allowed the ranking of the dams to prioritize the enforcement actions.

3 ASSESSMENTS OF ANA'S CLASSIFICATION OF DAMS BY HAZARD POTENTIAL

After the changes in the flood zone generation methodology and the complementary criteria for DPA classification, ANA returned to the dam's classification process. By then were classified 136 dams, and for all of them the simplified flood zone was used as a reference area of analysis. It turns out that the initial goal of this simplified method, which was to quickly generate a flood polygon from basic input data, was fully achieved. Even with the scarce data of technical characteristics of the dams, it was possible to establish the flood zone for all dams under analysis by ANA. And even with the manual adjustments and corrections that had to be made throughout the process, in most cases the final polygon was considered realistic, being suitable for DPA classification purposes.

The automation of the simplified method has made this tool simple and inexpensive, which can be made by people with few hours of training to perform it. Starting with some basic knowledge of the ESRI ArcGIS tool, it is possible that most of ANA's technicians, no matter what the professional background might be, can perform the procedure routines and generate the simplified flood polygon for a dam. In normal cases, i.e. dams not too large, valleys not too complicated, the experience shows that, after getting used to it, the method takes an average of two hours per dam to complete.

For enforcement bodies that have, sometimes, thousands of dams to classify, the generation of a flood zone in two hours by a technician with minimum training and basic knowledge of ESRI ArcGIS software is something that can quickly reduce the existing number of unclassified dams (approx. 80% of the dams according to 2016 Dam Safety Report[3]). It is possible to use this methodology for an initial assessment of the DPA in a quick way and that meets Law No. 12,334. In more complex cases it is recommended the use of more refined methods if there is quality data available.

This was the strategy used by ANA to classify the dams. The simplified flood zone generation methodology for all her dams was used, refining the analysis in more specific cases. This process was done at the beginning of 2017 and lasted approximately 3 months for its 136 dams. After the classification, all entrepreneurs were notified.

Now that there is no longer a great number of dams to classify, there is more time available for a more profound analysis. Even so, ANA still uses the simplified methodology initially, and if any doubts arise regarding the flood zone or the classification of the dam, and if the available data allows, more refined methods are used.

Table 1 summarizes the results obtained with the classification performed by ANA. It is observed that, although most dams are still classified as high DPA (61%), about 30% of them are classified as low DPA, which did not occur before the changes in the methodology and the addition of complementary criteria for DPA. In general, large dams have been classified as high DPA, and small dams as low DPA, which the experience has shown to be more realistic.

DPA	Quant.	Max Volume (hm^3)	Med Volume (hm^3)	Min Volume (hm^3)	Max height (m)	Med height (m)	Min height (m)
High	83	2400.0	93.6	0.2	69.4	24.7	6.0
Medium	12	4.8	1.4	0,1	16.0	11.2	5.2
Low	41	11.7	0.9	0,1	25.1	6.2	1.0

Table 1: Results of the classification regarding the DPA of the dams supervised by ANA.

For large dams, it has been verified that the flood zone simplified methodology is suitable for classification by DPA, since the extent of the flood zone obtained is enough to determine the environmental and socioeconomic impacts and potential loss of human lives. In Brazilian reality these large dams generate benefits for the region, attracting populations to its surroundings and downstream. So usually there are population nuclei in the area possibly hit by a dam failure, which leads to the classification as high DPA. In those cases, the simplified flood zone generation methodology is more recommended.

However, for small dams, it is necessary to be more careful in its use, mainly because of the imposed minimum distance of 6.7 km. This makes the flood polygon tend to be too conservative for very small dams because this distance is often higher than the real reach affected. This could lead to higher DPA ratings than they really should be.

Moreover, it was observed that the process of generation of the simplified flood zone shows some difficulties in flat regions, as is the case of the region of Brazilian Amazônia. In these regions, the available terrain data, like SRTM, is worse than the average, because it represents the top of the canopy of the forest. Hence, the resulting flood polygons often show great discontinuity or even make no sense. In these cases, many manual fixes are necessary, which introduces more uncertainty to the definition of the area eventually reached.

After using the simplified method, ANA corroborates the observation made by the creators of the methodology that it should be used only for classification by DPA. It cannot be used in flood maps because it does not allow to simulate several hydrodynamic aspects of the flood wave and should be noticed that:

- Neither the reservoir's affluent hydrograph nor the progressive development of the rupture breach is explicitly simulated and consequently, the characteristics of the variable regime associated with the propagation of the wave along the downstream valley are not shown by the simplified model;

- The model does not respect the continuity of the flow by admitting the permanent regime in each cross-section, that is, admits that the flow in each section is the estimated peak flow based on the empirical formulation;
- When it is admitted that the water level in the reservoir is constant and coincides with the coronation of the dam for estimating the slope of the energy line, it is ignored that during the rupture there is a progressive lowering of the level in the reservoir and the disregard the localized energy losses, for example, in river curves and confluences with other water lines;
- Once it is a steady state simplification, the simplified model does not allow to calculate in each cross-section, either the temporal evolution of the flow velocity, or the water level dynamics, parameters which, although very important for the PAE, are considered expendable to the classification by DPA.

4 CONCLUSIONS

The task of classifying the dams by DPA is not easy considering the Brazilian reality, mainly by the large number of existing dams, and the lack of construction and precise terrain data. The Brazilian Army, which is the institution in charge of providing accurate geographic information of the country, has been making efforts to improve the altimetric data, but the federal budget available for this project was specially limited in the late years. Furthermore, the forecast for the years ahead is not optimistic.

That is why ANA sought with the World Bank and LNEC the creation of a simplified methodology to allow the delineation of a flood zone, from easily obtainable data, and that was easy to use and replicate. The methodology created, after adapted by ANA, met all the objectives producing satisfactory results.

ANA's experience shows that this tool can be extremely useful to the enforcement bodies in reducing the number of unclassified dams, mainly for the large dams. For small dams, some care should be taken, since ANA's experience indicates that the flood zones generated are too conservative.

It should be emphasized that this methodology is recommended only to classify the dams by DPA, and should not be used in the elaboration of Emergency Action Plans nor orient emergency actions.

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