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HAZARD POTENTIAL CLASSIFICATION OF DAMS USING A SIMPLIFIED METHODOLOGY

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Abstract: *The National Dam Safety Policy in Brazil (NDSP) assigns the classification of dams to the regulating agencies, all dams having to be classified in terms of hazard potential. The lack of appropriate basic data, such as topographic maps, makes it impossible to rely on well-established methodologies and requires effort and creativeness to find appropriate alternative approaches. This paper describes a simplified methodology implemented for hazard classification purposes and compares its results with those produced by a standard and more complete model (HEC-RAS) using the same basic data. Downstream valley inundation area assessment is performed considering four dams of different sizes. The results, although denoting some differences, evidence that the simplified methodology produces credible results as far as the affected areas for potential hazard classification are concerned. The simplified methodology was used to classify the whole portfolio of 121 dams assigned to the National Water Agency (ANA) under the terms of the NDSP.*

1 - INTRODUCTION

Brazil has over 13,000 dams which ensure 70 % of electrical power generation and water supply for vast areas particularly afflicted by semiarid climate. Figure 1 illustrates the spatial distribution of these dams and identifies their main purpose. Although large experience has been accumulated in Brazil along many decades by the different players involved in dam projects, construction and operation, only recently federal legislation was issued. In fact, the National Dam Safety Policy in Brazil (*NDSP*) was established by Federal Law nº 12.334[1] published in September 2010. The main objective of this law is the enhancement of dam safety standards, the reduction of the number of accidents involving dams and the minimization of their consequences.

NDSP establishes federal and state agencies as the entities responsible for the surveillance of dam safety policy implementation. The dam allocation criteria to each agency are defined in accordance with the reservoir main use and/or the river reach jurisdiction. The National Water Agency of Brazil (*ANA*) is one of the 45 dam safety regulating agencies, and it is responsible for the surveillance of 121 multipurpose reservoirs, located in federal rivers and not involving hydropower as the main water use.

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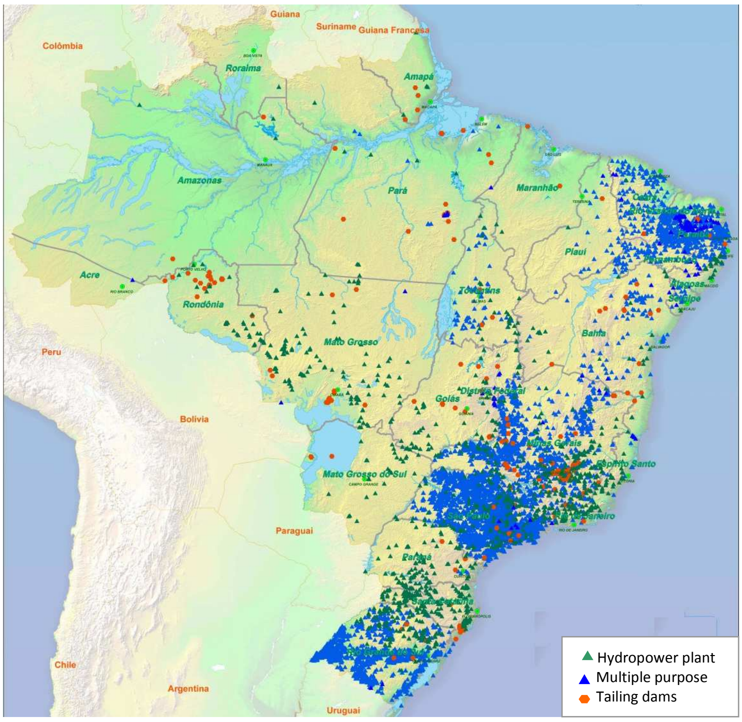


Figure 1: Dams distributed over the Brazil showing their main purpose.

The law assigns to the regulating agencies the task of dam classification, which comprises dam risk assessment and potential hazard evaluation in the event of dam failure. So, within the *NDSP*, the risk concept diverges slightly from the concept normally found in the literature, as it is restricted to the technical characteristics and conservation conditions of the dam and its appurtenances. This means that is the likelihood to failure, meaning the risk, is considered separately from the associated hazard. The general dam classification criteria to be used by the surveillance agencies were defined and published on a Resolution[2] in 2012 by the National Water Resources Council (*CNRH*), based on a proposal prepared by a working group of experts. The classification considers specific criteria for the impounding water dams and for the tailing dams.

Usually, classification procedures involve the access to data regarding the dam itself, namely its technical characteristics and conservation conditions, but also concerning the reservoir capacity and downstream topography and other characteristics, such as valley human occupation, economic activities and infrastructures, which are essential to assess the dam potential hazard. In accordance with the legal framework, any dam classified as high or medium in terms of potential hazard will fall within the scope of the *NDSP*, regardless of its height, reservoir capacity or dangerousness of accumulated residues. The dam classification also implies different requirements in terms of safety procedures to be fulfilled, meaning that the higher the class of the dam the higher the costs for the owner to comply with the *NDSP*. The owner can be a government or private agent with rights on the lands where the dam and reservoir are located, or anyone exploring them for his own benefit or for the community benefit.

ANA, supported by a program of technical assistance established with the World Bank, has been developing this initial work of developing methodologies and procedures since 2012, including the classification of 121 dams, having counted on this assignment on the expertise of the National Laboratory for Civil Engineering (*LNEC*), from Portugal.

This paper summarily describes the methodology defined for classifying the hazard potential of dams regulated by *ANA* and compares some results obtained with it against a more complete and generally accepted approach in which the dam break wave is simulated using the *HEC-RAS* software, developed by the *US corps of Engineers*.

2 – MAJOR CONSTRAINTS REGARDING HAZARD CLASSIFICATION

The available cartographic maps in Brazil vary in scale of detail according to the region, state, or municipality. The spectrum of the existing dams in terms of main purpose and location is quite wide and the lack of appropriate systematic topographic data covering the country is a major concern for the regulating agencies facing the legal requirement of classifying the dams within tight deadlines. To meet these requirements *ANA* had to put in place a quite simple and comprehensive methodology allowing the production of maps of potentially affected areas for the classification of its 121 regulated dams in less than 10 months.

The only scale available for topography of the whole country was the 1:1.000.000 or the Digital Terrain Model (*DTM*) provided by the *SRTM* mission[3] and remote sensing images providing a resolution similar to the one given by Google Earth and *ESRI* collected imagery. The information regarding the dams characteristics, spillways design flood discharges, reservoirs operation rules, dams materials and construction characteristics was very scarce. In some cases there was no reliable information regarding even dams' ownership or entities able to provide additional information other than their location obtained through remote sensing images. Presently, the inventory of dams is in its earlier stages.

For dams classified as high potential hazard the owner has to elaborate the Emergency Action Plan (*EAP*), whereas for the other dams it is a prerogative of the regulating agency to require it or not. For the *EAP* it is necessary to map the potentially flooded areas downstream. The methodology for simulating the dam failure and delineating the flooded areas within the *EAP* studies areas shall be the commonly accepted ones and the scarce available data will have to be enriched with newly gathered data to accomplish these studies.

3 – SURVEY OF AVAILABLE METHODOLOGIES

Dam break analysis has been a subject of applied research for the last four decades, being available a variety of approaches and software that produce generally well accepted results, but also requiring different levels of expertise, as well as types and volumes of data.

A survey of worldwide practices and recommendations regarding methodologies for the assessment of dam break inundation maps was initially performed[4]. Despite the many options available, it became clear that models' outputs are just approximations to what can occur in case of a dam break, which is a very rare event. Also, the more complete and accurate the models, the more demanding they are regarding user expertise, data volume, data quality, boundary conditions and calibration parameters.

The decisions regarding dam break software selection shall be driven by the type of use intended for the results. Normally dam break analysis is aimed at hazard classification, *EAPs* or environmental impact studies. Each of these different types of purposes involves different details and volumes of data and also requires different quality and types of results. A key element to consider when selecting a methodology and/or model regards the information available and the cost of getting key data when not available.

Among the necessary data, topography unarguably plays a crucial role in any dam break model. Sources of topographical input data may be contour maps at appropriate scales, hydrographic charts, aerial photographs, and more recently, satellite imagery and *DTM*. It is anyhow consensual that sufficiently detailed information can only be obtained from controlled field surveys for the majority of cases and this type of information is expensive[5].

Regardless the specific package or set of packages under consideration, dam break analysis is normally done simulating the following main components: dam failure simulation; generation of hydrograph at dam section; and flood routing.

Dam failure can be simulated by means of simplified models based on empirical equations that allow an assessment of the peak discharge or more complex approaches that simulate breach development and generate outflow hydrographs. The later require information concerning dam characteristics, reservoir initial pool elevation, inflow hydrograph and discharge characteristics of spillways. The influence of model accuracy in the simulation of dam failure is particularly relevant at the vicinity of the dam.

Different methods can be considered to simulate the flood routing. One may consider simplified empirical methods derived from statistical analysis of a significant number of numerical simulations and some actual dam break available data. These methods are rather straightforward to apply but involve significant levels of incertitude. Another rather robust approach is based on the solution of one-dimensional conservation of mass and storage-continuity equation, in what is named as hydrologic method. Some limitation has however to be taken into account when applying this routing method to dam break waves, as they have a considerable significant momentum, and this component is not taken into account in the hydrologic method. Finally, the more accurate approach – the hydraulic method that uses the Saint-Venant equations – allows a more complete reproduction of the wave propagation, but it requires considerably more data, namely regarding the river geometry and morphology. It is also more demanding in what concerns numerical calculation stability and convergence.

Dam hazard classification being *ANA's* intended goal, any methodology able to provide an estimation of maximum water levels at predefined cross sections downstream of the dam resulting from a breach event were considered adequate. This means that time for breach development, the associated hydrograph generated at dam section, as well as forecast of the wave arrival time, and the wave peak discharge along the valley were not required. This allows to infer that, as far as the hazard classification is concerned, hydrologic models, such as *HEC-HMS*, or hydraulic models, such as *DamBrk*, *HEC-RAS*, *SmpBrk* or *MikeFlood*, not only require excessive data volume but also deliver excessively detailed and unnecessary results. It was therefore decided to develop a simplified methodology based on existing recommendations for this type of approach and couple it with a Geographic Information System (*GIS*) using the available *SRTM DTM*. The implemented methodology incorporates, among others, many of the recommendations presented in the Dam Safety Guidelines from the Washington State[6].

4. DESCRIPTION OF THE SIMPLIFIED METHODOLOGY (*SM*)

It is consensual that the higher the dam the more destructive is the generated flood wave associated to its breaching, as more potential energy is involved. Also, the larger the reservoir capacity, the more destructive is the generated wave, as the hydrograph will involve a much larger volume and therefore, the duration of the flood will be longer for larger reservoirs.

Several authors have analyzed historical data of breached dams and attempted to setup simple equations to assess the peak discharge produced at the dam section in a breach event based on either dam height, reservoir volume, or a combination of both. As many real dam breach data were used, the resulting formulae encompass indirectly the time and mode of breach development that actually occurred in each accident. These expressions have, inevitably, a considerable margin of incertitude and are influenced by the specificities of the universe of dams considered, such as type and failure mode involved, so one shall adopt conservative criteria regarding the assumptions necessary to apply these equations.

Pierce at al.[7] analyze and compare a significant number of empirical equations aimed at the estimation of maximum discharge at the breached dam. These equations can be split into three groups based on the considered parameters, some depending on the maximum storage capacity of the reservoir V_{max}, some on the dam height H_{max}, and some other on a combination of these two variables. The equations analyzed by these authors are, however, based on a rather limited amount of dam breach cases. Pierce[8] re-analyzed the data considering an additional 47 dam breach cases, thus expanding the range of dam sizes, particularly on what concerns the dams with less than 10 m high. Pierce concluded that equations using just one parameter tend to underestimate maximum discharge, especially when small dams are involved and also that equations based on reservoir volume tend to produce more credible results than those based solely on dam height, these ones being recommended only when no data regarding the reservoir volume is available.

According to Pierce[8], regarding the equations using both dam height and reservoir volume, they produce generally better results, being the equation proposed by Froehlich (1995) the one allowing a better adjustment to the expanded dam breach data.

USACE - Mapping, Modeling, and Consequences Production Center (referred in [4]), also propose an equation, labeled as MMC, that is based on the reservoir volume. This equation was deduced upon an analysis of dam breach data from a universe of 145 dams. The equation tends to produce higher peak discharges for dams with larger reservoirs than the equation proposed by Froehlich (1995), so it was considered the use of both equations, and then the highest produced peak discharge becomes the adopted one.

The simplified methodology (*SM*) replaces the numerical simulation of the flood routing along the river valley by a semi-empirical expression. This involves a two-step approach: estimation of the maximum distance along the river where the dam breach produced wave will have significant destructive impact; then, estimation of peak discharge at various cross-sections along the river.

Regarding the maximum distance, several statistical studies of dam failures involving fatalities, namely the studies of Graham[9], dam break studies performed by the State of Queensland, Australia[10] and the Portuguese regulation on dam safety[11] were taken into account, leading to equations (1) and (2):

$$D_{max} = 8.870 \times 10^{-8} {V_{max}}^3 - 2.602 \times 10^{-4} {V_{max}}^2 + 2.648 \times 10^{-1} V_{max} + 6.737, \quad if \quad V_{max} \leq 1{,}000\ hm^3 \tag{1}$$

and

$$D_{max} = 100\ km\ , \quad if \quad V_{max} > 1{,}000\ hm^3 \tag{2}$$

D_{max} – maximum distance downstream of the dam (km);
V_{max} – maximum reservoir capacity (hm^3).

Regarding the peak discharge attenuation along the downstream valley, a pre-defined number of sections between the dam section and the most downstream cross-section of the affected area is established. The peak flow at those cross-sections is then estimated as a fraction of the peak flow at the dam section using semi-empirical expressions, instead of getting the hydrograph attenuation along the river as an output of a numerical hydraulic model. These expressions are byproducts of many routing data from real dam break cases and of detailed numerical simulations of a significant number of dam break case studies.

The attenuation of the dam break flood wave as it progresses downstream depends on a number of factors: the reservoir volume, the characteristics of the valley in terms of topography of the main channel and flood plains, the storage capacity of the valley, the thalweg slope, the roughness of the inundated areas, the variation of the cross-section along the path, tributaries, and transversal obstacles such as bridges or dams. Considering the simplified nature of the implemented method, and being the volume the most relevant of the above factors, only the reservoir volume was considered for peak discharge attenuation with the distance to the dam.

Several simplified routing approaches such as those proposed by Weltmore and Fread[12], Schaefer and Barker[13], *USBR*[14] and Dam Sector[15] were analyzed. These methods consider in general the distance to dam from the analyzed downstream river cross-sections and, depending on the authors, other parameters such as the Froude number or the relationship between the reservoir volume and the outflow hydrograph volume.

As the information available for the dams to be classified is limited, the equation proposed by the *USBR*[14] is adopted for reservoirs with capacity exceeding 6.2 hm^3, equation (3).

$$Q_x = Q_{max} 10^{-0.01243x} \quad (3)$$

Q_x – maximum discharge (m^3/s) at distance x from dam section (km);
Q_{max} – peak dam breach discharge at dam section (m^3/s);

For reservoirs with maximum capacity below 6.2 hm^3, the proposal of Dams Sector[15] was considered, which can be expressed by equation (4):

$$\frac{Q_x}{Q_{max}} = a.e^{b.x} \quad (4)$$

$$a = 0.002\ln(V_{max}) + 0.9626$$

$$b = -0.20047(V_{max} + 25000)^{-0.5979}$$

V_{max} – reservoir maximum volume (m^3);
Q_x – maximum discharge (m^3/s) at distance x from dam section (m);
Q_{max} – peak dam breach discharge at dam section (m^3/s).

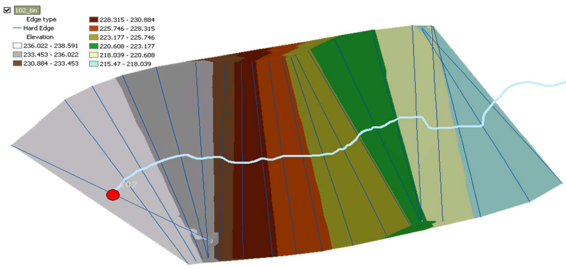
Having defined the maximum discharge as a function of the distance to the dam it is necessary to calculate the corresponding maximum water elevation. This is accomplished using the Manning-Strickler equation where a friction coefficient, a thalweg slope and an energy grade line must be assumed. The last two factors are derived from the topographic information of the *SRTM DTM* [3] (a coarse resolution model of 3 arc second cells - approx. 90m). Using the *SRTM*, 22 cross-sections along the river course are generated for maximum water elevation calculation.

Bearing in mind that the purpose of developing the *SM* was the dam hazard classification, and considering the incertitude, simplifications and inaccuracies already identified, conservative assumptions are adopted in the setting of these three factors. As far as the friction is concerned, the Manning *n* coefficient is adopted at a value of 0.067, meaning that rather rough river and flood plain are considered. Concerning the energy grade line, it is assumed that the reservoir water level remains at the original dam crest elevation (overtopping failure) and that the energy conditions at the most downstream section are those associated to uniform flow.

Considering this approach an approximate and very simplified flood routing can be estimated, assuming uniform steady flow at each cross section considering the estimated energy grade line slope in the Manning-Strickler equation.

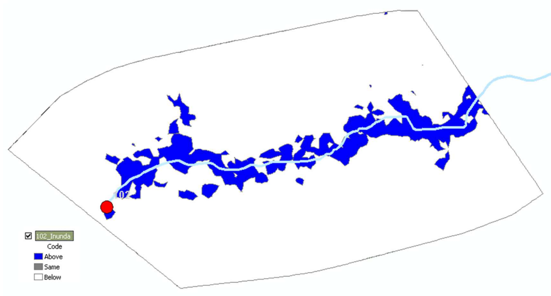
Using a *GIS*, the envelope surface of maximum water levels calculated at each cross section can be represented by means of a Triangulated Irregular Network (*TIN*), Figure 2a), which, when intersected with the *TIN* representation of the *SRTM DTM*, Figure 2b), produces a polygon that defines the potentially affected area, Figure 2c).

A comparison between complete dam break models and the *SM* in terms of required data, completeness of the covered zones and produced results is presented in Figure 3. It becomes evident that the *SM* has its own limitations, namely in what timeline events are concerned, making it not suitable for *EAPs* studies. However, the simplified methodology allows for a definition of the potentially affect areas by dam breach using a very limited set of data, thus fulfilling the requirements imposed by the *NDSP* to the regulating entities as far as the dam hazard classification is concerned.



a) maximum water elevation *TIN* in the cross sections

b) *DTM TIN* and generalized stream



c) inundation area (blue zone)

Figure 2: *GIS* layers.

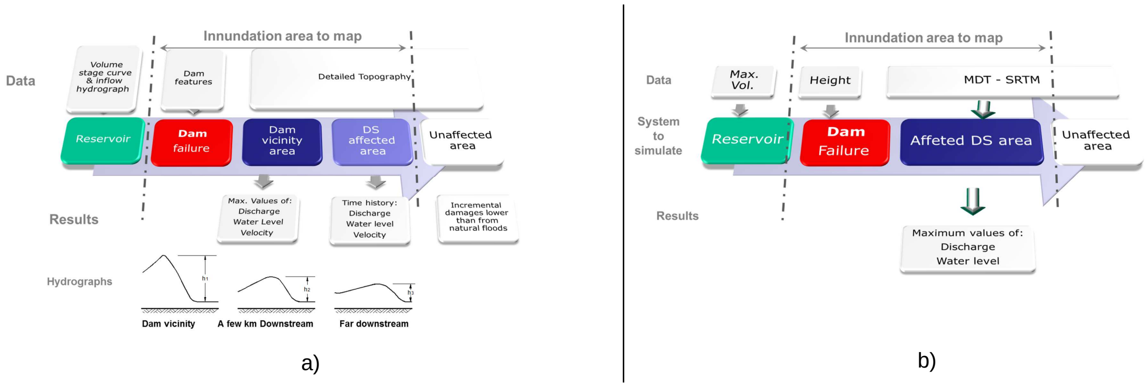


Figure 3: Data, model covered aspects and results from a) complete and b) simplified dam breach simulations.

5 – VALIDATION OF THE SIMPLIFIED METHODOLOGY

Results of the simplified methodology were compared with those resulting from simulations with the hydraulic numerical model *HEC-RAS*, a 1D widely used software developed by the *USACE*, which allows the simulation of the dynamic and transient behavior of abrupt front flood waves, such as the ones produced by a dam breach.

Some assumptions regarding boundary and initial conditions with *HEC-RAS* simulations had to be considered in order to make its results directly comparable with those provided by the simplified methodology. In fact, as no information regarding the reservoir stage-storage relationship was available, an approximation had to be considered. It was assumed that this relationship presents a homothetic behavior to curves of a set of dams with known reservoir stage-storage curves. A non-dimensional stage-storage curve was constructed based on this assumption (Figure 4), and therefore, case specific relationships were approximately assessed based on the known values of dam height and maximum reservoir capacity.

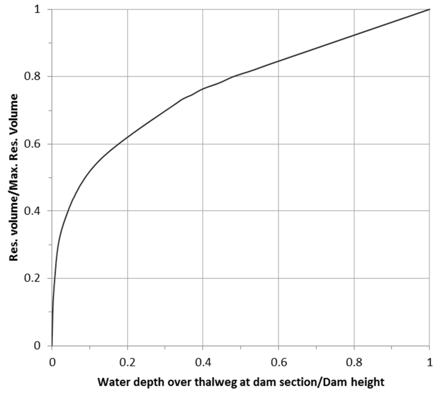


Figure 4: Non-dimensional reservoir stage/volume curve considered in *HEC-RAS* dam break simulations.

Trial and error simulations were run in *HEC-RAS* manipulating dam breach size and time of breach development in order to obtain an outflow hydrograph with a peak discharge close to the value produced by the empirical expression considered for the simplified methodology.

Uniform flow was considered at the ultimate downstream cross section of the *HEC-RAS* simulations, similarly to the assumption made for the simplified methodology.

Also, the same number of cross sections used in the simplified methodology (22 sections) was considered in order to keep geometries of the valleys directly comparable. Interpolation between the consecutive cross-sections was considered in order to ensure the required convergence criteria of the *HEC-RAS* formulation, based on the Courant number, in such manner that distances between consecutive interpolated cross-sections would be in the range 30m to 50 m. The Manning coefficient used in the simplified methodology, with a value of n=0.067, was kept also for the *HEC-RAS* simulations.

With the purpose of performing a sensitive analysis of the results against dam height and reservoir volume, four dams were considered for comparison purposes, the respective values of these parameters being: (1) Afl. Cór. Sta. Luzia - 2.7 m; 0.09 hm^3; (2) Mamão - 13.4 m; 1.18 hm^3; (3) Capoeira - 36 m; 53.45 hm^3; and (4) Descoberto - 34 m; 113.41 hm^3.

In Figure 5 the results for each of the four analyzed dams are plotted. In general, despite the conservative approach of the simplified method, *HEC-RAS* produces higher maximum flow depths, namely for the two larger dams – Descoberto and Capoeira dams.

A summary of the deviations in terms of peak discharge and maximum water depth for each analyzed dam is presented in Table 1. Despite some expectable deviations due to dynamic, transient and local effects incorporated in the *HEC-RAS* hydraulic model, but disregarded in the *SM*, one notices that the peak discharge attenuation is rather well reflected in both approaches. The two larger dams are about the same height, with Descoberto's reservoir having twice the capacity of Capoeira's reservoir. Results evidence that *SM* does not reflect the impact of height in the same way as *HEC-RAS* does. The results for Capoeira dam reveal an averaged error +1% of peak discharge vis-a-vis *HEC-RAS*, whereas for Descoberto dam the *SM* produces an averaged error of -20%. For the smaller dams an averaged error of +8% of peak discharge was obtained against *HEC-RAS* against *HEC-RAS*.

Dam Name	Cor. Sta Luzia	Mamão	Capoeira	Descoberto	Cor. Sta Luzia	Mamão	Capoeira	Descoberto
Dam height (m)	2.70	13.40	36.00	34.00	2.70	13.40	36.00	34.00
Res. Volume(hm^3)	0.09	1.18	53.45	113.41	0.09	1.18	53.45	113.41
Section	Qx - simplified vs. Hec-RAS				Max. water depth - simplified vs. HEC-RAS			
Max.	16%	34%	21%	-7%	-4%	22%	-8%	14%
Min.	-5%	-1%	-8%	-32%	-55%	-65%	-36%	-69%
Average	8%	8%	1%	-20%	-30%	-21%	-22%	-28%

Table 1 – Summary of deviations of *SM* results vs. *HEC-RAS* results.

The maximum water depths present a general trend of underestimation against the results of *HEC-RAS* (on average from -20% to -30%). However, locally, the difference between the two approaches may reach significant values. These differences are mostly due to local effects, in zones where the thalweg slope presents very large transitions from very steep to very mild, or even to counter inclined slope, Figure 5. These slope variations are mainly attributable to the poor resolution and low accuracy of the *SRTM DTM*. There is no evidence that *HEC-RAS* results can be taken as more realistic than those given by the *SM* as *HEC-RAS* may generate relevant hydraulic side effects due to inaccurate topographic factors.

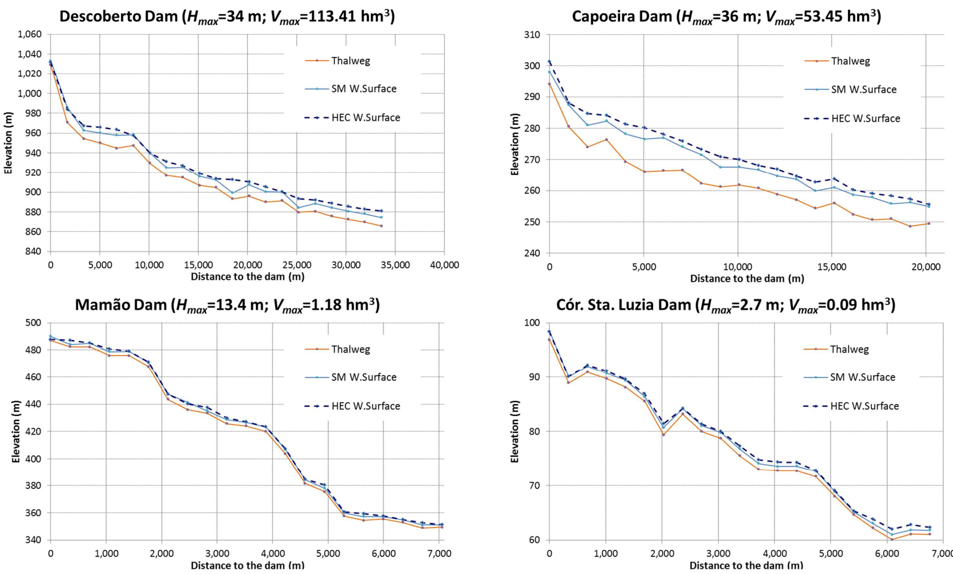
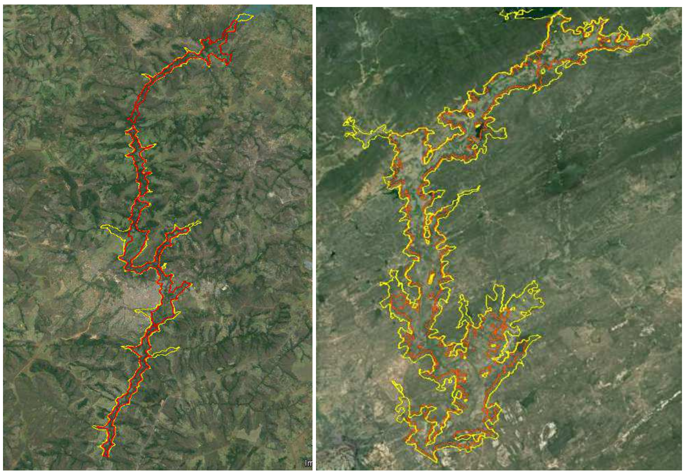


Figure 5: Water profiles considering the two methodologies (*SM* and *HEC-RAS*) for dam break simulation.

In practical terms, resulting contour maps for hazard classification are quite similar for the simplified methodology and *HEC-RAS* model, both producing maximum water levels at each considered cross-section, as depicted in Figure 6 for the Capoeira and Descoberto dams.



Capoeira dam Descoberto dam

Figure 6: Contour maps from SM (red line) and HEC-RAS (yellow line) for Capoeira and Descoberto dams.

6 – CONCLUSIONS

The legal obligation of classifying all Brazilian dams in terms of hazard potential in a very short time frame, posed considerable challenges to the involved regulating entities. Considering the available data and methods for the definition of the potentially affected areas downstream and the large universe of dams to classify, it became evident to the National Water Agency (*ANA*) that a simplified methodology (*SM*) and the automation of procedures would be necessary, although accepting inherent incertitude in the results. A methodology based on simplified hydraulic calculations, using *SRTM DTM* and *GIS*, was developed.

The comparison of the produced results shows that the *SM* is suitable for establishing the zoning of potentially affected areas in case of a dam failure for the sole purpose of dam hazard classification. Despite the advantages provided by the *SM* as a desktop classification tool, the results shall be confirmed with field visits where doubts and inconsistencies are significant leading to misclassification. This is particularly relevant for small dams and low populated valleys, as the maximum water levels involve considerable incertitude due to the coarse topography of the Digital Terrain Model (*DTM*) or for those dams located where the available satellite images used to identify buildings and infrastructure are of poor quality.

Further developments allowing even increased automation levels of the involved processes in the *SM* will allow its use for the hazard potential classification of the large universe of dams in Brazil. Expected advances in remote sensing will provide increasingly more accurate topographic data, and consequently, pave the way to improved accuracy of the *SM* results.

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