CALIBRATION METHOD FOR 1D HYDRAULIC MODELS USING HIGH DENSITY SATELLITE OBSERVED DATA

Rodrigo MARTINS LUCCI | Civil Engineer, Master of Science - Hydraulics and Environmental Engineering Dept. - School of Engineering - University of São Paulo

Jose Rodolfo SCARATI MARTINS | Professor - Hydraulics and Environmental Engineering Dept.- School of Engineering - University of São Paulo

RESUMO

Os modelos matemáticos são ferramentas indispensáveis para mapear impactos nos vales a jusante de barragens por meio de simulação de cheias e rupturas parciais ou totais. Independentemente da existência de modelos digitais de terreno adequados e dados de alta precisão, um processo de calibração é essencial para tornar o modelo representativo e reduzir suas incertezas. Os métodos usuais de calibração ajustam os coeficientes do modelo para corresponder os níveis de água calculados e observados para vazões conhecidas. Este artigo apresenta um método de calibração para ser usado na modelagem hidrodinâmica de vales a jusante com o uso de imagens de satélite de eventos de inundação para melhorar a resolução espacial dos dados disponíveis e, consequentemente, seu desempenho.

ABSTRACT

Mathematical models are indispensable tools to map potential hazards in river valleys downstream of dams' trough the simulation of flooded areas due to the occurrence of large floods and partial or total ruptures. Regardless the existence of adequate digital terrain models and high accuracy forcing data, a calibration process is essential to make the model representative and reduce its uncertainties. Usual calibration methods adjust model coefficients to match the computed and observed punctual water stages in a station for a known discharge assuming that the reach between two stages are well represented. This article presents a calibration method to be used in hydrodynamic mathematical modeling of downstream valleys with the use of satellite images taken during flood events to improve the spatial resolution of the available data and consequently, its performance.

1. INTRODUCTION

Mathematical models are essential tools in practically all components of 'water engineering enterprises' especially in studies related to risk and safety management of valleys under the effects of increasing hazards or the presence of dams. It is expected that the fluvial flow simulation models employed in floodable areas estimation have representativeness and efficiency compatible with the magnitude of the involved risks [1]. The calibration of hydraulic numerical models are processes to make the connection between the analytical concepts and the desired efficiency through the adjustment of the equation's parameters. Usually carried out through by 'trial and error' or 'automatic error mitigation' processes, the calibration aims to determine the hydraulic parameters linked to the friction factors and turbulence as Chèzy-Manning's roughness and others, based on observed water level and discharge in singular points at hydrological stations. The water level in the reach between two stations are ungauged and not considered when the model accuracy is evaluated, faking considerable errors in the identification of the flooded areas located in valleys, despite how sophisticated the model is [2].

In this context, it is very important for modelers to have an alternative calibration method that profit from the availability of the distributed remote sensing data, such as satellite or aerial images along the flood events to take into account the real water masses stored in the flood plains [3].

This article proposes and tests a calibration method based on satellite imagery which allows to distinguish different situations of occupation of the floodplains along the entire valley, increasing the spatial resolution of the model checkpoints and consequently its performance. The procedure shown here is also applicable to imaging technologies such as interferometer and LiDAR radars, which are increasingly being used in hydraulic modeling for flood studies. [4-6]. The method was developed using one-dimensional models, but can be extended to 2DH and 3D models, which are progressively becoming more accessible. [7, 8].

2. CONCEPTS AND FUNDAMENTALS

2.1 RIVER FLOW SIMULATION MODELS

Hydrodynamic mathematical models for river flow simulations are based on the equations that represent the dynamics of fluids in 3, 2 and one dimension, like RANS and Saint-Venant equations. Those equation consider mass balance and momentum, computing the main forces acting in the water like gravity, pressure, wind and shear stresses. This last one uses concepts as bottom shear stress, friction factors or turbulence that need guided and standardized calibration [9]. Currently, the software that make use of those equations is called mathematical model or hydrodynamic model, but, it is the tool that facilitate the use of the analytical conceptual equations through its sophisticated and user-friendly interfaces, making data entry and results analysis more agile.

2D flow models are also known as shallow water models, disregard the vertical acceleration of fluid particles because it is very small in relation to gravity acceleration, and so they can be called horizontal two-dimensional models (2DH). The 2DH is a simplification of the generic three-dimensional case and has great application in the studies of rivers, estuaries and lakes with small depths [10].

On the other hand, the 1D model, which is the simplification of the 2D model, considers the vertical and lateral mean values of a cross section of a river, and can be done by integration along the width. [11]When the main channel of the river is overcome, lateral runoff occurs to the floodplains with two-dimensional characteristics. In one-dimensional models, the calculation of the runoff in these plains can be treated in different ways, one of which is to use plain only for storage in the mass balance equation. This approach is suitable for large rivers that have floodplains with lots of [12]. Another way to address this problem is to divide the system into two separate channels [13-15].

Physical representation of the 1D modeled area is based on cross sections for the main channel and digital terrain models (DTM) or digital elevation model (DEM) for the floodplains. The solution is obtained by forcing the equations using flow and water level data derived from observed data series at gauges located upstream, lateral, and downstream limits. Among the results that a hydrodynamic model software can offer we highlight the water stage profiles along the channel and the flood maps based on the DTM which may contain depth information, NA elevation, velocity, wave arrival time, flood duration, etc.

The usual calibration parameter in hydraulic models is the friction factor representing the effect of the shear stress associated to the walls, bottom, and internal friction. For 1D models, Manning's Coefficient is used while the 2D and 3D's employ advanced formulations to close the momentum equations. One-dimensional models use cross sections composed by a main section associate to floodplains with different roughness coefficients at different water stages.

Various 1D, 2D and 3D hydrodynamic simulation software are available and we quote HEC-RAS [12], PCSWMM [1], Delft3D Suit [16]. HEC-RAS starting from version 5 introduced 1D and 2DH

simulation facility and several results through maps such as depth map, water level elevation, speed, speed x depth map, wave arrival time, flood duration etc.

2.2 MAPPING FLOODED AREAS

The flood map is the plant representation of the area occupied by water when the drainage structures are overloaded, and the water level exceeds banks. The advances in georeferenced information system (GIS) brought several ways for generation of flooded area maps. One of the simplest ways for generating flooded area is the inclusion of a virtual layer of water over the DTM or DEM adjusted at the predicted water level reached by the river in periods of high rainfall [17]. An alternative this purely geometric method is to use the water elevation from the hydraulic models combined to the terrain descriptors, described as hydrogeomorphological attributes and extracted directly from the DTM [18].

Rennó and Nobre [19, 20] proposed the Height Above the Nearest Drainage (HAND) model, a descriptor for mapping flooded areas. The HAND model uses the vertical distance for the nearest drainage to develop a static approach and map potentially flooded areas. The method uses normalized drainage topography (EA) and flow paths to delineate the vertical distances relative to the nearest river [20].

The above mentioned HEC-RAS software includes a tool for generating and viewing map results called RAS Mapper that generates several map results based GIS techniques integrated to the hydraulic model results [21]. The limits for the flood mapping extensions are stablished by edge lines defined by the extremes of the one-dimensional river cross sections [22].

One simple map generation technique is present in the model CLiv+ [23] to compare the water levels calculated by a 1D hydraulic model to the raster terrain elevation and set to each pixel the attributes '1-flooded' and '0-not flooded'. This approach considers the water level obtained from with the mathematical modeling at each cross section and includes the influences bridges and crossings, section bottlenecks and so. The step sequency to map a flooded area along a river reach can be described as:

- The water elevation is computed at a fixed spacing along the main channels axis that form the channel network by interpolation among the water elevation results at each timestep for each cross section.
- The routine runs over each channel in upward direction and creates at each point defined in the previous step an orthogonal line to the channel axis with a previously stablished distance to form a buffer. This orthogonal line

has the same water elevation attribute of the original channel axis point.
- Each pixel of the terrain elevation along the line is then compared to the elevation attribute. The binary state 'flooded' or 'not flooded' is set to the pixel. If the point is already marked by another orthogonal line (case of curves) the routine notes the greatest depth.
- The resulting raster map is then converted to closed surface areas.

2.3 DIGITAL TERRAIN AND SURFACE MODELS

DTM and DEM models represent the earth's surface and differ respectively by representing everything on the surface, vegetation, buildings, etc., and by representing the land itself, where vegetation is rooted and buildings are founded.

Several open access DEM are currently available such as the SRTM - Shuttle Radar Topography Mission, developed by NASA (National Aeronautics and Space Administration) and NGA (National Geospatial-Intelligence Agency) in the United States in 2000, the ASTER GDEM - Advanced Spacebone Thermal Emission and Radiometer Global Digital Elevation Model, developed by the consortium between the Ministry of Economy, Trade and Industry of Japan (METI) and NASA, and the derivatives of SRTM, such as data from Brazil in Relief from EMBRAPA and TOPODATA, made available by INPE - National Institute of Space Research.

Before using these digital surface models the accuracy of the altitudes provided must be carefully analyzed in order to establish the reliability of the products produced. One way to evaluate the altimetry of the MDEs is to compare the altitudes of the models with those of control points, such as the geodesic landmarks and perform a statistical analysis of the errors found between the altimetric 'real' evaluation and the one supplied by the digital model. Results can then be compared to the standards stablished by the agencies in charge of land management as, for instance, the IBGE in Brazil (Technical Standard of National Cartography Decree No. 89,817, of June 20, 1984)

3. THE PROPOSED ALTERNATIVE CALIBRAITION METHOD

The method proposed follow the ones proposed by di Baldassarre et. al. [3], Hostache et. al. [24], Domeneghetti [25], Garambois et. al. [2] and more recently Hosseiny [26], using machine learning approach. Unlike the conventional method of calibration that takes

into account few or even just a single point, the alternative method is elaborated based on the images captured during floods in rivers, and thus has a high density of calibration points, since each pixel of water in the flooded area is a spatial calibration point.

For this method, a recursive computation of the water elevation profile with 1D models or the water surface for the 2D is carried out with the boundary conditions of the same flood observed and captured by the obtained image. The calibration parameter (friction factors or Manning's coefficient) is set among a band of variation, covering total or partial areas and the result is stored for the uncertainty analysis.

The observed flood map can be extracted by several imaging classification methods through GIS applications. One of these methods is the automatic supervised classification process, which should be carried out with maximum impartiality in the process, so that subjective participation is only the definition of areas for spectral signature collection. These methods segment the image by connecting zones of the same spectral characteristic. To exemplify the concept, Figure 1 presents the satellite image dated January 21, 2016, from Planet Labs [27], an imagery repository with pixel size from 0,5

to 5 m, position accuracy of 10 m and radiometric resolution of 16bit. The left image is the original all-bands image and the right shows the image binary classified considering flooded and land pixels.

To perform the comparison between the observed flood and the one calculated by the hydraulic model, both must be converted to the binary form. The observed map has water represented by pixels of value 2 and earth per pixel of value 0, while the calculated map has the water represented by pixels of value 1 and earth per pixel of value 0.

These attributes are combined by the sum of these two areas, where each pixel of the calculated map is confronted to the respective pixel of the observed one. This crossed information allows to verify the correct answers and errors of the modeled results. Table 1 shows how pixel values of the flooded and earth classification of the observed and calculated images are considered, end the values assigned to the resulting crossed images.

The algorithm will seek the minimum point of the total error curve, which results from the sum of absolute error curves with "False positive" and "False negative" for each set of model roughness parameters.
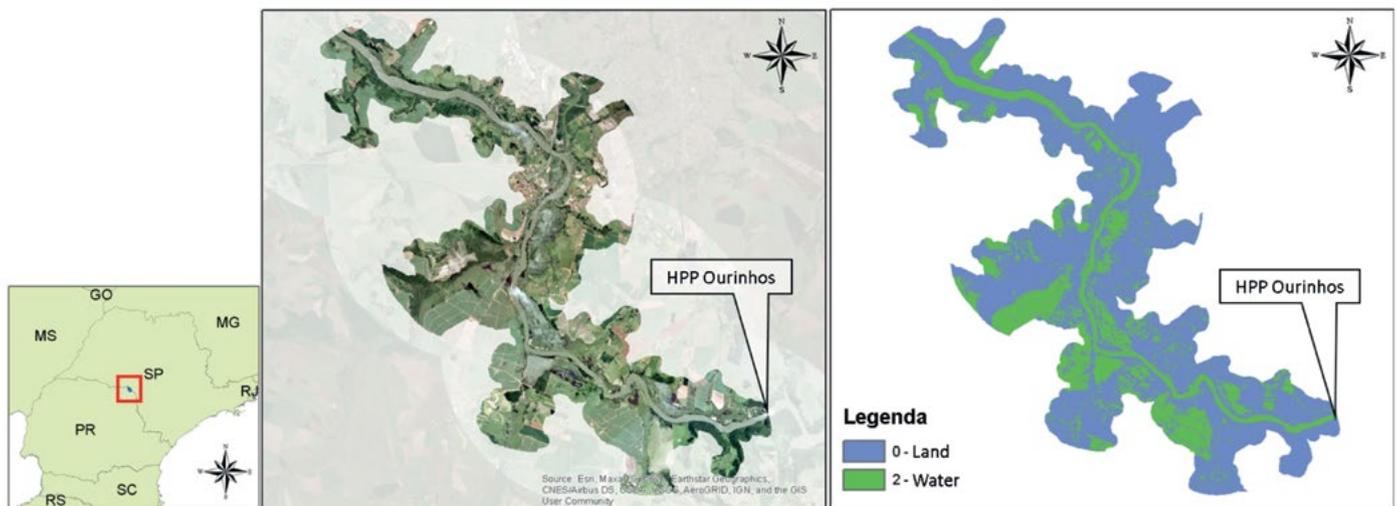

FIGURE 1 - Satellite Image of 21 January 2016 and binary classification

Classification	Pixel value	
	Observed	Deliberate
Earth	0	0
Water	2	1

Comparison	Calculated result	Observed image	Classification
calculated = observed	Earth "0"	Earth "0"	Negative "0" (0+0) (N)
calculated = observed	Water "1"	Water "2"	Positive "3" (1 +2) (P)
calculated flooded more	Water "1"	Earth "0"	False positive "1" (1 +0) (FP)
calculated flooded less	Earth "0"	Water "2"	False negative "2" (0 +2) (FN)

TABLE 1 - Pixel values of observed and calculated spots end Classification of the resulting crossed images pixels

4. CASE STUDY

4.1 STUDY AREA

This alternative calibration method was tested in the downstream valley of the Ourinhos Hydroelectric Power Plant (HPP) dam, located at Paranapanema River, State of São Paulo , Brazil, comprising about 52 km represented by 245 cross sections. Those sections were extracted from the DTM data of the São Paulo Metropolitan Planning Company – EMPLASA, that has a horizontal resolution of 5 meters. Figure 2 shows the cross sections and the limits of the area defined by the maximum computed flooded map plus an additional buffer to avoid including flooded pixels that don't represent flooding due to main section overflow.

These data were then combined with the cross sections along the reach for the representation of the main section. Figure 2 shows the simulation excerpt and an example of a cross-section in the HEC-RAS.

The first task was to evaluate the altitude accuracy of the DEM so that they can be used in water resource applications for better results. It is important to point out that the altimetric inaccuracy can lead to mistaken results of flood spots, both in the increase and in the decrease of the affected area. Thus, it is recommended that the altimetric evaluation be performed for each study, and for this it can be used the classification of the Cartographic Accuracy Pattern as a reference, and should be improved with the increase in the number of control points [28].

Indicator	EMPLASA	TOPODATA	ASTER
average	4.30	5.48	8.36
maximum	44.92	43.41	44.46
Minimum	0.01	0.01	0.09
median	1.84	3.70	5.86

TABLE 2 - Error (%) in relation to (RAAP) of the Brazilian Geodesic System (SGB)

Three different DTM were models available for the study area, produced by different agencies: TOPODATA prepared from data from the Shuttle Radar Topography Mission (SRTM), and ASTER, developed by the Mission Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER). Table 2 shows the error in relation to the High Precision Altimetric Network (RAAP) of the Brazilian Geodesic System.

4.2 CONVENTIONAL CALIBRATION OF THE ONE-DIMENSIONAL MODEL

To calibrate conventionally the 1D model discharges and water stage elevation were used at upstream border. At downstream limit the water elevation were imposed. Figure 3 shows the observed flood and the calibration results in the upstream border (Chavantes HPP). The calculated data showed good adherence to the observed data and the calibrated roughness represented by the Manning's number was 0.03 for the main trough and 0.085 for the floodplains.
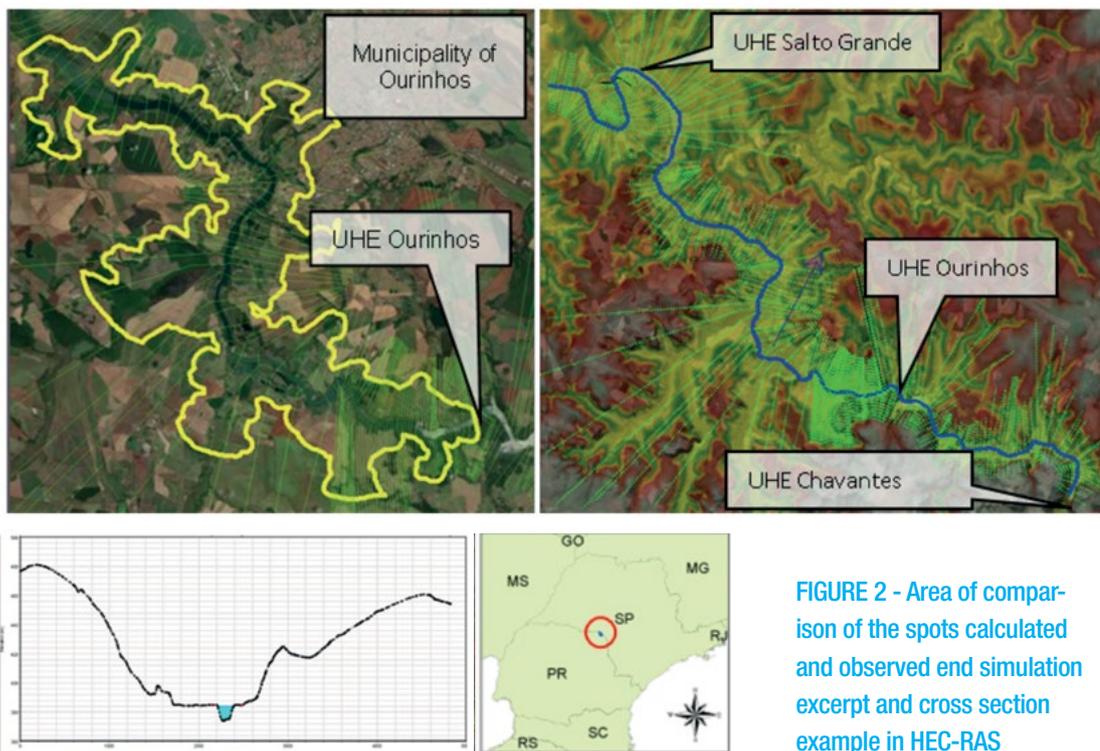

FIGURE 2 - Area of comparison of the spots calculated and observed end simulation excerpt and cross section example in HEC-RAS
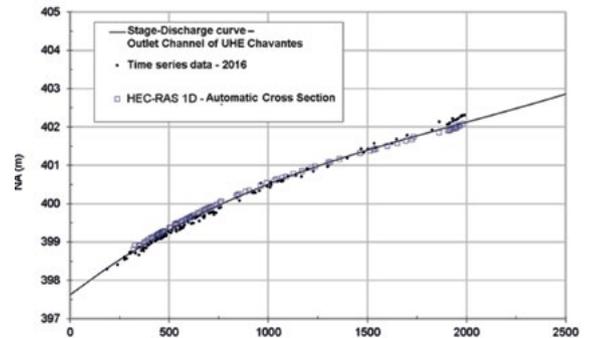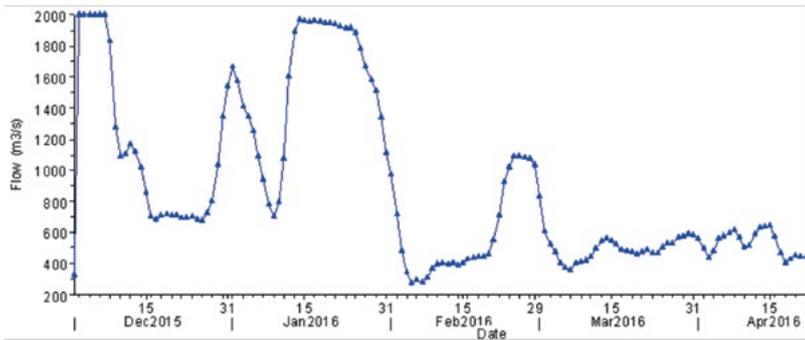
FIGURE 3 - Left: Hydrograph of the observed flood; Right: Model calibration

4.3 ALTERNATIVE CALIBRATION OF THE ONE-DIMENSIONAL MODEL

The alternative calibration of the 1D model included nine simulations with different roughness combinations for the mail channel and flood plains. To link the simulation result with the roughness applied in the cross sections (main and plain) the average of the composite roughness of each section was calculated. The HEC-RAS determines the total transport for each section by dividing the flow in the overbanks using the Manning's roughness values change points, and then sums all the values to calculate a water level in the section. Figure 4 shows the subdivision of the cross-section for the calculation of transport in the HEC-RAS.

The image of the selected valley area has 675,361 pixels and the values N (Negative), FP (False Positive), FN (False Negative) and P (Positive) of each simulation are presented in Table 3.
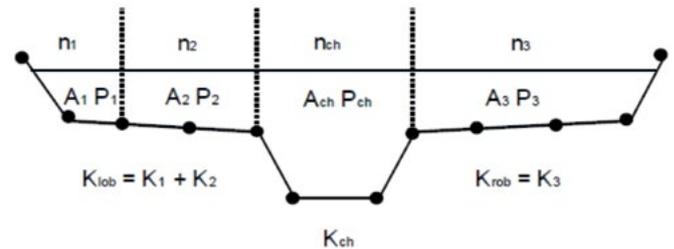

FIGURE 4 - Subdivision of the cross section for the calculation of transport in the HEC-RAS (USACE 2020).

Figure 5 the curves of the ratios between the calculated and observed for flooded and land pixels, and the curve of the Total Absolute Error. The minimum value of the absolute total error curve and corresponding Manning's roughness value (0.058) pointed to optimum calibration (0.7%).

A	B	C	D	E	F	G	H	I	J	K
				Pixel		E/C	F/D	|((C-E)/C)|	|((D-F)/D)|	I+J
Simulation	Roughness average	observed water	observed land	calculated water	calculated land	Calculated and observed water ratio (%)	Calculated and observed land ratio (%)	Absolute water calculation error (%)	Absolute land calculation error (%)	Total Absolute Error
1	0.0127			80343	595018	43.31%	121.47%	56.69%	21.47%	78.15%
2	0.0238			130507	544854	70.36%	111.23%	29.64%	11.23%	40.87%
3	0.0258			135542	539819	73.07%	110.20%	26.93%	10.20%	37.13%
4	0.0269			138548	536813	74.69%	109.58%	25.31%	9.58%	34.89%
5	0.0277	185497	489864	140489	534872	75.74%	109.19%	24.26%	9.19%	33.45%
6	0.0370			160156	515205	86.34%	105.17%	13.66%	5.17%	18.83%
7	0.0552			183515	491846	98.93%	100.40%	1.07%	0.40%	1.47%
8	0.0710			196210	479151	105.78%	97.81%	5.78%	2.19%	7.96%
9	0.0837			203709	471652	109.82%	96.28%	9.82%	3.72%	13.54%

TABLE 3 - Results of the comparison of the calculated and observed spots
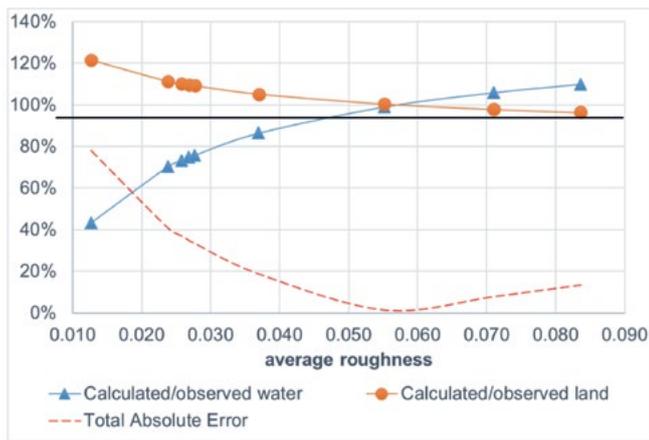
FIGURE 5 - Curves of the ratios between the calculation and the observation and curve of the Total Absolute Error.

4.3 COMPARISON BETWEEN TRADITIONAL AND ALTERNATIVE CALIBRATION RESULTS

The comparison of the results of the two calibration procedures implies larger total absolute errors. The result of the model calibrated by the alternative method showed good adherence at the traditional calibration point and the lowest Total Absolute Error.

Figure 6 (a) shows the comparison of the alternative calibration and the traditional one in the calibration point, with good adherence to the observed water level data, and Figure 7 (b) shows that the result of the alternative calibration at the minimum point of the Total Absolute Error curve (0.57%), while the result of the traditional calibration presented a total absolute error of 33.45 %.

When the comparison is performed between the corrected calculated flooded pixels and the total observed flooded pixels, that is, "positive" pixels divided by the total flooded pixels, the alternative calibration method presented a much better result than the conventional method.

The relationship between the false positive and the observed flooded pixels, which can be interpreted as all wrongly calculated
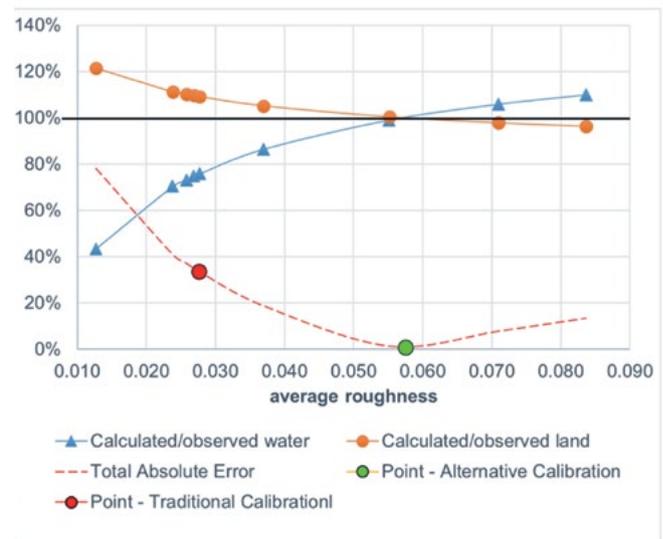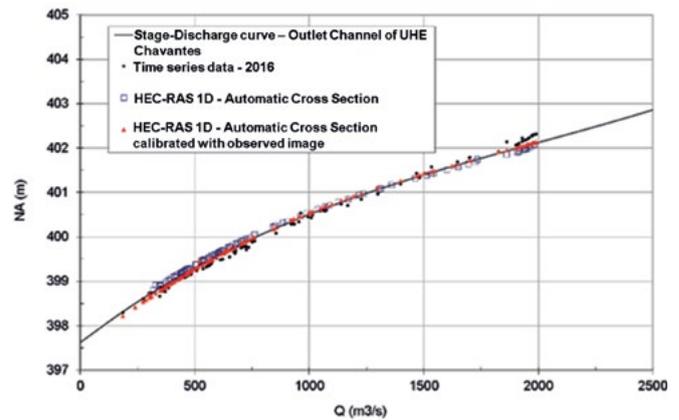

FIGURE 6 – (a) Result of the model calibrated for the Image observed in the ruler of the Trail channel of the Chavantes HUP and (b) for the Image observed in the downstream section of the Ourinhos HUP

flooded pixels divided by the total observed flooded ones shows that the model calibrated by the alternative method misses 21.84% percentage points less than the conventional method. Figure 7 shows the performance of the model calibrated by the conventional and alternative methods referring to the "positive" and "false positive" pixels in relation to the total flooded pixels observed.
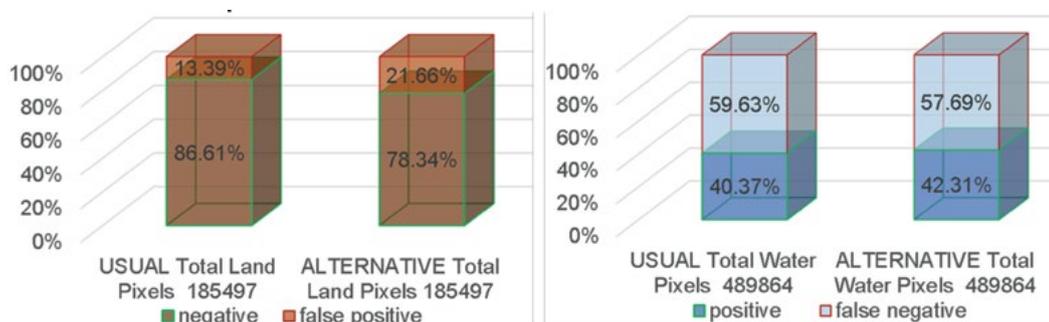

FIGURE 7 – Positive and false pixels positive relative to total observed water

5. CONCLUSION

Mapping flooded areas through a hydraulic model is a fundamental tool to analyze risk and vulnerability of territory due to several hazards as dambreaks and severe natural events. It involves the use of adequate DTM models and observed data as well as he representation of cross sections and correctly positioned obstacles to water flow. Calibration is a mandatory step to assure reliability of the results to prevent the underestimation of flooded areas and false impacts that affects planning and execution of emergence actions. The search for methods to improve model quality results has been an important issue in the last decade due to increasing demand of products to help mitigation of natural and man caused disasters. Emerging sources of spatial high-density information and GIS tools to manipulate data allow modelers to evaluate and enhance the accuracy of the results and minimize errors.

The traditional calibration methods using punctual stage-discharge data are inappropriate to consider water occupation of floodplains and results in unrealistic estimations of water levels and stored volumes, even when a more sophisticated conceptual techniques are applied as 2D or 3D.

The alternative method discussed in this article is a simple procedure that allows the model parameters adjustment based in recursive simulations for different roughness coefficients or other model parameter and the determination of the global or partial optimum value of resulting friction parameter that maximizes P(ositive) pixels and minimize F(alse) P(ositive) ones. The test performed over a real situation showed a significant superior performance when compared to an apparently good performance of the traditional method.

The abundance and availability of high resolution image data, as well as the downward trend in costs for the acquisition of this data due to technological developments and market competition, make the high density data calibration a simple and low cost method. The method can be applied regardless the dimensions used in modelling once the decision variable in optimization is linked to the resistance or friction parameter of the hydraulic model.

The image treatment and manipulation is also a simple and affordable task that can be carried out through open source GIS packages as well as the open use modelling packages like HEC-RAS.

It should be noted that for reliable high density calibration results, each step of the process should be developed with caution, specially the DTM model once each of these steps contributes significantly to a final quality result.

6. ACKNOWLEDGMENTS

7. KEYWORDS

Dam safety, calibration of hydraulic models, high density of observed data, satellite images, LIDAR

8. BIBLIOGRAPHIC REFERENCES

[1] PINOS, J, TIMBE,L. (2019) - "Performance assessment of two-dimensional hydraulic models for generation of flood inundation maps in mountain river basins," Water Science and Engineering, vol. 12, no. 1, pp. 11-18, doi: https://doi.org/10.1016/j.wse.2019.03.001.

[2] GARAMBOIS, P. A. et al. (2017) - "Hydraulic visibility: Using satellite altimetry to parameterize a hydraulic model of an ungauged reach of a braided river," Hydrological Processes, vol. 31, no. 4, pp. 756-767,doi: https://doi.org/10.1002/hyp.11033.

[3] DI BALDASSARRE, G,. SCHUMANN, G end. BATES, P. D. (2009) - "A technique for the calibration of hydraulic models using uncertain satellite observations of flood extent," Journal of Hydrology, vol. 367, no. 3, pp. 276-282, doi: https://doi.org/10.1016/j. hydrol.2009.01.020.

[4] WEDAJO, G. K. (2017) - "LiDAR DEM Data for Flood Mapping and Assessment; Opportunities and Challenges: A Review," Journal of Remote Sensing & GIS, vol. 06, no. 04, doi: 10.4172/2469-4134.1000211.

[5] HUȚANU, E., MIHU-PINTILIE, A., URZICA, A., PAVELUC, L. E., STOLERIU, C. C. and GROZAVU, A. (2020) - "Using 1D HEC-RAS Modeling and LiDAR Data to Improve Flood Hazard Maps Accuracy: A Case Study from Jijia Floodplain (NE Romania)," Water, vol. 12, no. 6, p. 1624, doi: 10.3390/w12061624.

[6] COOK, A. and MERWADE, V. (2009) - "Effect of topographic data, geometric configuration and modeling approach on flood inundation mapping," vol. 377, no. 1, pp. 131-142.

[7] TAYEFI, V., LANE, S. N. R., HARDY, J. and YU, D. (2007) - "A comparison of one- and two-dimensional approaches to modelling flood inundation over complex upland floodplains," Hydrological Processes, vol. 21, no. 23, pp. 3190-3202.

[8] PAPAIOANNOU, G., LOUKAS, A., VASILIADES, L. and ARONICA, G. T. (2016) - "Flood inundation mapping sensitivity to riverine spatial resolution and modelling approach," vol. 83, no. 1, pp. 117-132.

[9] VIDAL, J.-P., MOISAN, S., FAURE, J.-B. and DARTUS, D. (2007) - "River model calibration, from guidelines to operational support tools," Environmental Modelling & Software, vol. 22, no. 11, pp. 1628-1640, doi: https://doi.org/10.1016/j.envsoft.2006.12.003.

[10] WILLIS, T., WRIGHT, N. and SLEIGH, A. (2019) - "Systematic analysis of

uncertainty in 2D flood inundation models," Environmental Modelling & Software, vol. 122, p. 104520, doi: https://doi.org/10.1016/j.envsoft.2019.104520.

[11] PINOS, J., TIMBE, L. and TIMBE, E. (2019) - "Evaluation of 1D hydraulic models for the simulation of mountain fluvial floods: a case study of the Santa Bárbara River in Ecuador," Water Practice and Technology, vol. 14, no. 2, pp. 341-354, doi: 10.2166/wpt.2019.018.

[12] USACE (2020) - "HEC-RAS: River Analysis System - Supplemental to HEC-RAS Version 6.0 Beta - Hydraulics Reference Manual".

[13] FREAD, D. L.(1976) - "Theoretical Development of an Implicit Dynamic Routing Model," ed. Hydrologic Research Laboratory, Office of Hydrology, U.S. Department of Commerce, NOAA, NWS, Silver Spring, MD., presented at Dynamic Routing Seminar, Lower Mississippi River Forecast Center.

[14] SMITH, R. H.(1978) - "Development of a Flood Routing Model for Small Meandering Rivers," ed. Ph.D. Dissertation, Department of Civil Engineering, University of Missouri at Rolla, MO.

[15] BARKAU, R. L. (1981) - "Simulation of the Failure of Illinois River Levees," ed. Memo to File, St. Louis District, Corps of Engineers, St. Louis, MO.

[16] DELFT. (2013) – "Delft3D-FLOW Simulation of multi-dimensional hydrodynamic flows and transport phenomena, including sediments". The Netherlands. [Online]. Available: http://oss.deltares.nl/web/delft3d

[17] ECKHARDT, R. R. (2008) - "Geração de Modelo Cartográfico aplica ao mapeamento das áreas sujeitas às inundações urbanas na cidade de Lajeado / RS" Dissertação de Mestrado - Programa de Pós-Graduação em Sensoriamento Remoto do Centro Estadual de Pesquisas em Sensoriamento Remoto, UFRGS.

[18] GOERL, R. F. et al. (2017) - "O Modelo HAND como ferramenta de mapeamento de áreas propensas a inundar" XX Simpósio Brasileiro de Recursos Hídricos.

[19] RENNÓ et al. (2008) - "HAND, a new terrain descriptor using SRTM-DEM: Mapping terra-firme rainforest environments in Amazonia," Remote Sensing of Environment, vol. 112, no. 9, pp. 3469 - 3481, doi: https://doi.org/10.1016/j.rse.2008.03.018.

[20] NOBRE, A. D., CUARTAS, L. A., MOMO, M. R., SEVERO, D. L., PINHEIRO, A. and NOBRE, C. A. (2015) - "HAND contour: a new proxy predictor of inundation extent - Nobre - 2016 - Hydrological Processes - Wiley Online Library", doi: 10.1002/hyp.10581.

[21] USACE. (2016) - "HEC-RAS: River Analysis System - User's Manual Version 5.0," Davis, CA: United States Army Corps of Engineers.

[22] USACE. (2018) - "HEC-RAS: River Analysis System - Supplemental to HEC-RAS Version 5.0 User's Manual," Davis, CA: United States Army Corps of Engineers.

[23] CASTRO, M. M.C., MARTINS, J. R. S., JACOBSEM, F. R. D. S., da SILVA, T. B., MACEDO, E. P. And LUCCI, R. M. (2013) - "A utilização do modelo Cliv+ como ferramenta para a gestão de segurança em barragens," presented at the XX Simpósio Brasileiro de Recursos Hídricos - 2013, Bento Gonçalves, RS, Brazil.[Online]. Available:https://abrh.s3.sa-east-1.amazonaws.com/umarios/155/6eae72536 20555db5878caeb7c0b453f_661c0776b66d33dcd73d50fb832491bd.pdf.

[24] HOSTACHE, R., MATGEN, P., SCHUMANN, G., PUECH, C., HOFFMANN, L. and PFISTER, L. (2009) - "Water Level Estimation and Reduction of Hydraulic Model Calibration Uncertainties Using Satellite SAR Images of Floods," IEEE Transactions on Geoscience and Remote Sensing, vol. 47, no. 2, pp. 431-441, doi: 10.1109/TGRS.2008.2008718.

[25] DOMENEGHETTI, A. et al. (2014) - "The use of remote sensing-derived water surface data for hydraulic model calibration" Remote Sensing of Environment, vol. 149, pp. 130-141, doi: https://doi.org/10.1016/j.rse.2014.04.007.

[26] HOSSEINY, H., NAZARI, F., SMITH, V. and NATARAJ, C. (2020) - "A Framework for Modeling Flood Depth Using a Hybrid of Hydraulics and Machine Learning," Scientific Reports, vol. 10, no. 1, p. 8222, doi: 10.1038/s41598-020-65232-5.

[27] MARTA, S. (2018) - "Planet imagery product specifications," Planet Labs: San Francisco, CA, USA, p. 91.

[28] LUCCI, R. M.; MARTINS, J. R. S.; MACEDO, E. P, and da SILVA, T. B. (2012) - "Avaliação Altimétrica de Modelos Digitais de Elevação para a Utilização em Estudos de Linha D'água em Canais Naturais," in Anais do XXV Congreso Latinoamericano de Hidraulica, San José, Costa Rica.

··

Rodrigo Martins LUCCI

Civil Engineer, master's degree in Civil Engineering from the Department of Hydraulic and Environmental Engineering of the Polytechnic School of the University of São Paulo with more than 15 years of experience in preparation, management, and coordination of projects in the areas of hydraulics, hydrology and urban drainage. Andspecialist in hydrodynamic simulations, studies of dam rupture and estimation of flooded areas.

Jose Rodolfo Scarati MARTINS

Civil Engineer, Master, PhD and Free Professor in Engineering from the University of São Paulo, he is currently associate professor in the Department of Hydraulic and Environmental Engineering of the Polytechnic School of USP, where he works in undergraduate and graduate courses in civil engineering, environmental engineering and architecture. He is a researcher in the lines of Hydrodynamic Modeling, Urban Drainage and Dam Safety with a focus on three-dimensional hydrodynamic modeling and water quality of lakes and reservoirs, sustainable management of urban drainage, flood risk mapping and dam impact assessment.