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MODELING THE FLOW OF A RIVER USING THE MOHID PLATFORM

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Abstract. *This work presents the basis for a coupled model (precipitation/flow) of the Bengalas River, (Nova Friburgo, State of Rio de Janeiro, Brazil). which is a mountain river that drains a highly urbanized area. Here.was employed the platform MOHID Water Modelling System (MARETEC®), which, so far, had no reported application to mountain rivers. Different scenarios were evaluated in order to assess the platform performance itself. The promising results highlighted the potential of MOHID to simulate extreme events, as those recently occurred in the studied region.*

Keywords: *Nova Friburgo, Water Resources, Watershed, Bengalas River, MOHID*

1. INTRODUCTION

The preservation and proper management of water resources are some of the major concerns of today's society. This management requires a better knowledgement of the characteristics of the water bodies and, particularly for modeling purposes, it, is fundamental a good estimate of the catchment areas and its drainage system. These are essential informations for the generation of different scenarios regarding the impact caused by natural phenomena, as floods and urban floods, which are characterized by high level of water in the river channels after precipitation events in the basin. Muñoz (1997) mentions that in Brazil urban flooding is an increasing problem with severe consequences. Despite that, it is evident that this problem rarely is correctly assigned by the authorities, demonstrating a lack of coordination, beside other difficulties.

The modeling of these natural phenomena necessarily involves the knowledgment of the space and temporal distribution and the rainfall and the associated runoff fluctuations. With regard to runoff in rivers, it can be hydraulically modeled by mathematical models by one, two or three-dimensional approaches. Hydraulic simulations based on Partial Differential Equations (PDEs) are increasingly used for such predictions, such as the work done by Ogden *et al.* (2001), Fleenor and Jensen (2003) and Alcoforado and Cyril (2001). These simulations usually are done in non free sofwares.

This work presents the basis of a modeling of Bengalas River flow, located in the city of Nova Friburgo-RJ. This is a mountain river which drains the most urbanized area of that municipality. Here was employed the MOHID Water Modelling System, which has its source code openly available on the internet. It is noteworthy that studies involving a mountain river and its watershed has not yet been explored through the platform MOHID.

2. CASE STUDY: BENGALAS RIVER, NOVA FRIBURGO-RJ

The municipality of Nova Friburgo is located in the mountainous region of the State of Rio de Janeiro, limited by the geographical coordinates of parallel south $22^o11'$ and $22^o24'$ and meridians of longitude $42^o37'$ and $42^o27'$ (Correia, 2011). This municipality has a surface area of approximately $933km^2$, having an orthometric height of $846m$ at its headquarters. It is drained by three main basins: Grande River basin, Bengalas River basin and Macaé River basin. This work is focused on the Bengalas River basin, which has a surface area of approximately $192km^2$, being located in the most urbanized zone of Nova Friburgo city. The Fig. 1 shows the location map of this watershed.

According to Correia (2011), there are flooding records in Bengalas River basin since Nova Friburgo foundation, which occurred in the year of 1820. However, in recent years, floods have become more frequent and intense. As an example, we have the tragedy in the mountain region of Rio de Janeiro in the month of January 2011, the largest natural disaster ever occurred in Brazil.

Due to the constant occurrence of these events, the State Government of Rio de Janeiro, through the State Environmental Institute (INEA), created the Flood Warning System, in order to monitor the water levels on critical points of a number of cities, including Nova Friburgo. This monitoring is done via telemetry stations that is able to register both precipitation and water level at a time interval of 15 minutes. The Tab. 1 displays the coordinates of the five monitoring stations located within the boundaries of the Bengalas River basin.

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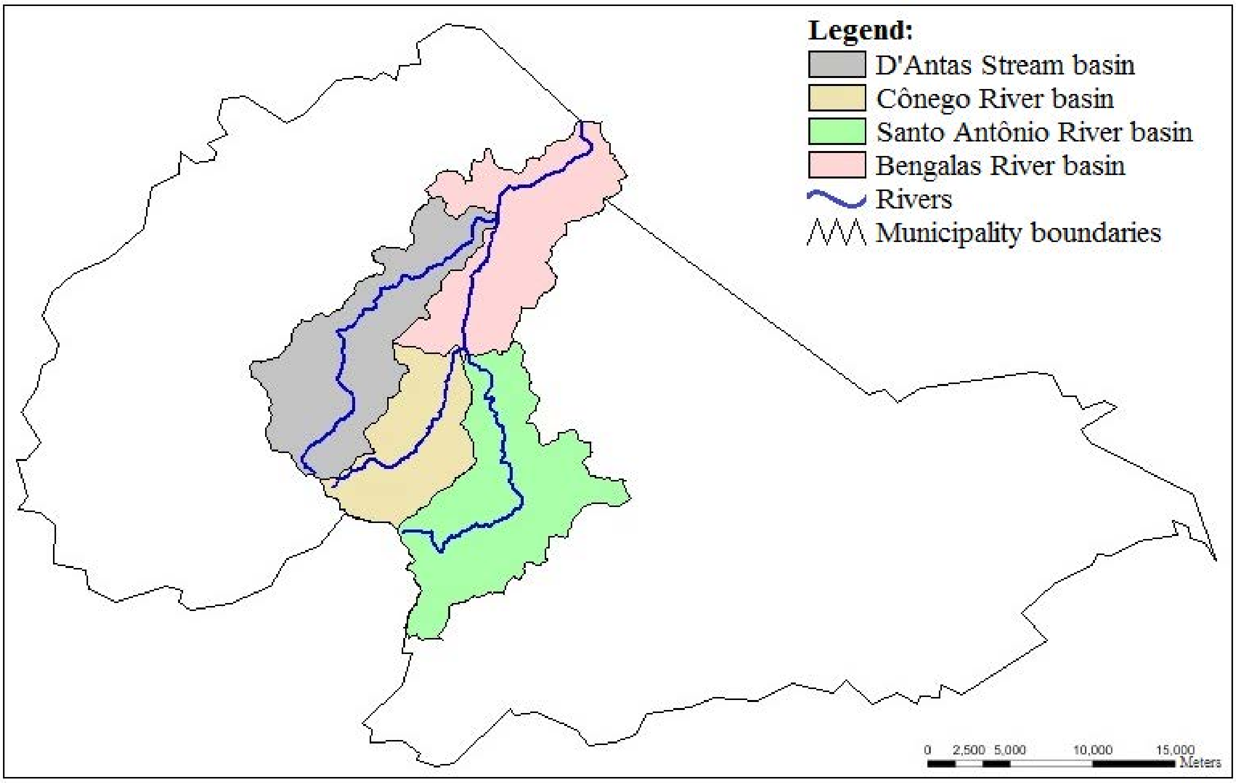

Figure 1. Bengalas River basin and their sub-basins: D'Antas Stream basin, Cônego River basin, Santo Antônio River basin and Bengalas River basin.
Source: The author, 2013.

Table 1. Monitoring stations present in the Bengalas River basin.

Estação	Latitude	Longitude
Conselheiro Paulino	$22^o13'42,47"S$	$42^o31'12,49"W$
Olaria	$22^o18'31,83"S$	$42^o32'31,96"W$
Pico Caledônia	$22^o21'33,11"S$	$42^o34'02,52"W$
Suspiro	$22^o16'46,43"S$	$42^o32'05,36"W$
Venda das Pedras	$22^o16'42,47"S$	$42^o34'53,51"W$
Ypu	$22^o17'45,09"S$	$42^o31'35,41"W$

Source: Flood Warning System (INEA, 2013).

3. THE PLATFORM MOHID

MOHID Water Modelling System is a modeling system developed over 25 years by a large team of technical staff of Marine and Environmental Technology Research Center (MARETEC®) belonging to the Instituto Superior Técnico (IST) and the School of Engineering of the Technical University of Lisbon, having company's cooperation Hidromod Ltda, including contributions from a permanent team of researchers, doctoral students Environmental and Mechanical Engineering Programs, as well as students of Masters in Modeling Environments Marine (MARETEC, 2012).

The development MOHID began in 1985 based on FORTRAN 77, and since then have been subjected to continuous improvement and updating, due to its application in many research and engineering projects. Initially, MOHID consisted of a two-dimensional model forced by tide used in the study of estuaries and coastal areas being resolved by the classic Finite Difference Method (Neves, 1985).

Currently, MOHID is developed in ANSI FORTRAN 95, allowing independence from the operating system (Windows, Linux, Unix, etc.), as well as easy deployment code in any environment (Precious 2010). In addition, this programming is object-oriented and makes use of the finite volume method to solve the equations, allowing the modeling of different physical and biogeochemical processes, as well as of different systems (marine, estuarine and river basins) (Souza, 2010).

This software contains the following numerical tools: MOHID Water (modeling of hydrodynamic processes, simulation of dispersion phenomena, wave propagation, sediment transport, water quality / biogeochemical processes in the water column and exchanges with the background), MOHID Land (watershed model), MOHID River Network (simulation of river networks) and MOHID Soil (water flow through porous media), which are available in MOHID GUI graphic interface (Fernandes, 2005; Braunschweig and Fernandes, 2010; Pessanha *et al.*, 2011).

This work presents results obtained in the MOHID Land numerical tool, which is a numerical model that simulates the processes occurring in watersheds, such as hydrological and biogeochemical processes (Braunschweig *et al.*, 2010). Furthermore, this model is integrated in the MOHID modeling system, incorporating the accumulated knowledge of this system over the years (Neves, 1985; Braunschweig *et al.*, 2004; Braunschweig *et al.*, 2005).

The Fig. 2 shows a schematic representation of the modules simulated in the MOHID Land.

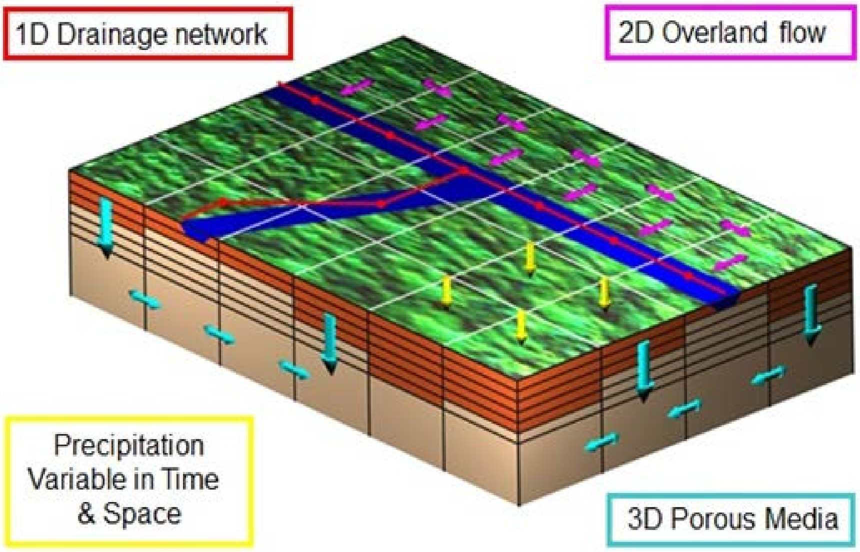

Figure 2. Schematic representation of hydrological processes simulated in MOHID Land: runoff channels that constitute the drainage network (red), runoff (pink), flow in the saturated and unsaturated soil (blue) and variable rainfall in time and space (yellow).
Source: Adapted from Braunschweig *et al.*, 2010.

MOHID Land calculates the channels flows in the drainage network, using an one-dimensional approach (integrated over the cross sectional area) by the means of the Saint Venant equations (Eq. (1)). On the other hand, the runoff in the basin is modeled by a two-dimensional approach (integrated over the depth), being, governed by the wave diffusion equation (Eq. (2)), while runoff in the zone soil makes use of a three-dimensional approach, being governed by the Richard's equation (Eq. (3)) (Braunschweig *et al.*, 2010). The full set of equations adopted in the MOHID Land are

$$\frac{\partial Q}{\partial t} + \frac{\partial}{\partial x}\left(\frac{Q^2}{A}\right) + gA\left(\frac{\partial h}{\partial x} + \frac{Q^2 n^2}{A^2 R_h^{4/3}}\right) \tag{1}$$

$$Q = \frac{A R_h^{2/3}\sqrt{\partial h/\partial x}}{n} \tag{2}$$

$$\frac{\partial \theta}{\partial t} + \frac{\partial}{\partial \overrightarrow{X}} K(\psi)\left[\frac{\partial \psi}{\partial \overrightarrow{X}} + \frac{\partial z}{\partial \overrightarrow{X}}\right] \tag{3}$$

where $Q(x,t)$ is the discharge channel; x and t are the variables of space and time, respectively; $A(x,t)$ is the cross-sectional area; g is the acceleration of gravity $(9.81 m/s)$; $h(x,t)$ is the depth of circulation; $n(x)$ is the roughness coefficient, $R(x,t)$ is the hydraulic radius; θ is the unit of soil; z is the vertical coordinate, in the positive direction from bottom to top; $\overrightarrow{X}$ is the vector containing the variable of position x, y and z, ψ is the hydrostatic pressure and $K(\psi)$ is the hydraulic conductivity.

4. DIGITAL TERRAIN MODEL

To perform the analysis of the hydraulic behavior of the Bengalas River, first was necessary to built the files containing the digital model of the area of interest, which contains the drainage network and the watershed bounded.

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The construction of the drainage network of Nova Friburgo and the delimitation of Bengalas River basin was made in the MOHID GIS graphic interface, version 4.9.2. The topographic information of the municipality were obtained by contour lines with contour intervals of $20m$, being provided by the Municipality of Nova Friburgo (DWG format files). Because MOHID is not able to "read" DWG files, the contour interval in that file were converted to the shapefile format, by mean of the ArcGIS 10 software. Once the shapefile was available, a TIN file was generated, being converted to a raster format with a resolution of 50 x $50m$. Finally, this raster file was exported to ASCII Raster. Figures 3 and 4 present, respectively, the file containing the adopted contours and the raster file.

The ASCII Raster file was imported by the MOHID GIS, being converted into a XYZ Points file, which is necessary to build up the a Hydrologically Correct Digital Terrain Model. These two files gave rise to the digital terrain model. Finally, with a depressions free model, was constructed a drainage network of the city of Nova Friburgo and Bengalas River basin.

The results obtained for the drainage network and Bengalas River basin was also been recreated in ArcGIS 10, by HEC-GeoRAS 10 extension, in order to verify the reliability of the data presented by MOHID GIS. The Figs. 5 and 6 show the comparison of the results obtained both by the MOHID GIS and the ArcGIS 10, as well the monitoring stations present in the Bengalas River basin regarding the constructions mentioned above, , as well the monitoring stations present in the basin mentioned in the Tab. 1.

A more detailed description of the construction of digital terrain model of Nova Friburgo can be found in Telles *et al.* (2012a and 2012b).

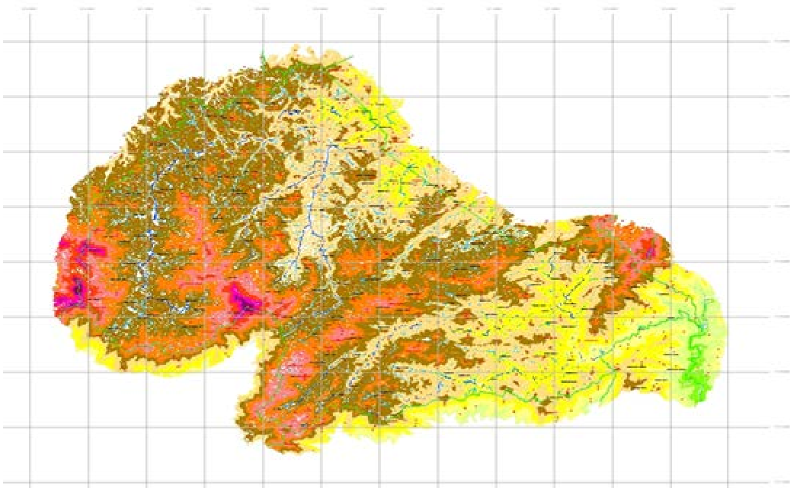

Figure 3. Contours with contour interval of $20m$ containing topographic information of Nova Friburgo.
Source: The author, 2013.

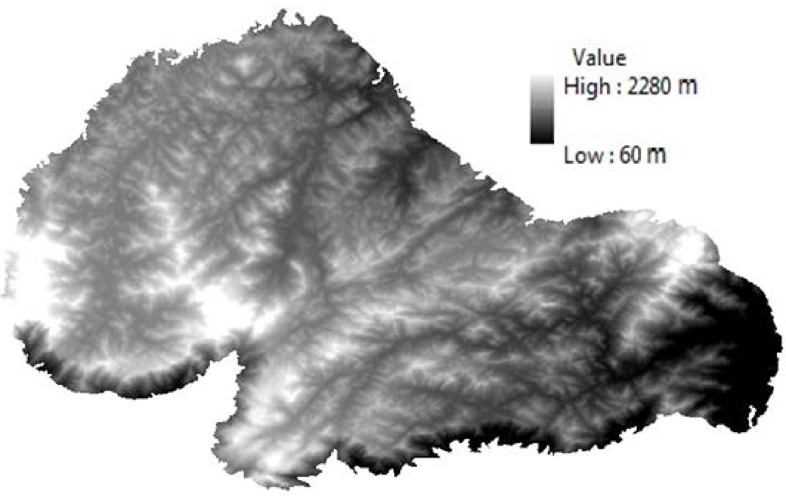

Figure 4. Raster file built in ArcGIS 10 resulting TIN file.
Source: The author, 2013.

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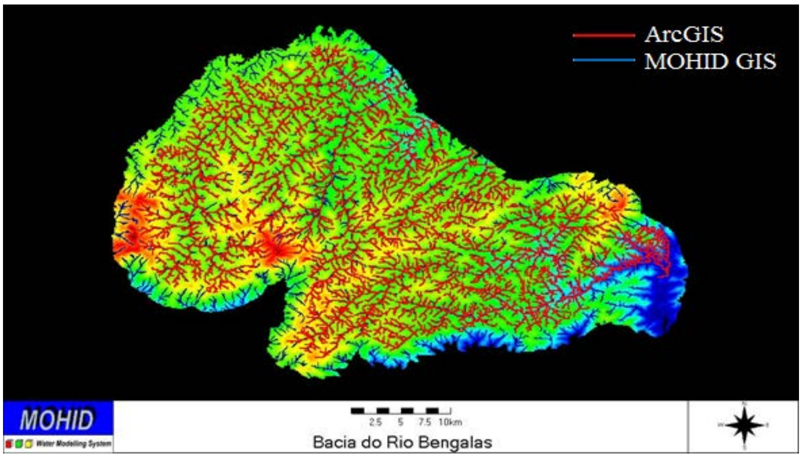

Figure 5. Drainage network of Nova Friburgo built by MOHID GIS and ArcGIS 10.
Source: The author, 2013.

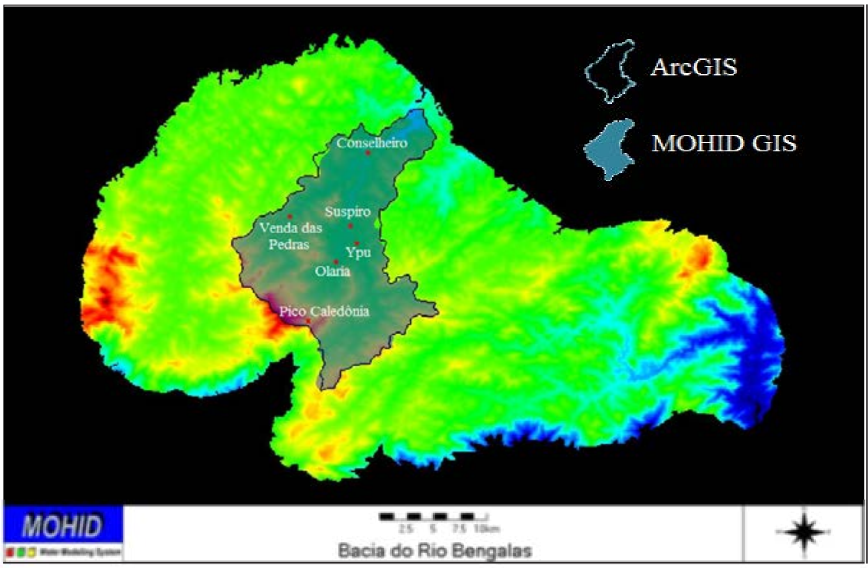

Figure 6. Polygon delimiter of Bengalas River basin built by software MOHID GIS and ArcGIS 10.
Source: The author, 2013.

5. RESULTS

The results of this section were obtained on a computer Core 2 Duo with 1.90 GHz processor and 2 GB of RAM.

Based on the digital model described in Section 4, it was performed the modeling involving some recorded precipitation events in the Bengalas River watershed, in order to assess the MOHID plataform performance to estimate the hydraulic behavior of the Bengalas River concerning flooding events.

For this initial work, we used the available precipitation data for the months of October and November 2012, representative of the beginning of wet season in the region of interest, which has the precipitation peak usually occurring between January and February. Both rainfall (mm), and water level (m) data were obtained from the website of the INEA (http://www.inea.rj.gov.br/). We analyzed three precipitation events, respectively one in October and two in November.

For the first precipitation event, we analyzed the period from 14:00 hours on October 28 to 00:00 hours on October 29. The second one covered the period from 12:00 hours on November 05 to 12:00 hours on November 06, while the third event occurred during the period from 15:00 hours on November 06 to 00:00 hours on November 07. The chosen intervals covered a period during which a relevant water level rising of Bengalas River could be recorded. In the three simulated events, we adopted a 60 seconds time step. With regard to execution time, the first, second and third events had a computational time of, respectively, 2, 11 and 1:30 minutes. Figures 7, 8, 9, 10, 11 and 12 show the time evolution of precipitation and the simulated water level.

In the rainfall data shown in Fig. 7, it can be seen that the greatest intensity of precipitation occurred at the Suspiro

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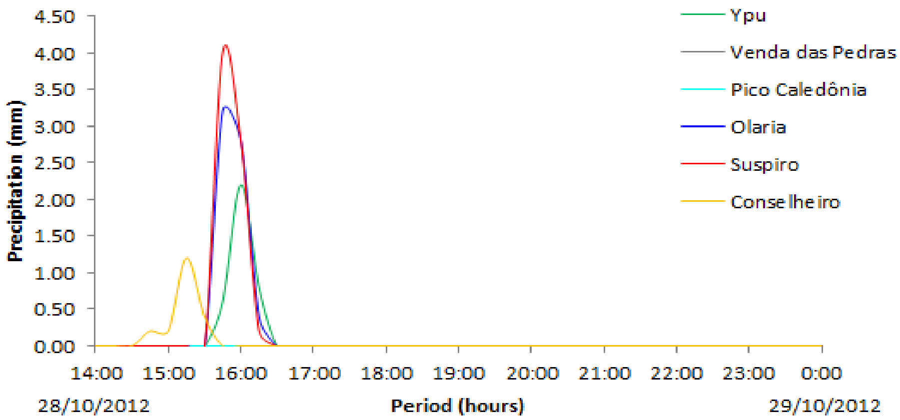

Figure 7. Time evolution of precipitation over the Bengalas River watershed in the period from 14:00 hours on October 28 to 00:00 hours on October 29.
Source: The author, 2013.

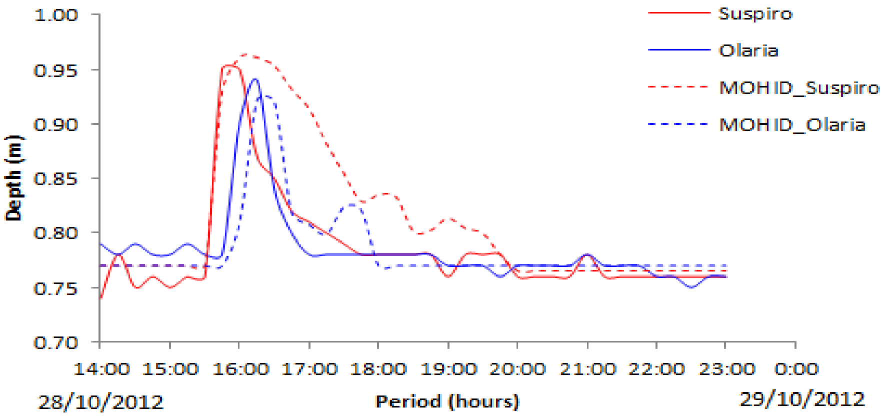

Figure 8. Water level in Bengalas River during the precipitation event occurred in the period from 14:00 hours on October 28 to 00:00 hours on October 29.
Source: The author, 2013.

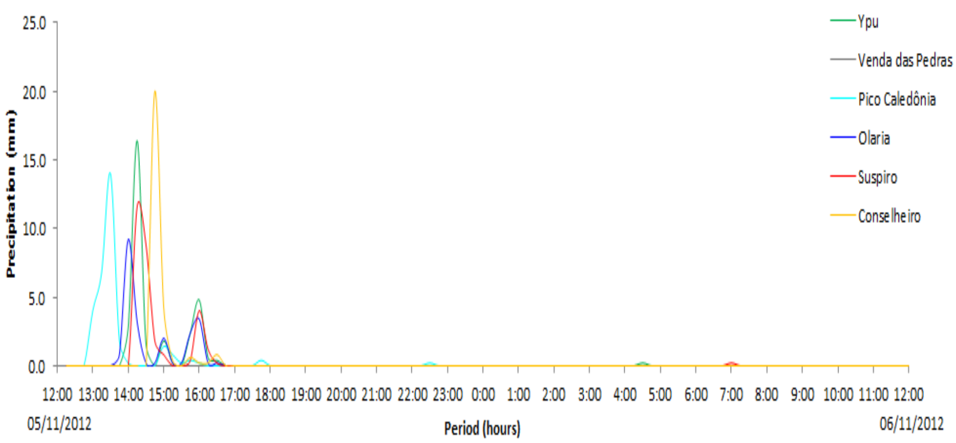

Figure 9. Time evolution of precipitation over the Bengalas River watershed in the period from 12:00 hours on November 05 to 12:00 hours on November 06.
Source: The author, 2013.

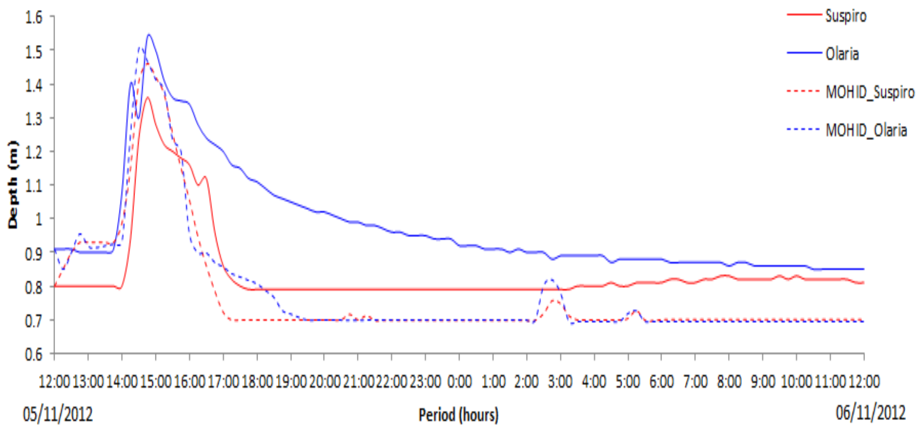

Figure 10. Water level in Bengalas River during the precipitation event occurred in the period from 12:00 hours on November 05 to 12:00 hours on November 06.
Source: The author, 2013.

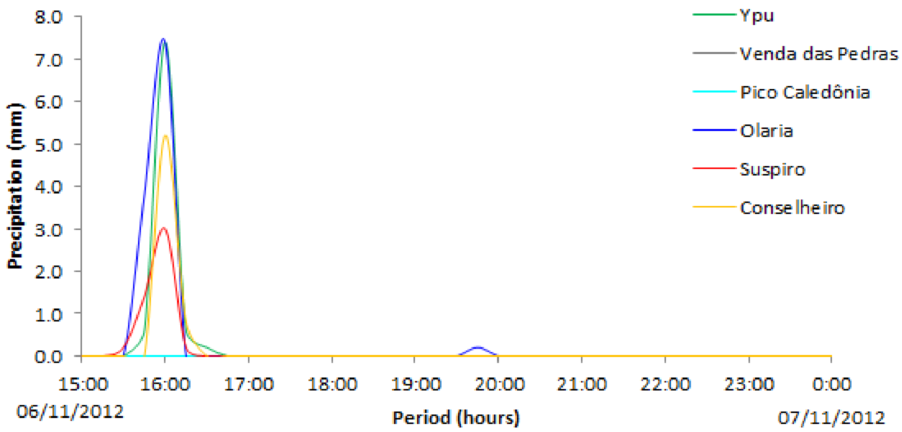

Figure 11. Time evolution of precipitation over the Bengalas River watershed in the period from 15:00 hours on November 06 to 00:00 hours on November 07.
Source: The author, 2013.

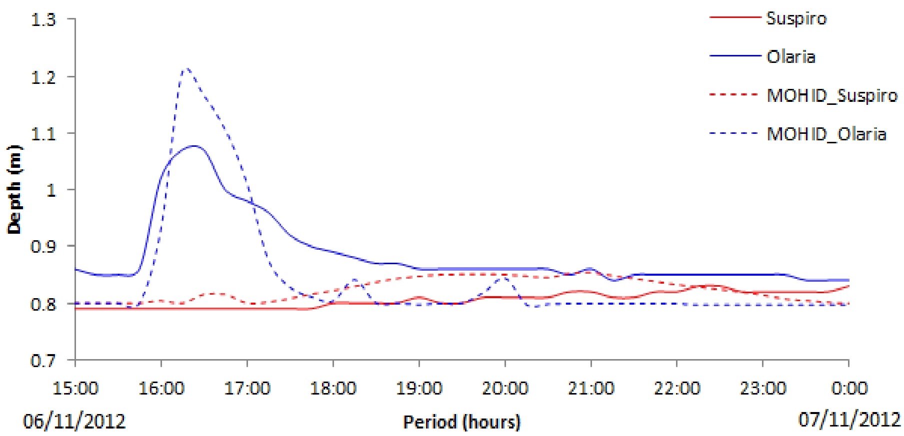

Figure 12. Water level in Bengalas River during the precipitation event occurred in the period from 15:00 hours on November 06 to 00:00 hours on November 07.
Source: The author, 2013.

station and, at the Pico do Caledonia, there wasn't occurrence of precipitation. These events are consistent with the results shown in Fig. 8, where it is observed that the Bengalas river showed higher water level in the Suspiro station than in Olaria. Furthermore, it is observed that the simulation performed in MOHID presents a better fit to the experimental data obtained at the Olaria station compared to water level at the Suspiro station.

In the event of precipitation shown in Fig. 9, there is a greater fluctuation in rainfall occurred between about 13:00 to 17:00 and, unlike what happened in the previous event, the elevations of water level at the Olaria station are larger that occurred in Suspiro. This is due to the occurrence of precipitation at the Pico Caledonia station fact not occurred in the previous event. Furthermore,, the higher cumputacional time spent to carry out the second simulation, in comparison with the other two, can be explained by stability constrains of MOHID, in response to the more intense precipitation occurred in this event, in a way that more interactions were required to stabilize the model.

Already in the third event analyzed, despite the occurrence of rainfall in all pluviometric stations, except at Pico do Caledonia, the Bengalas river showed no significant changes in the water level in the Suspiro station, as seen in Fig. 12.

Here it has to be mentioned that this first modeling approach have not considered any artificial building in the simulated domain, something that could increase the model complexity and certainly would make difficult a better fitting between calculated and observed data.

6. CONCLUSIONS

This work aimed to make the modeling of the hydraulic behavior of the Bengalas River based on precipitation events that occurred in its basin, located in the municipality of Nova Friburgo.

From the results shown in Figs. 8, 10 and 12, it is possible to conclude that modeling performed by the platform MOHID in all three precipitation events show good results, since it was possible to satisfactorily simulate the observed peak flow in some river reaches, despite the simplicities assumed by the model. It is worth to observe that this was the first application of MOHID Land to a mountain river.

Futures works will be focused on quantitative and qualitative assessment of MOHID plataform performance regarding more drastic events as that one observed in Nova Friburgo in January 2011.

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