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# FLOOD ESTIMATION USING INVERSE PROBLEM TECHNIQUES COUPLED TO MOHID PLATFORM

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**ABSTRACT**: In this research the MOHID Waters Modeling System is used in order to predict and analyze the hydraulic behavior of the main rivers that constitute the Bengalas river Basin, located in Nova Friburgo – Rio de Janeiro state, which covers the most urbanized city area. For this, techniques to solve Inverse Problems were used, more specifically, Luus-Jaakola (LJ) and Particle Collision (PCA) algorithms, coupled to the MOHID platform, in order to determine some of the key parameters required to model water bodies and their watersheds. It was used both topographic data from IBGE and also data provided by Nova Friburgo city hall, obtained after the preparation of the Stormwater Plan for the region of interest. With the model calibrated and validated by experimental data it was possible to estimate flooding in this region. It is noteworthy, that this is one of the first applications of MOHID platform to model a mountain river, as well as the first use of inverse techniques coupled to MOHID Land tool. The results were satisfactory as an aid to decision making, based on the prevention of damage caused by elevations of the water level that occurs frequently in Nova Friburgo and also to motivate further studies to improve this approach.

Key Words: Watershed, Nova Friburgo, Inverse Problems, Parameters Estimation, MOHID

## 1. INTRODUCTION

Studies involving watersheds are important because this is natural geographic location we checked the dependence of all components of the growth and development of society and defines the multiple uses of water resources management (Ecoeco, 1996).

Furthermore, according Cordeiro (2010), Brazil has the most extensive river system on Earth, containing approximately 55.500 km2, most of which formed by upland rivers, which have great economic importance because of its potential energy.

In this sense, according to Tucci (1998), the use of hydrological models becomes extremely useful tool because they allow represent, understand and simulate the hydrological behavior of a watershed through the settlement of their cases. These hydrological models are formulated from mathematical equations that describe the spatial distribution of precipitation, interception losses, evaporation, water movement in the soil caused by infiltration, percolation, and out of groundwater, surface runoff, and subsurface the outlets (Rennó, 2004).

A greater difficulty in using these models is related to the calibration. This calibration can be performed manually, which can be a time-consuming method, especially if the model to be calibrated uses a large number of parameters (Kondageski, 2008), or alternatively, these parameters can be determined directly by empirical formulation, or finally can estimated by techniques of inverse problems.

A good estimate of the parameters mentioned above is directly related to a problem that has been gaining attention in the current national scenario: floods caused by rising river levels.

The decision making and consequently the implementation and execution of preventive and palliative measures of the impact caused by the floods, necessarily requires improved management of flood risks, which has been emphasized by the importance of the damage caused by these phenomena – catastrophic in some cases – in recent years (Roux and Dartus, 2008).

Muñoz (1997) mentions that in Brazil urban flooding is a growing problem that causes great damage, since urban drainages, although assignment of municipalities, in most cases, resent the lack of coordination, lack of cooperation population, lack of resources and capacity management, resulting in a lack of priority for this activity.

In this work, it is performed the modeling of the hydraulic behavior of the drainage network of the Bengalas river watershed, which includes the most urbanized area. For the estimation of the parameters necessary to modeling, the Luus-Jaakola and Particle Collision Algorithm methods were used, coupled to MOHID platform. This Inverse Problem approach was not yet found in the scientific literature.

## 2. CASE STUDY

Nova Friburgo is a Brazilian town located in the mountainous region of the State of Rio de Janeiro, limited by the geographic coordinates of the south parallels 22º 11' and 22º 24' and meridians of longitude 42º 37' and 42º 27' (Correia, 2011). It has surface area of approximately 933 km$^2$ and it is 140 km distant from the state capital (Rio de Janeiro). It must be noted that the main part of city has an orthometric height of 846 m.

This municipality is drained by three principal basins: the Grande river basin, Bengalas river basin and Macaé river basin. This paper studies the Bengalas river basin.

The Bengalas river basin has an drainage area of approximately 192 km$^2$ and covers the most urbanized area of the city, having as main water course the river that gives name to it. Its four main sub-basins are: the D'Antas stream basin, Cônego river basin, Santo Antônio river basin and Bengalas river basin.

## 3. DIRECT PROBLEM

The direct problem proposed consists in modeling the hydraulic behavior of the main rivers that make up the Bengalas river basin. For this Saint Venant equations are used with the objective of analyzing rainfall events that occurred in the watershed of interest. They causes the increase in water levels in drainage channels and hence generate waves of floods that affect and provide risks to the population.

Saint Venant equations can be deduced from the Continuity and Momentum equations applied to a control volume within a moving fluid. These equations are formally described as (Steinstrasser, 2005):

$$\frac{\partial Q}{\partial x}+\frac{\partial A}{\partial t}+q=0 \text{ (Continuity)} \quad [1]$$

$$\frac{\partial Q}{\partial t}+\frac{\partial}{\partial x}\left(\beta\frac{Q^2}{A}\right)+Ag\left[\frac{\partial h}{\partial x}-S_0+\left(\frac{Q^2n^2}{R_h^{4/3}A^2}\right)+S_e\right]-\beta q v_x+WB=0 \text{ (Momentum)} \quad [2]$$

where $x$ [m] and $t$ [s] are the spatial and temporal variables, respectively; $Q$ [m$^3$ s$^{-1}$] is the discharge channel; $A$ [m$^2$] is the cross-sectional area; $q$ [m$^3$ s$^{-1}$] is the lateral contribution; $\beta$ [–] is the Boussinesq number; $g$ [m s$^{-2}$] is the gravity acceleration; $h$ [m] is the height of water depth; $S_0$ [m m$^{-1}$] is the slope of the channel bottom; $R_h$ [m] is the hydraulic radius; $n$ [s m$^{-1/3}$] is the coefficient that relates all elements that oppose the resistance of the channel flow, also known as the Manning roughness coefficient; $S_{ec}$ [m m$^{-1}$] is the load loss vortex; $v_x$ [m s$^{-1}$] is the speed of the lateral contribution; $W$ [m$^3$ s$^{-2}$] is the wind resistance coefficient and $B$ [m] is the width of the free surface.

According to Porto (1999), the Saint Venant equations described by Equations (1) and (2) applied to non-permanent flows, require numerical or analytical techniques developed for its solution, and a significant amount of hydraulic channel data especially when applied to natural waterways. In this paper the solution of the Saint Venant equations is given by MOHID platform, where it is solved numerically using the Finite Volume Method.

### 3.1 MOHID Platform

MOHID Water Modelling System is a modeling system developed over 25 years by a team of technical reviewers of Marine and Environmental Technology Research Center (MARETEC), from the Instituto Superior Técnico (IST) and the Engineering School of Lisbon Technical University, and the company's cooperation Hidromod Ltda (Maretec, 2012).

Currently, MOHID platform is developed in ANSI FORTRAN 95 and contains the following numerical tools: MOHID Water (modeling of hydrodynamic processes, simulation of phenomena of dispersion, wave propagation, sediment transport, water quality/biogeochemical processes in the column of water exchange 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 the MOHID GUI graphical interface (Fernandes, 2005).

The MOHID Land tool is a numerical model that simulates the processes occurring in watersheds, such as hydrological and biogeochemical processes (Braunschweig et al. 2010). Each process has its own spatial scales, and the module that calculates the flow in the drainage channels is one-dimensional in the direction of the channel, modeled by complete Saint Venant equations; the module runoff is two-dimensional horizontally ruled by Saint Venant equations in a simplified form (Diffusion Wave or Kinematics equations); and the module that calculates the flow in the soil zone is governed by the three-dimensional Richards equation (Braunschweig et al. 2010).

## 4. INVERSE PROBLEM

The objective of the inverse problem presented in this paper is to minimize the difference between experimental data of water levels present in the main rivers of the Bengalas river basin and their simulated data obtained by MOHID platform, MOHID Land tool. For this, the inverse problem presented here shall be implicitly formulated as an optimization problem, in which one seeks to minimize the sum of squares residuals given by the following equation (Silva Neto and Becceneri, 2012):

$$S(\vec{Y}) = \sum_{j=1}^{Nd} [h_{calc_j}(\vec{Y}) - h_{\exp_j}]^2 \qquad [3]$$

where, $\vec{Y}$ is the vector of unknowns formed by the minimum amount of water present in a cell of the MDT needed to start the flow [m] and the coefficient of roughness of the basin [s m$^{-1/3}$] and drainage network [s m$^{-1/3}$], $Nd$ is the number of experimental data, $h_{exp_j}$ [m] are the measured water levels in the river and $h_{calc_j}$ [m] are the water levels in the river obtained through the solution of the direct problem by means of MOHID platform and its MOHID Land tool.

The estimative of the vector containing the parameters of interest is taken by stochastic methods Luus-Jaakola (LJ) and Particle Collision Algorithm (PCA) with the purpose to minimize the sum of squared residuals, that is Equation (3).

### 4.1 Luus-Jaakola

The Luus-Jaakola (LJ) stochastic method was proposed by R. Luus and T. H. I. Jaakola in 1973 for solving nonlinear programming problems. The central idea of this method is to consider a extensive region of search covering the possible values of variables, and generate random solutions while the search region becomes smaller along the iterations (Luus and Jaakola, 1973).

First, are determined the search intervals for variables to be estimated according to the problem being treated, as well as the amplitude of these intervals, the number of times the search interval is reduced along the iterative process and the factor by which this interval will be contracted. It is still established, the number of possible solutions which will be generated each reduction of the intervals along of the iterative process.

Subsequently, it generates a random initial estimate and begins the iterative process in which the new estimates candidates are generated for solving the problem, based on the best solution found along the iterations. If the new solution is better than the estimate stored, there will be an update of the estimate stored. At the end of this iterative process is obtained by solving the inverse problem.

### 4.2 Particle Collision Algorithm

The Particle Collision Algorithm (PCA) proposed by Wagner Sacco in 2006 is a Metropolis which takes its inspiration in the nuclear particles collision process (Silva Neto and Becceneri, 2012), particularly in scattering and absorption by the same a core target. The particle that hits a nucleus with high fitness is absorbed and has explored its contour. If the particle reaches a region of low fitness, it is spread to another region (Sacco and Oliveira, 2006).

Similar to the Luus-Jaakola method in PCA is necessary to define the search range for the variables to be estimated according to the problem being treated, as well as the number of times that the iterative process will occur where new estimates are generated and evaluated according to the objective function. Moreover, it must also set the number of times that new solutions are generated around the best solution in order to exploit the potentially promising region. Finally, it generates randomly a vector containing initial estimates for each of the unknowns to be worked.

After that, the next step is the iterative process. In this process, it generates a new vector containing the estimates for each parameter of the problem. Subsequently, we evaluate this new solution, if the objective function value obtained is better than the best values already "stored" the parameters are updated and the area around this new solution found will be "mapped" through the generation and evaluation of a certain amount of possible candidates to solve the problem. However, if this new solution generated is not better, the algorithm checks the likelihood of it being accepted anyway. If the acceptance occurs, there is the exploit process its neighborhood, as described above. Moreover, there is no acceptance, a new estimate completely randomly will be generated and evaluated by the objective function in order to verify if it is accepted or scattered again. After this assessment, continuity is given to the iterative process until the number of outer iterations is reached.

## 5. RESULTS AND DISCUSSIONS

The estimation of the parameters of interest in the Bengalas river basin and its drainage network, represented by vector $\vec{Y}$, was based on the analysis of a precipitation event occurred in that region and based on the calibration of the mathematical model using the Luus-Jaakola and Particle collision Algorithm methods coupled to MOHID platform through its MOHID Land tool.

Measurements of precipitation [mm] and water levels [m] of the rivers during the event of interest were obtained directly from the official Rio de Janeiro state INEA site (http://inea.infoper.net/inea/), based on three stations of measurements which this institute installed in Nova Friburgo to register of water levels in the main rivers of the Bengalas river basin. These measurements are made in 15 minutes interval.

Already the Luus-Jaakola and Particle Collision Algorithm methods were configured with 10 external loops and 5 internal loops, while the coefficient of contraction of the search range for the Luus-Jaakoa method was set at 0.2.

In all tests performed here, the search range for the roughness coefficient of the drainage channel was [0.0100; 0.0400] [s m-1/3], for the roughness coefficient of the basin adopted the interval [0.0500; 0.2000] [s $m^{-1/3}$] and the minimum amount of water in the cell was [0.0500; 0.1000] [m]. While the initial water level of the drainage network to start the simulation was considered constant throughout the bed, taking the value of 0.50 meters.

For calibration of the mathematical model was chosen the precipitation event occurred 00:00 hours on January 11, 2011 at 18:00 hours the same day. Table 1 presents the statistical indices, while Figures 1, 2 and 3 shows the fit between the experimental and numerical data obtained after 10 runs the Luus-Jaakola and Particle Collision Algorithm methods, based on the best estimate of these methods.

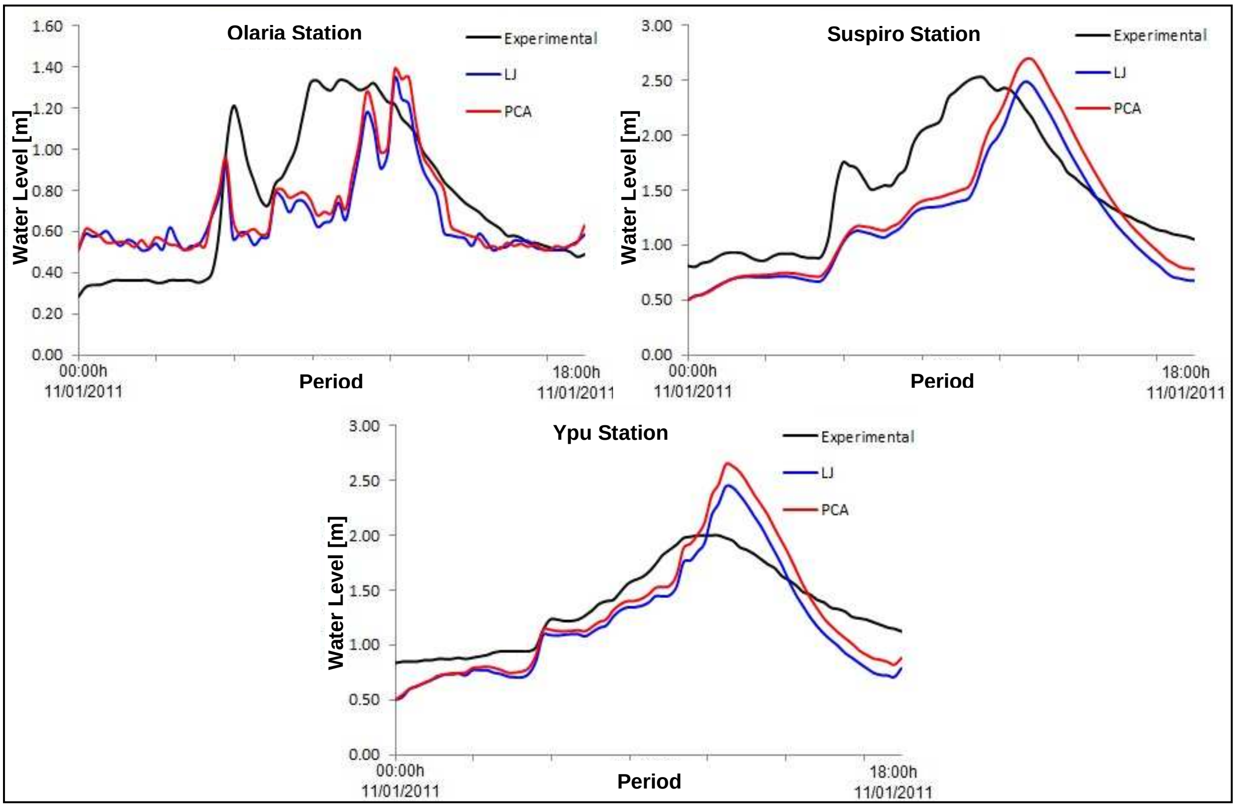
Table 1 – Statistical indices obtained with the estimative of the parameters of interest during the event of January 2011 using the Luus-Jaakola and Particle Collision Algorithm method.

| **Results** | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Indices | Roughness Channel [s $m^{-1/3}$] | | Roughness Basin [s $m^{-1/3}$] | | Minimum Amount of Water [m] | | Residual Equation 3 | |
| | LJ | PCA | LJ | PCA | LJ | PCA | LJ | PCA |
| Better | 0.0261 | 0.0300 | 0.2000 | 0.1544 | 0.0625 | 0.0589 | 41.6138 | 42.9016 |
| Worse | 0.0108 | 0.0030 | 0.2544 | 0.3388 | 0.0515 | 0.0514 | 45.9298 | 46.2883 |
| $\mu$ | 0.0200 | 0.0205 | 0.1831 | 0.1996 | 0.0600 | 0.0574 | 44.494 | 45.4173 |
| $(\sigma\ \mu\text{-}1)$x100 | 6.4258 | 7.4822 | 14.7522 | 16.5359 | 2.7523 | 3.0177 | 6.4950 | 7.0685 |

When one analyzes Table 1, it can be seen that the Luus-Jaakola method had a smaller variation in estimating parameters of interest when compared to the Particle Collision Algorithm.

On the other hand, in Figure 1, it is possible to check that there was a good agreement between experimental data and numerical results obtained by MOHID platform in the model calibration process in Olaria, Suspiro and Ypu stations. It is also verified that there was a small lag in the second flood wave in the Olaria station, a behavior that is repeated in the Suspiro station. The Ypu station has a difference in elevation of the peak of the flood wave.

Figure 1: Adjustment between experimental data and numerical results obtained with a best estimate of LJ and PCA methods in tracking after calibration of the model.




## 6. CONCLUSIONS

This study aimed to determine the minimum amount of water present in the cells of MDT for it to effectively contribute to runoff in the watershed, as well to estimate the roughness coefficients of the canal and basin and its influence on water levels (elevations) in the drainage network of the Bengalas river basin, using for this, the Luus-Jaakola (LJ) and Particle Collision Algorithm (PCA) methods coupled to the MOHID Land tool. These Inverse Problems approaches were not yet used in the scientific literature.

Regarding the calibration of the model, dated 00:00 hours on January 11th, 2011 at 18:00 pm the same day, it is concluded that there was good agreement between experimental and calculated data. However, there was a lag of the flood wave of the values of water depth obtained by Land MOHID tool with the data obtained from INEA.

Analyzing the statistical data shown in Table 1, the roughness coefficient of the basin was had higher standard deviations, while the minimum amount of water is who has the slightest deviation when compared with the other two parameters. This shows that the first parameter is less sensitive compared to the other. In contrast, the minimum amount of water was the most sensitive parameter, where even small changes cause substantial changes in the results.

Regarding the simulation time, it is important to highlight the speed needed to get the water levels in the simulations, where all tests, the runtime of the direct problem was less than 3 minutes and analyzed an event lasting 18 hours. Already the inverse problem is related to the runtime of the direct problem via MOHID platform interface MOHID Land.

Finally, given the results presented in Section 5, it is concluded that the approach involving the inverse techniques achieved a good adjust between experimental data and the calculated by the model, showing to be a promising tool for both the environmental point of view and from the point of view of aid to decision-making in flood events and predictions about the impact that the increase in water depth can cause.

As a suggestion to future works, we plan to perform a more careful analysis of the MOHID Land tool aiming to work with variable values along the canal, in order to improve the simulations, since in this initial approach it was considered averaged values for the parameters in the entire basin.

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