Numerical integrated water flow modelling of Quitite and Papagaio basins applied to erosive processes

Model numérique intégré du débit d'eau des bassins de Quitite et Papagaio apliqué aux processus érosifs

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ABSTRACT: Papagaio and Quitite basins, located in the city of Rio de Janeiro, Brazil are commonly subjected to annual high rainfall rates, which lead to two prevailing natural morphological processes: surface erosion and landslides. Since the basins are topographically mountainous, characterized by shallow soil depth, the landslides phenomenon are triggered normally by individual extreme rainfall events. Taking into consideration the vulnerability of the area during the raining seasons to sheetwash, the surface erosion caused by runoff is a dominant factor in transported sediment rates and constitutes the objective of this study. This article presents, by using Mike SHE software, traded by Danish Hydraulic Institute, an integrated numerical model of surface flow in Quitite and Papagaio's basins to evaluate the flow pattern and potential erosion caused by high velocity water profiles.

RÉSUMÉ: Les bassins de Quitite et Papagaio, situé dans la ville de Rio de Janeiro, Brésil sont généralement soumis à des taux élevés de précipitations annuelles, ce qui conduit à deux processus dominants naturels morphologiques: l'érosion de la surface du terrain et des glissements de terrain. Comme les bassins sont topographiquement montagneux, caractérisé par la profondeur du sol peu profond, phénomène des glissements de terrain est déclenchée par des événements de précipitations individuelles normalement extrèmes. Compte tenu de la vulnérabilité de la zone Pendant la pluie saisons à sheetwash, l'érosion de surface causés par le ruissellement est le facteur dominant dans les taux de sédiments transportés et constitue l'objectif de l'étude. Cet article présente, en utilisant le logiciel Mike SHE, négociés par l'Institut danois hydraulique, un model numérique intégré de l'écoulement de surface en bassins de Quitite et Papagaio pour évaluer le modèle d'écoulement et de l'érosion potentielle causée par des profils d'eau à grande vitesse.

KEYWORDS: water flow, erosion processes, integrated water flow numerical modelling, flow velocity

1 INTRODUCTION

The process of removal and transport of particles on slopes occurs simultaneously and is associated with energy flux (Julien 2010). The great majority of the precipitation events in the Papagaio and Quitite's basins are heavy rainfalls or storms, in which the kinetic energy and the speed of falling raindrops are considerable and able to disaggregate particles in the soil. The limit condition occurs when the sum of acting hydrodynamic forces momentum surpass the forces of resistance momentum (Julien 2010). The topographical surface is the flow boundary layer for surface flow, in which flow velocity, designated as shear velocity tends to zero.

Based on an integrated concept modelling, the numerical simulation of Quitite and Papagaio basins, made under a coupled approach aimed the evaluation of the annual variation of the water level in downstream rivers and the erosive potential of overland flow due to high intensity precipitation, recurrent in Brazil's tropical summer. The model comprises only run-off drained into rivers, since the water flow in porous medium was not simulated due to lack of information and connection with the underground water in some stretches, which would require thorough field investigation for the correct construction of the model. Besides, underground systems have a small effect in the upper and central areas of the basin, therefore, the addition of the saturated module would increase the computational simulation time without incurring in a significant gain in the results accuracy.

Integrated water flow models has received great attention in recent decades, since they are considered by many scientific communities as the controlling processes of the water balance in catchment scale (Kirkby 1991 and Beven 2001). Thus, there is a great effort in the elaboration of numerical models that describe the flux interdependence in different environmental domains, in order to obtain a further understanding of flow path developed in basins.

Freeze and Harlan were pioneers in creating a conceptual and theoretical model (Freeze and Harlan 1969). Later, Govindaraju and Kavvas developed an integrated model that considers the run-off and a one-dimensional channel and a variably underground saturated three-dimensional flow, in order to analyze the response of adjacent saturated local from rivers. Gunduz and Aral solved the problem of underground and superficial flow simultaneously in a single global matrix. Putti and Paniconi worked on numerical issues, verifying the influence of the time step in global convergence in a three-dimensional coupling of porous systems and one-dimensional surface system (Kollet and Maxwell 2006).

The simulated are is a natural region and a community lives in its valley. Flood events followed by landslides have already caused significant amount of deaths and economic damages throughout the past century. In a remarkable rainfall occurred on February 1996, more than a hundred landslides happened and hundred fifty houses were destroyed (Netto Coelho 1985).

Furthermore, the actual climate change patterns and the urbanization advances towards upper reaches of the basins, especially after 1960, have potentially increased the flood risk (Netto Coelho 1985). Therefore, understanding and finding a pattern of hydrological response in areas under intense rainfall rates are subjects of extremely importance.

Other erosion processes caused by water action, such as splash effect, is largely absent at the site of study due the presence of vegetation. Trees and plants allow the interception of water by its leaves and the posterior displacement of the water through the trunks and stems until reaching the ground.

Since pluviometry began to be monitored only after April 2010, the simulated years were 2011, 2013 and 2015, on its rainy season: February, March and April.

1 .1 *Area description*

The studied area is located in Tijuca's massif, Rio de Janeiro between parallels 2255´S and 2300´S and meridians 4320´W and 4310´W and covers an area of 120 km^2 characterized by dense forest at high altitudes, with significant urbanization derived from the city at lower elevations. The drainage flow pattern is radial, connecting the upstream regions with the marine-fluvial-plains and subsequently reaches of lacustrine systems and the sea (Fernandes 2010).

Located in the western part of Rio de Janeiro's city and occupying an approximately area of 5 km^2, Quitite and Papagaio's basins are composed of two main rivers, which are named precisely like the basins. The water path flow between them are mostly parallel, converging to Anil's river in lowers altitudes. The upward reach is characterized by a hilly terrain, whereas, in the downstream, the valley slopes smooth. The complex geology reveals the lithologic types: gneiss archer (50%), quartzite, tonalite, utinga granite, granite and basaltic rocks (Fundação Geo-Rio 1996).

1 .2 *Model description*

Built in a deterministic and distributed concept based on the moment and mass equations, Mike SHE is an integrated water modelling software. It couples with Mike 11 program, responsible for water flow calculation in rivers in a single dimension, solving Saint-Venant equations by finite difference method approximation. The run-off is obtained by an explicit algorithm describing the diffusive wave model. The flow is transmitted from one cell to another following the steepest terrain slope.

For the coupling, it is necessary to build the model in Mike 11 and Mike SHE separately and finally, connect them through links inserted in both programs. For the correct model integration, local coordinates and river sections must be consistent with the entire information specified in Mike SHE (Mike by DHI 2013). In connection with the MIKE SHE, the mapping of the hydrographic rivers network is limited to line geometry located on the boundaries that separate adjacent cells. Flow exchange between superficial flow and rivers occurs naturally by flow pattern defined by surface topography (Mike by DHI 2013).

The digital topographical map used was created from a LIDAR (Light Detection and Ranging) database. The degree of reliability of a surface numerical flow model simulation is directly linked to the quality of topographical data. Therefore, the advance of remote sensing technologies such as LIDAR, has enabled studies in smaller cartographical scales within extensive areas (Liu 2011). LIDAR provides improved information database regarding slope and drainage density (Vianello 2009).

To define manning's coefficient, factors that contribute to increased turbulence were observed, which causes retardation of water flow. For the superficial flow, the table elaborated by Yen and Chow in 1983 was used, taking into consideration the intense presence of vegetation in the region. Whereas for Quitite and Papagaio's rivers manning coefficients, the table developed by Chow in 1959 was used, considering that the site is mountainous, with steep banks and high density of vegetation and the river bed is covered by boulders, pebbles and gravels. These tables, available in literature, summarize the work of several researchers and seek to define a variation pattern of this coefficient.

The extension of the river banks ranged from 2 to 5 meters in Quitite and from 2 to 4.5 meters in Papagaio. The figure 1 shows the river model in Mike 11 coupled into the finite element mesh in Mike SHE.

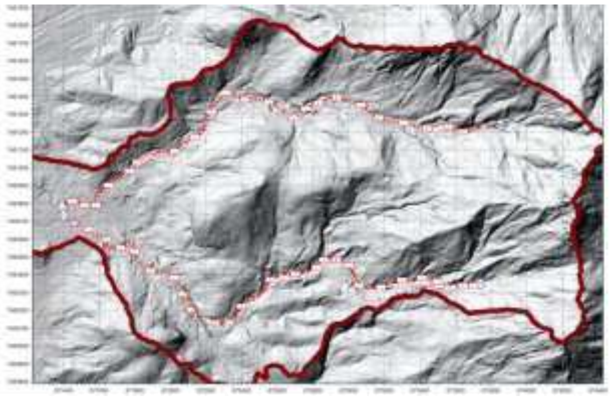

Figure 1. Topographical surface linked with Papagaio and Quitite rivers.

The climate of the region is sub-equatorial. It has commonly rainfall rates higher than average of the municipality of Rio de Janeiro, since it faces the ocean, preventing the movement of cold air masses from the site (Fernandes 2001). The rainfall data was obtained by Alerta Rio system managed by the Rio de Janeiro's city hall. The records are measured in mm / h at an interval of fifteen minutes.

Urbanization of the area is momentarily restricted the lower portion of th3 basin. Thus, human interference was not inserted in this model.

2 RESULTS AND DISCUSSIONS

Table 1 shows the highest rainfall intensity recorded every simulated year, which we highlight the 2011 summer season. Common intense precipitation rate ranges from 65 to 75 mm/h during this time of the year.

Table 1. Maximum measured precipitation of each simulated year

Year	*Rainfall intensity (mm/h)*
2011	163.8
2013	73.6
2015	73.2

The simulated results comprise water flow on surface and channels as well as the flow drained into rivers. Mike SHE program does not calculate flow velocities, necessary for the assessment of erosive processes. However, with the results of flow rate and height of water sheets it was possible to obtain the field velocity distributed in time and space for each cell, shown by the equation 1:

$$\vec{v}_x = \frac{Q_x(m/s)}{\Delta y(m)h(m)} \quad (1)$$

Where v_x is the velocity in the direction of steepest slope, Q_x (m^3/s), the flow rate of the element, h (m), the water sheet height and $\Delta y(m)$ the width of the finite element mesh, which in this case is equivalent to 25 meters.

Based on the table elaborated by Julien 2010, which relates the flow rate with the type and size of transported material, analyses were performed. The figure 1 reproduces de field velocity for the extreme rainfall event in 2011 at the beginning, peak and end of precipitation. During this period occurred transport on the slopes mainly from middle and large gravels. In some regions, marked in green tracks, the calculated velocities are sufficient to transport up of large pebbles. In some isolated points, was registered also values of 6.5 m/s, capable of carrying medium sized boulders.

Due to low velocity flow necessary for removal of fine particles, these are constantly transported by suspension and are accelerated. According to literature, part of transport energy the particles transfer to the sedimented particles on the surface from the contact between them. Thus, the amount of suspended matter increases. Additionally, particles are whirled through the turbulence generated by raindrops (Julien 2010 and Zepp 2014). However, the large-scale erosion demonstrated in the maps is limited to high intensity climatic events, quite frequent in the humid summer the region.

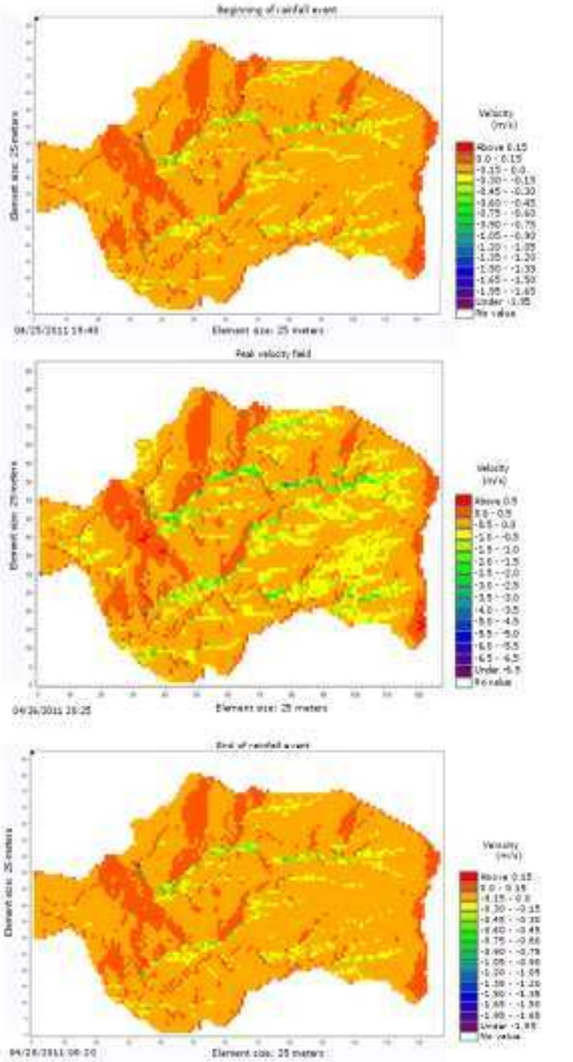

Figure 1. Topographical surface linked with Papagaio and Quitite rivers.

Identifying the critical velocity points, which 6.5 m/s velocity modules occurred, the figure 2 shows the water flow drained from the surface into the Quitite river. The peak flow during this exceptional rainfall in 2011 is approximately 37 m^3/s, while for commonly recorded heavy rainfall, this value reaches no more than 15 m^3/s. On the Papagaio river, flow rates vary up to approximately 3.0 m^3/s.

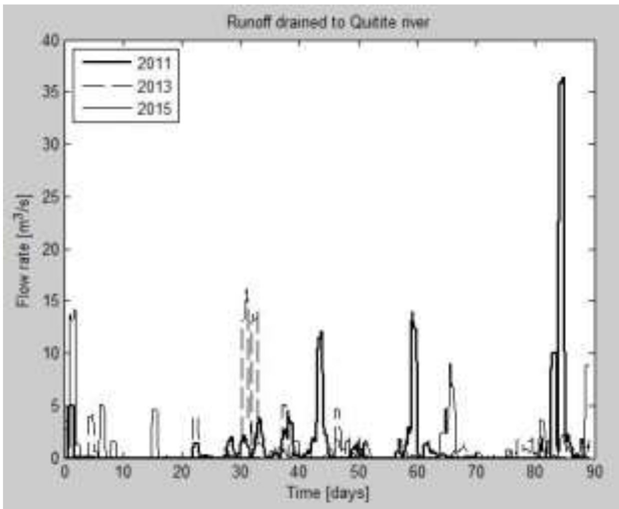

Figure 2. Runoff drained to Quitite river.

The flow in both rivers was analyzed from the variation of downstream water depths during the simulated years. The graphics 3 shows the distribution of water levels. The peak, reached in 2011 was 2.2 meters in Papagaio's river and 1.9 meters in Quitite's river. For other cases of heavy rainfall, these values do not exceed 1.2 meters in Quitite and 1.4 meters in the Papagaio's river.

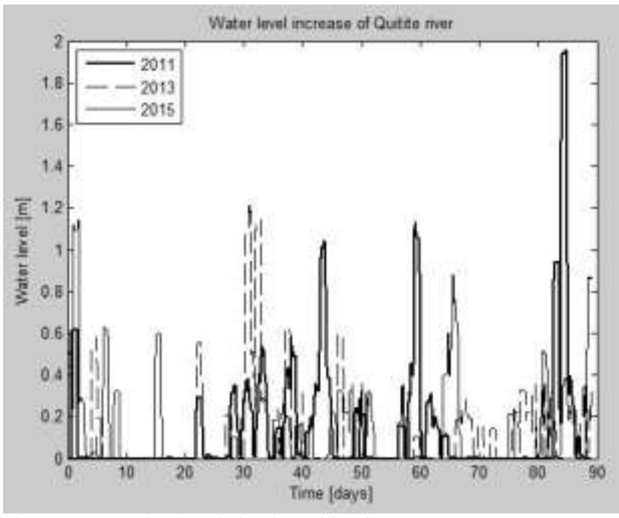

Figure 3. Water level variation in Quitite river.

3 CONCLUSION

The numerical analysis of Quitite and Papagaio basin was made by coupling the surface flow and rivers (Mike 11) module, to analyze the hydrological response of the region during the rainy seasons of the years 2011, 2013 and 2015. The integrated simulation calculated the volume of drained water from the surface into rivers and the erosive processes were evaluated in a qualitative analysis raised by high flow velocities modules. The surface velocity maps provided information on the particle-carrying capacity of the basin by precipitation peaks. Such data are extremely valuable in predicting the impacts of floods and are essential for identification of risk areas. This fact becomes even more relevant in the study area due to community existence downstream of the basin.

The results are based on a first numerical model of the region. The good quality topographical data enabled representation of complex features and relief details in the numerical model. Thus, critical points of flux convergence as well as sites that commonly have peak flows could be identifi ed.

In the years of 2013 and 2015, rainfall rates were very alike, with no precipitation above 100 mm / h. Therefore, the velocity profile was similar. In the peak velocity map corresponding to these years, water flow velocity is capable, mainly, to transport materials up to the range of large gravels. At some points, transport from large to very large gravels also occurs, while other stretches only removal of small pebbles is registrated. Finally, in isolated points, there is transport of large pebbles. This concludes the enormous erosion potential caused by runoff in the region not only during storms, but also during normal peak rainfall rates in the summer, which lies between 65 to 75 mm / h. Due to the fact that it is a region with a mountainous topography, in which there is a subsequent transport of sediments to rivers, the geomorphological processes, as a rule, act in order to make the slopes even more steep.

The integrated simulation allowed the construction of the model as a function of various parameters, and not just one as an individual approach. Furthermore, the coupling between the modules is done explicitly, that is, the equations are solved in different matrices, and therefore it allows process to be represented from different temporal and spatial complexities, being a great advantage for the user. This enhances the model reliability.

Mike SHE coupled approach, implies, however, that for each time step partial differential equations corresponding to every hydrogeological environment are calculated. This required great computational effort and increased simulation time. Besides network coupling caused reduction in the length of the rivers, being necessary an analysis by the user of the possible consequences of it.

The utilization of the diffusive model was positive, because it allowed wide flow depths variations between neighboring cells, feature commonly found in the region, which has abrupt alterations in the topography. However, the nonlinear behavior of the algorithm defined a small-time step for the simulation.

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