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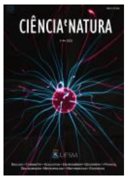

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Geosciences

Hydrological modelling applied to flooding assessment in the urban area of a coastal city in Brazil

Modelagem hidrológica aplicada à avaliação de alagamentos na área urbana de uma cidade costeira no Brasil

Marcos da Silva Lourenço[I], Ariana Paula Pernambuco Mafra[I], Francine de Almeida Kalas[II], Pedro Paulo Gomes Watts Rodrigues[II], Maria Inês Paes Ferreira[I], Jader Lugon Junior[I]

[I] Instituto Federal de Educação, Ciência e Tecnologia Fluminense, campus Macaé, Macaé, RJ, Brasil
[II] Universidade do Estado do Rio de Janeiro, Instituto Politécnico, Nova Friburgo, RJ, Brasil

ABSTRACT

The urban region of many coastal municipalities is marked by the growing process of urbanization of its marine river plain and presents great challenges related to the drainage of rainwater. This study seeks to verify the influence of the flood wave, coming from the upper part of the Macaé River hydrographic basin, in the flooding of the urban area, using MOHID platform, Land module, for the hydrodynamic simulation. The municipality of Macaé, located in the north of Rio de Janeiro (Brazil), has a dense network of tributary channels, built to drain more quickly the waters that accumulate in the floodplains during the rainy seasons. The current configuration of this system is insufficient to reconcile the current land use and runoff, and the floods impose several economic losses. Given this scenario, the Hydrographic Basin Committee of the region, through its Water Resources Plan, recommended studies on the theme, pointing out the need for a more detailed topographic description. The results of the model were compared with a rain that occurred in March 2018, which caused flooding in various points of the urban area. The methodology used can be applied in other municipalities with the same need.

Keywords: Flooding simulation; Hydrodynamic model; Hydrology; Macaé river

RESUMO

A região urbana de muitos municípios costeiros é marcada pelo crescente processo de urbanização de sua planície fluvial marinha e apresenta grandes desafios relacionados a drenagem de águas pluviais. Esse estudo busca verificar a influência da onda de inundação, proveniente da parte alta da bacia hidrográfica do Rio Macaé, na inundação da área urbana, utilizando a plataforma MOHID, módulo Land, para a simulação hidrodinâmica. O município de Macaé, situado ao norte do Rio de Janeiro (Brasil), possui uma densa rede de canais tributários, construída para drenar mais rapidamente as águas que se acumulam nas várzeas durante as estações chuvosas. A configuração atual desse sistema é insuficiente para conciliar o uso atual do solo e o escoamento, e as inundações impõem várias perdas econômicas. Diante desse cenário, o Comitê de Bacias Hidrográficas da região, através de seu Plano de Recursos Hídricos, recomendou estudos sobre o tema, apontando, sobretudo, a necessidade de uma descrição topográfica mais detalhada. Os resultados do modelo foram comparados com uma chuva ocorrida em março de 2018, que ocasionou inundações em vários pontos da área urbana. A metodologia utilizada pode ser aplicada em outros municípios com a mesma necessidade.

Palavras-chave: Simulação de cheias; Modelo hidrodinâmico; Hidrologia; Rio Macaé

Abbreviations

Integrated Watershed Resources Management – IWRM
River Basin Management Plans – RBMP
Hydrographic Region VIII – RH-VIII
Hydrodynamic Modeling – MOHID
Technical Superior Institute – IST
Digital Terrain Model – DTM
Cadastral Digital Plan – CDP

1 INTRODUCTION

Water resources management is a complex matter that involves multiple water uses linked to diverse interests and objectives of different stakeholders (Taha *et al*., 2019). To deal with such complexity, Brazilian Water Law (Lei 9433/97) establishes deliberative watershed committees composed by public, non-governmental and water users' sectors representatives as the locus of integrated watershed resources management (IWRM), and five management instruments, among which we can highlight the River Basin Management Plans (RBMP). A RBMP shall include a series of programs and management actions aiming to promote quali-quantitative water available to all intended water uses within the basin, comprising management actions aligned to continuous provision of ecosystem services parallel to human well-being (Terrado *et al*., 2016).

Starting from different scenarios, the RBMP of the Hydrographic Region VIII of the state of Rio de Janeiro (RH-VIII) was elaborated in a participatory process, between 2011 and 2014, in accordance to the principles of Brazilian Water Law, thus constituting one of the legal regional bases for water uses regulations and for other public policies, such as sanitation and land occupation plans.

The RH-VIII covers the Macaé River Basin, the Ostras River Basin, the Imboassica Lagoon Basin, and other small coastal creeks and wetlands as described elsewhere (Ferreira *et al*., 2018). Encompassing a preliminary cost analysis, the RH-VIII's RBMP proposes interventions to promote ecosystem recovery and water conservation, necessary to guarantee the multiple water uses of the regional river basins. The developed plan contains a diagnosis of 2012 current regional situation from which the necessary interventions to guarantee the quantity and quality of water and its multiple uses were delineated. Among the several reports that made up the final published version of RH-VIII's RBMP, the Flood Report Appendix stands out, and presents a review of the main previous studies on the subject, highlighting Macaé river watershed (INEA, 2012, 2013, 2014).

Macaé river watershed covers partially three municipalities (Nova Friburgo, Casimiro de Abreu and Carapebus) and totally Macaé municipality, supplying more than two hundred thousand people and all Campos Basin petroleum production facilities with water. In the 1960s, a series of retilinizations in water courses in the Macaé river Basin lower course was promoted, intending to reduce floods and drain wetlands, but areas with high flood risk still exist (Jeronymo *et al*., 2016).

In the scientific literature many studies using geotechnologies which aim to understand the problem and to propose solutions to mitigate flood events in urban regions are found (Trancoso *et al*., 2009, Cabral *et al*., 2014; Jeronymo *et al*., 2016; Oliveira *et al*., 2017; Simionesei *et al*., 2018, Tavares *et al*., 2019, Santana *et al*., 2021, Sales *et al*., 2021).

Thus, considering the actions described in the strategies of implementation of the RH-VIII's RMBP, this work aims to offer contributions to be incorporated into the plan's actions named "Proposal of structural interventions for flood control - H1" and "Proposal for non-structural interventions aiming to mitigate the impacts of flood - H2" (INEA, 2014). A literature survey on flood legislation applied to the State of Rio de Janeiro was performed by Silva *et al*., 2021.

The objective here is to verify the influence of the flood wave, coming from the upper part of Macaé river basin to the flooding of the urban area, through the use of a computational model. To implement the hydrodynamic model of the region with the tide variation and with the occurrence of extreme events of rainfall, the MOHID platform (Land module) was applied.

2 METHODOLOGY

2.1 Study area

The city of Macaé, RJ, is located in RH-VIII, which also includes part of the municipalities of Carapebus, Conceição de Macabu, Casimiro de Abreu, Nova Friburgo and Rio das Ostras (Figure 1) (CBH Macaé, 2018). This region concentrates the largest petroleum industrial park in the State of Rio de Janeiro. Located in its lower part, the city of Macaé, concentrates a large part of the coastal urban population that works for the sectors that support oil industry activities (INEA, 2018). In this context, the Macaé river basin suffered a significant increasement of land use in urban areas, resulting in problems of water supply and also with events of flooding to people, besides problems with erosion and rivers silting.

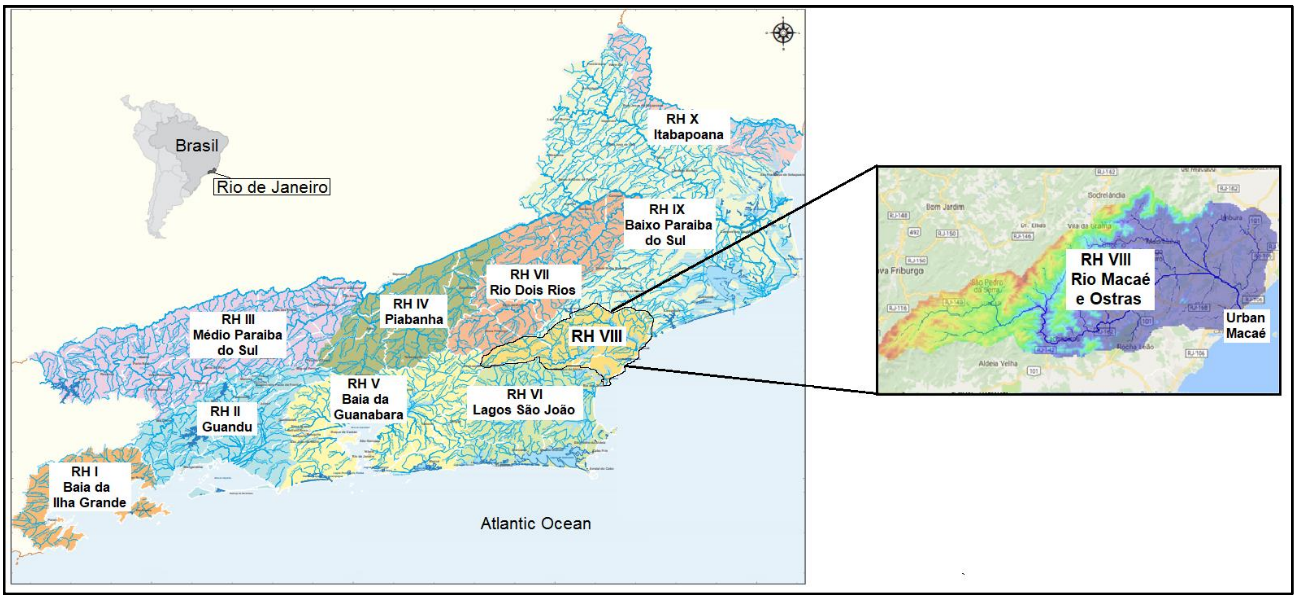
The RH-VIII's RBMP is now in its implementation phase. According to the RH-VIII's RBMP the main factors that contribute to the flooding of the urban area of Macaé city are:

a) The accumulation of water in the floodplains present in Macaé city urban areas, caused both by high rainfall in the upper part of the basin (mountain region) and by the difference of slope when the urban areas' river reaches, resulting in a water flow from a steep slope to an almost null profile (Assumpção and Marçal, 2012; Tavares *et al.*, 2018).

b) The typical soil of the region - gleissolo - is characteristically a soil of low permeability and is usually associated to the occurrence of sub-outcrop of water tables (Mendonça-Santos *et al.*, 2003; INEA, 2013).

c) The cyclical variation of sea level, by tides, affecting the flow of floods (Amaral *et al.*, 2004; Tavares *et al.*, 2018).

Figure 1 - Hydrographic region (RH-VIII) of Macaé and das Ostras Basin, with highlight of urban area and Macaé river. Maps adapted of Tavares (2017) and INEA (2018)



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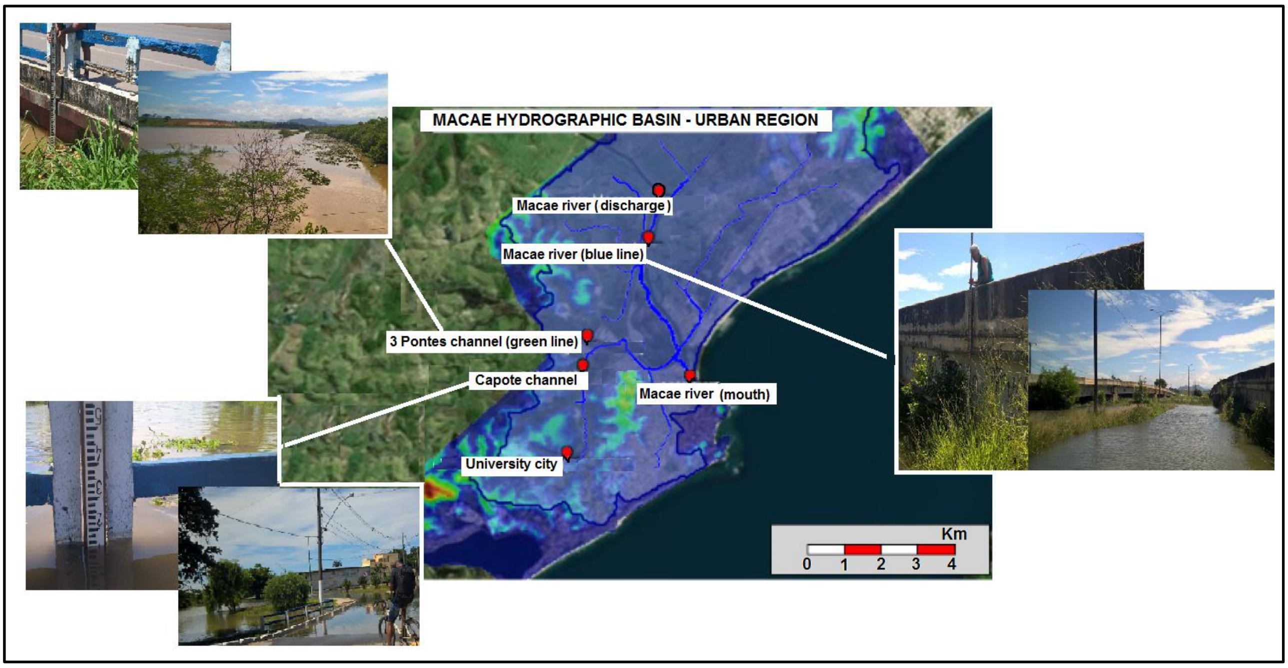
2.2 In situ measurements

Water level measurements were taken in some river sections in the urban area of the Macaé river basin in two different periods: March, 2018, after an extreme precipitation event (at quadrature tide); and May, 2018, after a long period without rain (at syzygy tide). The measured stations are presented on Figure 2.

Figure 2 - In situ measurement positions at urban region of Macaé hydrographic basin



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2.3 MOHID plataform

The MOHID (Hydrodynamic Modeling) is a three-dimensional hydrodynamic model, developed in ANSI FORTRAN95, with object-oriented language, which has been developed since the 1980s by the research group of the Technical Superior Institute (IST) of Portugal. This system of hydrodynamic modeling allows the simulation of different physical and biogeochemical processes in water bodies by means of the finite volume approach in the computation of state variables and flows (MARETEC, 2012).

The Land module is responsible for the simulation of hydrological processes in river basins (Braunschweig, 2004). This module simulates the surface runoff, the drainage network and the porous medium (unsaturated zone of the soil - above the water table and saturated zone of the soil - aquifer). The interaction between the different processes is dynamically calculated through hydraulic gradients, where each process has its own spatial scales (drainage network - 1D, surface flow - 2D and porous medium - 3D), each one can be simulated independently or combined with each other (Simionesei *et al*., 2015; MOHID, 2018).

The construction of the hydrological model in the MOHID Land module requires some steps to be performed, such as the creation of a digital terrain model (DTM), the design of the basin drainage network and the adjustment of the hydrological parameters. The DTM is the mathematical representation of the spatial distribution of the terrain altimetric values associated with an actual surface. After the definition of the DTM, the MOHID is able to automatically generate the drainage network of the hydrographic basin (Trancoso *et al*., 2009; MOHID, 2018).

2.4 Implementation of the topographic basemodel

The application of the proposed method is feasible when it has a topographic base with adequate resolution to produce a hydrodynamic model in whose waterways are as close as possible to reality. Thus, the studies were started with a first analysis of the Cadastral Digital Plan (CDP) 1:2000 of the urban area of Macaé, in AutoCad® (Figure 3), isolating the layers that represent the topography (level curves and quoted points), as well as the hydrography and street construction, since these are the elements that interfere objectively in the construction of the DTM and drainage network.

The initial analysis of the Macaé CDP 1:2000 allowed the adoption of some hypotheses, such as:

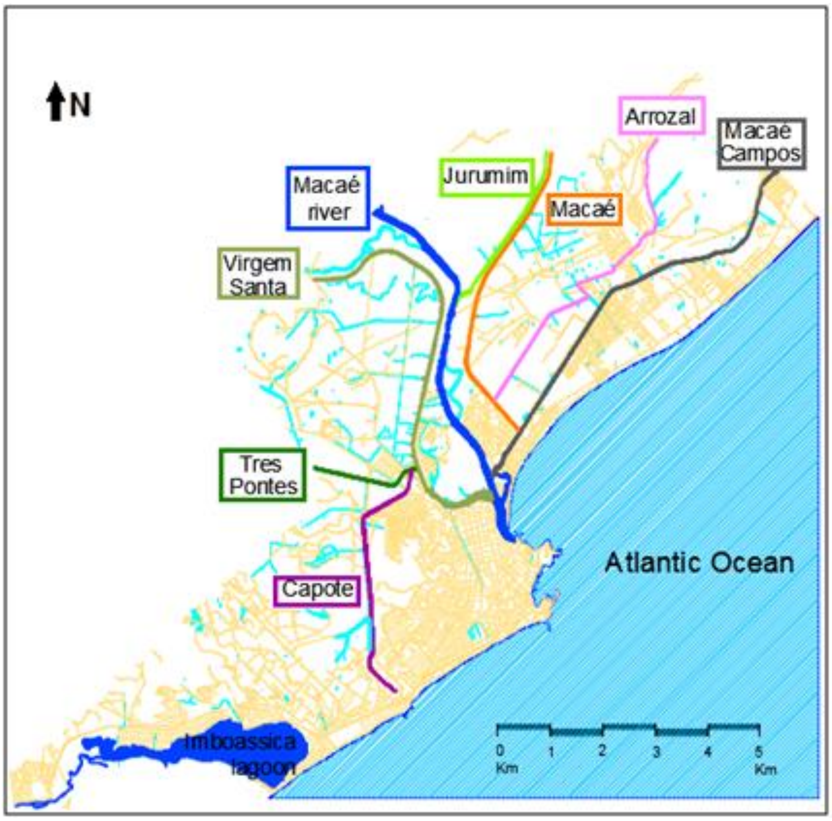
Since the plain topography is defined basically with quoted points, they would be enough to describe the topography in order to build the DTM.

Some meanders that disappeared after the river rectification were disregarded, although they could still function as communicating vessels between the rectified or built channels during actual flood events.

The drainage ditches branches of urban hydrographic network were disregarded in the hydrodynamic model due to their small flow capability during floods associated with severe rainfall events.

The model domain is shown in Figure 3, where are presented the Macaé river, the streets and the channels (Jurumirim, Arrozal, Macaé Campos, Virgem Santa, Três Pontes and Capote).

Figure 3 - Macaé CDP 1:2000, with principal channels (colors) and streets (orange) identified in AutoCad@ for the urban area of Macaé (RJ)



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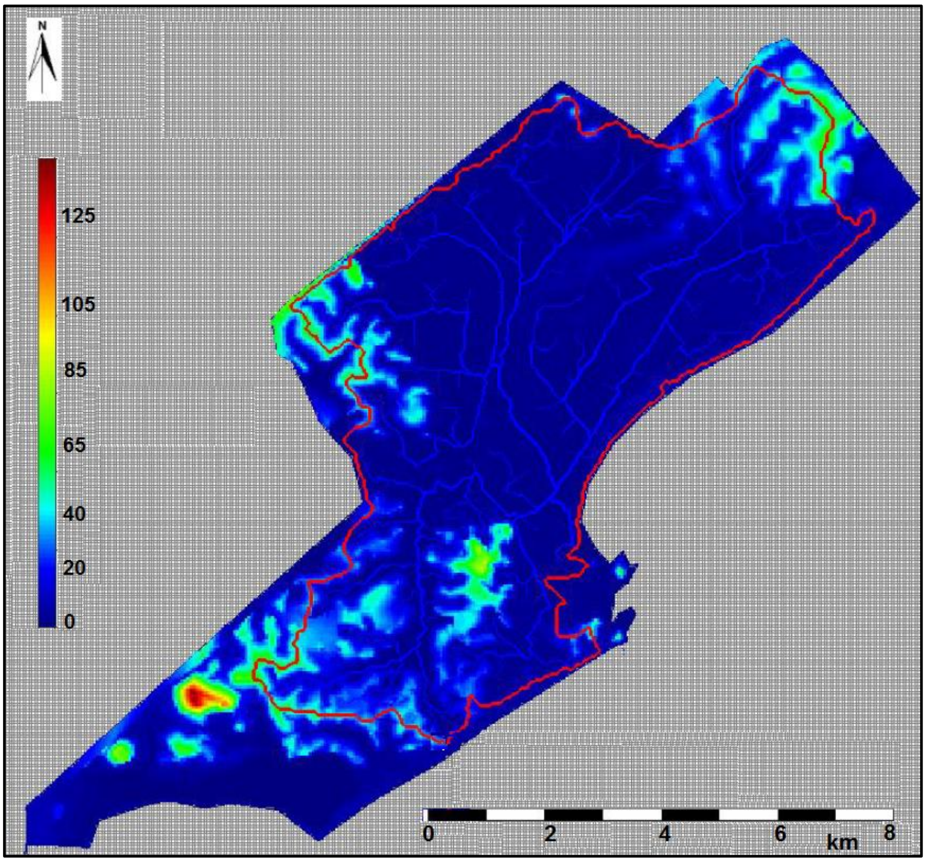
Based on the above hypotheses, the Macaé CDP was edited in order to remove the quoted points on bridges and culverts, among other depressions, to feed the MOHID Land simulator with the altimetric data.

2.5 Hydrodynamic model

The implementation of a hydrodynamic model in the urban area of Macaé can be synthetically subdivided in three groups of data: (i) the topographic basis where the phenomenon occurs; (ii) the forcing data to the hydrodynamic flow; and (iii) the specific conditions of simulation process.

Figure 4 - Construction of Macaé DTM in MOHID GIS tool



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The topographic basis conveniently edited in AutoCad® was implemented by GIS tool of MOHID platform and allowed the construction of a consistent DTM (Figure 4). For the drainage network design, it was necessary to assign the dimensions of the cross sections in each order adopted in the network of channels generated by the drainage system. In this way, the Macaé CDP (1:2000) was analyzed together with the region image in Google Earth©, in order to build the respective average widths for the three orders of channels defined for the drainage network. Fixed depths were assigned based on the mean depth of 2.40 meters of section SM 6 presented in Amaral (2003).

After producing the DTM and the drainage network of the Macaé river basin, for the construction of the hydrodynamic model the following additional considerations were made: severe events of rainfall were applied to model the flow on the basin; eventual occasional events of erosion or sedimentation in channel bed did not cause time variation in its geometry; and no singularities were causing narrowing of the channels.

The flows in the upper part of the basin (upstream of the Macaé city) were calculated according to the hydrodynamic model proposed by Tavares *et al*. (2019), in which the meteorological input data consisted of a 10-years project rainfall. The obtained data were applied according to a previous urban area flood study (Lourenço *et al*., 2018). The hydrograph is shown on Figure 5.

In the urban region, near the river estuary, downstream the Macaé city, the hydrodynamic model was forced by tide variation. The tide levels were calculated in the simulator using the prediction of the astronomical tide as input data (presented in Figure 6).

Figure 5 - Hydrograph for 10-years project rainfall in Macaé urban area for March, 2018

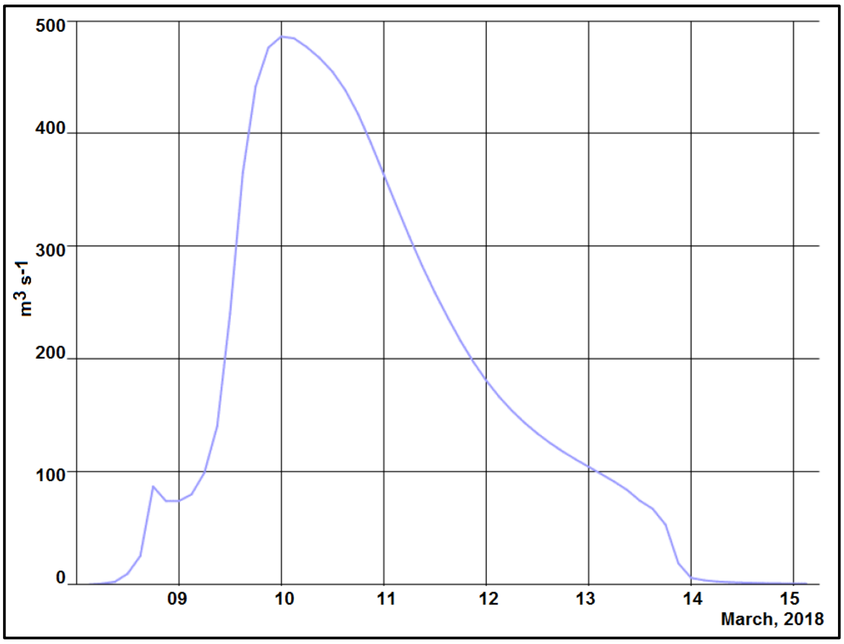

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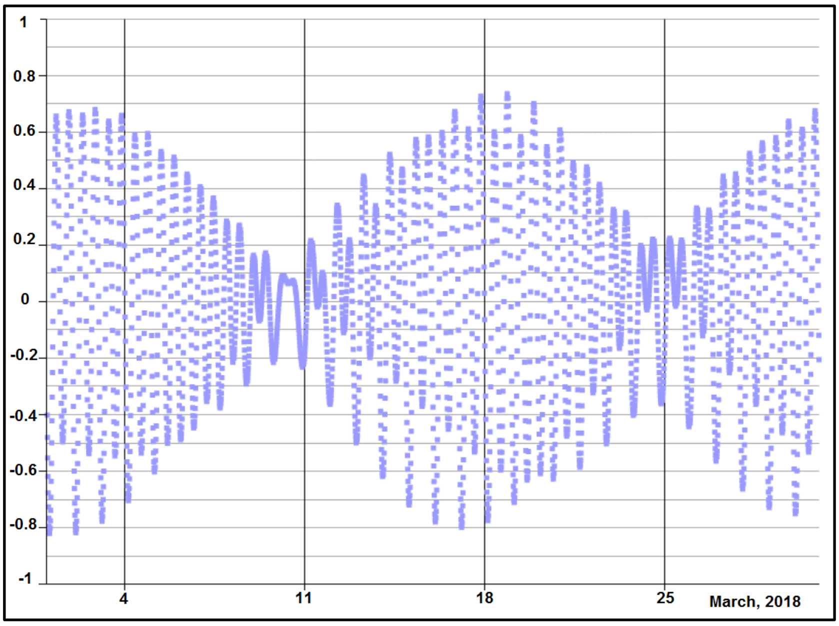
Figure 6 - Astronomic tide representation in March, 2018



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3 RESULTS AND DISCUSSION

3.1 Influence of the tide in the hydrographic network

In order to evaluate the behavior of the tidal variations in the water levels along the sections of the drainage network of the Macaé river, two simulations using two different time series representing, respectively, tidal elevations for syzygy and quadrature events were made done. The latter was implemented artificially relocating measurements to the same dates used for the syzygy, in order to allow the comparison of their effects in the same flooding event.

The model was implemented covering the period in which an extreme precipitation event occurred (March 10, 2018), causing flooding in the city. The absence of discharge originated from the continent was considered.

The simulated results for the water level were evaluated in two virtual stations, situated, respectively, upstream the urban region (Macaé-discharge) and on the river mouth (Macaé-mouth). These results are shown on Figures 7 (neap tide scenario) and 8 (spring tide scenario). As expected, the spring tide scenario presented a higher water level amplitude when compared to the neap tide scenario. Besides, the model was capable to reproduce the expected cyclic behavior of water level, essentially guided by the tidal oscillation.

Figure 7 - Results of the water level in the sections of the Macaé river, with quadrature tide

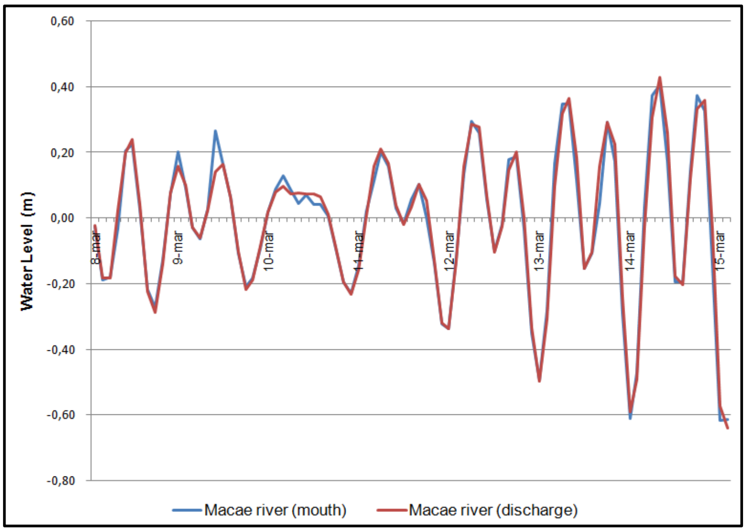

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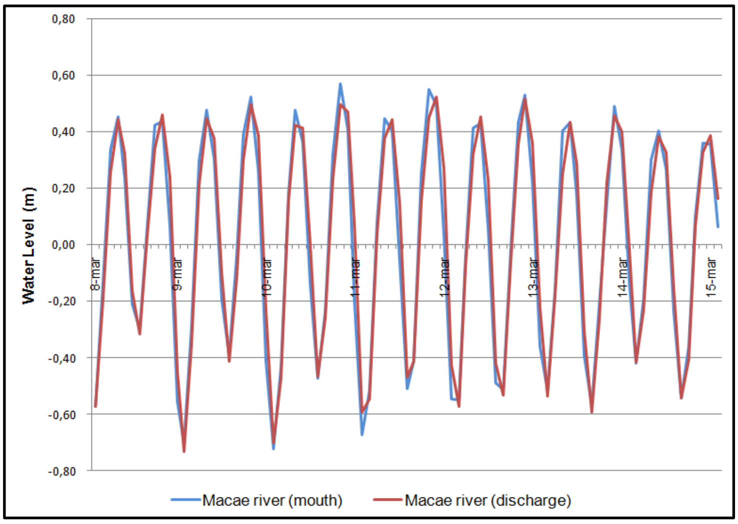
Figure 8 - Results of the water level in the sections of the Macaé river, with syzygy tide



Source: Author's (2022)

3.2 Influence of the tide in the runoff

In order to evaluate how different tidal variations amplitude would affect river flow during periods of extreme precipitation events, both neap and spring tide scenarios were simulated, assuming the 10-years project rainfall. The results were assessed in the Macaé-discharge and Macaé-mouth stations, as well as in two other virtual stations, Capote channel and Linha Azul stations (see Fig. 2), both situated in the urban region of Macaé.

Figure 9 shows the results for the Capote channel station. As expected, in the time period preceding the extreme event, the water level amplitude is considerably higher under spring tide than under neap tide. On the other hand, during the flood, the cyclical oscillations were no longer observed, with the two scenarios showing quite similar behavior, indicating that the river discharge, and not the tide phase, would be controlling the water level at this station.

Figure 10 shows that similar results were obtained in Linha Azul station. However, when compared to Capote station, it is possible to observe that there the flood extended over a larger period of time, something between 12 and 24 hours. The calculated water peak elevation for this station was 1.32 m, whereas in the Capote station it was 1.23 m.

Figure 9 - Results of the water level in the Capote channel, with 10-years project rainfall

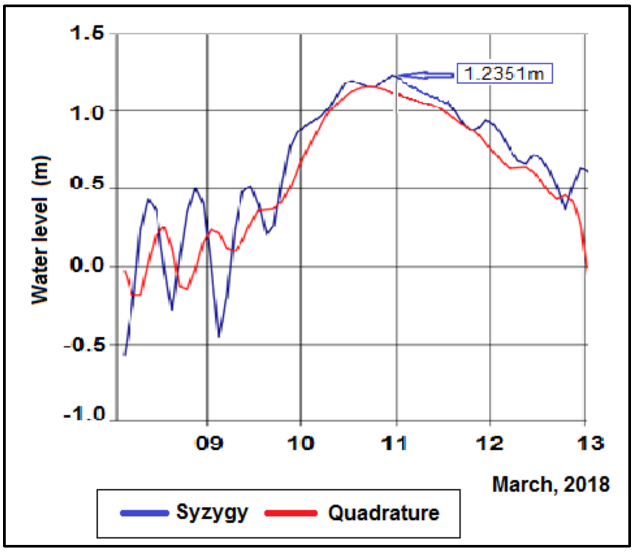


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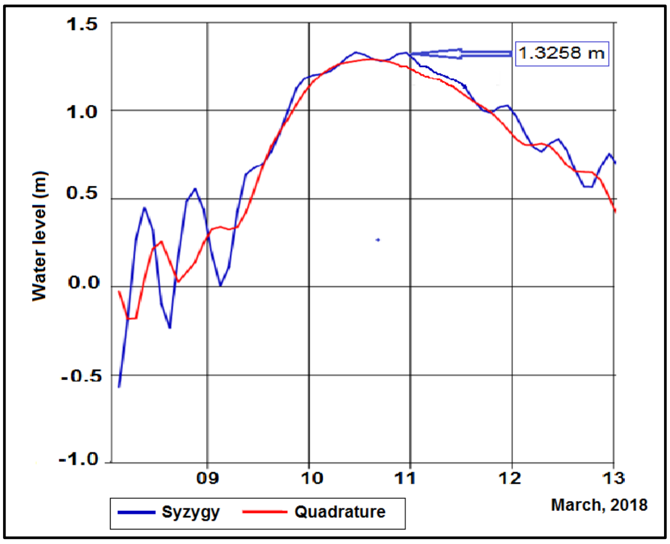
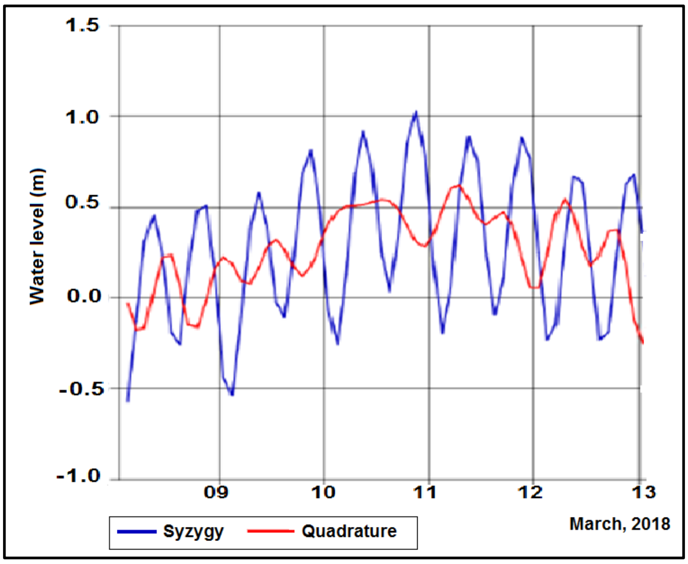
Figure 10 - Results of the water level in the Macaé river (Linha Azul), with 10-years project rainfall



Source: Author's (2022)

In the mouth section of the Macaé river (mouth station) the model calculated a considerable damping on the flood wave (Figure 11), possibly due to the increase of channel cross sections areas when approaching the estuary.

Figure 11 - Results of the water level in the Macae river (mouth), with 10-years project rainfall



Source: Author's (2022)

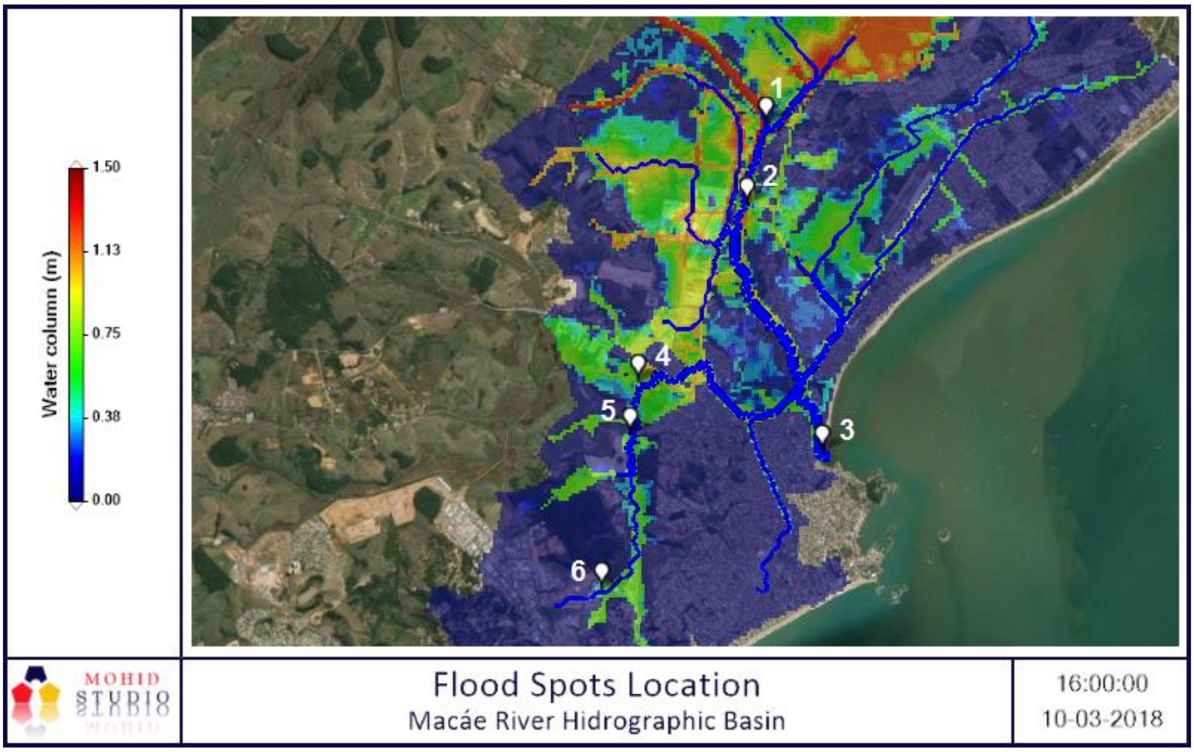
The model predicted that the flood wave peak could reach up to1.03 m at the high waters of a spring tide, whereas under a neap tide scenario the water level peak should reach up to 0.62 m. The extreme event dealt in this study occurred during a neap tide.

3.3 Spatialization and quantification of flood spots

The water level simulation in an extreme precipitation event allowed to identify the localities with flood spots (Figure 12). The water column heights varied according to the topography, reaching values around 1.50 m on the banks of the Macaé river, upstream the urban area.

According to the simulation, flooding begins with the overflow of the Macaé river trough the north of the Linha Azul station, and spreads eastward flooding the plains adjacent to the Jurumim Channel. The plains on the right bank of the main channel of the Macaé river and regions of Três Pontes and Capote Channels are also flooded. Finally, floods occupy the floodplains of the Macaé and with less intensity the banks of the Macaé-Campos’ channel.

Figure 12 - Peak flood simulated to March, 2018 with 10-years rainfall project

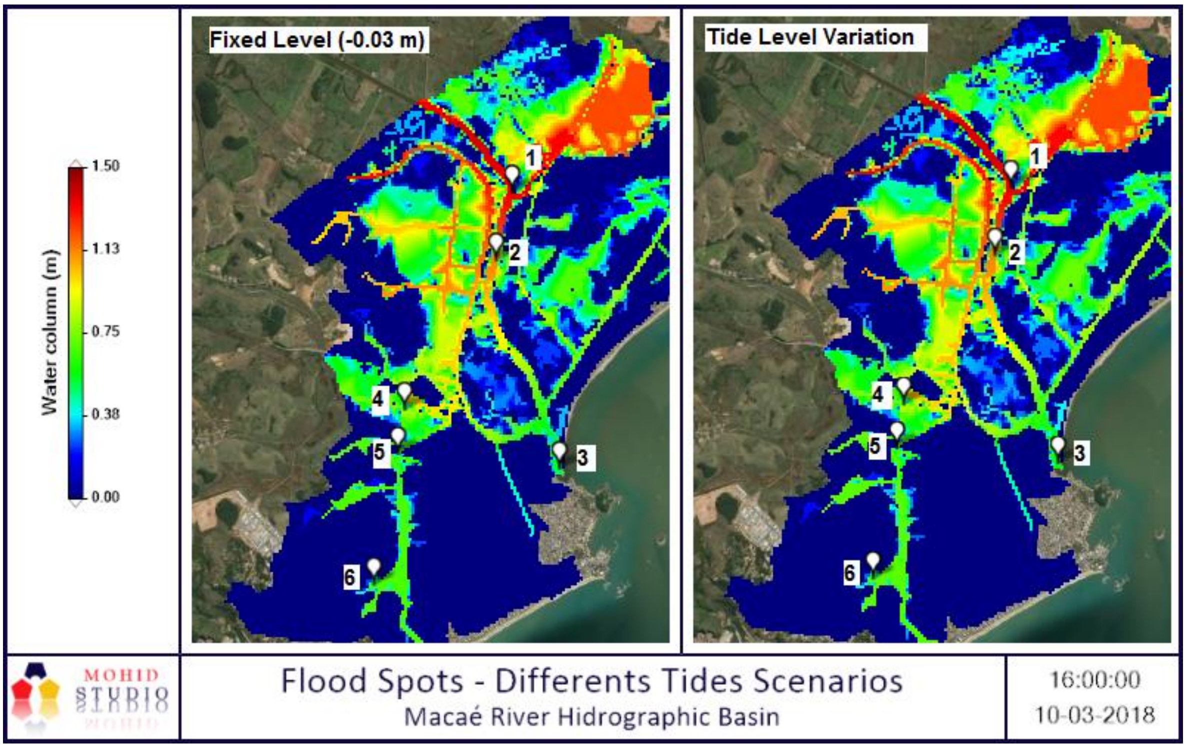


Legend: 1 - Macae river (outflow); 2 - Macae river ('Linha Azul'); 3 - Macae river (mouth); 4 - Três Pontes ('Green line'); 5 - Capote channel; 6 - University city.
Source: Author's (2022)

Figure 13 compares the spatial distribution of floods, considering, respectively, a fixed and variable level (according to a neap tide) at the mouth of the Macaé river. Although, visually speaking, no difference was detected between these two scenarios, the calculated results indicated that the maintenance of a fixed level and the adoption of a tidal fluctuation at the mouth of the river would lead to a maximum height of 1.56 and 1.50 m, respectively, showing that a neap tide would have no relevant effect on the level of water dammed in the urban region.

Regardless of the adopted scenario, the region with the largest floodplains was formed in the on the left bank of the Jurumim channel, with heights of up to 1.15 m.

Figure 13 - Flood spots simulated to different tide level scenarios

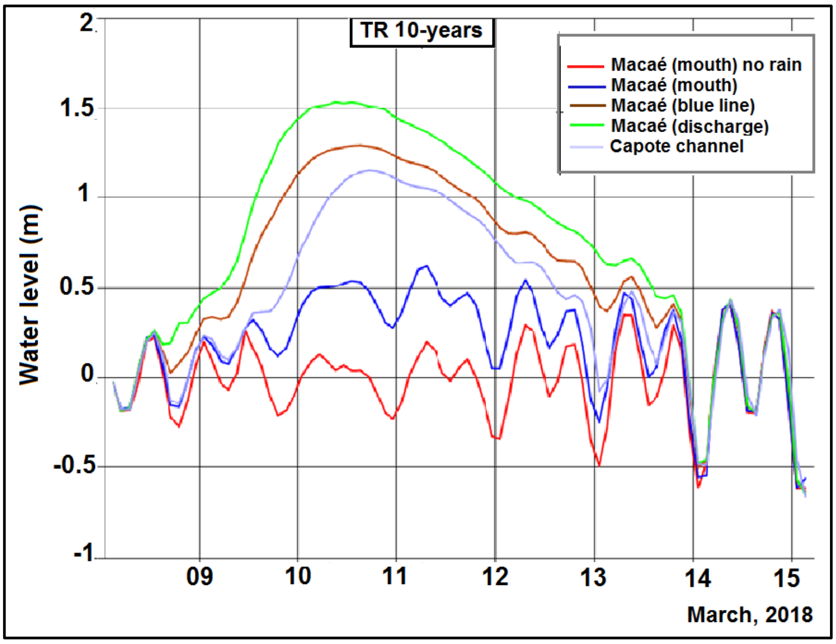


Legend: 1 – Macaé river (outflow); 2 – Macaé river ('Linha Azul'); 3 – Macaé river (mouth); 4 - Três Pontes ('Green line'); 5 - Capote channel; 6 - University city
Source: Author's (2022)

3.4 Influence of the flood wave in the urban area

The influence of the flood wave from the upper part of the basin is discussed in this section. Figure 14 shows the hydrographs calculated at some stations positioned along the Macaé river. It is observed that the elevation peak decreases as the section approaches the mouth, ranging from 1.53 m in the Discharge station to 0.62 in the Mouth station. In the same way, the residence time of the flood decreases towards the mouth. Considering as a flood any water level above 1.00 m, the flood residence time decreases from 60 hours in the Discharge station to 30 hours at Capote station.

Figure 14 - Water level Simulation from the model of 10-years project rainfall and hydrographs of flow in the stations of Macaé river

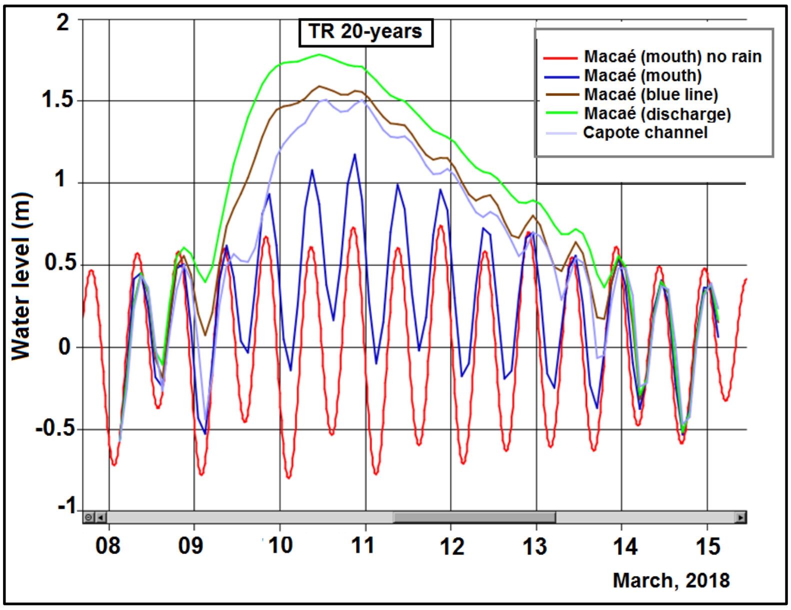


Source: Author's (2022)

Another evaluation was done simulating a 20 years-recurrence time rains, assuming a spring tide scenario. The simulated hydrographs in the same virtual stations are presented on Figure 15. Compared to the previous scenario, an increase of the maximum level in all the sections was observed. That increase became more pronounced towards river mouth. Likewise, residence times increased from 60 h to 72 h in the Discharge station, and from 30 h to 52 h in the Capote station, when compared to the previous scenario.

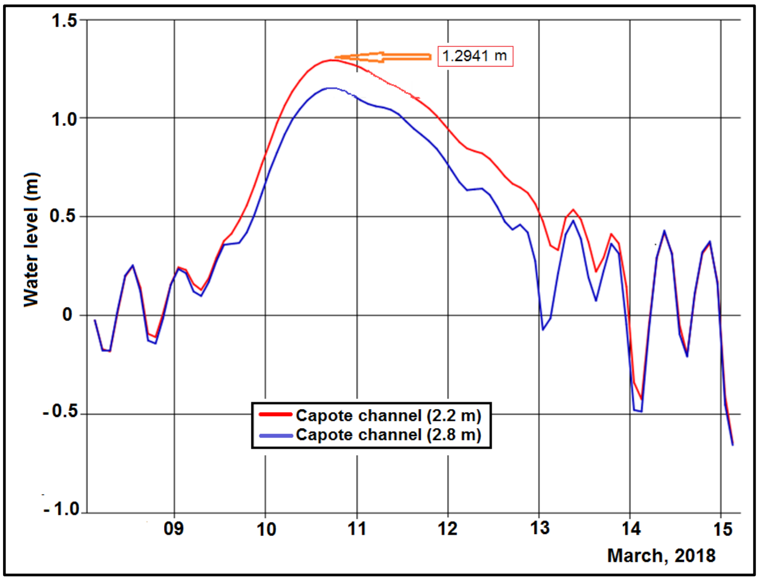
A final scenario was evaluated by imposing a modification on the depth of the 3rd order sections of the drainage network, reducing them from 2.80 to 2.20 m, keeping the other conditions as specified in the first scenario. The calculated results for the Capote station are shown on Figure 16. It can be seen that this reduction in depth resulted in an increase of around 0.15 m in the elevations of the maximum level. On the other hand, the residence time increased from 30 h to 44 h. These results can help to plan interventions in the channels aiming more efficient drainage processes.

Figure 15 - Water level Simulation from the model of 20-years project rainfall and hydrographs of flow in the stations of Macaé river



Source: Author's (2022)

Figure 16 - Water level Simulation for Capote channel varying the depths of Macaé river (mouth)



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4 CONCLUSIONS

The methodology presented in this article can be applied in other cities located near the coast to study the simultaneous occurrence of rainfalls and flooding events.

The simulated scenarios discussed here allowed understanding important aspects about flood dynamics in the hydrographic network that drains the urban region of Macaé.

The model was able to simulate the Macaé river flow and the runoff in the urban region considering the role of the tides in the downstream boundary.

In the future, the model can be used to forecast the results of interventions in the urban region and decide if they are adequate to bring effective solutions to the city land occupation pattern and are adherent to municipal sanitation plan.

It is worthwhile noticing that Jurumirim microbasin area is involved in a gas processing facility environmental permit that if approved will result in an increase in soil waterproofing rates and consequently will lead to higher residence times on the area. Running the model with this new scenario will also contribute to decide about location alternatives for this huge enterprise.

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Authorship contributions

1 – Marcos da Silva Lourenço
Engenheiro Civil, Mestrado em Engenharia Ambiental pelo Instituto Federal Fluminense
https://orcid.org/0000-0001-8665-7019 • marcoslourencomarcos@gmail.com
Contribution: Conceptualization | Data curation | Formal Analysis | Investigation | Methodology | Software | Validation | Visualization |

2 – Ariana Paula Pernambuco Mafra
Engenheira de Controle e Automação pelo Instituto Federal Fluminense
https://orcid.org/0000-0002-5345-8993 • mafra.ariana@gmail.com
Contribution: Investigation | Visualization |

3 – Francine de Almeida Kalas (Corresponding author)
Doutorado em Modelagem Computacional pela Universidade do Estado do Rio de Janeiro
https://orcid.org/0000-0002-9258-4677 • francine_kalas@hotmail.com
Contribution: Conceptualization | Investigation | Validation | Visualization |

4 – Pedro Paulo Gomes Watts Rodrigues
Doutorado em School of Marine Science and Techonology pela Newcastle University
http://orcid.org/0000-0002-9602-9785 • pedropaulowatts@gmail.com
Contribution: Conceptualization | Methodology | Validation |

5 – Maria Inês Paes Ferreira
Instituto Federal de Educação, Ciência e Tecnologia Fluminense, Campus Macaé, Engenharia Química, Doutorado em Ciência e Tecnologia de Polímeros pela Universidade Federal do Rio de Janeiro
https://orcid.org/0000-0002-6865-0929 • ines_paes@yahoo.com.br
Contribution: Conceptualization | Methodology | Validation |

6 – Jader Lugon Junior
Instituto Federal de Educação, Ciência e Tecnologia Fluminense, Campus Macaé, Engenharia Mecânica, Doutorado em Modelagem Computacional pela Universidade do Estado do Rio de Janeiro
https://orcid.org/0000-0001-8030-0713 • jlugonjr@gmail.com
Contribution: Conceptualization | Funding acquisition | Methodology | Software | Supervision | Validation | Visualization |

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