

## RUNOFF SIMULATION IN THE URBAN AREA OF THE CITY OF MACAÉ, RIO DE JANEIRO, BRAZIL<sup>1</sup>

### SIMULAÇÃO DO ESCOAMENTO SUPERFICIAL NA ÁREA URBANA DA CIDADE DE MACAÉ, RIO DE JANEIRO, BRASIL

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**Abstract:** Motivated by the high prevalence of flooding in the city of Macaé, the main objective of this work was to analyze the behavior of the river basin that encompasses the Praia Campista and Imbetiba neighborhoods to provide support for urban managers in projects and in the establishment of public policies focused on water resources. To achieve this objective, it was necessary to develop the delimitation of the hydrographic basin of the urban region that encompasses the Praia Campista and Imbetiba neighborhoods in the city of Macaé; simulate surface runoff in the region delimited by the river basin; obtain water depth data in the natural channels simulated in the model and; obtain water depth data at previously determined points in the river basin. As a result, it was possible to monitor and determine the water column value, representing the surface runoff in the river basin, and the depth in the drainage channel.

**Keywords:** Runoff. Urban drainage. Flooding. MOHID.

**Resumo:** Motivado pela alta prevalência de ocorrências de alagamentos na cidade de Macaé, o objetivo principal deste trabalho foi analisar o comportamento da bacia hidrográfica que engloba os bairros Praia Campista e Imbetiba para dar subsídios para os gestores urbanos nos projetos e no estabelecimento de políticas públicas voltadas aos recursos hídricos. Para atingir esse objetivo, foi necessário desenvolver a delimitação da bacia hidrográfica da região urbana que engloba os bairros Praia Campista e Imbetiba na cidade de Macaé; simular o escoamento superficial da região delimitada pela bacia hidrográfica; obter dados de profundidade da água nos canais naturais simulados no modelo e; obter dados de lâmina de água em pontos previamente determinados na bacia hidrográfica. Como resultado, foi possível acompanhar e determinar o valor de lâmina de água, representando o escoamento superficial na bacia hidrográfica, e a profundidade no canal de drenagem.

**Palavras-chave:** Escoamento superficial. Drenagem urbana. Alagamento. MOHID.

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<sup>1</sup>Trabalho aprovado no III Encontro de Sustentabilidade em Projeto (ENSUS), que ocorreu nos dias 30, 31 de julho e 01 de agosto de 2025, na Universidade Federal de Santa Catarina (UFSC), Florianópolis/SC.

## 1 INTRODUCTION

The city of Macaé, the study region of interest in this work, before 1970 had an economy based on sugarcane production, dairy farming, artisanal fishing, and small consumer goods industries. Then Petrobras© (the Brazilian oil company) decision to establish its exploration and production operations base in Macaé changed the regional production structure. The municipality became a logistics hub for the Petrobras© and afterward other companies in the sector followed. Macaé's rapid population growth led to an evolution of the city disproportionate to the availability of urban infrastructure services, in terms of housing, living conditions, and services (Piquet, 2007). Furthermore, all this change created problems related to irregular occupation of the coastal landscape and disorderly growth in environmentally sensitive areas, such as mangrove, sandbank, and lagoon ecosystems (Ressiguiier, 2011).

According to Freitas (2015), the spatial characterization of the city of Macaé is formed by regions that naturally flood. Furthermore, the straightening of rivers located in the low-lying areas of the municipality of Macaé in 1950 resulted in the elimination of ecosystems such as forests and mangroves along the banks, marshes and wetlands located in the plains, and backwaters and indentations within the river, which ensured the conservation of various aquatic species. This set of actions also significantly reduced the biodiversity of the plain crossed by the Macaé River, eliminating many plant and animal species. The decrease in river depth also increased the frequency and intensity of floods in the lower reaches of the Macaé River basin.

Still according to Freitas (2015), the city of Macaé is located on a plain, in a low region, against the sea, which receives water discharge from higher regions, with low absorption soil. It is a naturally floodable region, in which water retention areas were reduced, and swamps and lagoons drained, which allowed the occupation and use of areas previously subject to flooding. The urbanization of Macaé is common throughout much of Brazil, driven by the presence of an industrial sector and immigration to create a productive workforce (Piquet, 2011). Subsequently, the city received investments in infrastructure, education, and healthcare, primarily aimed at serving local businesses. In the educational sector, the city benefited from the

incentives brought by the presence of universities, which also made the city a university hub (Silva; Carvalho, 2019). Furthermore, the impermeability of cities exacerbates water accumulation (Miguez; Veról; Rezende, 2016).

According to the Digital Atlas of Disasters in Brazil (Brazil, 2024), the city of Macaé has a high prevalence of flooding. A combination of factors contributes to flooding, especially given its climate, which favors heavy rainfall, which may be becoming less frequent due to climate change. The constant rainfall, which can be exacerbated by climate change, the favorable soil and vegetation, the urbanization model characterized by a lack of prior housing planning, and urban drainage systems that have proven ineffective at containing surface runoff, leave the city vulnerable to flooding and inundation events.

Across the planet, we can observe an increase in extreme weather events and their intensity. Most recently, we can cite: In Morocco, there were two major extreme rainfall events: one on September 8, 2024, causing house collapses and deaths (ATTAC/CADTM Morocco, 2025), and another in October 2024 in the desert of southwestern Morocco, forming lagoons. In the latter, due to the amount of rainfall and its extremely rare nature, it was assumed to be caused by climate change (The Edition, 2024). Spain, in October 2024, also suffered extreme rainfall, resulting in material losses and 158 deaths (AON, 2024; Reuters, 2024).

In 2024, there was also an event in the state of Rio Grande do Sul, Brazil, considered the worst climate tragedy in the history of Rio Grande do Sul. The heavy rains that hit the state in May 2024 killed 183 people and caused significant material losses (CNN Brasil, 2024). The event was also attributed to extreme rainfall caused by climate change, combined with poor local urban drainage and the region's terrain prone to flooding.

Recently, on April 4, 2025, in southeastern Brazil, six municipalities in the state of Rio de Janeiro were severely affected by heavy rainfall. Among the affected cities, Angra dos Reis experienced flooding, landslides, river overflows, and damage in several areas of the city, resulting in the displacement of people. In Petrópolis, a river overflowed, and several areas of the city suffered flooding and landslides. In the city of Rio de Janeiro, trees fell and flooding occurred (G1 News, 2025).

In relation to the Sustainable Development Goals (SDGs) of the United Nations

(UN), in Goal number 13 “Take urgent action to combat climate change and its impacts”, we have item 13.3 “Improve education, awareness-raising and human and institutional capacity on climate change mitigation, adaptation, impact reduction and early warning” (UN, 2015), which deals precisely with the importance of studying the impacts of climate change.

The continuous growth of urban areas and the increasing public awareness of the environmental impacts of storm water have raised interest on the quality of receiving water bodies. The limitations of traditional urban drainage schemes have been acknowledged and new approaches that use more natural methods for retaining and/or disposing of storm water have been introduced. The efforts have been directed at improving urban drainage systems by introducing mitigation measures to limit the negative environmental impacts of storm water. These mitigation measures are generally called best management practices sustainable urban drainage system (SUDS), or low impact development (LID), and they include practices such as infiltration and storage tanks that reduce the peak flow and retain some of the polluting materials (Freni; Mannina; Viviani, 2010).

Stormwater drainage in urban areas has become a challenge due to the rapid and random growth of urban areas, removal of vegetation, reduction in the effectiveness of drainage infrastructure, and climate change. Sustainable Urban Drainage Systems (SUDS), Low Impact Development (LID), Best Management Practices (BMP), Water Sensitive Urban Design (WSUD) and the Sponge City Programme (SCP) are various aspects for urban stormwater management in a few parts of the world (Rentachintala; Reddy; Mohapatra, 2022).

There is growing interest in applying resilience to address the challenges of urban climate change (Friend; Moench, 2013). Within development projects, much effort in promoting urban climate resilience is directed towards influencing policy, with a special emphasis on mainstreaming into policy and planning (Friend *et al.*, 2014).

Urban hydrology plays a vital role in the urban stormwater management system. However, optimal results can only be possible when the combined effect of climate change, land use patterns, water reuse, water treatment, environmental aspect, and societal aspects are considered. There is a need to provide sustainable and resilient urban drainage systems to manage stormwater more efficiently

(Rentachintala; Reddy; Mohapatra, 2022). The theme of Sustainability motivates national events and research (Ferrolí; Librelotto, 2017; Souza; Dumet-Montoya; Junior, 2025).

Considering the importance of this topic today, this work aimed to analyze the behavior of the hydrographic basin that encompasses the Praia Campista and Imbetiba neighborhoods in the city of Macaé, located in the state of Rio de Janeiro, to provide subsidies for urban managers in projects and in the establishment of public policies aimed at water resources.

For achieve this, it was necessary to develop the delimitation of the hydrographic basin of the urban region that encompasses the Praia Campista and Imbetiba neighborhoods in the city of Macaé, Rio de Janeiro; simulate the surface runoff of the region delimited by the hydrographic basin; obtain water column data in the natural channels simulated in the model; and obtain water column data at previously determined points in the hydrographic basin.

## **2 METHODOLOGY**

For this study, the initial data used were the altitudes of a section of the urban area of Macaé obtained through aerial photogrammetry and made available by the Macaé City Hall, with horizontal 50 meters (m) spacing between altitude points. The aerial photogrammetry required manipulation, as done by Lourenço *et al.* (2022). The grid used in this study featured square cells measuring 10 meters (m) on a side, thus requiring triangulation of the altitude measurements. The Macaé River and its tributaries will be represented by 5-meter-deep channels. The smaller open channels will be represented by 4-meter depths.

In order to cover a wider area (Figure 1), altitude data from TOPODATA, the Brazilian Geomorphometric Database, a database of the National Institute for Space Research (in Portuguese, Instituto Nacional de Pesquisas Espaciais -INPE), were also used (Brazil, 2025). Altitudes (Figure 1) are represented with a color gradient, in which the blue color represents altitudes from 0 to 22 meters, green from 22 to 45 meters, from 45 to 56 meters there is a color scale from green to yellow, and from 56 meters to 68 meters there is an orange scale, and from 68 meters onwards there is a red color scale.

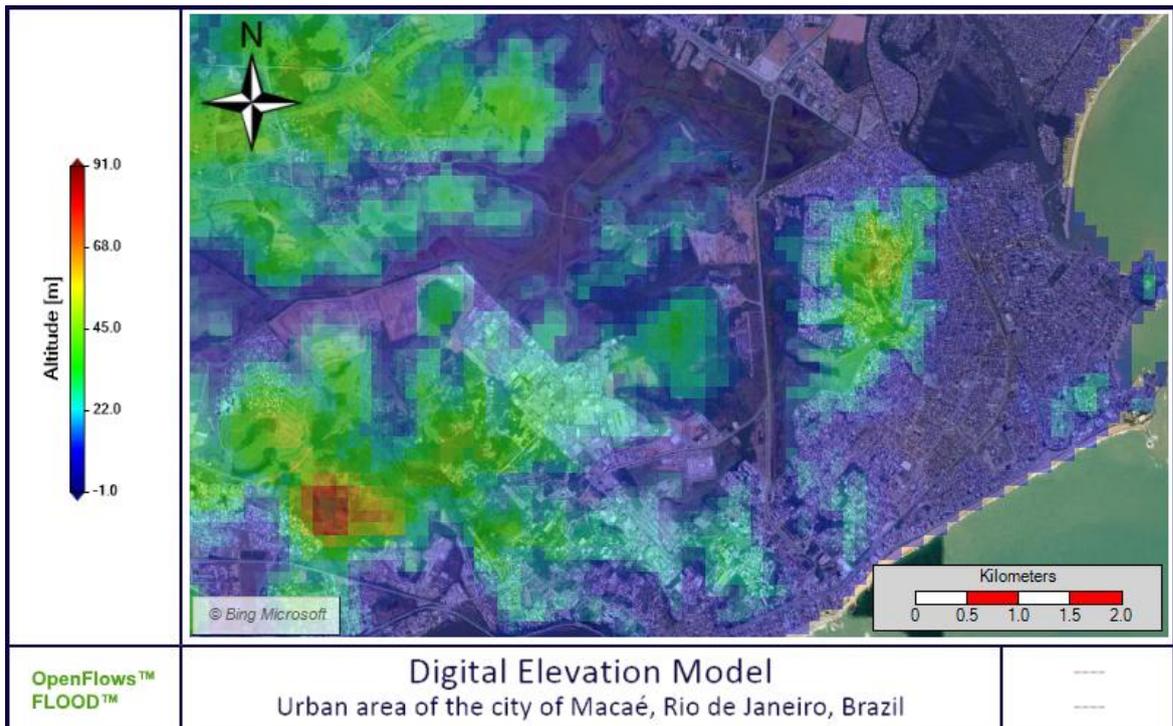
This article delimited the watershed that encompasses the Imbetiba and Praia Campista neighborhoods in the municipality of Macaé (Figure 2). The aim is to analyze the results obtained by simulating this watershed with a rainfall intensity of 3 mm per hour. The modules activated in this article were basin, atmosphere (rainfall data), drainage, and runoff (surface runoff).

Figure 3 shows the Macaé River watershed, taken from the Environmental Atlas of the Macaé River Watershed (Freitas, 2015). This article aimed to study the watersheds of the Praia Campista and Imbetiba neighborhoods, which are not included in the Macaé River watershed. This occurs because there is an elevation, represented in green color in Figure 1, isolating the watersheds of the Praia Campista and Imbetiba neighborhoods. Since any hydrographic basin is delimited by the highest points around it, therefore, due to the separation caused this elevation, the hydrographic basin of the Macaé River does not include the hydrographic basin of the Praia Campista and Imbetiba neighborhoods.

MOHID is a model that uses the Open Flows Flood© interface commercially available from Bentley© (Souza *et al.*, 2024). MOHID enabled the delimiting of the watershed of interest. Observation points, such as meteorological stations, were created around the watershed model, and observation points were created along the simulated river course for the basin encompassing the Imbetiba and Praia Campista neighborhoods in the municipality of Macaé. These selected regions were defined creating a file with coordinates of the cells of interest, allowing for a better understanding of the simulation results for previously selected strategic positions.

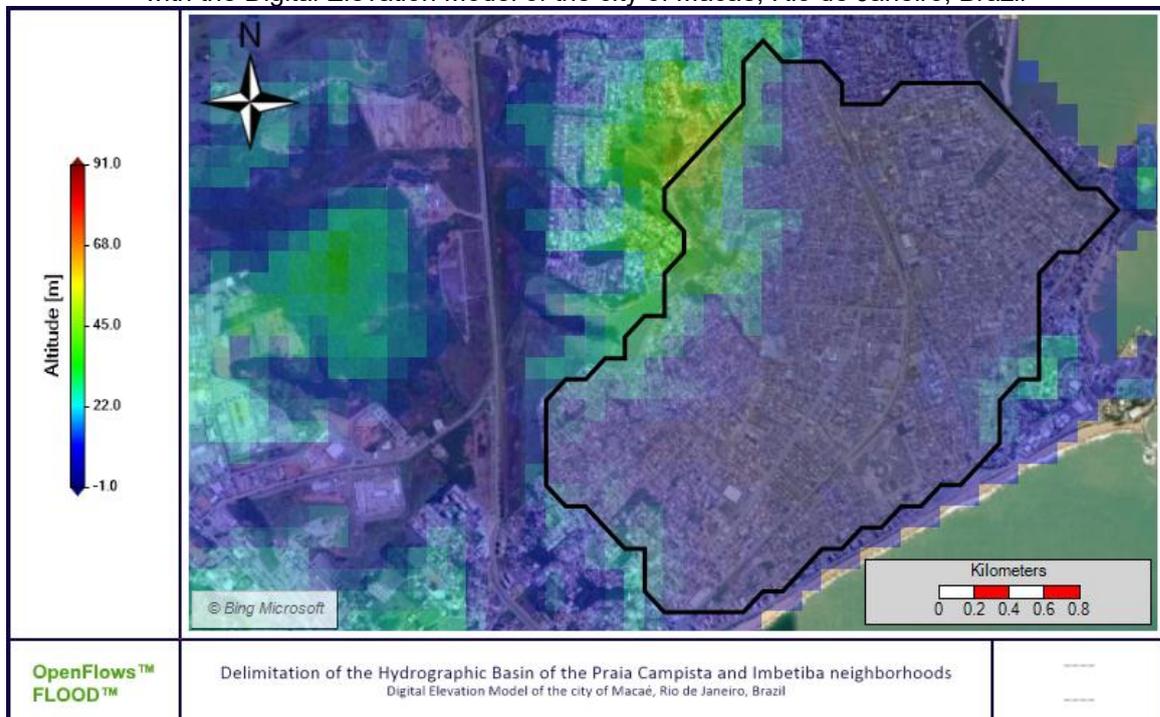
Considering that a high-rainfall day ranges from 60 to 100 mm of rain per day, a hypothetical day with 72 mm of accumulated rain was adopted. The rainfall distribution was constant over time, thus assuming a 3 mm/h rainfall rate during the 24-hour simulation.

**Figure 1** - Digital Elevation Model developed for the city of Macaé, Rio de Janeiro, Brazil



**Source:** Prepared by the authors (2025).

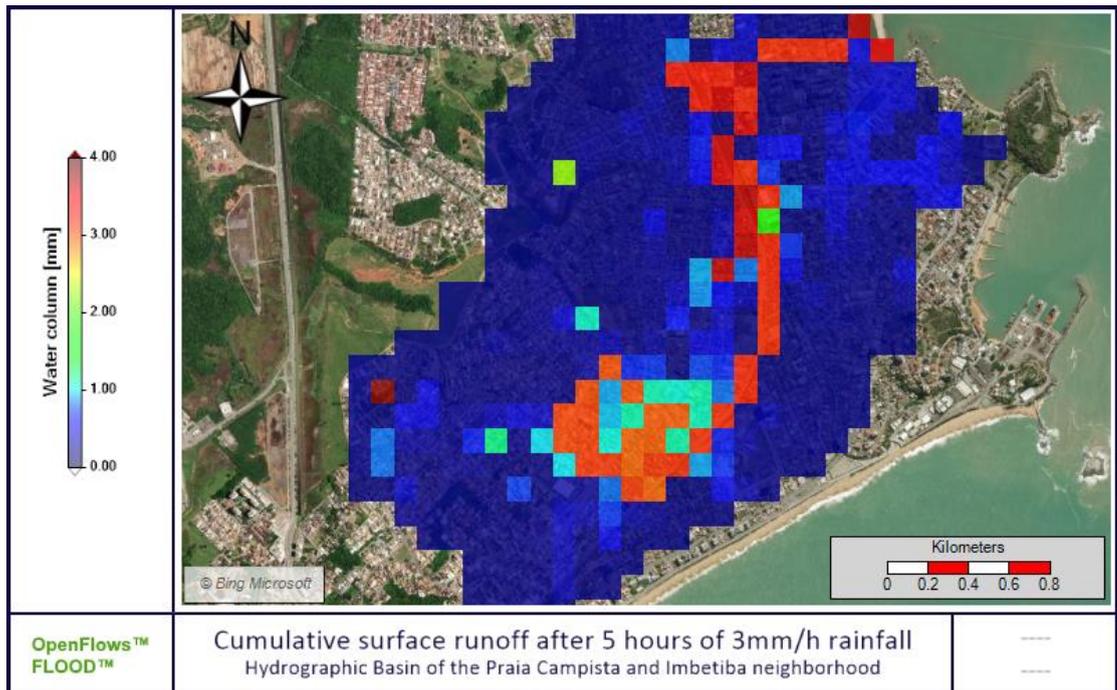
**Figure 2** - Delimitation of the Hydrographic Basin of the Praia Campista and Imbetiba neighborhoods with the Digital Elevation Model of the city of Macaé, Rio de Janeiro, Brazil



**Source:** Prepared by the authors (2025).



**Figure 2** - Cumulative surface runoff after 5 hours of simulation.



**Source:** Prepared by the authors (2025).

## 4 DISCUSSION

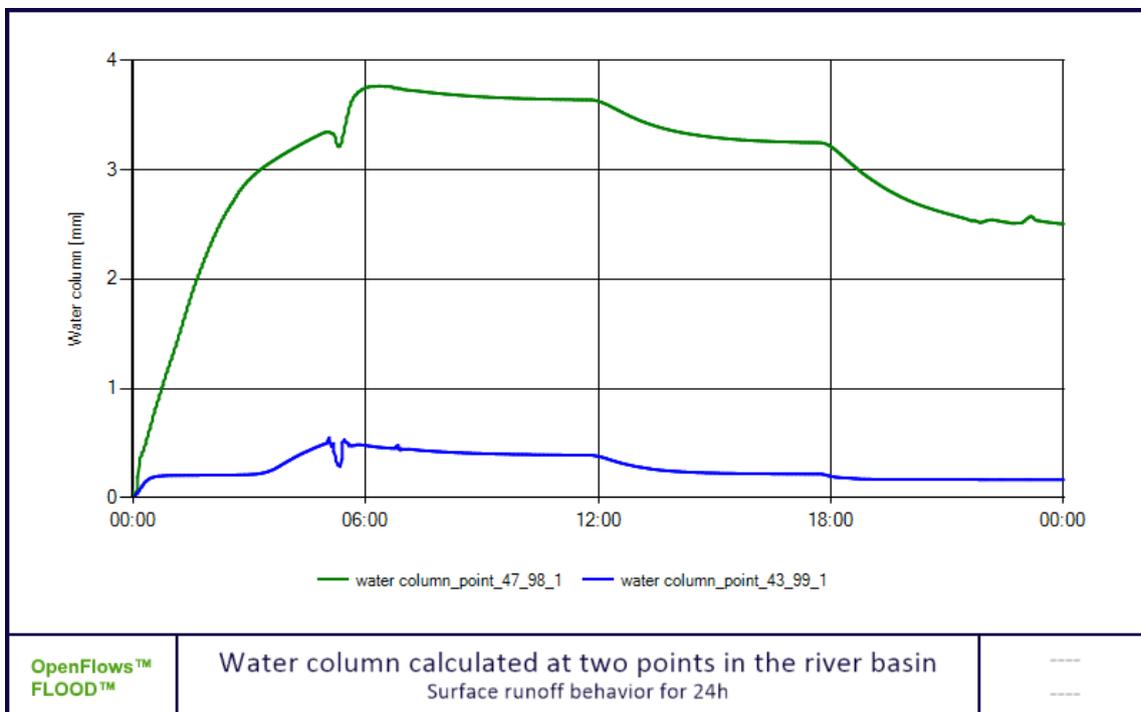
With the observation points created in MOHID, it was possible to monitor and determine the behavior of a set of cells of interest, and its water column value, representing the surface runoff in the hydrographic basin (Figure 5), the depth in the drainage channel (Figure 6), for a previously defined rainfall of 3 mm per hour, in a 24-hour simulation, with the end time also defined in advance.

The cells chosen for analyzing the drainage channel depth are not the same as those chosen for the water depth result. For the drainage channel, observation points were defined in the cells that comprised the channel simulated in the model. In Figure 7, the dark green and dark blue circles represent the water depth observation points in the surface runoff, cells "47\_98" and "43\_99," respectively. Also in Figure 7, the light pink, light green, light blue, and yellow circles represent observation points in the drainage channel that the model simulated based on the terrain topography at points 25, 9, 1, and 3, respectively.

In Figure 7, it can be seen that the circles representing computational

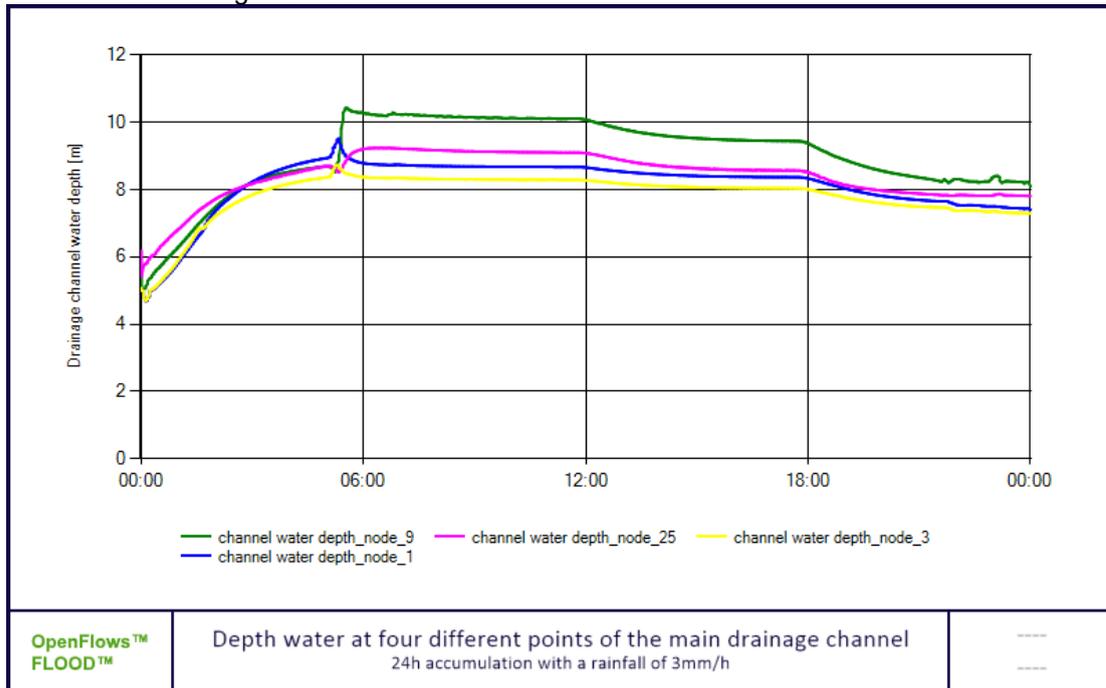
observation points (pink, light green, light blue, and yellow) for the drainage channel depth do not exactly coincide with the region where a real artificial channel of the drainage network exists, despite being close. This fact highlights that these regions are low-lying areas, susceptible to overflow of existing channels, and require greater attention. In Figure 6, for example, at the light green observation point, for a simulated rainfall of 3 mm/h, the depth of the natural drainage channel simulated in the model reaches 10 meters.

**Figure 5** - Water depth simulated over 24 hours for a rainfall of 3 mm per hour at observation points in the Praia Campista and Imbetiba neighborhood watershed



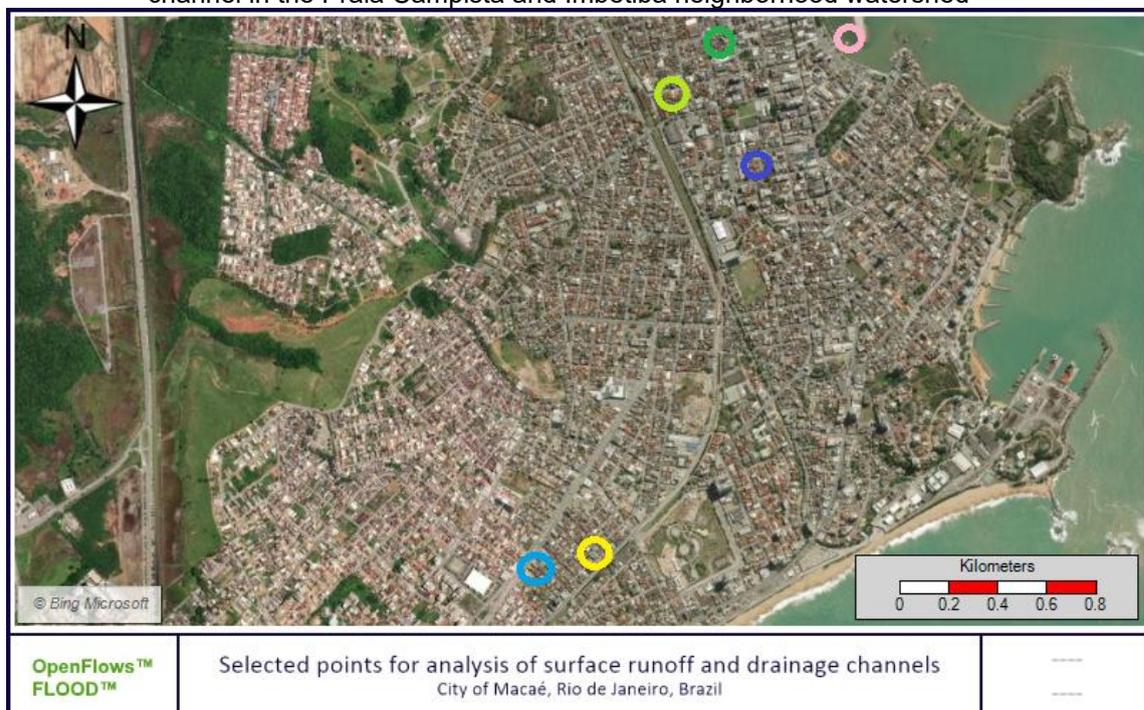
**Source:** Prepared by the authors (2025).

**Figure 6** - Depth of the drainage channel simulated in 24h for a rainfall of 3mm per hour at observation points in the Hydrographic Basin of the Praia Campista and Imbetiba neighborhoods



Source: Prepared by the authors (2025).

**Figure 7** - Observation points chosen to determine the water depth and the depth of the drainage channel in the Praia Campista and Imbetiba neighborhood watershed



Source: Prepared by the authors (2025).

## 5 FINAL CONSIDERATIONS

For urban planning purposes, based on the results obtained, we suggest paying attention to the region surrounding the city's existing artificial canals, which presented a higher water depth, approximately 10 meters. This is because the computational model assumed that this region would generate a drainage canal, based on the area's altitudes, and due to a depression created to represent the existing artificial canal nearby.

It can be concluded that the MOHID software provides the necessary data for the construction of the Watershed of the Praia Campista and Imbetiba neighborhoods in the city of Macaé, Rio de Janeiro. It also has the potential for predictive analysis of flooding events caused by rainfall of varying magnitudes and periods to be determined in advance, as well as flooding caused by overflows in the drainage canal. This is corroborated by other findings (Sales *et al.*, 2021; Souza; Junior, 2023).

The results presented, despite being local, represent the contribution of modeling to the solution and prevention of flooding in cities, which can be applied more broadly in Brazil. They can predict disasters related to extreme rainfall, enabling preparation for and mitigation of these events through joint actions between public agencies, companies, and researchers in the field.

It is possible to simulate stormwater management strategies, such as sustainable urban drainage projects or more sustainable construction, and compare urban drainage modifications, as well as verify whether they would actually bring improvements to the city under study. This would contribute to the practical applicability of the study and its impact on public policy formulation.

## ACKNOWLEDGEMENT

CAPES, Coordination for the Improvement of Higher Education Personnel: 001.CNPq, Brazilian Council for Scientific and Technological Development.FAPERJ, Carlos Chagas Filho Foundation for Research Support of the State of Rio de Janeiro

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Artigo recebido em: 28/08/2025 e aceito para publicação em: 19/12/2025

DOI: <https://doi.org/10.14488/1676-1901.v26i1.5674>