https://doi.org/10.71573/qkbb2s88

Urban drainage system design in a coastal lowlands city using a multilayer quasi-2D modeling - Case Study of Maricá, Brazil.

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Abstract

Urban drainage systems (UDS) are crucial for managing stormwater in cities. The failure of UDS can lead to severe flooding, causing damage to infrastructure, property, and environment. Their design and implementation often face significant challenges and in coastal lowland cities, these challenges are compounded by the influence of sea tides. Designing these systems in areas with tidal influence requires careful consideration of factors such as sea level rise, tidal patterns, and the topography, making the use of simplified hydraulic equations, such as Manning, unfeasible, as it does not represent the backwater effect. The complexities of these designs and the use of unreliable methods often result in increased costs and technical difficulties, making it a critical area of urban planning and engineering. This paper aims to present the design process of the urban drainage system in a coastal lowland city using the multilayer quasi-2D model MODCEL. The simulation was developed for a study area located in Maricá, Rio de Janeiro, Brazil. The area has a disordered urban occupation aggravating the challenge of project. The design process with hydrodynamic modelling resulted in a functional drainage network, capable of draining a 10-years storm considering backwater effects of high tide and river stage rise.

Highlights

- Coastal lowland cities grapple with unique urban drainage challenges.
- Use of hydrodynamic modelling can increase reliability of urban drainage design.
- Multilayer quasi-2D modeling is capable of simulating flows on urban surfaces.

Introduction

The process of urban occupation, once established, can be irreversible. Given this reality, it is necessary to observe the consequences arising from this practice, which is often disorderly and poorly planned, such as: soil impermeability, increased surface runoff, overloading of drainage networks, flooding and damage to infrastructure, in addition to potential impacts on public health and the economy. According to Mascaró & Yoshinaga (2005), drainage systems are one of the components of urban infrastructure, therefore, keeping in mind the importance of planning this system, as well as its consequences. Thus, one of the possible means for this is through representation through hydrodynamic modeling of canals, urban areas and green areas. According to Tucci (2008), hydrodynamic modeling is a fundamental mechanism that allows representing, understanding, and simulating the hydrological behavior of a river basin through mathematical models. According to Sousa (2017), Quasi-2D models are models that aim to reproduce the flow of urban floods along the river course together with the respective floodplains around it through interconnected “webs” (or also called cells) that communicate through connections. In addition, it is worth noting that hydrodynamic modeling allows increasing the reliability of urban drainage projects, especially in cities on coastal plains, considering the backwater effects of high tide levels. From this perspective, multilayer Quasi-2D hydrodynamic modeling allows simulating flows on urban surfaces together with drainage network pipes in an integrated manner. Therefore, the objective of this work was to show the process of designing the drainage system of a local area in a coastal lowland city, settled at the Rio de Janeiro Metropolitan Region, Brazil, using a multilayer quasi-2D hydrodynamic model, the MODCEL.

The study area was chosen to study the difficulties common to coastal cities: plains with low elevations, little slope, river levels close to the surface, and maritime influence on tides. In addition, the area in question has an aggravating factor: disorderly urban occupation on the riverbank, which hinders its expansion. Another factor that is important to mention is the irregular use of waterways as a way to receive and transport clandestine sewage from homes built around them. It is worth noting that this situation is currently changing, following the implementation of the sanitation regulatory framework in 2021, which provides for the construction of the sewage collection system. This will be the subject of study to complement this work in the near future.

Method

The methodological stage was subdivided into 8 parts: 1. Delimitation of the watershed to define the study area; 2. division of the watershed in cells, in accordance to proposed drainage network; 3. determination of the flow centers; 4. determination of the connections between cells based on flow patterns; 5. determination of the connections coefficients and numerical information, such as the width of the streets, diameter of the pipes, Manning coefficients, and other information; 6. determination of the runoff of each cell; 7. running the model; 8. Making adjustments in the estimated dimensioning according to the flood stain, along with implementing design changes necessary to minimize the saturation of the drainage system. The last two steps (7 and 8) are executed iteratively until the most suitable result for the functioning of the drainage networks is achieved.

As Sousa *et al.* (2022) explain, the Cell Model (MODCEL) simulates terrestrial surface runoff by working in an integrated manner, using information specific to each cell in order to adequately represent their respective properties. This information is: the total area of the plain, where precipitation occurs; storage area, where water concentration is applied; and land use and occupation properties, which are essential for estimating runoff generation. Thus, MODCEL also has a hydrological modulation in which it performs the precipitation-runoff transformation only in each cell, in a unitary and globalized manner, using the main analytical methods (Figure 1a). Therefore, Sousa *et al.* (2022) emphasize that in urban cells, the most varied levels and formats of streets, sidewalks, and buildings can significantly affect the storage capacity of the cells. This situation is exemplified in Figure 1b.

MODCEL offers several advantages for drainage simulation, particularly in urban flood modeling. Based on published works (Oliveira *et al*., 2023; Sousa *et al*., 2022; Miguez *et al.*, 2017), one can highlight some key benefits, as: **Systemic Approach** – MODCEL considers the entire basin as an interconnected system, rather than focusing solely on individual drainage channels; **Pseudo 2D Representation** – It models urban surfaces using a spatial network of homogeneous compartments (flow cells), allowing for a more detailed hydrodynamic analysis while solving 1D equations; **Integration of Different Flow Types** (**multilayer modelling**)– The model links surface flow, channel flow, and underground pipe flow, providing a comprehensive view of urban drainage dynamics; **Flood Control Design** – MODCEL helps assess the impact of urbanization on natural flow patterns and supports sustainable flood control strategies; **Unified Simulation for Sewer Systems** – The MODCEL-MHUS variant enables simultaneous analysis of stormwater and sanitary sewer systems, identifying inefficiencies and proposing integrated solutions. Several scientific studies have compared MODCEL with other widely used hydrological and hydraulic models, including IBER, SWMM, and MIKE FLOOD.

Pérez-Montiel et al. (2022) conducted a study in Riohacha, Colombia, comparing MODCEL with IBER, a physically based 2D hydraulic model. The findings revealed that MODCEL performed slightly better in both calibration and validation phases, particularly due to its lower sensitivity to topographic data resolution. MODCEL's flexibility in representing urban drainage structures, such as manholes and underground networks, was highlighted as a significant advantage. In contrast, IBER faced challenges in accurately modeling these features without high-resolution digital terrain models.

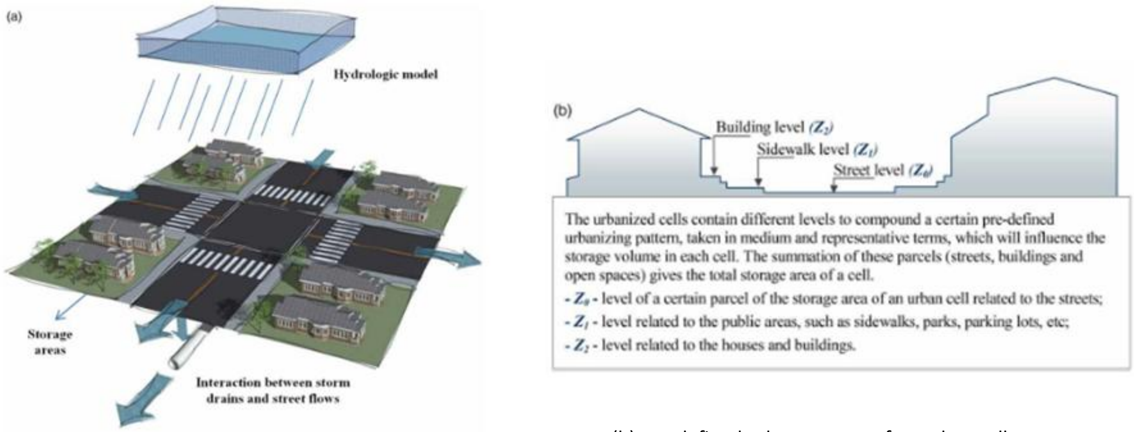
However, MODCEL requires a deep understanding of the physical system and is less user-friendly compared to IBER. In a case study of the La Riereta watershed in Sant Boi de Llobregat, Spain, Miguez *et* al. (2017) compared the use of MODCEL with the Storm Water Management Model (SWMM). The results indicated that MODCEL effectively represented minor drainage networks and overland flow, providing comparable results to SWMM.

MODCEL's ability to simulate both surface and subsurface flows, along with its flexibility in incorporating various urban features, made it a valuable tool for urban flood modeling. In benchmarking tests, MODCEL's performance was evaluated against MIKE FLOOD and InfoWorks ICM (Sousa *et al*., 2022). The comparisons focused on water levels simulated at predefined control points. The differences among the models were generally not significant, indicating that MODCEL can produce results comparable to these well-established models.

The design of the drainage network (Figure 2) was made considering the slope of the surface in order to direct the rainwater runoff to the region's watercourses, in accordance with a traditional engineering project for urban drainage. For each drainage manhole, which are represented by cells, it was connected a surface cell, divided according the topographic and urban patterns.

The determination of the connections was made according to their flow specificity: drainage network, representing pipes flow between two manholes; weir, representing the flow between surface and channels or rivers; surface flow, representing flows over the streets, through rivers and channels and over non occupied areas; and gutters; representing the connection between streets and the drainage stormdrains. See Figure 2.a.

Furthermore, the cells were classified according to their type: natural plain, urbanized plain, channel (representing water bodies) and well (representing manholes), respectively. The illustration of cell division can be seen in Figure 2.b. The need for structural reinforcement in several sections is highlighted due to the low elevation, which compromises the necessary covering for the distribution of stresses resulting from soil movements.



(a)Sketch of a flow-cell behavior (b) pre-defined urban pattern of an urban cell

Figure 1. Representative diagram of water flow (Sousa, 2022).

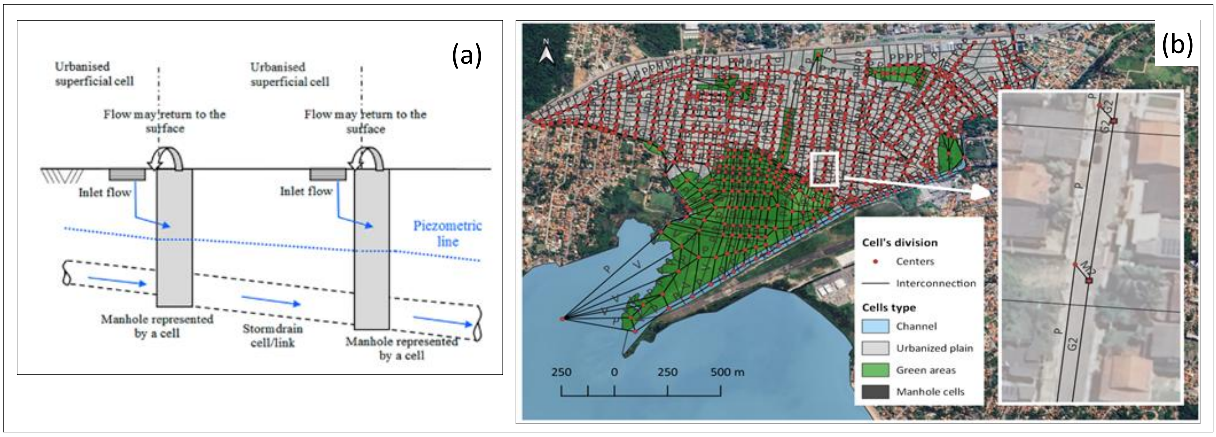


Figure 2. (a) Representation of flow under pressure in a drowned storm drain (Miguez *et al.*, 2017), and (b) Cell's division.

Finally, the last step consisted of iteratively running the model and making adjustments based on the drainage system's performance. This performance was evaluated by the longitudinal water level profiles of drainage network and water level series in manholes. The result of the simulation will be discussed in the next topic.

Case study

The case study is located at Maricá city, in the Metropolitan Region of Rio de Janeiro, Brazil. According to information from the Brazilian Institute of Geography and Statistics (IBGE), the municipal territorial area is estimated at 361,572 km² (2023), the resident population is equal to 197,277 people (2022), and the population density is around 545.61 hab./km² (2022).

The specific urban watershed studied is located at a region close to Lagoa de Maricá, where the drainage system flow into. This lagoon is directly influenced by the sea, adding another layer of complexity to the drainage system design. The watershed is defined by Ludegero River, ate the east side, and the Búris Stream, ate the west side, both of which flow into the Maricá Lagoon (Figure 3).

The location has Highway RJ 106 as an access road that connects the municipality with other neighboring cities, and acts as a physical barrier to upstream flows, defining the northern boundary of the urban watershed. It is important to mention the common challenges of designing the drainage system in a coastal city due to the susceptibility to tidal influences, sea level rise and complex topography. In the case study region, the altimetric elevations of the surface vary between 0.40 m and 8.00 m (Figure 3), according to the digital terrain model (DTM), a georeferenced file in "raster" format made available by metropolitan plan of the state of Rio de Janeiro: modeling the metropolis (PDUI).

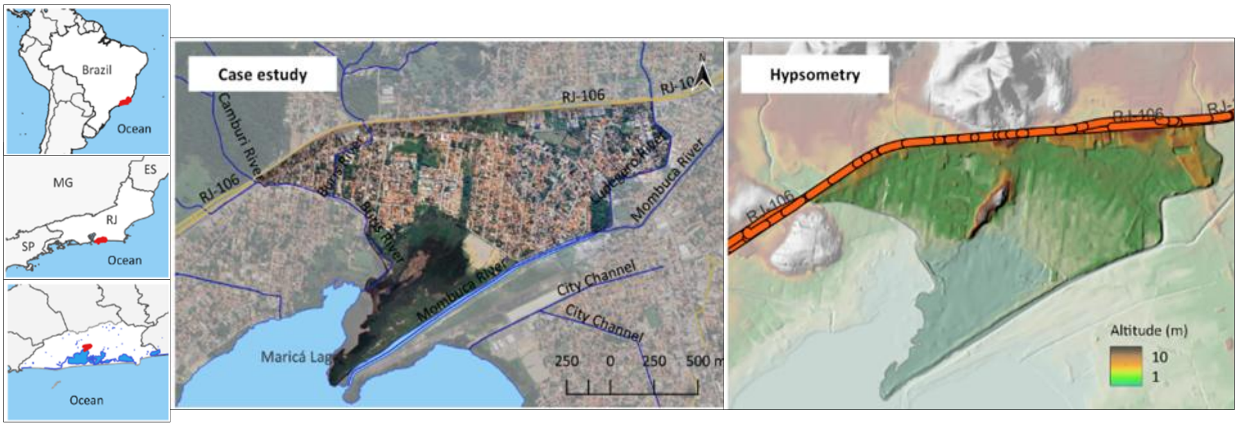


Figure 3. Localization of case study and terrain levels.

Results and discussion

The design of the drainage system was successful using the Quasi-2D model, which was able to represent the backwater effect caused by the water level in the lagoon. Therefore, as a consequence of high-water levels downstream, the final system has 4,798 meters working under pressure, which corresponds to approximately 7.0% os total and 4,453 meters, which corresponds to approximately 6.5% operating with a pipe filling greater than 75% of its capacity. Figure 4 shows the filling ratio in each reach of the drainage network. The remaining 86.48% of the system is operating at acceptable levels of performance The total length of the drainage network is 68,413 meters.

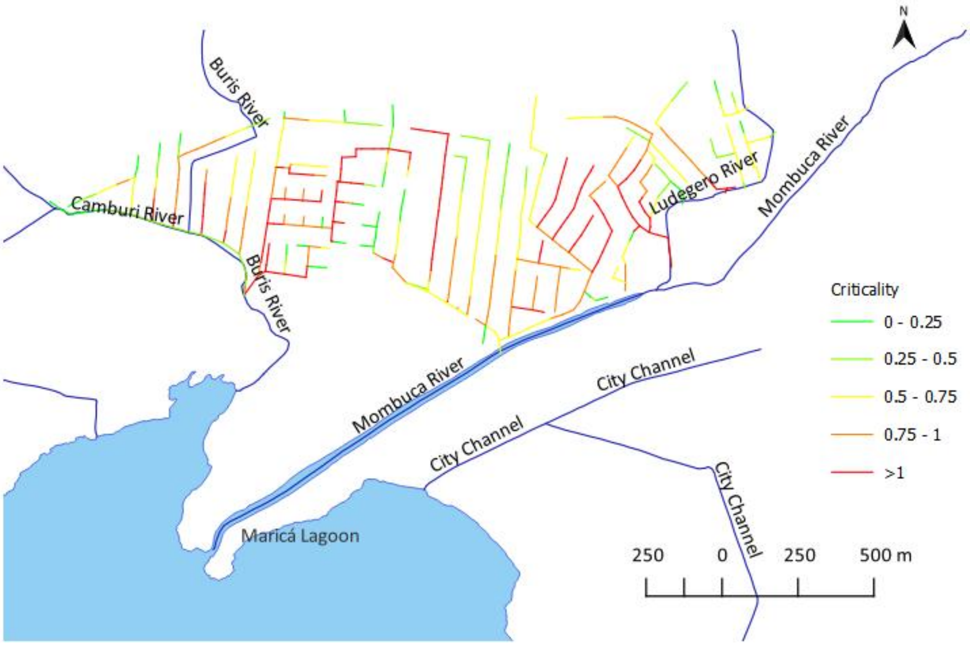


Figure 4. System drainage's critical levels.

The drainage system can be implemented and will be able to perform its function with some observations. As can be seen in Figure 4, a large part of the drainage system is functioning in a saturated manner. This situation is accentuated when peak flows reach their maximum value. Furthermore, it is worth noting that the lagoon system in the region is influenced by the sea and ocean, contributing to the flooding of local watercourses. Furthermore, it is one of the best drainage options, as a form of rapid drainage, given the urban density of the study area. The drainage levels are very close to the river levels, a factor that makes drainage difficult.

Conclusions and future work

In future work, the focus will be on simulating interactions within the sanitary system. This involves the integration of various components such as wastewater collection, treatment, and disposal systems into the existing hydrological models. By incorporating the sanitary system, we aim to achieve a comprehensive understanding of how urban water systems function holistically.

It is interesting to note that the location of the case study area is mostly flat. It is desirable to incorporate complementary measures to assist in urban drainage and mitigate the effects of flooding, such as Nature-Based Solutions, construction of reservoirs, and others. It would be better to adopt more superficial drainage solutions, avoiding stormdrains. However, the next step of the project will focus on interferences between the drainage system and the sewage system, as this is a reality that Brazil faces and that negatively contributes to the degradation of urban water bodies in the main Brazilian metropolitan regions.

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