


 <https://doi.org/10.71573/vv3r2x37>

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Drainage system obstructions in real time simulation and its impacts on urban floods modelling

Paula Morais Canedo de Magalhães¹  <https://orcid.org/0000-0002-3610-4894>, Laís Brilhante da Cunha^{1, *},
Matheus Martins de Sousa¹ & Marcelo Gomes Miguez¹  <https://orcid.org/0000-0003-4206-4013>

¹Environmental Engineering Program—PEA, Polytechnic School, Federal University of Rio de Janeiro, Rio de Janeiro 21941-909, Brazil.

*Corresponding author email: lais.cunha@poli.ufrj.br

Abstract

The urbanization process significantly alters the hydrological flow patterns of natural watersheds, resulting not only in an increase in liquid flows but also in the amount of eroded sediments transported by surface runoff. In the context of urban flood modeling, the effects of sediment incorporation into the drainage system are generally limited to an increase in the roughness coefficient or the application of a reduction factor in the system's hydraulic capacity. This modeling approach decreases the reliability of extrapolating the results obtained for different situations used in model calibration, as it does not simulate the system clogging process itself but rather the effects it causes. Thus, the objective of this paper is to present the incorporation of a sediment transport and deposition module into MODCEL, a *quasi*-2D hydrodynamic model, to simulate the transport and deposition of sediments inside urban drainage pipes in real-time simulation, based on the moving bed approach. It was observed that the incorporation of the moving bed did not introduce significant complexities into the calculations nor compromise the model's performance, yielding more reliable results, especially for predicting simulation scenarios.

Highlights

- The sediment calculation module simulates the clogging of urban drainage system
- The sediment calculation module does not compromise the hydrodynamic model's performance
- Hydrodynamic model prognosis becomes more reliable when simulating the storm drains clogging

Introduction

The urbanization process significantly alters hydrological flow patterns. Urban watersheds produces greater and faster surface flows, reducing water infiltration and retention (Rosa et al., 2020). This fact results in higher peak flows, lower base flows, shorter concentration times, and degraded river ecosystems (Özer & Yalçiner Ercoşkun, 2024). One of the main consequences of urbanization, particularly when implemented without adequate control, is the increased vulnerability to flooding and inundation in urban areas (Bibi & Kara, 2023; Hassan et al., 2022).

Even in the beginning of increasing concerns related to urban floods and the imbalances resulting from this process, Leopold (1968) highlighted that the urbanization process also changes the production of sediments. These changes contribute to an increase in the volume of solid material carried by the runoff (Campos, 2001). These sediments can promote a series of changes in the drainage performance, especially in terms of siltation effects (Konrad, 2003).

In many developing countries it is common to find rivers silted up or strangled by landfills and various types of inadequate construction. Urban storm drains are also compromised or have reduced hydraulic

efficiency, largely due to the massive presence of sediments and solid waste (Lamond & Bhattacharyamis, 2012). This buildup leads to partial blockages and, in some cases, renders the system completely inoperative. This condition represents a real challenge in stormwater management, in practice, but also causes problems to modeling simulations.

The effects of incorporating sediments and solid waste in hydrodynamic simulation are not directly considered in most models. The usual modelling procedure only considers the water flowing through cross sections with no sediments. Eventual restrictions or obstructions to flow are represented by an increase in the roughness coefficient. When considering the effect of partial obstructions, this is, in general, pre-evaluated depending on the previous conditions observed in the basin and does not change during the event, therefore, it refers to an average constraint value applied throughout the modelling process. It is a possible (and frequent approach) targeting the representation of peak discharges and maximum flood levels, but the evolution of this phenomenon is not really represented

Therefore, although this procedure can produce good calibration results, it also reduces the reliability in predicting the flooding behavior in situations different than that used in model calibration, given that the obstructions associated with a specific event/moment may not occur in the same way in future simulation scenarios. Thus, the more accurate the representation of physical reality is, the more reliable will be the resulting model predictions.

In this way, this paper aims to present a new computational module for MODCEL (a *quasi*-2D hydrodynamic model of flow cells, designed for modelling floods in urban setups) (Miguez, 2001; Miguez et al., 2017). This new module allows simulating the transport and deposition of sediments inside urban storm drains. The sedimentation process is represented in real-time simulation, leading to gradual loss of the cross-sectional area. This new approach seeks to better represent the flow behavior in urban drainage pipes and its impact in flooding water depths, especially in terms of permanence time of flooded area.

Method

To evaluate the responses of this new proposed module, a comparison between two approaches in urban flood modelling was made. The first approach is the most traditional one, where the discharge restriction is given by an increase in the roughness coefficient. The second one considers the gradual loss of cross-sectional flow area due to sedimentation processes.

To achieve this, this work followed three phases. The first phase is the model calibration and simulation considering only the hydrodynamic processes. This phase will serve as a representative of the most traditional modelling approach and was made with the hydrodynamic model called MODCEL. This is a multilayer quasi-2D hydrodynamic model that represents flood routing through rivers, flood plains and urban environments using a network of one-dimensional connections. This model has numerous applications in flood control and mitigation projects and international recognition validated by several publications (see, for instance, Miguez et al., 2017, Sousa et al. 2022).

The second phase is the determination of the volume of eroded soil inside the basin that will reach the drainage system. This determination is made with the Revised Universal Soil Loss Equation - RUSLE. Eroded sediment loads were translated into boundary conditions for drainage cells, assuming uniform grain size (d_{50}) to simplify transport calculations.

The third and final phase is the simulation of the sedimentation processes. This phase used the same base model of the first phase, but adding the module to calculate sediment transportation and siltation inside storm drains. This change requires a new calibration.

This sediment transport and deposition module performs the mass balance of sediments at the bottom of each element that represents storm drains and manholes, calculating the sediment transport over time according to hydrodynamic characteristics of flow (Rosman, 2022). Thus, by determining the solid discharge and determining the sedimentological phenomena, it is possible to understand the morphological changes that the drainage system elements undergo (Cruz, 2018).

There are several formulas for calculating sediment transport available in specialized literature, but this work used the Engelund-Hansen formula for sediment transport, due to the type of simulated sediment transport and its validity range (Engelund & Hansen, 1967).

Case study

To evaluate the responses given by this new module, the watershed defined at Julieta Niemeyer Street was chosen as a case study. This street is located in the São Conrado neighborhood in the city of Rio de Janeiro – RJ/Brazil (Figure 1), in a region that was hit by a critical storm on February 15, 2018, which caused closures, displacements, power outages, flooding, and 4 fatalities.

The drainage of this area is highly dependent on the proper functioning of its micro-drainage system, as Julieta Niemeyer Street is intersected by the Lagoa-Barra Highway. The Lagoa-Barra Highway is a high-speed road built at a higher elevation, which poses a significant constraint to surface runoff.

This choice took into account the availability of information regarding the registration of the drainage network and the amount of precipitation and significant flooding heights. The peak intensity of this event was estimate with a return period of 29 years, according to the Intensity-duration-frequency curve of RIOÁGUAS (2010). It is also interesting to note that this value is close to that recommended by the Ministry of Cities for major drainage projects in Brazil.

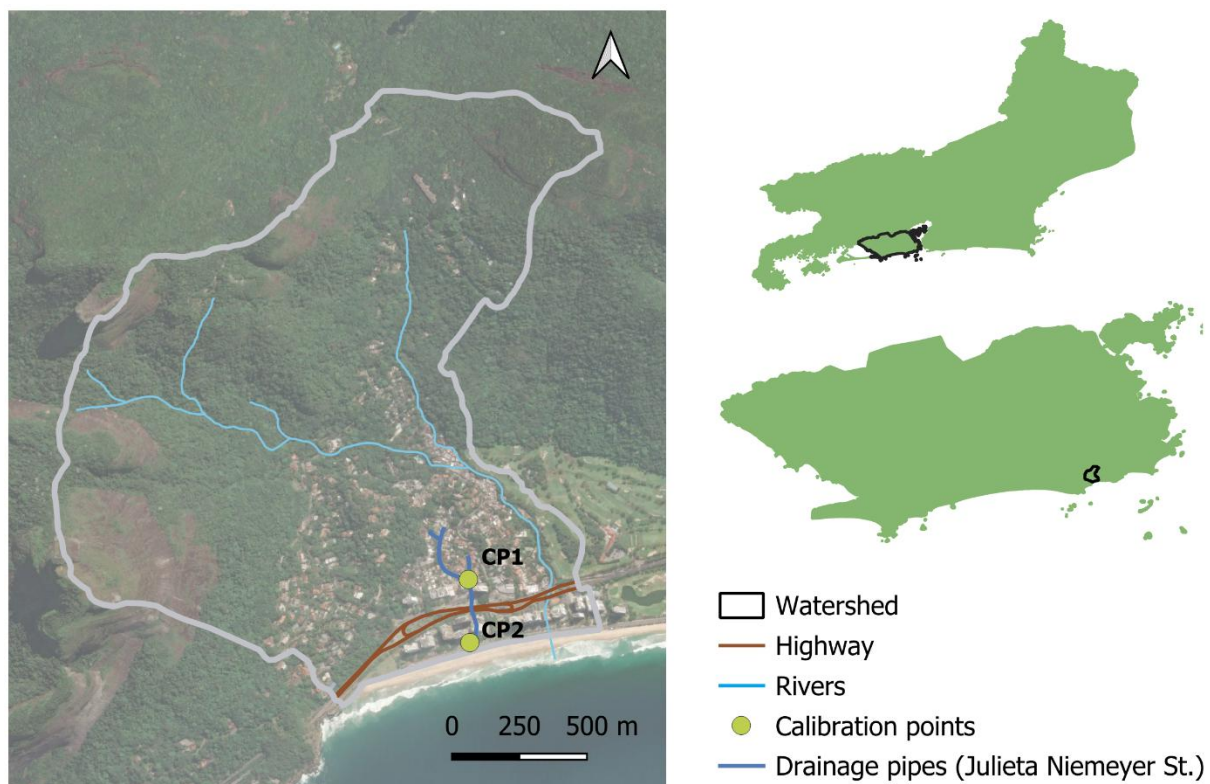


Figure 1 – Localization of the studied area and of the calibration points.

Results and discussion

The model calibration compared the simulated water depth with flood records in two points outside the drainage network, following the adapted calibration procedure of de Oliveira et al. (2019). The calibrated model found a value of 0.023 for the roughness coefficient in the storm drains, which corresponds to a concrete pipe with significant flow restrictions, when compared to a fully functional one.

In the following, the RUSLE was used to estimate the total volume of eroded soil in this basin, reaching a total amount of 237.9 m³.

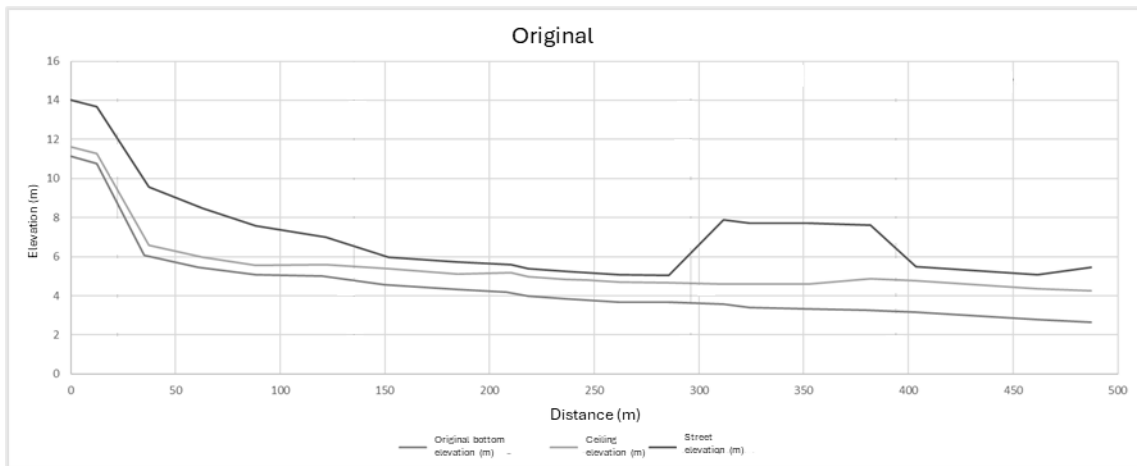
At last, the same calibrated model obtained in the first step received a boundary condition with the soil input found in the second step. This change led to a new calibration in which the roughness coefficient was adjusted to a value of 0.013 which is very close to those suggested in the technical literature for the type of pipes found in the region. This fact shows that if the restrictions imposed by siltation in the pipes is represented in the model, the roughness coefficient is able to maintain its expected value, granting more accurate predictions. Moreover, by representing the siltation process, the pipes condition can change during the event, better

representing the flooding duration. The comparison between the models' results and the water depth values observed at the calibration points are shown in Table 1.

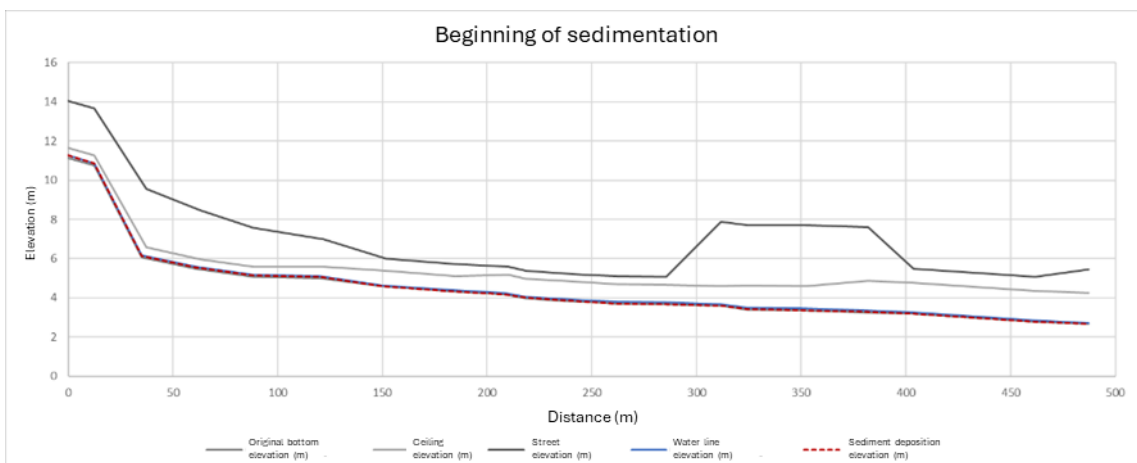
Table 1. Comparison between the observed and modeled water depths for the two calibration points.

Calibration Points	Observed water heigh (m)	Modelled water heigh – Phase 1 (m)	Modelled water heigh – Phase 3 (m)
CP1 - Julieta Niemeyer Street	1,30	1,31	1,31
CP2 - Prefeito Mendes de Morais Av.	1,35	1,33	1,32

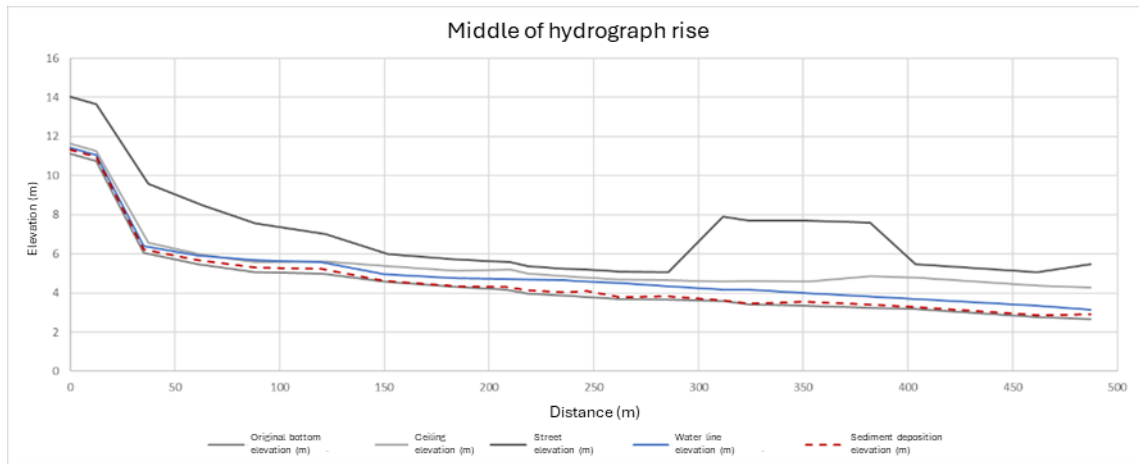
In order to observe the evolution of both the gallery bottom and the water line, 5 key moments were selected during the simulation and the profile of the drainage line was plotted for each of these moments. They are: initial moment of the simulation, prior to the beginning of the flows (Figure 2-a); initial moment of sedimentation inside the drainage pipes (Figure 2-b); moment equivalent to half the rise of the hydrograph, where some points of greater sediment accumulation can already be observed (Figure 2-c); moment equivalent to the peak of the hydrograph, where it is possible to observe some points with significant accumulation of sediments, in addition to considerable accumulation of water on the surface (Figure 2-d); and, finally, at the end of the simulation representing the new bottom level of the silted drainage pipes (Figure 2-e).



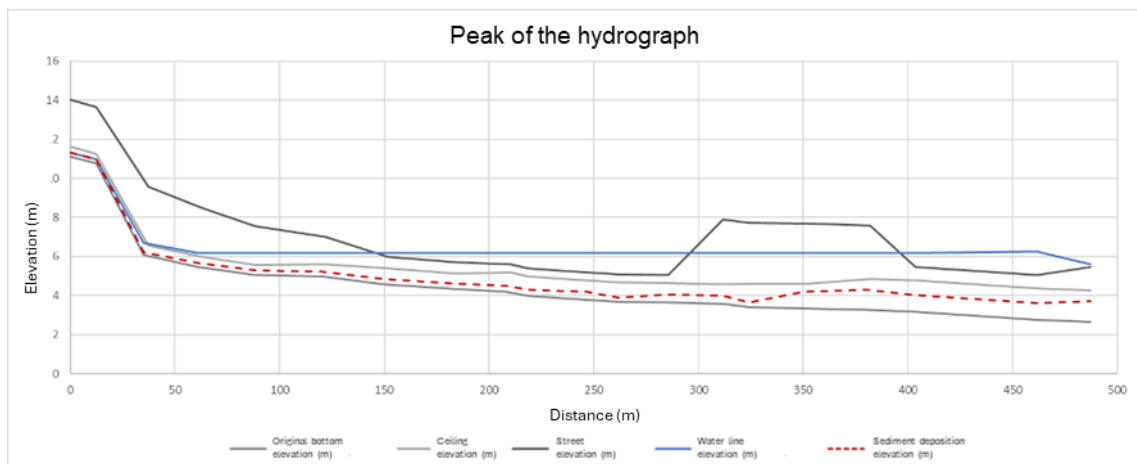
(a)



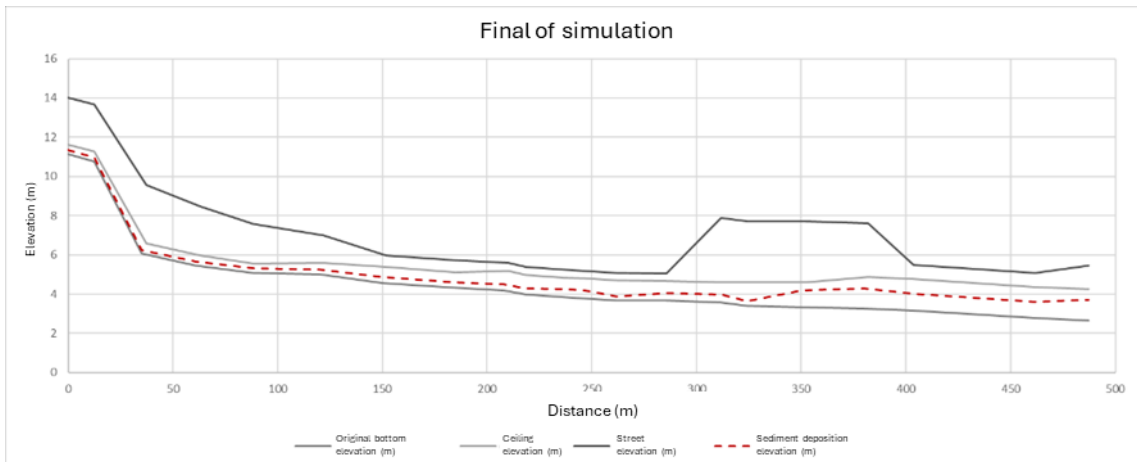
(b)



(c)



(d)



(e)

Figure 2 – Evolution of the water depth and bottom elevation of the drainage line on Julieta Niemeyer Street.

After that, an analysis of the urban drainage pipes restrictions was carried out. It was observed that from the 237.9 m³ of sediment considered in the simulation, around 213.2 m³ were retained in the galleries and the rest was carried downstream, to the outflow in the sea. This led to an average obstruction of 43%. However, it is important to note that this obstruction is not constant throughout the network, with greater sediment accumulations being observed in the lower and flatter regions, as conceptually expected.

In this case, although the hydraulic capacity of the system was significantly reduced, a total clogging of the network was not observed. However, this effect especially impacts the time required to roads returning to their normal operating conditions. When comparing the 2 approaches, it was observed that the second setup has an emptying time greater than the first one, as can be seen in Figure 3.

As the drainage of this area relies heavily on the proper functioning of the micro-drainage system, whose hydraulic capacity has been compromised by sediment accumulation, the drainage efficiency of Julieta Niemeyer Street has been significantly impaired.

This result is consistent with the report from Rio-Águas (the municipal company responsible for maintaining the drainage network), dated March 22, 2018, which was issued a few days after the simulated event (Rio-Águas, 2018).

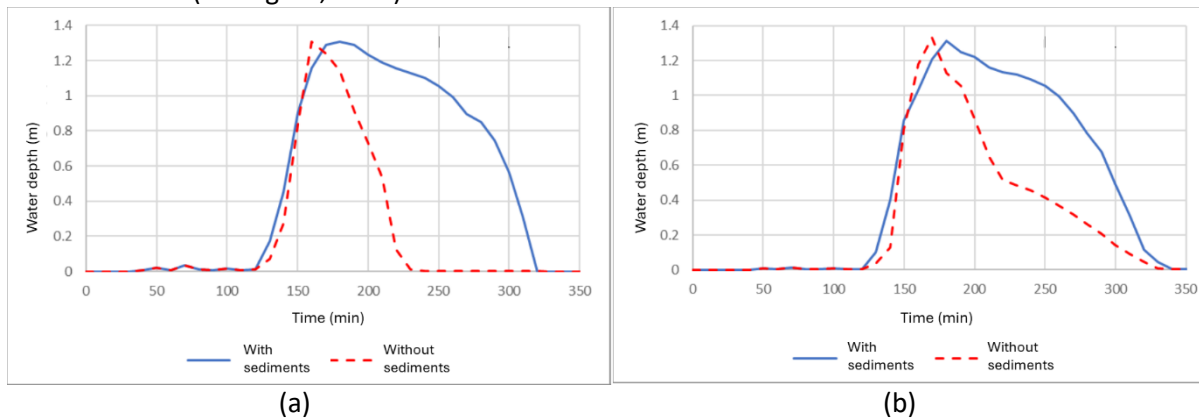


Figure 3 – Water level elevation of the two simulation approaches in calibration point: (a) CP1 and (b) CP2.

Conclusions and future work

This work presented a new module of MODCEL that allows the simulation of a real-time loss of cross-sectional flow area inside storm drains, which intensifies the urban flooding processes. In general lines,

- The results obtained are in line with what was conceptually expected, indicating that the changes made to the MODCEL model fulfilled the proposed mission of modeling the flooding process in an urban watershed integrated with silting up the drainage pipes.
- In terms of computational performance, it was observed that the adoption of this new module of sediment transport and deposition did not add complexity to the calculations to the point of impairing the model's performance.
- The developed method can be replicated to other cases, since the problem of urban flooding intensified by the urbanization process and the loss of hydraulic performance of drainage structures is a reality in several cities.

Acknowledgement

The authors would like to acknowledge the UNESCO Chair for Urban Drainage in Regions of Coastal Lowlands at the University of Rio de Janeiro, Brazil (UFRJ), and the Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq) [167721/2023-2 e 303862/2020-3] for the funding.

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