

WATER DEPTH ANALYSIS IN THE ADOPTION OF SUSTAINABLE URBAN DRAINAGE TECHNIQUES WITH THE APPLICATION OF COMPUTATIONAL MODELING AND GIS SOFTWARE FOR A RESIDENTIAL NEIGHBORHOOD

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Abstract:

The increase in the world's urban human population generated the scarcity of natural resources. Then, to minimize local drainage problems caused by unplanned urbanization, this paper proposes to analyze results simulated using compensatory measures in the Imboassica neighborhood, city of Macaé, State of Rio de Janeiro, Brazil. It objectives assess the model's response to different choices of Coefficient of Manning and Curve Number. In addition, It compares the influence of the height of buildings and roads on the distribution of water in space. This paper uses the MOHID Platform by means of the OpenFlows Flood© software to simulate 10 and 50 years return period Rain Design for the studied region. It simulated the adoption of Compensatory techniques in sustainable urban drainage, the use of green roof and permeable pavement. The changes adopted for different uses of the territory were described using the QGIS© software. It was possible to conclude that the difference in the water depth decrease ranges from about 11.1% and 14.3% because of adopting the compensatory measures for the 50 and 10 years return period Rain Design, respectively. Another evaluation performed was the change of the topography data, considering information of the height of buildings and the roads.

Keywords: Rain Design, Sustainable Urban Drainage, Coefficient of Manning, Curve Number, Urbanization, Sustainable Development, Macaé, Brazil.

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INTRODUCTION

The urban population has grown substantially. Approximately 54% of the world's population lives in urban areas, and this figure is expected to grow to 66% by 2050 (Andimuthu *et al.*, 2019). In China, the urban population increased by 1.2% representing 45.77% of the country's population in 2008 (Kuang *et al.*, 2013). In 2019, according to the World Bank, the urban population in China was already 60%. In Brazil, the urban population was 87% (The World Bank, 2019). The African continent, in turn, had an average urbanization rate of 37% in 2014 (Ebeke & Ntsama Etoundi, 2017). Globally, the population peak will only be reached in 2064 (Vollset *et al.*, 2020).

The expansion of the urban fabric transformed areas of cultivated land, pastures and forests into built-up areas with impermeable surfaces. These impermeable surfaces cover approximately 1.3% and 9% of the land areas of the United States and Europe, respectively (de Colstoun *et al.*, 2019; Scalenghe & Marsan, 2009; Yan *et al.*, 2015). The China has the largest area of impermeable surfaces, covering approximately 63% of its land (Elvidge *et al.*, 2007; Yan *et al.*, 2015), having these areas in the years 2000 to 2008 increased 53.3% in China (Kuang *et al.*, 2013; Yan *et al.*, 2015).

Development

It can be seen that the consumption of material goods, services, and especially energy, are parameters for defining a country's development. The planet, however, does not sustain that all countries reach the consumption levels of those considered developed. For this reason, it is essential, so that there is equity among the population of the countries, that the more developed ones create ways to change their lifestyle, their consumption pattern and, above all, change the current urbanization model. It is necessary because in addition to polluting more, it generates more waste. It has an objective to creating a more sustainable development model that can be followed for other countries in the future (May, Lustosa & Vinha, 2003).

According to Herrington (2021), the collapse of society would be predicted for 2040, this conclusion is due to an industrial projection of our global civilization, which is heading towards declining economic growth in the next decade. Nonetheless, Herrington (2021) emphasized that although the model shows the social impact of economic and industrial growth, it is not intended to scare people and it does not translate into the extinction of humanity, but rather that "economic and industrial growth will stop and, then, will decline, which will affect food production and living standards." The purpose of this study is a warning, as human activity can be regenerative and our productive

capacities can be transformed, creating a world full of opportunities that is also sustainable. Available data suggest that what is decided in the next ten years will determine the long-term fate of human civilization.

According to a statement from the United Nations, Madagascar is the first country in the world to suffer extreme hunger due to climate change. The southern region of the island of Madagascar is facing the worst drought in 40 years (UN, 2021). The availability of water is a relevant factor in various parts of the world. Because of drought, to be possible mentioned some projects that aim to propose solutions for water scarcity. Marvella Farms is a project that proposes a greenhouse with a hydroponic system and solar energy for food production in Djibouti, a country in Africa. The International Agricultural Technology Transfer Center (In portuguese "Centro Internacional de Transferência Tecnológica Agropecuária- Ciitta"), in partnership with the Valmont company, it intends to transfer modern irrigation techniques through the Green Imperative project to Nigeria, a country in Africa. Valmont has installed a 100% solar-powered irrigation center pivot in the desert of Sudan. In addition, a structure called Warka Water Towers has been developed in Ethiopia, comprising a bamboo tower that collects fresh water from the air (Othmani *et al.*, 2021).

Urban drainage

Countries like China, India, Indonesia, Pakistan, Afghanistan, Germany, Greece, Italy, Nigeria and Ethiopia suffer from flooding in urban areas (Agbola *et al.*, 2012; Memon *et al.*, 2015; Schulte in den Bäumen *et al.*, 2015; Lian *et al.*, 2017; Recanatesi *et al.*, 2017; Bathrellos *et al.*, 2018; Erena *et al.*, 2018; Jatmiko, 2018; Oskorouchi *et al.*, 2018; Andimuthu *et al.*, 2019). This demonstrates that the need for planning in urban drainage is worldwide. As it is related to urbanization, it also needs to be considered when studying a sustainable development model.

Urban drainage is an engineering technique to capture and direct rainwater, which will not infiltrate the soil due to its waterproofing. However, it only seeks to transfer the water accumulation to another region, which may not be prepared to receive it (Bouarafa *et al.*, 2019).

Despite the belief that technologies will solve the needs of maintaining human life in the future, it is important to think about the conservation of the environment, so that it is not necessary to create solutions to issues that could be avoided. Sustainable urban drainage proposes to mitigate the impacts of urbanization on the hydrological cycle, most often through infiltration, and reduce the volume of water that is directed to the channels (Bouarafa *et al.*, 2019). The

Sustainable Drainage Techniques are highly recommended and applied in various parts of the world, where the terminology varies according to the region, however, it has the same fundamentals (Zhou, 2014).

In Europe, the Sustainable Urban Drainage System is known by the acronym SUDS, and is used with a focus on maintaining public health, protecting natural water resources, and biological diversity for future needs (Hellström *et al.*, 2000; Willems *et al.*, 2012; Zhou, 2014). In Australia, the term Water-Sensitive Urban Design known by the acronym WSUD is mainly used to refer to planning and engineering that aims to sustainably integrate water into the urban landscape, minimize environmental degradation and achieve harmony between water bodies and cities (Roy *et al.*, 2008; Zhou, 2014). The same term in the United States and Canada is known as Low-Impact Development and describes an approach of integrating natural processes with the urban environment to recreate and conserve water management ecosystems, seeking on a small scale hydrological conservation to mitigate the various impacts of urbanization (Dietz, 2007; Elliott & Trowsdale, 2007; Zhou, 2014).

In New Zealand these practices are called Low Impact Urban Design and Development (Zhou, 2014). Denmark and the Netherlands have promoted urban transformation projects known as “Water in Urban Areas” that comprise sustainable drainage areas (Zhou, 2014). In Sweden these practices are known as “Sustainable Urban Water Management” which aim to protect water resources in urban areas (Hellström *et al.*, 2000; Zhou, 2014).

Urban drainage consists of structural and non-structural measures. Structural measures are the best known and most used, but the use of non-structural measures is becoming more and more common, due to a global mobilization to have ecological measures in the mitigation of rainwater runoff (Uvini Srishantha & Upaka Rathnayake, 2017).

Sustainable urban drainage offers a sustainable solution to flooding. It changes the engineering system traditionally linked to pipelines. We can define it as the practices and systems that use and enhance natural systems, in other words, infiltration, evapotranspiration, filtration, retention and reuse (Uvini Srishantha & Upaka Rathnayake, 2017).

Sustainable urban drainage can add aesthetic, social and environmental values to the urban area and can promote more sustainable development. If carefully planned, it can be part of urban green infrastructure, adapting cities to respond to climate change and recreational services (Zhou *et al.*, 2013).

It became possible to think about the creation of small lakes, or green spaces, that promote the transformation of the urban landscape. Other strategies

are: water trenches, ecological swale, rain gardens and green roofs (In portuguese “trinchieras de infiltração”, “canais de drenagem”, “jardins filtrantes” and “telhados verdes”), that when designed correctly, they can serve both as recreational experience sites and to temporarily accumulate rainwater in extreme rain events (Zhou *et al.*, 2013).

Sustainable drainage techniques have become an effective way of approaching the natural hydrological cycle of the region prior to urbanization. Among these techniques, one can mention the capture of rainwater, in other words, rainwater harvesting, permeable pavements and green roofs (Rodríguez-Sinobas *et al.*, 2018).

The permeable paving (known as permeable pavements in the United Kingdom, and pervious paving in North America) are considered to be a cost-effective sustainable drainage system that reduces rainwater runoff, reducing localized flooding. It consists of a system composed of a permeable concrete cover in the upper layer, and an underlayer composed of coarse aggregates. Concrete must have a porosity of 15 to 35% to allow rapid percolation of water. In practice, there are many variations in layer thickness and composition, but all are intended to store rainwater until it infiltrates the soil or is drained. It can be designed for total infiltration, partial or only for storage, in the last two cases, the soil has drains that will direct the water (Kia *et al.*, 2017).

In the city of Chicago, green roofs have created a habitat for bee communities within the urban environment (Tonietto *et al.*, 2011). Green roofs have become mandatory for new flat-topped buildings in some cities, this has generated a considerable increase in urban beekeeping. This increased connectivity between cities and bee habitat has been observed in Asia, Europe and North America (Hofmann & Renner, 2018). The legislation that made the presence of green roofs mandatory is a non-structural measure, while the green roof itself is a structural measure of sustainable urban drainage.

The green roof is a revegetation infrastructure. Revegetation is a sustainable urban drainage technique. It appears more on roofs as they are common areas in urban areas. However, “The Great Green Wall” is also a revegetation technique that favors infiltration and reduces surface runoff, which in turn reduces soil erosion. This technique was implemented in China (Tan & Li, 2015), and it is being implemented in the Sahara to combat soil erosion, and in the attempt to contain desertification (Goffner *et al.*, 2019).

In the district of Valdebebas, in the Northeast of Madrid, Spain, a sustainable drainage system was installed in 2017. It proved to be beneficial in several aspects: it reduced the volume of water going to the canals by 41%, reduced energy consumption and production of greenhouse gases by approximately 10%.

In addition, there were considerable savings for the municipality, largely due to the combined sewage and drainage system in Madrid, that is, the water abstracted, regardless of the source, is treated (Rodríguez-Sinobas *et al.*, 2018).

Modeling for urban drainage

The planning in urban drainage needs to incorporate models with predictive capabilities that generate quantitative results, as they will allow measuring the response of the effects of each scenario and technique before its application, helping in decision making regarding the selection of the most efficient types of urban drainage. With these models it is possible to simulate the sustainable drainage techniques that will best behave through the system forecasts. Many models are presented in the literature (Zhou, 2014).

Scientific discoveries, in addition to generating progress, determine how society advances (Barros, 2012). Part of this process is in the way the articles are prepared (Miglioli, 2012; Perlin *et al.*, 2018). The choice of hydrology analysis method needs to be aligned with the expected results, and the software are innovations that play a fundamental role in this process.

Through the modeling of water phenomena, Bacalhau *et al.* (2016) defined strategies for the operation of a reservoir in the state of Pernambuco, Brazil. The state of Pernambuco has a history of flooding (Batista *et al.*, 2020). In addition, the reservoir is a sustainable urban drainage method, as it stores rainwater, reducing surface runoff and minimizing the overflows of drainage channels on days of intense rain.

OBJECTIVES

The general objective of this work is to simulate proposals for compensatory measures for urban drainage in the Imboassica district, city of Macaé, State of Rio de Janeiro, Brazil. The specific objectives would be:

- Evaluate the model's response to different choices of Manning's Coefficient.
- Evaluate the model's response to different Curve Number choices.
- Compare the influence of the height of buildings and roads on the distribution of water in space.
- Evaluate the model's response to two types of topography.
- Evaluate the model's response for two return periods for Design Rain (10 and 50 years).

MATERIAL AND METHOD

The chosen study area was Bairro Imboassica. The city of Macaé is a suitable region for work due to its history of flooding (Tavares *et al.*, 2018). The watershed of the Imboassica district is largely urbanized by the presence of a residential condominium (Fig. 1). The adopted techniques can be applied to other regions, in this case, the residential condominium located in the upper part of the Hydrographic Basin of the Imboassica neighborhood will be used for the adoption of compensatory measures.

The OpenFlows Flood© program was used to elaborate scenarios with different soil characteristics and two distinct topographies. In the first moment, 2 simulations (1 and 2) were performed considering the natural topography of the terrain using altimetry data from the TOPODATA project (Geomorphometric Database of Brazil) of the National Institute for Space Research (INPE). In the second moment, to two simulations (3 and 4), the houses' height were increased by 10m and the height of the road outside the residential condominium was increased by 1m. The four simulations ran for the 10 years return period Rain Design, and the 50 years return Rain Design.

It adopted different values of Manning's Coefficient to study the transport of water in the drainage channels formed in the model according to the soil of the region. The Manning's Coefficient seeks to reflect the roughness of the channel and its interference with the water flow (Zhang *et al.*, 2019). The values used in this study were taken from Gribbin (2014) on pages 390, 391 and 392. The table of values for the Manning's Coefficient is extensive and Table 1 represents only the values used in this study.

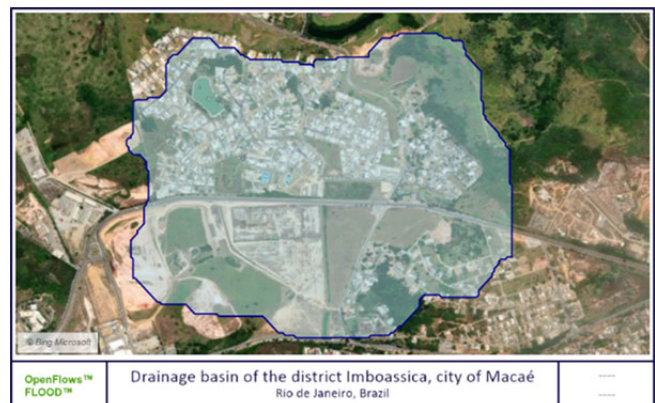


Fig. 1 Neighborhood region with the outline of the Bairro Imboassica basin.

Table 1. Part of the table with values for the Manning's Roughness coefficient in (m³/s) (Gribbin, 2014).

Closed manholes	
↳ (A) Polyvinyl Chloride (PVC)	0.007-0.011
Natural Channels (Watercourses)	
↳ (A) Smaller watercourses	0.030-0.035
↳ Fairly regular section	
↳ A little grass and herbs, little or no weeds	
Natural Channels (Watercourses)	
↳ (A) Smaller watercourses	0.030-0.050
↳ Fairly regular section	
↳ Dense grass growth, depth of runoff significantly greater than grass height	

In order to model the surface runoff of the study regions according to the soil, the formulation with the Curve Number was used. The Curve Number is a parameter used to describe the potential of surface runoff water, considering the losses that occur in part by the volume of water that infiltrates (percolating into the porous soil medium) and in part by evapotranspiration, being lost to the atmosphere by evaporation and transpiration of plants. The Curve Number therefore depends on the characteristics of the soil and its coverage (Miguez *et al.*, 2016).

The Curve Number is mainly about representing different hydrological conditions, being adjusted according to four different types of soil and different patterns of use and occupation. The quantification of this parameter is done through a series of pre-established values (Miguez *et al.*, 2016). The values used in this study were taken from Gribbin (2014), more specifically, on pages 448 and 449, being presented in **Table 2**.

The value used for the vegetated area, was considered as Forest or Wood, for the Curve Number, 50 was chosen instead of 55 due to the presence of sandy clay soil in the region, but with good depth. It was chosen for the exposed soil region, the value of 70 instead of 67 due to the proximity of the soil found in regions with grass, where the value of 77 was adopted. The value adopted for the compensatory measure with green roof was 83. The value adopted for the compensatory measure of permeable pavement was 86 instead of 85. To understand the adopted soil groups, were used the values established in the book by Miguez *et al.* (2016), as shown in **Table 3**.

In the entire basin, a Rain Design was considered for the city of Macaé, adopted for a return period of 10 years and then for 50 years.

The definition of precipitation adopted in the model was established from the formulation of Intensity, Duration and Frequency (IDF) of Intense Rainfall (Miguez *et al.*, 2016):

$$I = \frac{aT_r^n}{(t+b)^m}, \quad (1)$$

where a , b , m , n are parameters that depend on the geographic space where precipitation is being analyzed; t is the rain duration time in minutes (min); T_r is the return time (years).

In this work, the maximum precipitation equation for the city of Macaé described below will be adopted:

$$I_{max} = \frac{444,258 * T_r^{0,263}}{(t+6,266)^{0,655}} \quad (2)$$

where t was taken as the concentration time t_c defined in Equation (3). Where I_{max} is the maximum precipitation (mm/hour).

Due to the simplicity and good acceptance of the California Culverts Practice formula (Miguez *et al.*, 2016), opted for your choice, which is presented in Equation 3.

$$(1) t_c = 57 * \left(\frac{L^3}{H}\right)^{0,385} \quad (3)$$

where t_c is the concentration time (min); where L is the length of the channel (km); where H is the unevenness between the highest point of the basin and the outlet (m).

Table 2. Part of the Table with values used for the Curve Number (Gribbin, 2014).

Description of coverage	Groups			
	A	B	C	D
Type of coverage and hydrological condition				
Impervious areas: Paved; open ditches	83	89	92	93
Woodland: Woodland protected from grazing, and bush adequately cover the ground	30	55	70	77
Weeds (Mixture of grass, weeds and herbs with weeds as the main element): Less than 50% ground cover	48	67	77	83
Impervious Areas: Streets and gravel roads	76	85	89	91

Table 3. Table with soil hydrological groups

Group A	Sandy soil, with low total clay content (less than 8%), without rocks, without clayey layer and not even densified to a depth of 1.5m. The humus content is very low, not reaching 1%
Group B	Sandy soils that are less deep than those in group A and have a lower total clay content, but still less than 15%. In the case of purple earths, the limit can go up to 20% thanks to the greater porosity. The two humus contents can rise to 1.2% and 1.5% respectively. There can be no gravel or clay layers up to 1.5m, but a layer more densified than the surface layer is almost always present.
Group C	Muddy soils, with a clay content of 20% to 30%, but without impermeable clayey layers or containing gravel to a depth of 1.2m. In the case of purple earths, these two maximum limits can be 40% and 1.5m. At about 60cm in depth, a layer is more densified than in group B, but still far from the impermeability conditions
Group D	Clayey soils (30% to 40% of total clay) and with a densified layer approximately 50 cm deep or sandy soils such as B, but with an almost impermeable clayey layer or horizon of rolled pebbles

Source: Miguez *et al.* (2016).

Using Equations (1) to (3), it is possible to establish the evolution of precipitation intensity over time with a time series and use it in the simulation of urban drainage.

The calculated concentration time for the drainage basin was 45 minutes, however, we consider rain of 1 hour in duration. The simulation was done for two hours, right after 1h of simulation with rain, a simulation of 1h without rain was performed, because it was expected to visualize the drop in the rain curve in the second hour of simulation. As in heavy rain events, precipitation is usually continuous, but with a different intensity of rain, it was considered a rainfall of 1 hour, 15 minutes more than the concentration time of the drainage basin, to compensate for the second hour without rain. The simulation was run for a period of 2 hours, in a hypothetical period of the day, in this case, this time was from 12:00 to 14:00.

It performs simulations 1 and 3, a land use shapefile was created in the QGIS© software to differentiate the terrain by types of soil infiltration. The shapefile was imported into the OpenFlows Flood© hydrological

program and the Curve Number values were adopted for vegetation of 50, exposed soil of 70, Field with grass of 77 and urban area of 89, and Manning values for vegetation of 0.035, Soil exposed of 0.030, Field with grass of 0.033 and urban area of 0.011 (**Fig. 2**)

It is becoming aware of sustainable urban drainage techniques; it is possible to adopt the one that best fits local possibilities. Thus, to perform simulations 2 and 4, the OpenFlows Flood© file was used with Curve Number values for vegetation of 50, exposed soil of 70, Field with grass of 77 and urban area of 89, and Manning's values for 0.035 vegetation, 0.030 exposed soil, 0.033 grass field and 0.011 urban area (**Fig. 2**). In addition, it is more viable compensatory measures that were added to the implementation in a residential condominium, which were: permeable pavement in the condominium's paving area and green roof in houses. Thus, **Fig. 3** illustrates the inclusion of the Curve Number of 86 and Manning's values of 0.025 in the green roof, and the Curve Number of 83 and Manning's values of 0.016 used to designate the permeable pavement range.

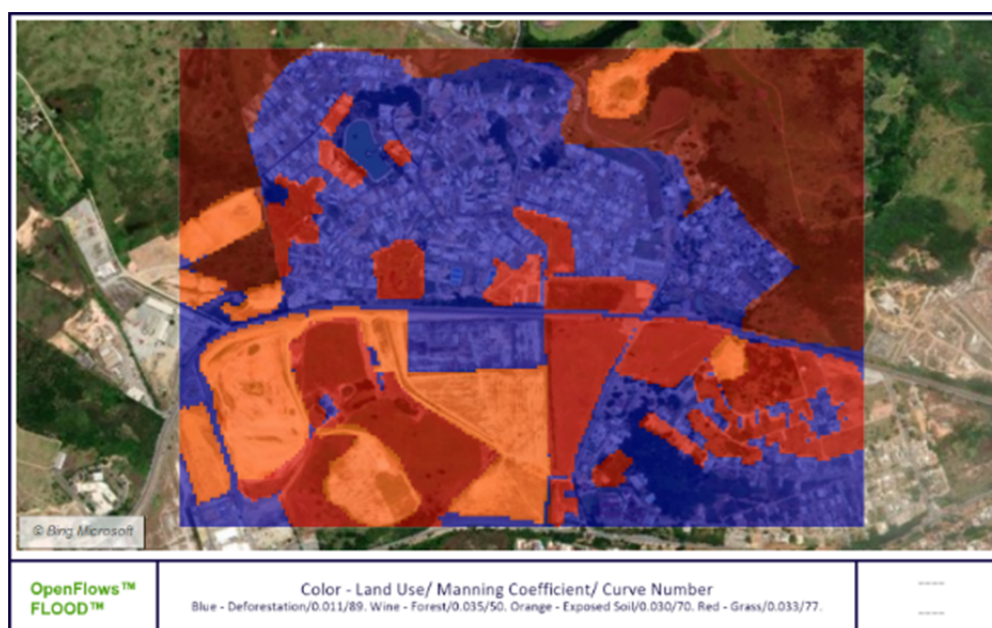


Fig. 2 Image with Curve Number and Manning's values definitions without compensatory measures.

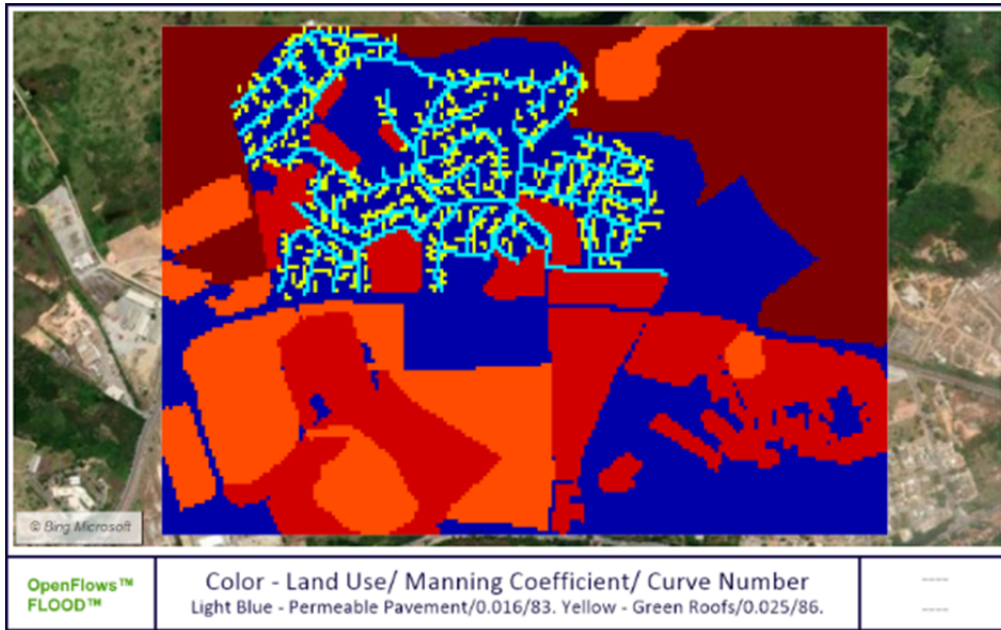


Fig. 3 Image with Curve Number and Manning’s values definitions with compensatory measures.

In summary, the four models made can be written as follows:

- Modeling 1: soil classification in QGIS with different Curve Number, natural terrain altitude, variable Manning’s values.
- Modeling 2: Changing the Curve Number and Manning’s values of Modeling 1 to include compensatory measures
- Modeling 3: QGIS soil classification with different Curve Number, 10m house altitude, 1m road altitude, variable Manning’s values.
- Modeling 4: Changing the Curve Number and Manning’s values of Modeling 3 to include compensatory measures

RESULTS

The simulation ran for 2 hours, with a hypothetical time from 12:00 to 14:00. It was observed that both for the 10 years Rain Design (Fig. 4) and for the 50 years Rain Design (Fig. 5) the compensatory measures represented by simulation 2 generated a decrease in the water depth in the middle of the drainage basin of the Imboassica neighborhood. This finding was also observed for the 10 years Rain Design (Fig. 6), when compared to the 50 years Rain Design (Fig. 7), it is noted that the compensatory measures represented by simulation 4 generated a decrease in the depth of water in the middle of the drainage basin of the Imboassica district.

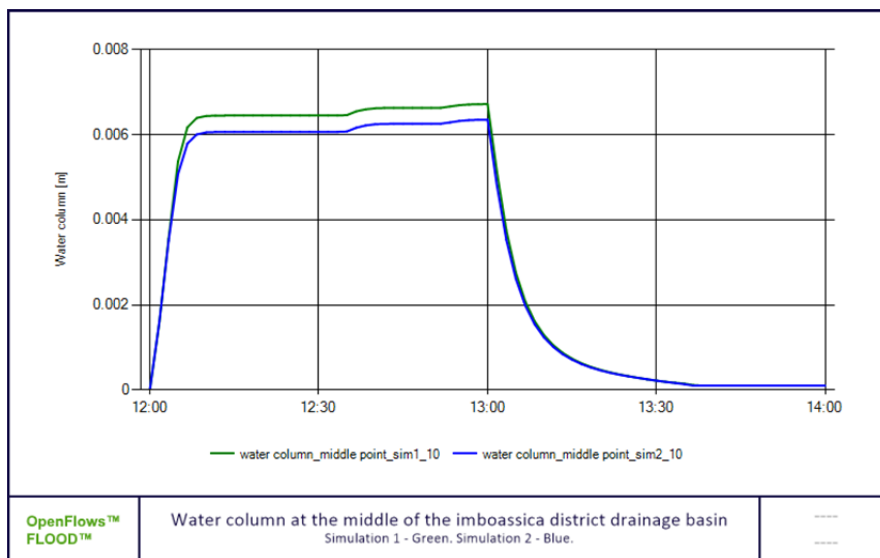


Fig. 4 Graph of the water column of the middle of the drainage basin in simulation 1 and in simulation 2 for the 10-year design rainfall.

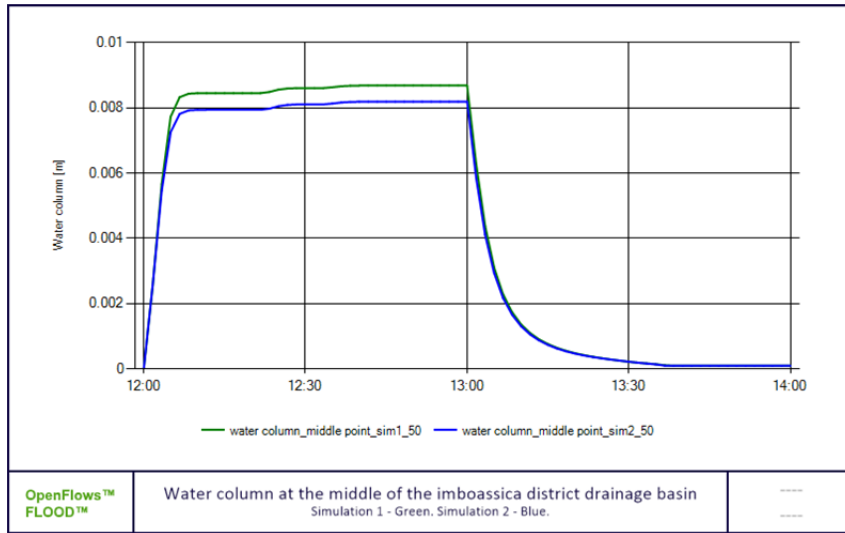


Fig. 5 Graph of the water column of the middle of the drainage basin in simulation 1 and in simulation 2 for the 50-year design rainfall.

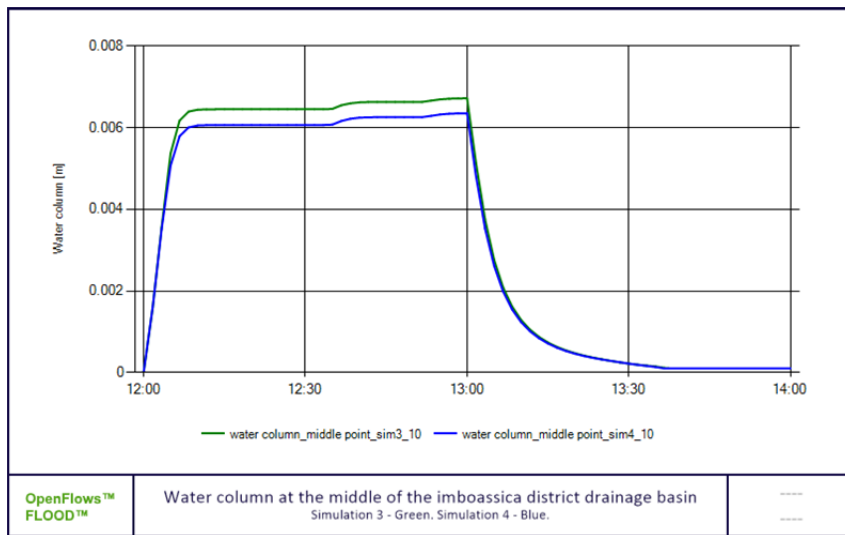


Fig. 6 Graph of the water column of the middle of the drainage basin in simulation 3 and in simulation 4 for the 10-year design rainfall.

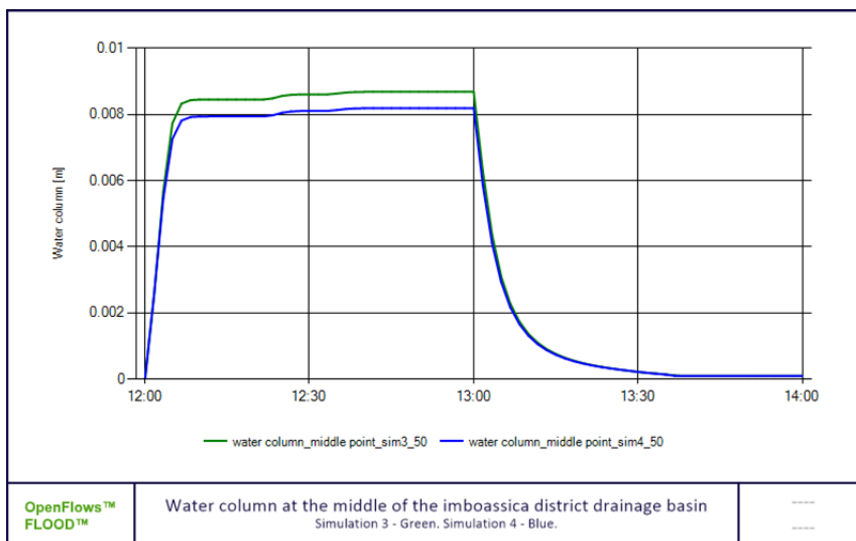


Fig. 7 Graph of the water column of the middle of the drainage basin in simulation 3 and in simulation 4 for the 50-year design rainfall.

When comparing **Fig. 4** with **Fig. 6**, when we consider the height of the houses and the road for 10 years Rain Design, there is no significant change in the depth of the drainage channel. The same thing happens when comparing **Fig. 5** with **Fig. 7** for 50 years Rain Design.

CONCLUSION

It was also possible to observe an influence of infiltration due to the adopted Curve Number value, as the water depth tends to decrease with the presence of compensatory measures in the simulation. However, infiltration was less expressive and could have greater significance when increasing the regions with compensatory measures. The difference in the water depth is 0.009mm to 0.008mm, that is, a reduction of 11.1%, and 0.007mm to 0.006mm, that is, a reduction of 14.3% with the compensatory measures adopted for a project of return rainfall of 50 and 10 years, respectively.

When considering the terrain topography, there was no significant change in the Runoff when considering the height of the houses and the road in the simulation. As a result, the distribution of water in space had no significant change. In addition, there was no significant delay in the arrival of water to the drainage channel between simulations. Thus, the influence of friction due to the terrain represented by the Manning's Coefficients had little relevance, which may be due to small regions with compensatory measures.

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