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Analysis of the Viability of Implementing Sustainable Proposals to Reduce Tunnel Flooding in Recife, Pernambuco

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ABSTRACT

Flooding in urban centers has been treated as a direct consequence of excessive rainfall, without considering the integrated functioning of the drainage system. These problems have caused engineers to propose auxiliary solutions or techniques that assist urban drainage. The objective of this study was to analyze the technical feasibility of using compensatory measures such as permeable pavement, for tunnel accesses, as an aid to existing drainage. The soil of the unpaved regions, which represent only 16.3% of the study area, was characterized using the Beerkan method, followed by an analysis of the water balance of the region using the Hydrus-1D computational model, in order to determine the rainfall on the unpaved regions surrounding the tunnels. The water balance of this portion of the study area showed that, of the 239.69 mm.m⁻² that precipitated over unpaved areas, 88.15% infiltrated and the remaining 11.85% ran off or evaporated. In addition, infiltration tests showed that the soil is mostly sandy and capable of permitting infiltration of the water precipitated during the year studied, so the proposal to use permeable pavement at the entrance and exit of the Chico Science Tunnel is viable, minimizing flooding as well as maintenance costs for the booster pumps used by the current drainage system.

Análise da Viabilidade de Implantação de Medidas Sustentáveis para Reduzir Alagamentos nos Túneis de Recife, Pernambuco

RESUMO

Os alagamentos de centros urbanos têm sido tratados como consequência direta do excesso de chuva, sem considerar o funcionamento integrado do sistema de drenagem. Tais problemas fizeram com que a Engenharia propusesse soluções ou técnicas auxiliares visando assistir a drenagem urbana. Deste modo, objetivou-se analisar a viabilidade técnica do uso de medidas compensatórias como o pavimento permeável nos acessos de túneis, como um auxílio à drenagem existente. Para isso, o solo das regiões não pavimentadas, os quais representam apenas 16,3% da área de estudo, foram caracterizados mediante o uso do método Beerkan e, em seguida, realizada uma análise do balanço hídrico da região mediante o uso do modelo computacional Hydrus-1D, afim de se conhecer o aporte pluviométrico sobre as regiões não pavimentadas nos entornos dos túneis. O balanço hídrico desta porção da área de estudo mostrou que dos 239,69 mm.m⁻² que precipitaram sobre as áreas não pavimentadas, 88,15% infiltrou e os demais, 11,85%, escoaram ou evaporaram. Além disso, os ensaios de infiltração mostraram que o solo é majoritariamente arenoso e capaz de permitir a infiltração da água precipitada durante o ano estudado, de modo que a proposta de se utilizar o pavimento permeável na entrada e saída do túnel Chico Science é viável, uma vez que alagamentos seriam minimizados, bem como os custos de manutenção das bombas de recalque do atual sistema de drenagem também seriam reduzidos.

Introduction

Rapid urban population growth has generated significant changes in the environment, such as impermeabilization and lack of land use planning. Such modifications have had major sanitary and environmental impacts on society,

especially with regard to urban drainage, due to sediment and solid waste being transported to the drainage network (Hansmann, 2013). Neves and Tucci (2011) stated that the material that enters the collection network accumulates and reduces the

useful area of the pipes, consequently reducing drainage capacity and the quality of the drained water. Obstruction of pipes, as well as their obsolescence, has generated major disturbances during periods of heavy rainfall.

However, the problem of urban flooding has been treated as a direct consequence of excessive rainfall, without taking into consideration how urban drainage functions as an integrated system. This has led engineers to seek local solutions, intervening to mitigate the effects of precipitation in the urbanized basin, that is, in making the drainage system adequate to handle new flows generated after the resident population increase in urban centers (Rezende, 2010).

Rain is one of the principal constraints of flooding, as flood events are a consequence of the inadequacy of the drainage network to remove the precipitated water volume (Perez, 2013). Its damages are numerous, affecting and interfering with many facets of urban life, such as habitation, transportation, sanitation, and public health, among others (Rezende et al., 2013).

For this reason, the ability to predict the flow of a basin based on its drainage system is a great tool available that helps in facing problems such as flood control, dimensioning of hydraulic structures, and water supply (Guo et al., 2018). Rainwater, when it reaches the ground surface, can seep or infiltrate into the soil. If the intensity of the rainfall is greater than the soil absorption capacity, a surface runoff of surplus water will occur, which will flow into the rainwater catchment system. However, this water can pool in some areas of large urban centers, generating inconvenience and costs that must be borne by public administration.

In addition, these runoffs are often influenced by high rates of soil impermeabilization, which decrease infiltration of water into the soil, increase flow velocity, and water volume, generating new points where flooding occurs (Aragão et al., 2017). The use of compensatory techniques for storm water management therefore has been widely suggested (Oliveira et al., 2016; Silva Junior, et al., 2017; Silva, 2018).

The increasing frequency of flooding in large urban centers has been punishing to many cities, causing major economic losses and increased environmental liabilities. Addressing this problem requires study, planning, and watershed interventions (Wdowinski et al., 2016).

Recife is one of these cities that has frequently suffered from flooding, which causes major disruptions, especially in tunnels. Such structures are constantly threatened during rainy seasons, especially when the tide is high (Cabral

and Alencar, 2005; Silva Junior et al., 2017). This is because most Brazilian coastal cities are cut by canals or rivers that rise and fall with the tide.

In order to assist in the drainage of these tunnels, booster pumps have been installed. However, this measure is quite costly due to high energy consumption and the constant need for maintenance. In addition, the use of these pumps often turns out to be ineffective, because they are unable to handle water removal at sufficient speed and only operate well after a considerable amount of water has accumulated (Moreira, 2014).

Other authors (Coutinho, 2011; Miguéz et al., 2014; Silva, 2018) have suggested the use of compensatory techniques to reduce flooding in large urban centers. Such suggestions are due to the fact that the traditional drainage measures used are not sufficient to ensure that no flooding occurs on rainy days.

In order to reduce the constant flooding in tunnels, the aim of this study is to analyze the feasibility of implementing compensatory measures, such as permeable pavement, on the roads that border or give access to the tunnels, to assist in the drainage of nearby unpaved areas.

Materials and Methods

Study area

The neighborhood of Madalena is one of the main crossroads connecting major traffic routes and important centers of Recife, such as the medical center, located in the neighborhood of Ilha do Leite, and the BR-101 and BR-232 highways, which provide access to the Federal University of Pernambuco (UFPE) and the Pernambuco Supply and Logistics Center (CEASA/PE). It also hosts the Engineering and Management programs of the University of Pernambuco and the Ademar da Costa Carvalho football stadium, in addition to housing a great many residential buildings and power substations.

The area shown in Figure 1 covers 14.284 m², with the location studied and the points where soil samples were collected marked. In the regions of natural soil, 2.330 m², approximately 16.3% of the total area studied, point samples were collected for the purposes of laboratory testing. The points chosen are within Bandeira Square, located along the margins of the Chico Science Tunnel, a wooded area without large impermeable areas. The locations chosen are relevant to because they are natural drainage points. Because they are sparsely wooded, and the trees found there have a deep root system, the surface structure of the soil remains

unaltered by the vegetation, and consequently, maintains its infiltration capacity unaltered.

Figure 1. a) Area marked for study, in red, and collection points 1 and 2, b) side view.

This tunnel, built in the Madalena neighborhood in 2000, was designed to improve traffic flow at the intersection between Avenue Abdias de Carvalho and Avenue Beira Rio (Lins et al., 2017). Chico Science Tunnel is approximately 96 m long and 21 m wide, with a height at the inlet and outlet of 4.70 m. Within the structure, there are four one-way vehicle lanes and a pedestrian walkway, separated from the roadway by concrete blocks. Rua do Paissandú passes above the tunnel, with four lanes, two in each direction, ending at Avenida Sport Clube do Recife. Along the banks of the Capibaribe River is a retaining wall, separating the mangrove from the tunnel. In addition to the Chico Science Tunnel, the city of Recife has four other important tunnels, which were all designed to relieve traffic or facilitate access to certain neighborhoods, such as the Abolition Tunnel, which connects the east and west corridors of the city of Recife.

Infiltration tests

Soil samples for collected at the marked locations (Figure 1) for particle size analysis, and to calculate of bulk density, initial moisture, and final moisture. In addition, infiltration tests were performed using a single ring infiltrometer to determine the hydrodynamic behavior of the soil.

The granulometric analysis of the soil was performed using the method from NBR 7181 (ABNT, 2016). This standard requires that samples be sieved to separate the sand fractions (with diameter greater than or equal to 0.075 mm) from the silt and clay fractions (with diameter less than 0.075 mm). The finer material must then be submitted to a sedimentation process, thereby obtaining the quantities of clay and silt present in each of the collected samples (Densimeter Method).

For the infiltration tests, a constant volume of water (300 mL) was placed inside the infiltrometer, and the time it took for this amount of water to infiltrate the soil was measured, leaving a thin layer of water covering the soil between additions of the same volume so that no air would enter the pores. The process was repeated until the intervals between water infiltration times were constant (Siltecho et al., 2015). Because they have soils with similar textural classification, Loamy sand and Sand, respectively, the duration of the trials for both test locations were approximately 15 minutes.

From the infiltration tests, ordered pairs were obtained, referring to the accumulated volumes of infiltrated water and the total time elapsed during the test. The accumulated infiltration curve was adjusted using the mathematical model proposed by Haverkamp and

Parlange (1986), Beerkan method. (Oliveira et al., 2018).

This method's experimental procedure is performed in two stages, the first being a granulometric analysis (Particle Size Distribution - PSD) and the second being infiltration tests performed with a cylindrical infiltrometer (Siltecho et al., 2015).

From the data obtained from the infiltration and particle size tests, the Beerkan method was then used to obtain the shape (n , m e η) and normalization (θ_s , K_s e h_g) parameters of the curves for water retention in the soil, $\theta(h)$, and saturated hydraulic conductivity, $K(\theta)$, by the van Genuchten relations of Brooks and Corey, Equations 1 and 2, respectively.

$$\frac{\theta - \theta_r}{\theta_s - \theta_r} = \left[1 + \left(\frac{h}{h_g} \right)^n \right]^{-m} \quad (1)$$

where $m = 1 - \frac{2}{n}$ (Burdine, 1953),

$$K(\theta) = K_s * \left(\frac{\theta - \theta_r}{\theta_s - \theta_r} \right)^\eta \quad (2)$$

and $\eta = \frac{2}{nm} + 2 + p$.

Where θ , θ_r , and θ_s represent volumetric, residual, and saturated humidity ($\text{cm}^3\text{cm}^{-3}$), respectively, K_s is the saturated hydraulic conductivity, h is the matric potential (cm), h_g is the water bubbling pressure in the soil (cm), η is the shape parameter for the hydraulic conductivity curve and for Burdine (1953) $p = 1$.

Hydrus-1D and simulations

The simulation of water transfer in the soil using Hydrus-1D was constructed from a layer 300 cm deep and subdivided every 10 cm for boundary conditions. The vegetation present at the collection sites was not considered in the

simulations, because the treetops do not cover a large area and the undergrowth was disregarded.

The Hydrus-1D computational model solves numerically the Richards equation (Simunek et al., 2013), Equation 3.

$$\frac{\partial \theta}{\partial t} = \frac{\partial [K(\theta) \frac{\partial h}{\partial z}]}{\partial z} \quad (3)$$

Where t is the time (h) and z represents the spatial coordinates (cm).

For the upper boundary conditions, the atmospheric parameters of wind speed, maximum and minimum temperatures, amount of sunshine, precipitation, and relative humidity were used to estimate the daily reference evaporation, by means of the Penman-Monteith model, described by the Food and Agriculture Organization (FAO). These atmospheric data, dated between 01/01/2019 and 07/31/2019, were obtained from the National Institute of Meteorology (INMET) database, Curado station, where the meteorological sensor measurements are taken daily. For the lower boundary condition, constant pressure was considered (Figure 2).

During this period, the accumulated precipitation over the study area was approximately $1699.40 \text{ mm.m}^{-2}$, with two major rainfall events occurring, with daily accumulated values of 90.40 and 147.20 mm.m^{-2} . In addition, this location went through recurring rainless periods, with rainfall below 2.00 mm.m^{-2} , that lasted up to nine days.

The maximum and minimum temperatures reached their lowest averages during the wettest months, from May to June, as shown in Figure 3. The days with the highest insolation periods, between January and February, were those with the lowest rainfall, and consequently, the lowest relative humidity values. Over the period, wind speed varied very little, averaging 4.80 km.day^{-1} .

Figure 2. Schematic drawing of the soil profile with upper and lower boundary conditions.

Figure 3. Hydrogram for the period from 01/01/2019 to 31/07/2019.

Technical viability

In order to analyze the technical feasibility of the installation of permeable pavement, it was considered that the water table depth at the study site is shallow because the study area borders a portion of the Capibaribe River. This area is influenced by the tides, so that in periods of full moon or new moon, the water table rises and may cause some flooding in the Chico Science Tunnel, even on sunny days. Therefore, compensatory measures should be implemented at the entrance and exit of the tunnel, where the quota is higher and the water table is deeper.

Results and discussion

The granulometric analyses showed that one kilogram of the soil from Region 1 is composed

of 844 g of sand, 128 g of silt, and 24 g of clay, while one kilogram of soil from Region 2 contains 930 g of sand, 46 g of silt, and 24 g of clay. These soils are mainly composed of sand and are classified by the EMBRAPA manual (1997), as Loamy Sand and Sand, respectively.

According to Di prima et al. (2018), the potentiality for water infiltration into the soil depends directly on the particle size composition. In addition, they also state that the rate of water infiltration into clay soils is usually lower when compared to the rate of water infiltration into predominantly sandy soils.

It can therefore be said that, based on the results of the granulometric tests, the soil from Regions 1 and 2 should have good infiltrability, allowing for the installation of permeable pavement that would help reduce the surface runoff

of rainwater, at the entrance and exit of the Chico Science Tunnel. However, the use of permeable pavement together with other compensatory techniques is not necessary, considering the effectiveness of the natural soil in allowing water to infiltrate corroborating with what was evidenced by Silva (2018).

The estimated results for both shape parameters and saturated hydraulic conductivity of the soils of both regions were obtained through the infiltration tests using the Beerkan method, presented in Table 1. In order to validate the data, the estimated coefficient of determination, R^2 , was calculated for the estimated data and the results obtained from the tests, with values of 95.40 and 98.60% for the soils of regions 1 and 2, respectively.

The values obtained for the shape parameters of the retention curve, n and m in Table 1, show that, the smaller they are, the higher the value of η , because the values of these parameters directly influence the value of η , as can be seen in Equation 2. Consequently, the higher the values assumed by η , the lower the values of saturated hydraulic conductivity as well as showing the results of Holanda et al. (2019).

These values for saturated hydraulic conductivity refer to how much water is able to infiltrate into the soil, so the higher they are, the more water is able to infiltrate. If, in 2016, the proposed compensatory technique had already been implemented, the accumulated precipitation of 178.20 mm on May 30, as stated by Silva (2018), which has a return time of five years, would not cause flooding in the Chico Science Tunnel, because the soil allows for an infiltration of between 777.60 and 3024 mm of rain. However, as the rainfall peak occurs within a few hours, the soil would allow much of the rainfall to infiltrate, minimizing possible flooding as it would reduce the amount of water accumulated inside the tunnel.

Holanda and Soares (2019), when studying rainfall data from the Madalena neighborhood for the same period in 2017, showed that the most intense rain events that occurred in the months of June and July would not have caused such significant flooding if the impermeable area were not so high (83%). This is due to the fact that the soil below the impermeable portion is mostly sandy, even though it is near the Capibaribe River.

Table 1. Estimated hydrodynamic soil parameters

Location	K_s (mm.day ⁻¹)	θ_0 (cm ³ .cm ⁻³)	θ_s (cm ³ .cm ⁻³)	n	m	η
1	3,024.00	0.011	0.353	1.797	0.444	5.508
2	777.60	0.000	0.334	1.824	0.452	5.425

Note: θ_0 and θ_s represent the initial and saturated humidity values, respectively; K_s is the saturated hydraulic conductivity; and n , m , and η are the shape parameters of $\theta(h)$.

The proposed permeable pavement implementation, maintaining the exposed soil beneath it, is still supported by the results from the simulation of infiltration, evaporation, and runoff rates for the first seven months of 2019, performed with Hydrus-1D. In this case, the water balance obtained, shown in Figure 4, demonstrated that approximately 239.69 mm.m⁻² of the water that precipitated over the unpaved regions of areas 1 and 2 infiltrated into the soil, 88.15% of the total precipitated. The remaining 11.85% either drained or evaporated, similar to what was observed by Holanda and Soares (2019).

Comparison of precipitation, infiltration, evaporation, and runoff values during the wettest period, i.e., from April to July, shows that infiltration (red curve), follows precipitation (black curve), as shown in Figure 4a. On May 9, for example, infiltration levels are consistent, when compared to rainfall, as well as increased runoff and reduced evaporation on rainy days, Figure 4b. This increase and the decrease in evaporation values is expected, because there is less sunshine during the rainier months, while the maximum temperatures are lower, Figure 5.

By simulating the infiltration capacity of the permeable pavement and comparing it with the infiltration capacity of the soil, Figure 6 shows that a similarity between the curves corroborating the results obtained by Holanda and Soares (2019) for the soils of the same area. This demonstrates that, if applied to the soil present in this region, the permeable pavement is capable of allowing water that would enter the tunnel, to be able to completely infiltrate into the soil, reducing the costs of using booster pumps to reduce the frequency and intensity of flooding in the tunnels.

By analyzing the feasibility of the implementation of permeable pavement in large open-air parking lots in the city of Recife, located in a region neighboring the study area, Silva (2018) showed that on days of heavy rain (162.40 mm and 178.20 mm), there was a reduction of up to 77.57% and 64.60%, respectively, in water depth present at these locations, considering that the drainage system was unobstructed. These results show the effectiveness of permeable pavement in reducing flooding in large urban centers, providing evidence to support the proposal presented in this study.

Figure 4. Water balance from January to July 2019.

Figure 5. Temperature and insolation values for the period from January to July 2019.

Figure 6. Simulated infiltration curves for natural soil and permeable pavement.

Beyond this, the use of this type of pavement has been proposed to reduce the maintenance costs of booster pumps, which are currently being used. Such costs include energy consumption, preventive and corrective maintenance of machinery, and daily maintenance by workers at the locality. These pumps are only turned on after water has begun to accumulate within the tunnel, causing disturbance to passers-by because the road is already flooded.

Conclusion

The saturated hydraulic conductivity values found for the soils present in the unpaved portions of the study area are high, reaching over 3000 mm.day^{-1} . These high K_s values are a striking feature of soils that have sandy textures, containing up to 90% sand. Even with high daily precipitation rates, the amount of water accumulated in the tunnels and the frequency of flooding is therefore reduced.

Based on the results of the water balance, it can be seen that the amount of surface flow is low (maximum 0.72 mm), however this volume of water has been sufficient to generate flooding at the site. It is therefore concluded that the proposed use of permeable pavement at the entrance and exit of the Chico Science Tunnel is viable, because a portion of the rainwater does runoff and accumulate within the tunnel will be reduced. This would remove the need to use booster pumps to reduce flooding within the tunnel, lowering the operating costs of these facilities.

In addition, because the soils at points 1 and 2 near the tunnel entrance and exit are

favorable for water infiltration, the use of other compensatory techniques (infiltration trenches, retention basins, detention basins, rain gardens, etc.) together with the permeable pavement would only incur unnecessary costs to implement these improvements in the drainage system.

The scenario of constant flooding that occurs in the Chico Science Tunnel is repeated in the other tunnels of Recife-PE (Felipe Camarão, Abolition, Mayor Augusto, and José de Castro), making through traffic impossible during periods of heavy rain. The implementation of compensatory techniques in the vicinity of these projects may therefore prove to be a solution to reduce flooding, as proposed for the Chico Science Tunnel.

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References

- ABNT. Associação Brasileira de Normas Técnicas, 2016. NBR 7181: Solo - Análise granulométrica. Rio de Janeiro.
- Aragão, R., Cruz, M.A.S. Correia, E.C.O. Machado, L.F.M., Figueiredo, E.E., 2017. Impacto do Uso do Solo pelo aumento da Densidade Populacional sobre o escoamento numa área urbana do Nordeste Brasileiro via Geotecnologias e Modelagem. *Revista Brasileira de Geografia Física* 10, 543-557.

- Burdine, N.T., 1953. Relative permeability calculations from pore-size distribution data. *American Institute Mining and Metallurgy Engineering* 198, 71-77.
- Cabral, J.J.S.P., Alencar, A.V., 2005. Recife e a Convivência com as Águas. In: Hydroaid (Itália), PMSS/ Ministério das Cidades. (Org.). *Gestão do Território e Manejo Integrado das Águas Urbanas*. Brasília: Ministério das Cidades, 111-130.
- Coutinho, A.P., 2011. Pavimento permeável como técnica compensatória na drenagem urbana da cidade do Recife. Dissertation (Master's). Recife, UFPE.
- Di Prima, S., Lassabatère, L., Angulo-Jaramillo, R., Pirastru, M., Cerdà, A., Keesstra, S., 2018. Laboratory testing of Beerkan infiltration experiments for assessing the role of soil sealing on water infiltration. *Catena* 167, 373-384.
- EMBRAPA. Empresa Brasileira de Pesquisa Agropecuária, 1997. *Manual de Métodos de Análise de Solo*. Rio de Janeiro.
- Hansmann, H.Z., 2013. Descrição e Caracterização das Principais Enchentes e Alagamentos de Pelotas-RS. Monograph (Environmental and Sanitary Engineering). Pelotas, UFPEL.
- Haverkamp, R., Parlange, J.Y., 1986. Predicting the water retention curve from particle size distribution: I Sandy soils without organic matter. *Soil Science* 142, 325-335.
- Holanda, M.A.C.R., Soares, W.A., 2019. Analysis of the effect of impermeability of urban soils on the infiltration of rainwater in the city of Recife, PE. *Revista Ambiente e Água* 14, 1-10.
- Holanda, M.A.C.R., Soares, W.A., Silva, S.R., Oliveira, D.B.C., 2019. Sensitivity of the Hydrus-1D model to changes in hydrodynamic parameters in yellow latosol. *Revista AIDIS de Ingeniería y Ciencias Ambientales: Investigación, desarrollo y práctica* 12, 467-481.
- Lins, E.J.M., Burgos, R.D.F., Monteiro, E.C.B., 2017. Os novos túneis urbanos da cidade do Recife: Casos de Degradação Prematura de Estruturas de Concreto. *Revista de Engenharia e Pesquisa Aplicada* 2, 157-166.
- Miguéz, M.G., Veról, A.P., Mascarenhas, F.C.B., Santos, R.B., 2014. Storage measures as compensatory techniques for urban lowlands flood control. *International Journal of Sustainable Development and Planning* 9, 225-236.
- Moreira, M.F., 2014. "Tapacurá estourou!": a vulnerabilidade da cidade anfíbia (Recife-PE) aos episódios de inundações e o bairro da Madalena. Thesis (Doctorate in Human Science). Florianópolis, UFSC.
- Neves, M.G.F.P., Tucci, C.E.M., 2011. Composição de resíduos de varrição e resíduos carreados pela rede de drenagem, em uma bacia hidrográfica urbana. *Revista de Engenharia Sanitária Ambiental* 16, 331-336.
- Guo, A., Chang, J., Wang, Y., Huang, Q., Zhou, S., 2018. Flood risk analysis for flood control and sediment transportation in sandy regions: A case study in the Loess Plateau, China. *Journal of Hydrology* 560, 39-55.
- Oliveira A.P., Barbassa, A.P., Gonçalves, L.M., 2016. Aplicação de técnicas compensatórias de drenagem na requalificação de áreas verdes urbanas em Guarulhos – SP. *Periódico Técnico e Científico Cidades Verdes* 4, 87-101.
- Oliveira, D.B.C., Soares, W.A., Holanda, M.A.C.R., 2018. Análise de Desempenho de modelos de infiltração unidimensional de água no solo. *Águas Subterrâneas* 32, 35-42.
- Perez, L.P., 2013. Índice de vulnerabilidade urbana a alagamentos e deslizamentos de terra, em função de eventos extremos de clima, na Região Metropolitana de São Paulo: uma proposta de método. Thesis (Doctorate in Physical Geography). São Paulo, USP.
- Rezende, O.M., 2010. Avaliação de medidas de controle de inundações em um plano de manejo sustentável de águas pluviais, aplicado à Baixada Fluminense. Dissertation (Masters in Civil Engineering). Rio de Janeiro, UFRJ.
- Rezende, O.M., Miguez, M.G., Verol, A.P., 2013. Manejo de Águas Urbanas e sua Relação com o Desenvolvimento Urbano em Bases Sustentáveis Integradas Estudo de Caso dos Rios Pilar-Calombé. *Revista Brasileira de Recursos Hídricos* 18, 149-163.
- Siltecho S., Hammecker C., Sriboonlue V., Clermont-Dauphin C., Trelo-Ges V., Antonino A.C.D., Angulo-Jaramillo R., 2015. Use of field and laboratory methods for estimating unsaturated hydraulic properties under different land uses. *Hydrology Earth System Sciences* 19, 1193-1207.
- Silva, A.C., 2018. Modelagem hidrológica-hidráulica para atenuação de alagamentos no entorno da Escola Politécnica de Pernambuco. Dissertation (Masters in Civil Construction). Recife, UPE.
- Silva Junior, M.A.B., Silva, S.R., Cabral, J.J.S.P., 2017. Compensatory alternatives for flooding control in urban areas with tidal influence in Recife - PE. *Revista Brasileira de Recursos Hídricos* 22, 1-12.
- Simunek, J., Sejna, M., Saito, H., Sakai, M., van Genuchten, M. Th., 2013. The HYDRUS-1D Software Package for Simulating the One-Dimensional Movement of Water, Heat, and

Multiple Solutes in Variably-Saturated Media.
Department of Environmental Sciences
University of California Riverside. Riverside,
California 1, 1-308.

Wdowski, S., Bray, R., Kirtman, B.P., Wub, Z.,
2016. Increasing flooding hazard in coastal

communities due to rising sea level: Case study
of Miami Beach, Florida. Ocean & Coastal
Management 126, 1-8.