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WATER MANAGEMENT AND URBAN FLOOD MITIGATION: STUDIES AND PROPOSALS FOR THE MACAÉ RIVER BASIN IN BRAZIL

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Abstract: This article presents a literature review about urban floods, with a specific analysis concerning the Macaé River basin in Rio de Janeiro, Brazil. The main topics of the study are: (i) legal framework of water resources management; (ii) overview of urban floods in Brazil, focusing on the city of Macaé; (iii) methods of control and mitigation of urban floods; (iv) hydrological and computational modeling applied to the study of floods; and finally, (v) characterization of the Macaé River basin, with an emphasis in the context of floods and inundations. The research confirms the relevance of flood studies for the region, both by the expressive record of flooding events and by the lack of recent investigations about this issue. According to the current trend practiced in flood management, proposals for the city should be based on integrated interventions that consider the peculiarities of the basin. Compensatory techniques and the renaturalization of rivers and streams are two prominent approaches to this context. The modeling of the basin and the simulation of these measures can provide data that will support the basin management plan and the work of other relevant public institutions.

Keywords: Mohid land; drainage network; runoff; flood management

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INTRODUCTION

The population density in urban areas is increasing in Brazil, a phenomenon that generates disordered and accelerated growth, causing a set of changes in the environment. Disorderly occupation is remarkable specially in lower relief areas, where regions under risk are subject to occupation (Guerra & Cunha, 2001). In this context, the inadequate occupation of river plains and the consequent impermeabilization of soils result in both floods and inundations. The occupation of river plains is an historical process associated with the preference for occupation in areas of multiple uses of water (Guerra & Cunha, 1998).

The floods, on the other hand, at first a natural phenomenon, are aggravated by intrinsic relief characteristics. Under the geomorphological perspective the rivers and the weather are conditioning agents in the transport of weathered materials from high to low areas (Guerra & Cunha, 1998). In the state of Rio de Janeiro, for example, the higher rainfall incidence between the months of October and March (INMET, 2015) contributes to the occurrence of the phenomenon.

In that way, floods and inundations are outstanding issues that should be managed in the planning of the territory occupation. The Brazilian environmental legal system, the National Water Resources Policy (NWRP), enacted by the Law 9.433/1997, with the aim of managing conflicts, based on the *river basin* as the territorial unit. (Brasil, 1997). The Brazilian regulation (NWRP) also created the National Water Resources Management System (NWRMS), ensuring shared management between governments and civil society gathered in the Hydrographic Basin Committees' (HBCs) (Brasil, 1997; Barreto, 2009). The HBCs are collegiate participatory bodies that are responsible for the approval of the Water Resources Plan, one of the main instruments of water resources management (Brasil, 1997; INEA, 2013).

In general, the solution to many issues related to water management is focused on the adoption of structural and non-structural measures (Tundisi, 2003). In the case of flood control, there is a growing concern with non-structural measures, with emphasis on regulation of land use and occupation; the zoning of floodplains; the insurance against floods; the prediction of floods; the warning systems; and civil defense (Millar, 1994).

Tucci (1997) stresses that the impact of floods and inundations should be avoided, preferably adopting non-structural measures, a set of mitigation and adaptation techniques not based on traditional large scale flood defenses. In dense urban areas, however, the seizure or transfer of residents to other locations outside the risk zone is a complex issue. In such cases, the procedures are based mainly on preventing floods with the construction of dams and reservoirs (Pires & Santos, 1995).

Barriers to water resources management are imposed by the lack of monitoring data. According to Christofoletti (1999), this difficulty can be overcome using synthesis and simulation models, which are capable of generating artificial sequences. In the case of flood control, for instance, the absence of actual measures to handle the maximum river flow can be surpassed with adjacent floodplain models (INEA, 2013).

It is possible to identify an evolutionary line in technologies and approaches for urban drainage, starting with the implementation of traditional measures and moving towards new and more sustainable alternatives (Miguez *et al.*, 2016). Compensatory techniques and renaturalization of rivers and streams, for example, are important, but still restricted in Brazil. The ideal solution should be defined taking into account the characteristics of the river, the benefit of the flood reduction, as well as the social impacts (Tucci, 1997).

To evaluate the performance and effectiveness of these measures, the implementation of mathematical models for the formulation of predictive scenarios is a well-established approach to water resources management (Tundisi, 2006). Despite of the inherent simplifications of the models, computational modeling is an important tool to subsidize the decision makers' tasks (Pessanha, 2012).

The aim of this work was to present a literature review on urban floods, their current management techniques, converging on the Macaé River basin. This review is divided into five major areas: (i) legal framework of water resources management; (ii) overview of urban floods in Brazil, from a national perspective to a local centered in the city of Macaé; (iii) methods for urban floods management; and (v) characterization of the Macaé River basin, with a focus on the flood and inundation events.

LEGAL FRAMEWORK IN BRAZIL

Brazilian laws guarantee broad protection to water, even at the constitutional level, as this issue is a longstanding theme in the country's legislation. One of the first articles of the 1988' Brazilian Federal Constitution establishes that water belongs to the State (Brasil, 1988). Almost ten years after, the National Water Resources Policy (NWRP), also known as the Law of Waters, was set (Law 9433/1997; Brasil, 1997), determining bases, objectives, general guidelines of action and instruments that would enable the management of water resources in the country (Brasil, 1997). Among its main foundations, the NWRMS establishes the river basin as the territorial unit of management for participatory Hydrographic Basin Committees (Brasil, 1997). These Committees should be decentralized and should be constituted by both public institutions and common users (Brasil, 1997).

The Hydrographic Basin Committees are collegial bodies from various water user sectors, civil society organizations or public authorities, and constitute an unprecedented organization in the Brazilian institutional reality. They play a key role in the constitution and approval of Basin Plans, which are long-term water master plans, with planning procedures for a defined period.

OVERVIEW OF URBAN FLOODS: FROM BRAZIL TO MACAÉ

Urban floods constitute natural disasters that drastically affect society with deaths and homeless people, as well as material damages. The source of official database on the incidence of critical events in Brazil is the National Secretariat of Civil Defense (NSCD), attached to the National Integration Ministry (NIM) (ANA, 2015). After Castro (1998), the NSCD defines the events of floods as "1) flood of river caused by heavy rains or melting snow; 2) temporary and mobile elevation of the water level of a river or lake; 3) inundation". The events of floods can be further classified in the following categories (Brazil, 2013, p. 77):

Inundation: overflow of water from normal river, sea or lake runaways, from dams or from the accumulation of water due to faulty drainage in areas not normally submerged;
Flood: elevation of the water level of a river, above its normal flow, usually synonymous with inundation;
Flash flood: characterized by a significant volume of water flowing on the surface of the soil, with great speed, resulting from heavy rains;
Overflow: resulting from water accumulation in the streets and urban perimeters, caused by heavy rainfall in cities with faulty drainage systems.

According to the latest edition of the Brazilian Yearbook of Natural Disasters (IBGE, 2013), these occurrences still have a significant impact on the Brazilian society. As shown in **Table 1**, the sum of floods, flash floods and overflows covers about 44% of the total number of people affected by environmental disasters. The first among them are drought events, which add up to 50.85% of the total occurrences.

Many flood events have occurred in the Southeast of the country in recent centuries 1900 and 2000. In the state of Rio de Janeiro, according to a survey conducted by the Fire Department, 23 relevant events were recorded over a period of 300 years (from 1711 to 2011).

An outstanding episode occurred in the Mountain Region of Rio de Janeiro in 2011, with over a thousand deaths and considered the greatest natural disaster in the Brazilian history. The city of Nova Friburgo had the highest number of victims: 389; followed by Teresópolis, 324; Petrópolis, 65; and more than 30 dead in Sumidouro, São José do Vale do Rio Preto and Bom Jardim (Santos, 2011).

According to CEPED UFSC (2013) between 1991 and 2012, the State of Rio de Janeiro had 56 official records of exceptional floods, characterized as disasters. In this study, the city of Macaé registered eight overflows: three in 2007, three in 2008 and two in 2009. Four of these events were considered among the most severe natural disasters in the period, as shown in **Table 2**. In 2007, Macaé had 143.117 people affected, out of a total of 206.728 inhabitants, representing about 70% of the city population. (IBGE, 2013).

According to another study, conducted by TEC RJ, Macaé has been the most affected, with a total of 447.4 thousand people involved, which highlights the severity of the occurrences of floods in the city (TEC RJ, 2012; Barboza, 2014).

Table 1. Distribution of people affected by natural disasters in Brazil in 2012

Events	Death	Injured	Sick	Homeless	Displaced	Missing	Affected	Percentage
Droughts	6	0	14,214	30	750	0	8,956,853	50.85%
Forest fires	0	0	0	0	0	0	37,338	0.21%
Mass movements	26	10	2	1129	2801	0	123,555	0.72%
Erosion	0	0	5	81	2105	0	55,653	0.33%
Overflow	5	6	6	1,048	954	0	24,581	0.15%
Flash flood	26	6,580	14,318	49,769	26,2851	2	1,856,359	12.41%
Inundation	14	2,409	10,665	52,041	21,6349	2	5,185,018	30.98%
Frost	0	0	0	0	0	0	30,777	0.17%
Hail	0	11	4	418	7,971	1,040	103,265	0.64%
Tornado	0	2	0	1	20	0	4,310	0.02%
Gale	16	150	13	5,769	13,220	0	599,905	3.51%
TOTAL	93	9,168	39,227	110,286	507.021	1,044	16977614	100%

Source: Adapted from the Yearbook of Natural Disasters (IBGE, 2012).

Table 2. Distribution of people affected by the most severe events.

Year	City	Mesoregion	Homeless	Displaced	Affected
2007	Belford Roxo	Metropolitan region	384	2,317	181,300
2007	Macaé	North of the state	-	104	143,117
2008	Macaé	North of the state	14	8	105,000
2007	Macaé	North of the state	5	161	85,268
2009	Macaé	North of the state	-	10	75,000
2008	Belford Roxo	Metropolitan region	-	-	30,000
2010	Petrópolis	Metropolitan region	-	-	30,000
2006	Belford Roxo	Metropolitan region	7	13	27,000
		TOTAL	410	2,613	676,685

Source: Adapted from the Brazilian Atlas of Natural Disasters (CEPED UFSC, 2013).

URBAN FLOODS: CAUSES, APPROACHES AND MITIGATION TECHNIQUES

Urbanization is one of the most impacting anthropic actions, due to alteration of the primary characteristics of the soil. Rapid urban growth has aggravated the problems of floods, because developments tend to suppress the original vegetation cover, increasing impermeabilization of soils, introducing artificial drainage structures and occupying the riverine plains (Miguez *et al.*, 2016).

Tucci (1997) points out that flooding in urban areas occur basically due to two processes, either alone or in association:

> **Floods due to urbanization**: the increase in the frequency and magnitude of floods due to soil occupation with impermeable surfaces and networks of drainage channels. In addition, urban developments can produce obstructions to outflow such as embankments and bridges, inadequate drainages and silting;
> **Floods in riverside areas -** the natural floods that affect the population that lives in the largest riverbed. These natural floods occur due to human occupation of the riverbed, with a recurrence time[1] of 2 years.

These processes generate impacts that change the water balance, resulting in increased peak flows (**Fig. 1**). Soil impermeabilization with the construction of roofs, streets, sidewalks and parking areas decreases infiltration and increases runoff. Likewise, with urbanization, the volume of water that should gradually runoff and be absorbed by plants, is replaced by direct draining into channels, requiring greater flow capacities of the sections (TUCCI, 1995).

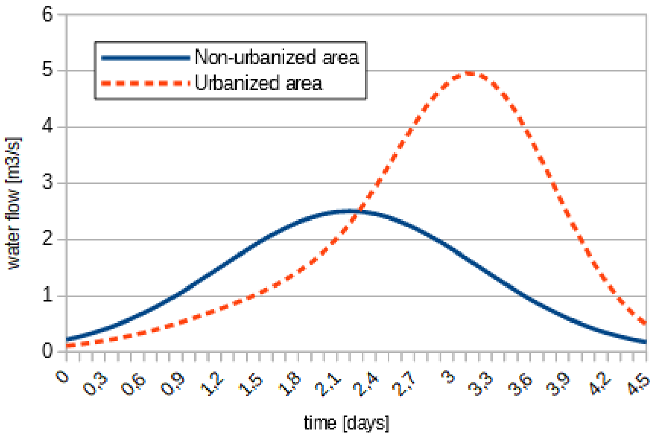

Fig. 1 Hydrograph for urbanized and non-urbanized areas

The traditional urban drainage system is composed of micro drainage and macro drainage systems. Urban micro drainage is defined by the rainfall water system and includes the pavement of streets, guides and gutters, street drains, rainwater network and also small channels. It is designed for the outflow of water volumes of 2 to 10 years recurrence period. The macro drainage is intended for the final displacement of the waters collected by the micro drainage, conducting the flows from the lots and the streets. It is generally constituted by larger dimensions open or closed contour channels, designed for outflows of 25 to 100 years recurrence period (São Paulo, 1999; NUCASE, 2007).

Considering the two main causes of flood mentioned earlier, mitigation can be done as follows: (I) for urban macro drainage: reservation of urban space for lateral or linear parks in the rivers to reduce the flow velocity of floodwaters and the retention of sediment and waste; (II) for riverine areas: mapping of flood zones, defining high and low occupancy risk areas (NUCASE, 2007).

[1] The period or time of recurrence (TR) is the inverse of the probability p of a hydrological event to be matched or surpassed in any year (TOMINAGA, 2013).

Appropriate drainage projects are, therefore, fundamental in the solution of the flood problem. Different approaches have been designed in the scientific community, according to the most pressing needs of each case. However, it is possible to identify an evolutionary line, from a hygienist conception, usually associated with traditional practices, to the most recent procedures of sustainable urban water management associated with urban projects (Miguez *et al.*, 2016).

The state of the art in water resources management basically contemplates two different approaches for the control of the amount of runoff water in urban areas: 1) the focus on the increasing hydraulic conductivity and 2) on water storage. It should be noted that these two approaches are not mutually excluding. Within this focus there are two practices: the traditional ones, generally more directed to conductivity increasing; and the sustainable management ones, more focused on the storage and infiltration approaches (São Paulo, 1999).

Table 3. Structural measures for flood management.

Structural Measures	Characteristics	Main Advantage	Main Disadvantage	Usage
Extensive				
Control of vegetation cover (reforestation)	Interferes in the precipitation-flow process, reducing the maximum flows. Contributes by reducing soil erosion, which gradually increases the level of rivers and aggravates floods.	Reduction of peak flood	Can be impractical for large areas due to costs	Small river basins
Intensive				
Dams or polders	They are lateral walls of earth or concrete, inclined or straight, constructed to a certain distance of the river banks. Their function is to protect the riverside areas against the overflow.	High degree of protection of an area	Significant damages in case of failure	Great Rivers
River modifications (dredging, cutting of the river loops, river deepening)	They are obtained by increasing the cross section or the speed of the river.	Increased flow, expanded protected area	Local effect (unblocking); negative impact on rivers with alluvial bottoms (cutting of the river loops)	Small rivers (clearing); narrow flood area (cutting of the river loops)
Reservoirs	It retains part of the flood volume, reducing the natural flow. The retained volume in the period of the high flows is drained after the reduction of the natural flow	Downstream control	Difficult location, high construction costs and need expropriations	Intermediate river basins

Source: Adapted from TUCCI (1993).

The predominant conception of urban drainage in Brazil is still based on the "classical system" (NUCASE, 2007). In this perspective, there is an appreciation of great interventions in natural environment, stimulating constructions, such as the channeling of water bodies, which results in increased rates of rainwater flow (Baptista *et al.*, 2011).

The classical system is a set of structural and non-structural measures. In general, as shown in **Table 3**, structural measures constructions are engineering works that can be: (i) *extensive*, when they act in the river basin, trying to modify the relations between precipitation and flow; or (ii) *intensive*, when they act directly in the river, accelerating, retarding or diverting the flow (Tucci, 1993). The author points out that the idea that flooding can be controlled is a human naivety and that the measures are designed to minimize the consequences. In this sense, the very expression "flood control" has gradually been replaced by "flood management", a recognition that human capacity is limited to face this phenomenon. Non-structural measures, in turn, are those in which losses are reduced by a better coexistence of population with floods. These are: (i) regulation of land use or zoning of floodable areas, in line with the City's Master Plan; (ii) flood-proof buildings based on a set of techniques; (iii) flood insurance, a monetary protection against possible losses; and (iv) prediction and alert, which is a system of acquisition, data transmission and prediction of floods, generally a Civil Defense assignment (Tucci, 1993).

Among the new techniques, the so-called Compensatory Measures aim at the retention of rainwater and the resumption of natural phenomena from the hydrological cycle, such as the infiltration of

Table 4. Advantages and Disadvantages of some Compensatory Measures.

Compensatory Measures	Advantages	Disadvantages
Cistern (for individual houses or group of houses) Miguez *et al.* (2014)	1. Water can be used to: a) fire protection b) watering of lands c) industrial processes d) refrigeration 2.It reduces direct runoff on the surface, occupying small areas 3. The ground or space above the cistern may be used for other purposes	1. Relatively high costs 2. Cost may be restrictive if the cistern receives water from large drainage areas. 3. Maintenance required. 4. Restricted access. 5. Need for underground space.
Hanging garden Pregnolato *et al.* (2016) Yang *et al.* (2015)	1. Aesthetically pleasing 2. Reduction of direct runoff on the surface 3. Reduction of noise / heat levels	1. High loads on roof and construction structures 2. Expensive to install and to maintain
Roof storage (using narrow vertical conductive pipes) Mostafizur Rahman *et al.* (2016)	1. Delay of direct runoff on the surface 2. Thermal insulation effect of the building: a) water on the roof b) through circulation 3. It can facilitate fire fighting	1. High structural load 2. The water inlet of the conductive pipes requires maintenance 3. Formation of overloads 4. Infiltration of water from the roof to the building
Roof with increased roughness	1. Delay of direct runoff on the surface and some reduction of it (detention in ripples or gravel)	1. Relatively high structural load
Permeable pavement (parking and alleys) Maochuan *et al.* (2018) a) parking with gravel b) holes in waterproof floor (diameter of about 6 cm) filling them with sand	1. Reduction of direct runoff on the surface 2. Replenishing of the water table 3. Gravel pavement may be cheaper than asphalt or concrete	1. Clogging of holes or pores 2. Compaction of soil below the pavement or decrease of soil permeability due to gravel 3. Difficulty of maintenance 4. Grasses and weeds can grow on the pavement

Source: Adapted from SÃO PAULO (1999).

water into the soil (Miguez *et al.*, 2016). In this conception, events such as storage, infiltration and use of rainwater in the plots themselves are favored by permeable forms of pavement (MMA, 2016). Some of these measures are presented in **Table 4**.

The effect of these measures were studied in Brazil, with emphasis on the cities of the state of São Paulo. Tominaga (2013), for instance, has analyzed the damping effect of peak floods with the implementation of compensatory measures, using the SWMM model, in the city of São Paulo in 209 scenarios for the Corrego da Luz basin. In this study, among the simulated measures, peak flood damping was verified in all 209 analyzed scenarios. The highest damping values were verified for the rainfall with a smaller return period, for example, 2 years. The highest reduction of peak floods was verified for 30-minute rainfall. In this context, the permeable pavement has presented one of the highest performances in the reduction of the peak flood (Tominaga, 2013).

Another measure for flood management that is highlighted in the literature is the renaturalization of rivers and streams. Experiences in Europe, especially in Germany, show that the recomposition of rivers is feasible even with the constraints imposed in rural and urban environments (Binder, 1998). According to the State Department of Environment and Sustainable Development of Rio de Janeiro, and considering the basic lines of renaturalization of rivers in Europe, renaturalization has two fundamental functions (Binder, 1998; Benigno *et al.*, 2003): (a) Recover rivers and streams in order to regenerate as close as possible to a natural biota, through regular management or renaturalization programs; and (b) Preserve the natural flooding areas and prevent any uses that avoid this function.

One of the methodologies for renaturalization is to remove the retaining walls from the river banks, and follow the river, while it resumes the formation of small loopings in its lower part. Monitoring is crucial throughout this phase, due to the risk of flooding in riverine regions. Many natural flood areas can be transformed into municipal parks (Binder, 1998). However, Tucci (1997) emphasizes that, in any expropriated area by the government, the implementation of public infrastructures, parks or sports areas must be carried out, otherwise there is risk of invasions.

The renaturalization has been studied in the state of Rio de Janeiro, although the researches are still scarce. A study of the effects of renaturalization in the lower stretch of the São João River suggests that the same procedure should be done in other stretches of the river. The authors of the study suggest that a barrier should be constructed allowing water to flow through the old river bed. In this case, regardless the fact that the river was straightened a few years before, the study showed that the old bed was preserved, and could reutilized. The renaturalization of the river would promote the recovery of wetlands that would be important for the ecosystems in the region (Benigno *et al.*, 2003).

The construction of a simple deterministic numerical model[2] was also considered in this study. It started with the drainage basin area, which contemplates: (i) the outflow through different types of soil that form the region; and (ii) the flow rate generated in each section of the river. In addition, community and local farmers should be kept constantly informed about the results so that they can address their doubts and the answers can redirect the research (Benigno *et al.*, 2003). Although it is a preliminary study, it was considered a major advance for the management practices of water resources in the state of Rio de Janeiro, as opposed to the adoption of traditional urban drainage techniques.

MODELING APPLIED TO THE MANAGEMENT OF FLOODS AND INUNDATIONS

Hydrological and hydraulic models are essential tools for river basin management, as well as for planning actions to mitigate the impacts of floods. The hydrographs of floods generated by the hydrological models are used as input data in models, allowing calculation of levels and flows of streams. Current models integrate the hydrological and hydraulic processes into only one tool and are often associated with Geographic Information Systems (GIS) (Tominaga, 2013).

The modeling of drainage network allows the evaluation of different scenarios and a planning of action on them. The application of hydrological or hydraulic models is called hydraulic-hydrological simulation, where simulations require the solution of systems of equations, demanding the use of computational tools to process calculations (Canholi, 2014). Canholi (2014, p.134) structured the hydraulic-hydrological modeling and simulation steps according to the: 1) Choice of models and determination of parameters and input variables required for modeling; 2) Choice of software and preparation / insertion of input data; 3) Simulation; 4) Calibration of the model parameters; 5) Interpretation of results.

Several software packages are capable of carrying out simulations of hydrological and hydraulic processes. The following topics present some of them, especially the MOHID Land.

HEC-HMS and HEC-RAS

The HEC (Hydrologic Engineering Center) platform, developed by the U.S. Army Corps of Engineers, simulates large river basins and complete macro drainage networks. It has different modules that allow the execution of various simulations in water resources management (HEC, 2016).The module HEC-HMS (Hydrologic Modeling System), simulates the rainfall-flow transformation process in basin and sub-basin systems (Oliveira & Salla, 2017). The HEC-RAS (River Analysis System) module, enables one-dimensional simulation of runoff in open channels, under a permanent and non-permanent regime and also in the mobile bottom condition (sediment transport) (Canholi, 2014).

SWMM

The SWMM (Storm Water Management Model) platform is a hydrological-hydraulic software developed by the U.S. Environmental Protection Agency (USEPA) for the simulation of runoff in urban areas. SWMM is a dynamic model of rainfall-flow transformation capable of simulating continuous or discrete rainfall series, as well as hydrodynamic processes in the hydrographic network (Tominaga, 2013). SWMM uses a distributed approach for the calculation of flows, integrating micro and macrodrainage modeling. This integrated simulation of the network of galleries with the surface runoff allows the simulation of floods (Canholi, 2014).

[2] The deterministic models are those that present the perspective that they are not prone to be idealized throughout their elaboration and have adequate purpose for management objectives (Pessanha *et al.*, 2012).

MOHID Land

MOHID is a three-dimensional numerical modeling system developed by Instituto Superior Técnico (IST) at MARETEC (*Marine and Environmental Technology Research Center*; MOHID, 2018). This system allows the adoption of an integrated modeling philosophy, as it uses not only processes (physical and biochemical), but also different scales (enabling the use of network models) and systems (estuarine basins) (MOHID, 2018).

The philosophy of the MOHID model allows its application in one, two and three-dimensional approaches. The subdivision of the software in modules, as well as the flow of information between them was studied by the MOHID developers for many years. Currently, the software is composed of over 40 modules, which add up to more than 150,000 of programming lines. Each module is responsible for managing a certain type of information, providing greater realism and specificity to the model (Juliano *et al.*, 2012).

MOHID Land is a spatially distributed model for the properties of water basins and inland watercourse. It deals with specific processes that occur in these areas, such as: surface runoff, seepage and drainage network (Mohid Wiki, 2018; Tavares *et al.*, 2017). It displays a link with MOHID Water with the Discharge Module, allowing basin management and flood simulation (MOHID, 2018). The software has been used in urban flood studies, enabling the development of an Integrated Flood Simulation System in the Espírito Santo Estuary (Maputo Bay, Mozambique) (Malhadas *et al.*, 2012).

The drainage flow areas in the network use a one-dimensional approach, integrated over the cross-sectional area, with Saint Venant´s equation, **Eq. (1)**. The flow in the basin is modeled by a two-dimensional approach (integrated in the depth), represented by the wave diffusion equation, **Eq. (2)**. Finally, the surface flow, considers of a three-dimensional approach, with Richards equation, **Eq. (3)** (Braunschweig *et al.*, 2010, Telles *et al.*, 2013).

$$\frac{\partial Q}{\partial t} + \frac{\partial}{\partial x}\left(\frac{Q^2}{A}\right) + gA\left(\frac{\partial h}{\partial x} + \frac{Q^2 n^2}{A^2 R_h^{4/3}}\right) \qquad (1)$$

$$Q = \frac{A R_h^{2/3}\sqrt{\partial h/\partial x}}{n} \qquad (2)$$

$$\frac{\partial \theta}{\partial t} + \frac{\partial}{\partial \overline{X}} K(\psi)\left[\frac{\partial \psi}{\partial \overline{X}} + \frac{\partial z}{\partial \overline{X}}\right] \qquad (3)$$

From **Eq. (1)**, Q is the discharge; x and t are the variations of space and time, respectively; A is the cross-sectional area; g is the acceleration of gravity (9.81 $m.s^{-1}$); h is the depth; n is the roughness coefficient; R is the hydraulic radius; In **Eq. (2)**, the variables and constants are repeated. From **Eq. (3)**, θ is the soil humidity; z is the vertical coordinate, in the positive direction, from the bottom up; - Vector X represents position of x, y and z; ψ is the hydrostatic pressure; and K is the hydraulic conductivity (Telles *et al.*, 2013).

MACAÉ RIVER BASIN IN THE CONTEXT OF FLOODS AND INUNDATIONS

The Macaé and Ostras Hydrographic Region is located on the north-central coast of the State of Rio de Janeiro, between the Low Paraíba do Sul Hydrographic Region and the São João River and Lakes Hydrographic Region (**Fig. 2**). It is constituted by the river basins of the following rivers: Macaé, Ostras, Lagoa de Imboassica and by small streams and coastal lagoons. It covers the entire territory of the cities of Rio das Ostras, Macaé, Nova Friburgo, Casimiro de Abreu, Conceição de Macabu and Carapebus, totaling an area of 1978 km² (SEA, 2014).

The Water Resources Plan for the Macaé and Ostras Hydrographic Region (WRP Macaé/Ostras, 2016) aimed at a diagnosis, a water resources plan, and the design of the interventions to ensure water quantity and quality for multiple uses. Among the several reports that make up the Plan, the Flood Report reviews research on floods in the Hydrographic Region (INEA, 2013).

The Macaé River is sourced in the Macaé de Cima Mountain Range in Nova Friburgo, flowing into the Atlantic Ocean near the city of Macaé (CBHMACAÉ, 2018). Besides its numerous tributaries, the sub-basin of the São Pedro River (**Fig. 3**) and the transposition of the Macabu River basin (IPGA, 2015) also constitutes to the Macaé river basin. In the end of the 1960's, straightening works modified some 60 km of the main channel, by the extinct National Department of Works and Sanitation (NDWS). This process brought impacts, such as silting in the terminal portion of the Macaé river, contributing to frequent and intense floods (IPGA, 2015; Assumption & Marçal, 2012).

The upstream hydrographic system of the Macaé River can be characterized as a large area of springs and erosive channels that efficiently produce and release matter and energy to the lower stretches. In the upstream region, matter and energy are processed with reduced velocity down to the rectified parts, where there is an increase in the transportation capacity until the estuary of the River in the city of Macaé (Lima & Marçal, 2013).

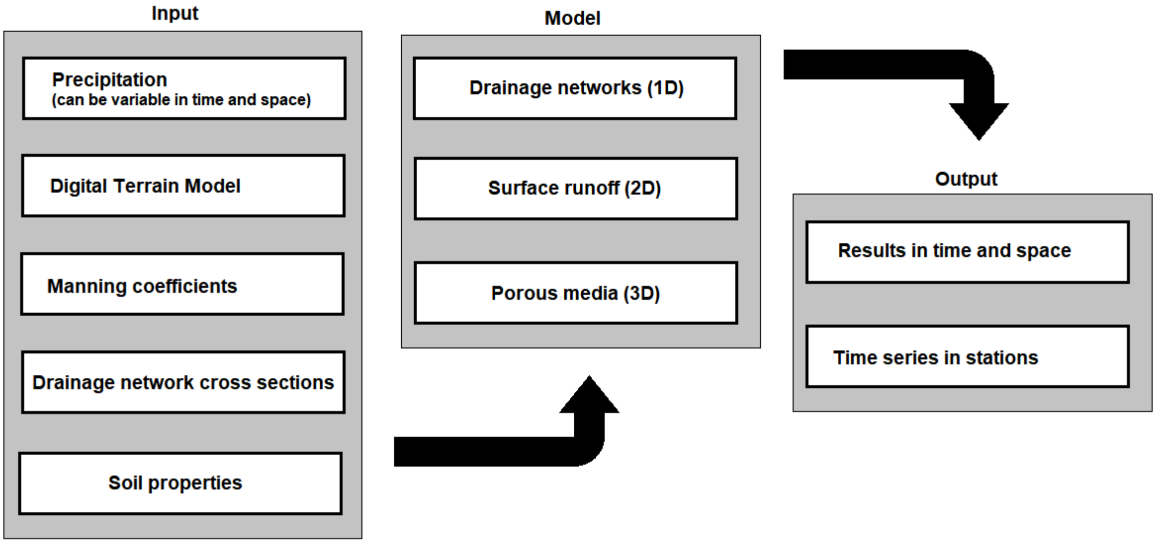

Fig. 2 Schematic representation of MOHID Land model.

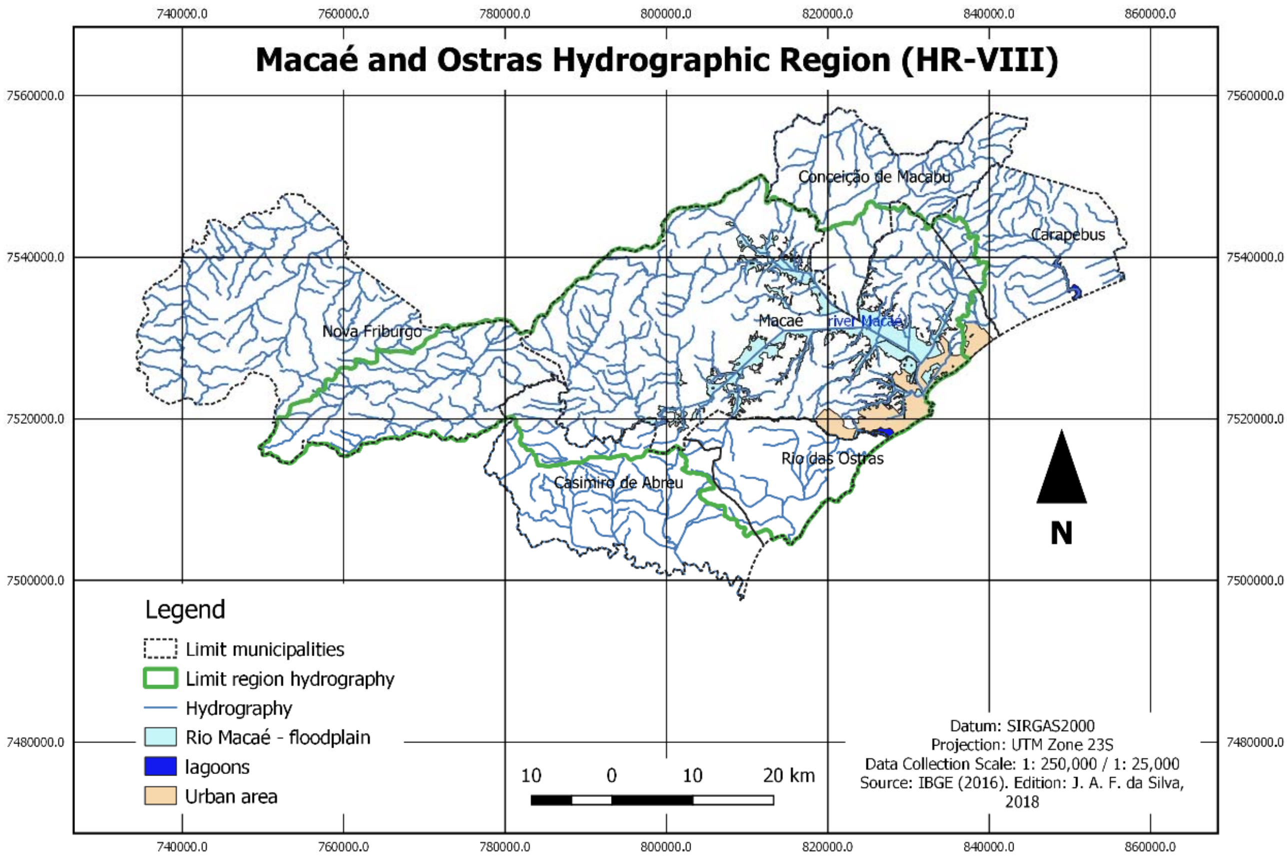

Fig. 3 Macaé and Ostras hydrographic region (HR-VIII).

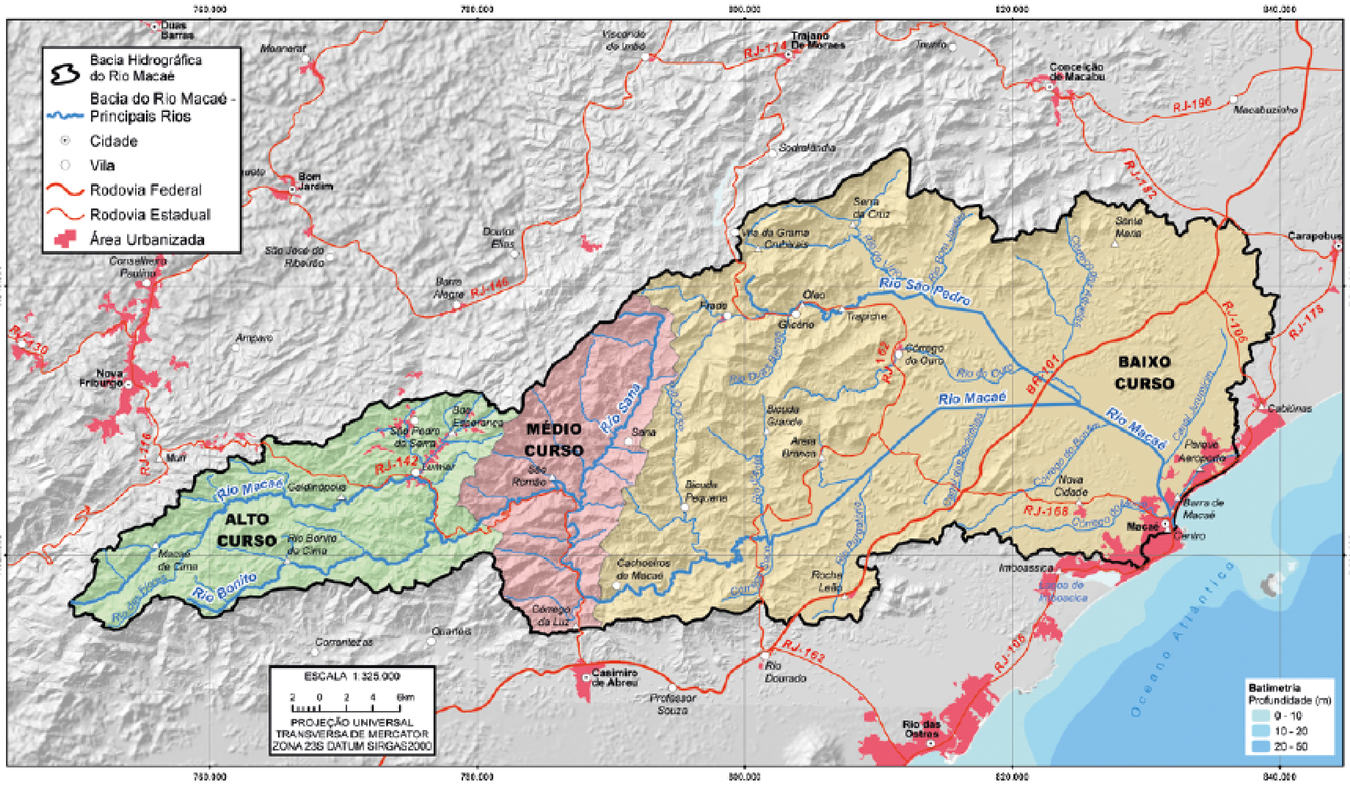

Fig. 4 Compartmentalization map of the Macaé River basin.
Source: Atlas of the Macaé River basin. IPGA, 2015.

The floods on the Macaé River are determined by several factors. According to INEA (2013), the difference in altitude between the upper and lower reaches of the Macaé River basin is one of the most relevant factors (**Fig. 4**). The main river slope presents two distinct stretches: the first, located about 65 km upstream of the mouth, in the elevated part of the basin, with a slope of 10 m km^{-1} or more; and the second section, which presents a smaller slope according to **Fig. 5** (INEA, 2013).

The contribution of a large number of tributaries in the upper reaches of the river is also a condition that significantly favors the formation of floods. In the upper regions, the confined or partially confined condition of the river bed promotes higher velocity to the water. In the lower zone of the basin, the slope is reduced, with consequent decrease of the water speed. As a result, during periods of intense rainfall, the inundation of the fluvial plains is inevitable. In these areas, the wave caused by the flood is laterally attenuated as it spreads across the fluvial plain rather than downstream (INEA, 2013).

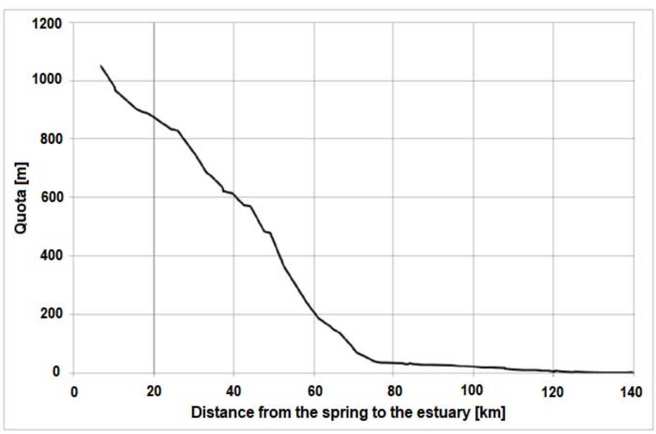

Fig. 5 Longitudinal profile of the Macaé River.

A flood study about the Macaé River basin was carried out by FGV (2004), identifying the main flood problems in the city and some possible alternatives for their control.

1. Dredging of the river bed in the final section of the river;
2. Construction of dikes around low inhabited areas, forming a polder;
3. Construction of a dam, with the formation of a flood control reservoir.

A summary of the study results can be listed as follows: (i) the simulations indicated that the effect of dredging on this section of the river is quite localized, but could reduce inundation levels by about 20 cm; and (ii) the flood control reservoir would not have the capacity to mitigate the floods from tributaries of the Macaé River, especially from the São Pedro River; (iii) finally, the implementation of a dam on the São Pedro River, to work together with the Macaé River dam, is proposed (FGV, 2004).

DISCUSSION

Urban floods are among the five natural disasters that affect Brazilians the most. The last edition of the Brazilian Yearbook of Natural Disasters (IBGE, 2012) revealed that, in 2012, from all disaster events considered in the period, the sum of floods, flash floods and inundations cover about 44% of the total number of people affected by this problem. The data point out the relevance of a study about floods for the country, and especially for the state of Rio de Janeiro, where, according to CEPED UFSC (2013), there are 56 official records of exceptional floods characterized as disasters from 1991 to 2012.

The city of Macaé has been suffering for a long time from floods, with a large number of inhabitants affected. In two official studies, Macaé recorded at least eight occurrences of floods from 1991 to 2012: three in 2007, three in 2008 and two in 2009. Four of these eight incidents were considered among the most harmful events for the population in the period (IBGE, 2013). In this document, it is registered that Macaé presented 143,117 affected people out of a total of 206,728 inhabitants in the 2007 flood, representing 70% of the population. From 2012 onwards, no official data were recorded, regardless several events have been published in the internet, demonstrating that the problem still persists.

Regarding techniques for flood management, there is a gradual paradigm shift in urban drainage approaches and methods. The bibliographical research of this article allowed us to identify an evolutionary line, ranging from traditional practices to the modern ones, concerning the sustainable management of urban waters and the design of cities (Miguez *et al.*, 2016). Although the predominant conception of urban drainage in Brazil is still based on the "classical system", its complementation by new and more sustainable techniques is desirable.

The effectiveness of these measures, together with the use of computational modeling, has been the target of some studies in Brazil. Using the Compensatory Techniques, Tominaga (2013) analyzed the damping effect of peak floods through the SWMM model (TOMINAGA, 2013). In relation to Renaturation, a preliminary study of its effects on the water regime of the lower São João River, Benigno *et al.* (2003) considered the construction of a deterministic numerical model contemplating: (i) the water flow through the different types of soil that exist in the region; and (ii) the flow generated in each section of the river.

In Macaé, the main study carried out on floods considered the effect of three traditional structural measures as discussed in the previous item. Due to the limitations of these techniques, and to the current state of the art in urban drainage, it can be concluded that new studies about floods in the city Macaé should evaluate the effects of new practices to deal with this issue. Among them, there are Renaturalization and Compensatory Techniques, which can be used in an integrated way with other techniques already implemented in the traditional urban drainage system, as well as they can be simulated and evaluated through computational modeling.

CONCLUSION

Urban floods are one of the most common and severe natural disasters in Brazil, which point out the importance of this study. There were, in the state of Rio de Janeiro, between 1991 and 2012, 56 official records of exceptional floods characterized as disasters. The city of Macaé presents a prominent position in the state and national statistics on this issue, since it presents a recurrent record of floods with a large number of inhabitants affected.

The literature on mitigation and management of urban flood is vast and follows different approaches. Nowadays the traditional *modus operandi* is being complemented by techniques of systemic vision, which aim to restore the hydrological cycle prior to urbanization. In this context, although the concept of urban drainage in Brazil is still based on the "classical system", it is necessary to take into account the emergence of modern and more sustainable techniques. The implementation of these new measures, even though still incipient in the country, when associated to the use of computational modeling, has been object of some studies in Brazil.

Research focused on flood control and mitigation proposals for the Macaé region, however, are scarce and are not in line with the current practices evidenced in the literature. It is believed that future studies on the subject should evaluate the effects of new urban drainage practices in relation to floods in the city. Among the possible practices to be evaluated, Renaturalization and Compensatory Techniques must be highlighted since they can be used in an integrated way or associated with the other techniques already implemented in the traditional urban drainage system, as well as they can be simulated and evaluated through computational modeling.

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