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INTEGRATED MODELING APPROACH TO SIMULATE HYDROLOGIC PROCESS IN URBAN WATERSHEDS

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ABSTRACT: Correct prediction of flood extents in urban catchments has become a risk issue especially in Amazon region where there is a vast drainage system associated to intense rainfall. This paper's main purpose is to simulate a set of physical attributes in watersheds with limited self-adjusting capacity in urban expansion areas associated to the process of urban growth in Metropolitan Region of Belém (RMB), State of Pará, Brazil. The wet lowlands are the typical environment where two major processes occur: urban pluvial flooding, because of run-off accumulation and fluvial flooding, as result of riverbanks overflowing. In the characterization of water balance and rainfall (13 years), to simulation of discharge values, the following elements were used: monthly average, annual cumulative, return time and probability distributions and the method of SCS (Soil Conservation Service). In the physical characterization of watersheds it was employed: geological units, terrain units, altimetry (digital elevation model) and morphometric elements. The return time for 5 years considering the methods of Pearson Log-type III (3542 mm), Log-Normal (3537 mm), Ven Te Chow (3533 mm) and Gumbel (3497 mm) implies in a high probability of flooding periods recurrence. The SCS method indicated that the largest flows are expected in Una basin (3.81 m^3/s), Água Preta basin (1.79 m^3/s) and Val-de-Cans basin (1.15 m^3/s). The simulation model was capable of incorporating all the drainage elements and their interactions properly, for an accurate prediction of urban flooding. The continuous monitoring of rainfall in association with the physical parameters controlling the processes that occur in watersheds can provide a more effective flood prediction, useful in the urban flood disaster prevention system.

Key Words: water balance, flood, catchments, Metropolitan Region of Belém.

1. INTRODUCTION

The urban space requires areas for expansion of housing, locomotion and business units. The watersheds are commonly altered spaces. They are usually modified in terms of their morphological characteristics, quantity and quality of water (Ferrer *et al*., 2012). An urban or urbanizing watershed is one in which impervious surfaces cover or will soon cover a considerable area. Impervious surfaces include roads, sidewalks, parking lots and buildings. Urbanization changes a watershed's response to precipitation, the most common effects are alteration in velocity of infiltration, increase of peak discharges and runoff and occurrence of flood or overflow (Chen *et al*., 2005).

The variable factors that affect floods are (Black 2004, Selaman *et al*., 2007, Machado *et al*., 2010, Daniel *et al*., 2011): drainage basin characteristics (drainage area size, drainage area shape, drainage area orientation, terrain slope, land use, watershed development potential, geology, soil type, surface infiltration, storage, antecedent moisture condition and storage potential, as overbank, ponds, wetlands, reservoirs, channel, etc.); stream channel characteristics (channel slope, channel geometry, channel configuration, natural and controls, channel modification, aggradation/degradation); flood plain characteristics (type of soil and groundcover); and meteorological characteristics (precipitation amount, time rate of precipitation, hyetograph, storm cell size, storm cell distribution, storm direction and precipitation type).

The hydrologic characterization of catchments in urbanized areas allows the identification of consequences of channeling, channel narrowing and modification of the original topography, in order to reduce the impacts (Ferrer *et al*., 2012). The elements commonly analyzed are: morphometry, that requires only the topographic and drainage network information (Barbosa *et al*., 2012); and the runoff behavior, that is more complex because it should result from continued monitoring, but in most of the cases it is idealized by formulation of models. Watershed models can be divided into event-based and continuous-process models. The event-based models are those considering the individual process such as precipitation, runoff events with a focus on infiltration and surface runoff. The continuous-process models account for all water balance components, from soil water capacity of retention (infiltration, aquifer recharge) to storm events (Daniel *et al*., 2011; Das *et al*., 2012).

Hydrologically there are two fundamental urban watershed functions: collection of the water from rainfall and storage (recharge of surface water and groundwater). Thus, the definition of an urban watershed is dependent of storage and runoff components, as well as the existence of a defined drainage system. The stream-watershed system may include some or all of the storage types that occur on the landscape, with emphasis on the storage in soil, stream, vegetation and wetlands (Black, 2004).

In this paper, the association between hydrological behavior and morphometric analysis aims to define a theoretical model that identifies the effects of floods in river basins, especially when topographic characteristics favor such conditions, in environments with missing or insufficient information. Morphometric studies involve evaluation of streams through the measurement of various stream properties. Detailed analysis of drainage parameters is a great help in understanding the influence of drainage morphometry on hydrological behavior and their characteristics (Bagyaraj and Gurugnanam 2011), specially the runoff characteristics of the area and potentiality of watershed deterioration (Das *et al*., 2012).

In this application, the city of Belém (mouth of the Guamá river with Guajará Bay) was adopted as geographic space, more precisely the central region that is highly urbanized and where seasonal flooding occurs during the rainy season (Moraes *et al*., 2005). However, it is observed that even outside of this period the channeled courses tend to expand their effect, generating flooding and overflow (Gregory and Mendes 2009); but ir depends on local flow conditions and can result in significant losses to the surrounding communities. In general, when the excess water, including the rainfall excess, becomes overland runoff and flows on the surface toward the lowlands, the result is the occurrence of flood or overflow points.

The study area is located in northern Brazil, in a hot and humid climate (type Afi by the Köppen System), with a mean annual temperature of 25 °C, air humidity above 80% and a mean rainfall of 2889 mm/y. There is a reduction in rainfall between June and November which is “the less rainy season”, called summer, and an increase between December and May, which is the “rainy season”, called winter (Böck *et al*. 2011). The area receives large volumes of freshwater discharge and experiences macro tidal regime. The Guamá Bay is a highly dynamic area, under the influence of both fluvial and marine systems; formed by the Guamá/Acará–Moju rivers, it is connected to the right margin of the Pará River (Gregório *et al*., 2009, Bezerra *et al*., 2011). This estuary system is most important considering ecological, tourism and social aspects. The Metropolitan Region of Belém, as well as many other industries, cities, villages and communities, are on its shores.

2. MATERIALS AND METHODS

The methodology consisted of two stages, the first associated to physical characterization and the second based in the estimation of hydrologic components. The parameters analyzed were: geological units, morphometric variables, digital elevation model of the terrain and water balance. As a product, a theoretical model applied to Guamá river floodplain in Belém (Figura 1) was proposed. The stream-watershed system adopted include some parameters that occur on the floodplains areas; where some hydrological characteristics can play an intervening and complex role, interacting with different functions under various flow circumstances. The database adopted were: SRTM (Shuttle Radar Topography Mission) images for digital elevation model, time series of rainfall, temperature and evaporation (2000-2012) generated by

National Institute of Meteorology (INMET) and the geological map units adapted from Costa *et al*. (2002). The flood points were georeferenced from the records of Civil Defense of the State of Pará.

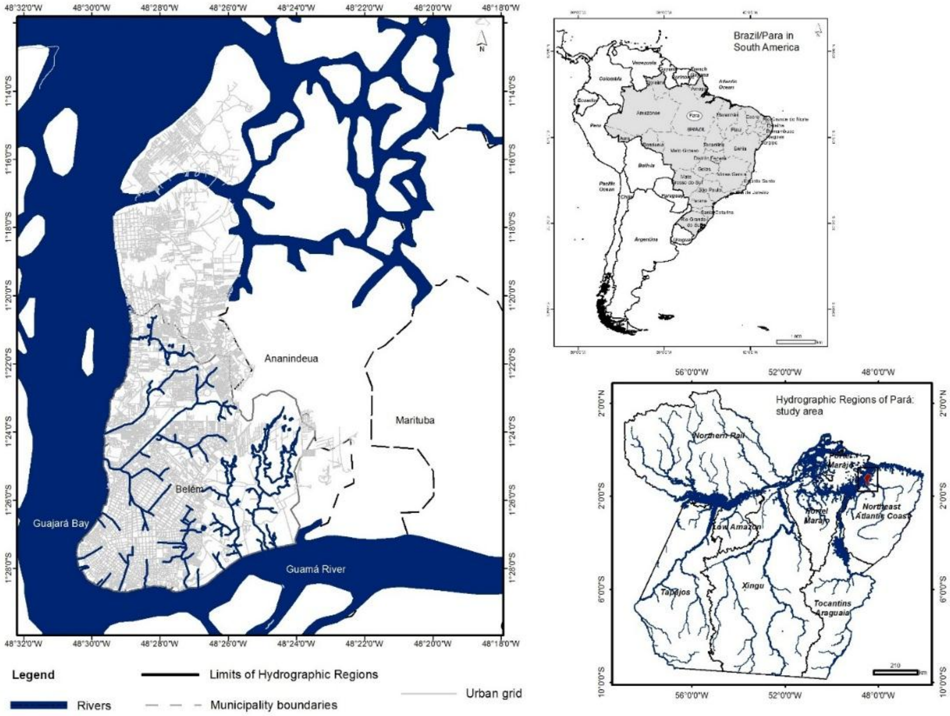


Figure 1: The study area.

2.1 Morphometric analysis

The morphometric analysis is carried out through measurement of linear, areal and relief aspects of the basin and slope contribution (Soni *et al*., 2013). The main parameters analyzed were: Stream Order, Area, Perimeter, Mean Slope, Form Factor, Circularity Ratio, Elongation Ratio, Drainage Density, Stream Frequency, Topographic Texture, Constant Channel Maintenance, Relief Ratio, Extension of the Surface Route, Gradient Channels and Drainage Efficiency Index (Table 1). To determine the morphometric network characteristics the Digital Elevation Model (DEM) was used to identify the altitudes of the beginning and end of each river segment. The DEM generated in GIS environment (Arc Hydro extension) was used to generate the drainage network (incorporating streams and lakes previous digitalized from cartography in 1:250.000 scale). In the proper determination of flow direction and flow accumulation, DEM sinks were identified and filled. The boundaries of the watersheds (eleven) were defined by the topographic divisors identified in the DEM.

2.2 Analysis of water balance components, precipitation, evaporation and temperature

The evaluation of rainfall, evaporation and temperature series (13 years) considered: monthly mean, annual mean, cumulative annual, return period (RP - the inverse probability of the rain event recurrence interval being equaled or exceeded in any given year) and probability distribution. According to Selaman *et al*. (2007), it is possible to estimate the frequency and magnitude of a given event using an empirical distribution function. Some of the probability distributions commonly used for hydrologic variables were: Lognormal, Ven Te Chow, Log-Pearson Type III and Extreme Value Distribution or EVI – Gumbel Distribution.

Table 1: The morphometric parameters used from Das *et al*. (2012), Fernandes *et al*. (2012), Pareta and Pareta (2012) and Altaf *et al*. (2013).

Parameters	Formulae
Stream order (U)	Hierarchical rank (Strahler Scheme)
Stream length (Lu)	Length of the stream
Form factor (Rf)	$Rf = A/Lb^2$; A = Basin area (km²); Lb= Basin length
Circularity ratio (Rc)	$Rc = 4\pi(A/(P^2))$; π = "Pi" value that is 3.14; A = Basin Area (km²); P = Basin perimeter (km)
Elongation ratio (Re)	$Re = Dc/l$; Dc = Diameter of the circle of area equal to the basin; l = Main channel length
Drainage density (Dd)	$Dd = Lu/A$; Lu = Total stream length of all orders; A = Basin area (km²)
Stream frequency (Fs)	$Fs = Nu/A$; Nu = Total number of streams of all orders; A = Basin area (km²)
Topographic texture (Tt)	$Tt = 10^{0,219649+1,115 logDd}$; Dd = Drainage density
Constant channel maintenance (Cm)	$C = (1/Dd)$; Dd = Drainage density
Relief ratio (Rr)	$Rr = \Delta a/l$; Δa = Total basin relief (Maximum Height – Minimum Height); l = Main channel length
Extension of the surface route (Es)	$Es = (1/(2Dd))$; Dd = Drainage density
Gradient channels (G %)	$G = (\Delta a/l) * 100$; Δa = Total basin relief (Maximum Height – Minimum Height); l = Main channel
Drainage efficiency index (IED)	$IED = G * Dd$; G = Gradient channels; Dd= Drainage density

The principal use of monthly water balance models has been to investigate the importance of different hydrologic variables in diverse watersheds specially where there are interventions that can interfere in one or more variables. In water balance, the temperature was used as a driving force to estimate potential evapotranspiration by the Thornthwaite and Mather approach (Carvalho *et al*., 2011), which along with monthly rainfall was used as input data. In order to determine the water balance at a site, it is necessary to have the following specific information: (a) latitude; (b) mean monthly air temperature; (c) mean monthly precipitation; (d) necessary conversion and computation tables; and (e) estimation of water-holding capacity of the soil depth for which the balance is to be computed.

2.3 Estimation of flow rates

The SCS (Soil Conservation Service) method was used to assess the behavior of the flow. The SCS (Table 2) is widely used by water resources engineers to determine peak flows of a stream at a given location. This method allows the evaluating of flows peak of floods based in the range between the height of rainfall retained in the basin after the start of runoff and retention capacity (Tramblay *et al*., 2010); this equals to the ratio between effective rainfall and runoff potential. The values obtained were compared and evaluated with the response of hydrographic units according to the variability of rainfall.

The major factors that determine SCS method are the cover type, hydrologic condition and antecedent runoff condition. Another factor considered is impervious areas, if they contribute directly to the drainage system or if the flow spreads over pervious areas before entering the drainage system. Impervious surfaces cover partially most of the urban areas, consequently the urbanization tends to decrease the time of concentration (Tc), increase the peak discharge (qp) and reduce the overland flow lengths by conveying storm runoff into a channel as soon as possible. If the channel design hadsefficient hydraulic characteristics, the runoff flow velocity should increase and travel time should decrease (Liu and Li, 2008; Altaf *et al*., 2013).

Figure 2 is a flow chart that shows the adopted procedures. In the figure, the diamond-shaped box labeled "Parameters" directs the appropriate method based in hydrological or morphometric component.

Table 2: Hydrological characterization, based in Liu and Li (2008), Tramblay *et al*. (2010) and Needhidasan and Nallanathel (2013).

Parameters	Formulae
Time of concentration (Tc)	$Tc = 57 * (^{l^3}/_{H})^{0,358}$; l = Main channel length (m); H = Maximum height difference along the l (m)
Potential maximum retention (S_{max})	$S_{max} = (^{25400}/_{CN}) - 254$; CN = Runoff curve number
Equivalent precipitation (P_{eq})	$P_{eq} = {}^{(\sum_{i=1}^{n} P_i * A_i)}/_{(\sum_{i-1}^{n} A_i)}$; P_i = Rainfall (mm); A_i = Basin area (m²)
Peak discharge (q_p) (m³/s)	$q_p = \frac{2*P*A}{2,67*[0,5*(1/5)*Tc+0,6*Tc]}$; P = Rainfall (mm); A = Basin area (m²); Tc = Time of concentration
Runoff coefficient (C)	$C = {}^{q_p}/_{P}$; P = Rainfall (mm); q_p = Peak discharge (m³/s)
Water storage (ΔS)	$\Delta S = Pm - (1,24 * 10^{-4} * Pm^{0,759} * A^{0,968}) - ETP$; P_m = Long period average rainfall (mm); A = Basin area (km²); ETP = Potential evapotranspiration corrected (mm)

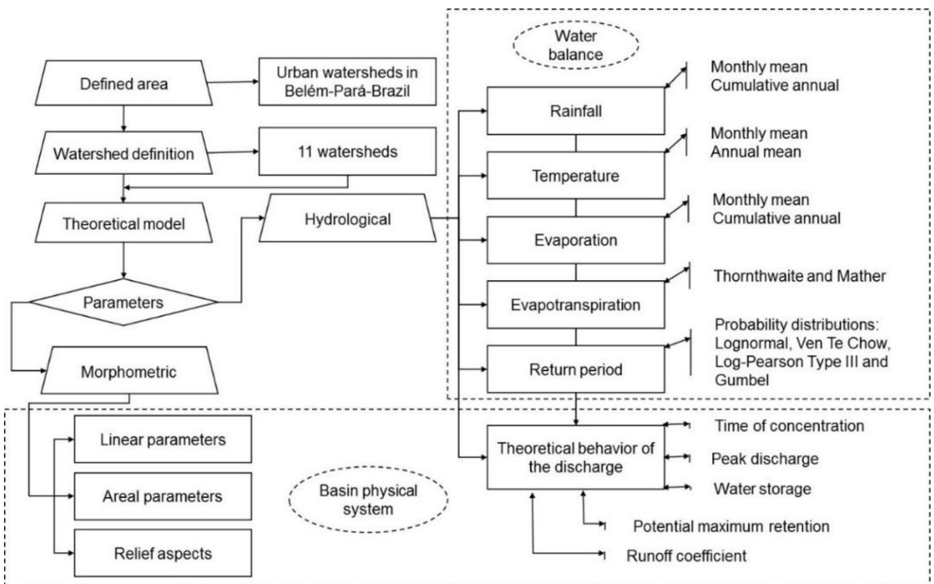


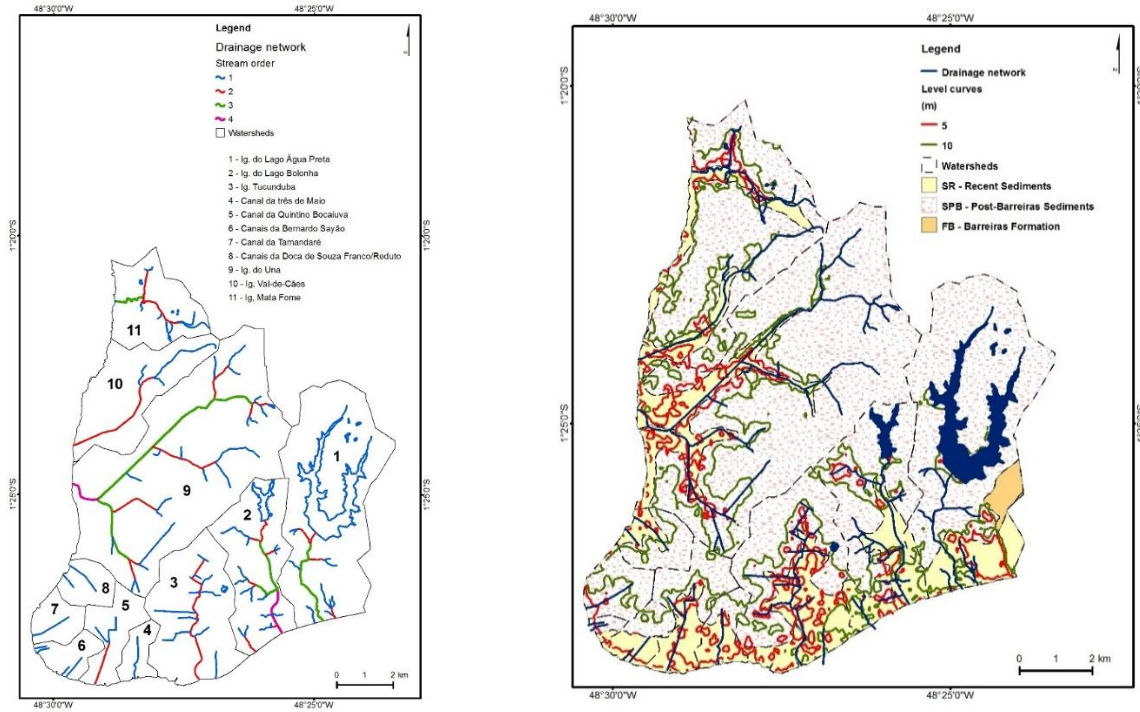
Figure 2: Flow chart of the adopted procedures.

3. RESULTS AND DISCUSSIONS

3.1 Watersheds and morphometry

The study area is formed by 11 watersheds, out of which only three (Bolonha, Água Preta, Mata Fome) retain their natural characteristics; the others are channeled with a high degree of waterproofing. Six (06) basins account for about 88% of the total area (Bolonha, Água Preta, Tucunduba, Una, Val-de-Cães, Mata Fome) indicating a partial spatial fragmentation. The drainage pattern is partly dendritic and centrifugal, characterized by a high topographic (> 10 m) extending from the central portion to northeast. The pattern of lineament directions are: NE-SW, NW-SE and NS. The channeling of waterways is especially accentuated in NE-SW and NS standards (Figure 3a).

The Recent Sediments (contour below 5 m), Pós-Barreiras Formation (contour above 5 m) and Barreiras Formation (restricted to Água Preta area) are the geological units present in the watersheds (CPRM 2002). The Pós-Barreiras Formation (sandy-clay, coarse grain size, yellowish and unconsolidated) is predominate in most intensively channeled rivers, with low slopes and high waterproofing; these characteristics facilitate the increase of floods. The Recent Sediments (characterized by detrital lateritic, Sub-Recent and Recent alluvial, of quaternary age; the last two are constituted by unconsolidated alluvial sediments) are in a lower percentage, but form the floodplain areas, with a high degree of sealing (Figure 3b).

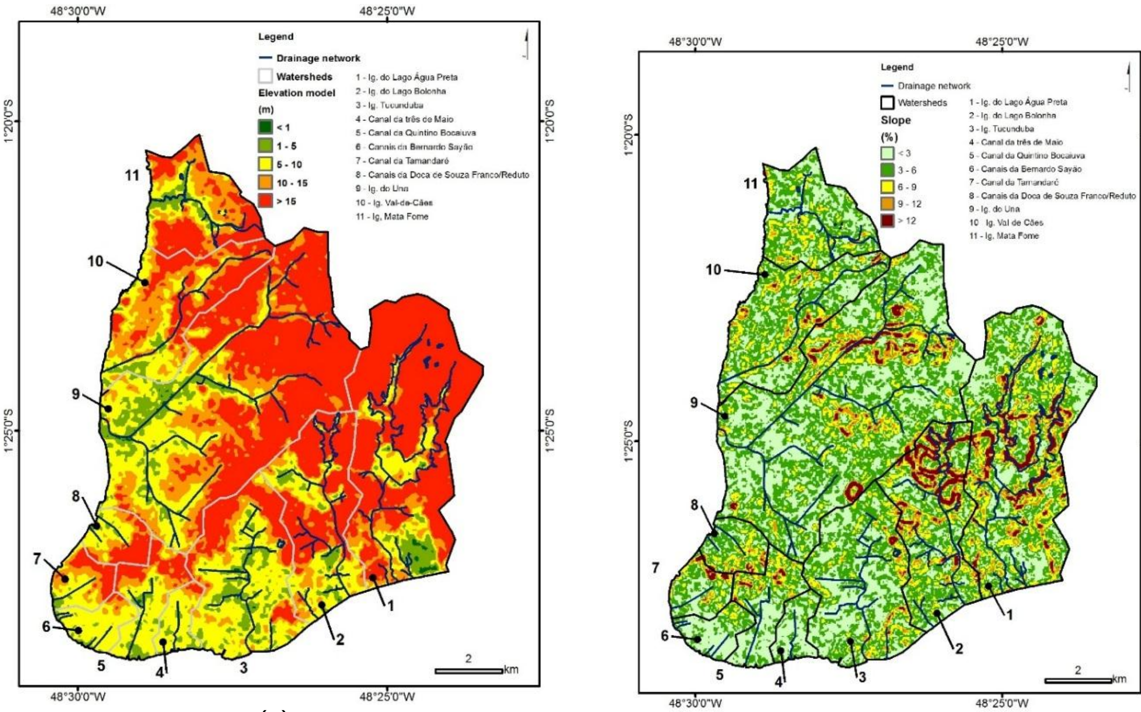


(a) (b)

Figure 3: (a) Drainage network pattern. (b) Geological unit distribution by watershed.

The most intensely channeled basins are characterized by the lower slope (<6%), except for Tamandaré and Doca de Souza Franco/Reduto channels, whose headwaters are near the quotas superior to 10 m (Figure 4). The number of Form factor (Rf) obtained can be associated to changes caused by tributaries loss and channeling process, with values that deviated of the reference standard (circular basins are nearby 1). Channels of the first order (Strahler) are predominant (59%); with only two basins as fourth order. The basins that showed higher drainage density (Dd) were those that maintained most of its tributaries (Bolonha, Água Preta, Mata Fome, Tucunduba, Una). The most intensely channeled basins showed the highest constant channel maintenance (Cm) and lower values of drainage density (Dd) (Figure 5).

The Figure 6 illustrates the parameters evaluated comparatively. There is a variability between drainage network, drainage area and relief variation (Rf, R, G and Tt), associated with a low Dd and Es. This result show a concentrated network around main channels with few tributaries. The Figure 7 shows these results in three separate groups, according to their relative frequency. The first (Água Preta, Bolonha, Tucunduba) concentrates the highest values of Dd and Fs, predominating the occurrence of sandy-clay sediments in two distinct areas: the headwaters with more than 10 m height and the mouth with less than 5 m. The second (3 de Maio, Quintino Bocaiuva, Bernardo Sayão, Tamandaré) is concentrated in lower areas (0 and 5 m), with recent sediments and higher IED, coinciding with the highest percentage of water channeled and points of flooding and overflow. The third (Doca de Souza Franco/Reduto, Una, Val-de-Cães, Mata Fome) has the highest percentage area above 5 m of height, occurrence of sandy-clay sediments and higher values of Cm, generally associated with basins that were partially channeled.



(a) (b)

Figure 4: (a) Elevation model and (b) slope distribution.

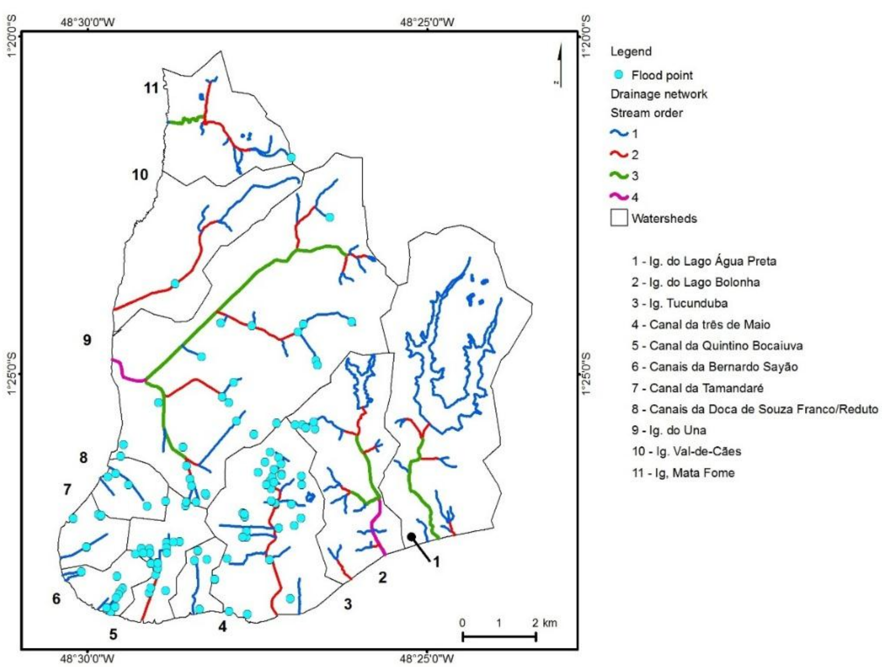


Figure 5: Flood areas by watershed.

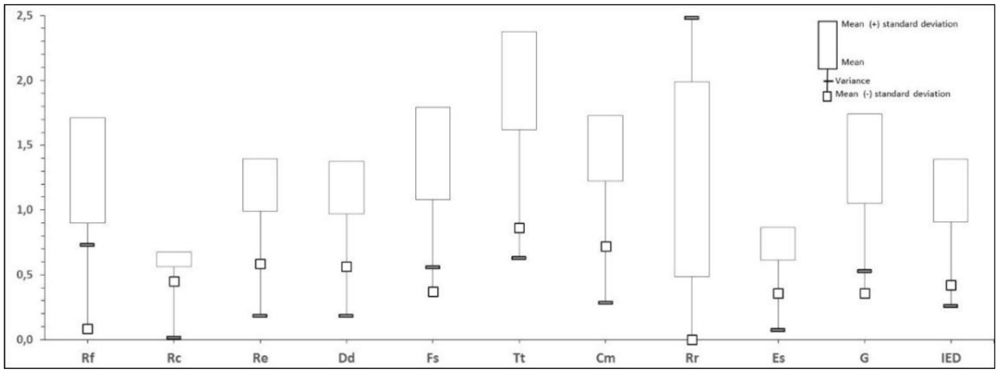


Figure 6. Morphometric parameters: Form factor (Rf), Circularity ratio (Rc), Elongation ratio (Re), Drainage density (Dd) (Km/Km2), Stream frequency (Fs) (n./km²), Topographic texture (Tt), Constant channel maintenance (Cm) (km), Relief ratio (Rr), Extension of the surface route (Es) (km), Gradient channels (G) (%) and Drainage efficiency index (IED).

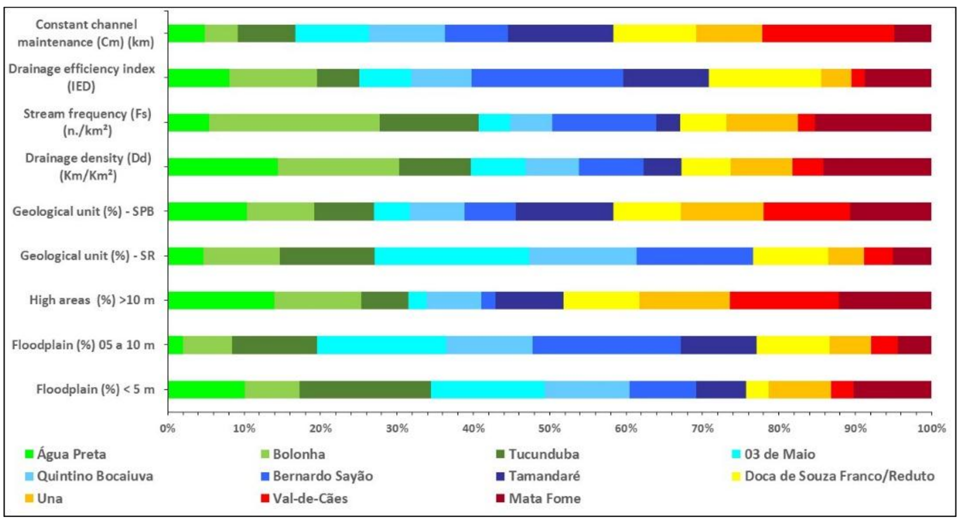


Figure 7: Comparative Analysis (relative frequency): geological units (SPB – Pós Barreiras sediments; SR – Recent sediments), floodplain coverage area and morphometry.

The urban watersheds characterized in Belém showed that: a high percentage of Dd and stream frequency (Fs) is associated with plain relief, impermeable coverage, high landscape dissection and runoff potential. Analysis of form factor (Rf) reveals that sub basins having low Rf have less side flow for shorter duration and high main flow for longer duration. Circulatory ratio (Rc) values approaching 1 indicates that the basin shapes are circular and, as a result, it gets scope for uniform infiltration and takes a long time to reach excess water at basin outlet, which further depend on the existing geology, slope and land cover (Pareta and Pareta, 2012). Analysis of elongation ratio (Re) indicates that the areas with higher Re values have high infiltration capacity and low runoff (Altaf *et al*., 2013). Constant of channel maintenance (Cm) depends on the rock type, permeability, climatic regime, vegetation cover and relief as well as duration of erosion (Das *et al*., 2012). All the sub basins have low Cm values; it indicates that these sub basins are under the influence of structural disturbance, low permeability and high surface runoff.

3.2 Estimative of water balance behavior

The analysis of water balance components was consistent with the variability shown by morphometric characteristics. The rainfall behavior indicated that from January to July is the wettest period with the most intense months in March and April (491.9 and 462.1 mm respectively, monthly average). The wettest years (above the average plus standard deviation, equal to 3568.2 mm) were 2006 (3663.8 mm) and 2011 (3592.2 mm), considering only above average (3286.5 mm), the following years can be included 2012 (3563.5 mm), 2005 (3528.5 mm), 2009 (3463.6 mm), 2000 (3352.1 mm), 2008 (3339.6 mm) and 2001 (3304.2 mm) (Figure 8a, c).

Figure 8: (a) Rainfall and evaporation by year; (b) Probability distribution functions and Return Period (RP); (c) Rainfall, temperature and evaporation by month; (d) Water balance in the study area; (e) Estimated peak discharge and runoff coefficient (ETR = Real evapotranspiration, P = Monthly average rainfall, EVP = evaporation, 1 - Água Preta, 2 - Bolonha, 3 - Tucunduba, 4 - 3 de Maio, 5 - Quintino Bocaiuva, 6 - Bernardo Sayão, 7 - Tamandaré, 8 - Doca de Souza Franco/Reduto, 9 - Una, 10 - Val-de-Cães, 11 - Mata Fome). Database (2000-2012) from National Institute of Meteorology (INMET).

The analysis of rainfall from the probability distribution showed a minor variation to the return period of 5 to 10 years and higher to 25 and 50 years. The accumulated rainfall in 2006, 2011 and 2012 was above the estimate for a return period of 5 years in the methods Log-Pearson Type III (3542.30 mm), Log-Normal (3537.43 mm) and Ven Te Chow (3534.09 mm); also including 2005 with Gumbel (3498.12 mm). Therefore, in the study area, the return period has been less than 5 years since half of the analysis period (Figure 8b).

The extreme events during Belém's rainy season can be induced by: the Intertropical Convergence Zone (ITCZ), lines of instability, deep wet convection and the interaction between some or all these elements (Tavares and Mota, 2012). The result is the bimodality of rainfall during the wet season, with a relatively minimum of rainfall in July and August, which leads to a separation of the rainy season into an early season (May-June-July) and a late season (August-September-October) (Wang *et al.*, 2006; Small *et al.*, 2007).

However, it is necessary to know the magnitudes of extreme rainfall events over different parts of the area (watersheds) to act against the pluvial flooding (Guhathakurta *et al*., 2011).

Pluvial flooding refers to flooding events that are caused by extreme rainfall; such floods occur when urban drainage systems are overwhelmed by excessive water flow or at impervious surfaces with consequent low permeability (De and Jamadar 2012). The Figure 5 shows the points of overflow occurrence, some of them reflect the flash floods. Flash floods are associated with short, high-intensity rainfalls, mainly of convective origin, that occur locally; it usually impacts basins with less than 1,000 km², with response times of a few hours or less, depending on the size of the concerned catchments, land use modification and water balance system (Marchi *et al*., 2010).

The water balance evaluation identified the basins with greater vulnerability to loss of water potential and the most critical period of the year when it can happen. The precipitation evaluated by probability distribution functions and precipitation reference (based on basin area) can generalize some results, but in the absence of local rain gauges this arrangement allowed the division of the area considering its response to rainfall distribution (Figure 8d). The basins with higher deficit values are the most impervious (Tucunduba, 3 de Maio, Quintino Bocaiuva, Bernardo Sayão, Tamandaré, Doca de Souza Franco/Reduto); they also have also the most concentrated points of flooding. The water accumulation in other watersheds results of the drainage area or types of use and land cover (forest areas or more permeable surfaces) (Mitchell *et al*., 2008).

The estimate flow values considered the lowest return period (Gumbel - 3498.12 mm). The application of the SCS method indicated that the watersheds with largest area and more number of tributaries tend to achieve higher flow rates, while the most strongly channeled (first and second order) would present minor values. The largest flows could occur in the basins of Una (4.051 m³/s), Água Preta (1.91 m³/s) and Val-de-Cães (1.22 m³/s). As morphometric analysis indicated, the most intensely channeled basins located in the central region must have lower values and flow (Figure 8e).

Therefore, the definition of an urban watershed depends on the existence of identifiable storage-runoff components as well as the existence of a defined drainage system. Change of land use within the watershed greatly affects the collection capacity and consequent runoff behavior of the watershed (Black 2004). If the land use changes are local, the water balance is dominated by local characteristics. For land use changes that cover larger portions of the watershed, the impacts may also be observed (as in the study area) in the annual water balance.

The proposed simulation model did not consider the effect of the tides. Hydrodynamics in this area is highly influenced by the tides and by the discharge of Rivers Guamá, Acará and Moju (Acará-Moju), subject to annual variations, which depend mainly on the seasonal rainfall pattern (Böck *et al*., 2011). The effect of tides is mainly observed during high tide, when it coincides with rainy periods or high intensity rainfall. The occurrence of flooding points is immediate and the flow depends mainly on the reduction of rainfall. The model allowed the estimation of flow behavior in the basins that have no hydrological monitoring, but present recurring flooding. The SCS method enabled to identify a behavioral tendency for local flows and the expected flow (Liu and Li, 2008, Tramblay *et al*., 2010). However, the results can vary with the changes in design of the drainage system, arising from urbanization, loss of its natural features by plumbing, channeling and floodplain backfill.

4. CONCLUSION

The urban land use change and its consequent problems gives an example of how severely urban growth on a city's fringes can affect environmental features, such as water balance, in quantitative terms. Urban space growth leads to increased flood risk by alterations in water balance components, especially the runoff properties. The main application of the model is to identify a hydrological behavior linked to urban watersheds and enable proposition of measures to manage the floodplain areas. The floodplain regulation should be based on establishment of land use criteria, integrated with urban planning activities. In Belém's watersheds, it was possible to identify two different zones. The first is called floodway and is associated with areas subject to frequent flooding. The other is the flood fringe, which constitutes regions that may be flooded during more severe storms, although presenting only storage effects.

The methodology allowed associating several parameters for the characterization of urban watersheds, but the results are limited to the use or one season (rainfall) and no water levels measurement in the channels, therefore with a monitoring network the values can be better calibrated. The model improved with more field information (water levels, discharge) allows the identification of a behavior pattern, which favors the occurrence of floods, sealing conditions and land use effects.

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