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Hydrological and hydraulic modelling applied to the mapping of flood-prone areas

Modelagem hidrológica e hidráulica aplicada ao mapeamento de áreas inundáveis

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ABSTRACT

Overbank flooding caused by historically high flows, such as that in the Rio Mundaú watershed (lying between the states of Alagoas and Pernambuco) in 2010, has been the cause of widespread damage. The purpose of work described in this paper was to propose a mapping of areas liable to flooding in the township of Rio Largo (Alagoas) in the Rio Mundaú watershed by means of an "off-line" coupling of the hydrological/hydraulic models (MGB-IPH/HEC-RAS), through consideration of extreme floods with different return periods for discharge. The hydrological model had a parameterization appropriate for extreme floods, using as input rainfall data with different return periods. Calibration and validation of the hydrological model were adequate in drainage areas larger than 1500 km^2, but were less acceptable in headwater drainage areas where different geology and soil cover gave rise to surface runoff. The hydraulic model showed good agreement with point observations of flood levels in 2010 in both rural and urban areas along the water-course ($R^2 = 0.99$; RMSE = 1.41 m and CV (RMSE) = 0.04). In urban areas distant from the river, however, flood levels were over-estimated, indicating a need to use more detailed Digital Elevation Models. Flood events with return period greater than 50 years have the potential to cause great damage (floods exceeding 0.46 km^2 in the urban area). The study showed that the use of coupled models was a viable approach for mapping areas liable to flooding, when it is not possible to analyse local flow frequencies in support of a hydraulic model.

Keywords: *Floods. Models. Coupling.*

RESUMO

Inundações ribeirinhas ocasionadas por cheias históricas, como, por exemplo, no ano de 2010 na bacia hidrográfica do rio Mundaú (entre os estados de Alagoas e Pernambuco), promovem danos de grandes proporções. O objetivo deste trabalho foi propor um mapeamento de áreas inundáveis no município de Rio Largo (Alagoas), bacia hidrográfica do Mundaú, através de acoplamento "off-line" de modelos hidrológico/hidráulico (MGB-IPH/HEC-RAS), considerando eventos de cheias extremas com diferentes tempos de retorno de vazão. Foi utilizada uma parametrização voltada para eventos extremos de cheia no modelo hidrológico, utilizando como entrada dados de chuva para diferentes tempos de retorno. A calibração e validação do modelo hidrológico foi adequada em áreas de drenagem superiores a 1.500 km², o que não foi verificado em áreas de drenagem próximas a nascentes, as quais possuem geologia e tipo e cobertura do solo que propiciam escoamentos superficiais. O modelo hidráulico indicou boa correspondência com os dados pontuais das marcas de cheia do ano de 2010 em áreas rurais e urbanas perto do curso d'água ($R^2 = 0,99$; RMSE = 1,41 m e CV (RMSE) = 0,04). Entretanto, em áreas urbanas distantes do rio, houve uma superestimação, assinalando a necessidade do uso de Modelos Digitais de Superfície mais detalhados. Eventos de cheia com tempo de retorno acima de 50 anos possuem grande potencial de danos (inundação acima de 0,46 km² na área urbana). Este estudo indicou o uso de modelos acoplados foi viável para representar o mapeamento de áreas inundáveis, quando não é possível realizar uma análise de frequência local de vazões para subsidiar o modelo hidráulico.

Palavras Chave: *Inundações. Modelos. Acoplamento.*

INTRODUCTION

Overbank floods resulting from high flows have had important socio-economic consequences all over the world. During the period from 2001 to 2014, more than a billion of the world's people were affected by flooding, and almost 80 thousand died (EM-DAT/OFDA/CRED, 2015). The main hydrologic-hydraulic factors giving rise to flooding are relief, type and intensity of precipitation, vegetation cover, drainage capacity, geology, river morphology with extension of channel and floodplain, channel-floodplain interaction and roughness.

To minimize the socio-economic impacts of flooding, solutions for preventing it have consisted of either structural or non-structural measures. Usually, non-structural measures are financially more viable, focussing on prevention and conservation to give better harmony between the environment annd urban areas along the river (TUCCI, 2007).

One of the more widely known non-structural measures is the mapping of areas susceptible to flooding, a financially viable option which is useful in risk studies. Flood mapping commonly uses 1D and 2D hydraulic mathematical models (conceptual or empirical) to represent the hydraulic phenomena that determine water-levels (1D and 2D) and the area flooded These hydraulic models can also be coupled to hydrological models (COLLISCHONN; COLLISCHONN; TUCCI, 2008; COLLISCHONN et al., 2007; PAIVA; COLLISCHONN; BUARQUE, 2013; PAZ et al., 2011) and to atmospheric models (DMITRIEVA; PESKOV, 2013; SRINIVAS et al., 2013; TRAPERO; BECH; LORENTE, 2013), to give a complete conceptual representation of all the processes involved.

The coupling of hydrological and hydraulic models has been a valuable tool in flood studies (BALLESTEROS et al., 2011; BONNIFAIT et al., 2009; GRIMALDI et al., 2013; PAZ et al., 2011; SARHADI; SOLTANI; MODARRES, 2012; SURIYA; MUDGAL, 2012), because it enables future scenarios to be simulated from limited input data. Moreover, this coupling combined with additional data and modelling procedures, such as remote-sensing (BATES et al., 2006; CHORMANSKI et al., 2011; RABER et al., 2007) and Geographical Information Systems (GIS) (CASAS et al., 2006), adds greatly to the optimization and display of results.

Hydraulic modelling requires information that adequately represents flooded areas, including (a) data or estimates of flows upstream of the reach of interest (SARHADI; SOLTANI; MODARRES, 2012) and (b) good quality data on regional topography and bathymetry (HORRITT; BATES, 2001; NICHOLAS; WALLING, 1997). Lack of adequate topographic and bathymetric data can cause problems for the description of flooded areas given by the hydraulic model (HARDY; BATES; ANDERSON, 1999; HORRITT; BATES; MATTINSON, 2006; SANDERS, 2007), because the channel bed and morphology of the region adjacent to the water-course are inadequately represented.

In general, townships within the Mundaú hydrographic basin have urbanized flood-plains and experience repeated flooding, sometimes causing extreme damage (1914, 1941, 1969, 1988, 1989, 2000, 2010), showing their fragility in the face of flood events (FRAGOSO JÚNIOR; PEDROSA; SOUZA, 2010). After the damage in the Mundaú basin caused by the floods of 1988 and 1989, studies recommended protective measures such as increased drainage capacity, containment of flood-water by reservoirs, reforestation, channel works and the installation of flood warning and control systems (ALAGOAS; PNUD; OAS, 1990). Despite these many recommendations no action, either structural or non-structural, was effectively undertaken. Furthermore, river-side townships in the Mundaú basin have had no studies that quantify the extent of flooding caused by extreme events, even though such studies would yield information relevant to society and underwrite planning and management for public policy and decision-making.

Hence, the aim of the present work is to explore the possibility of mapping areas liable to flooding in the township of Rio Largo (AL) by means of coupled hydroloical and hydraulic models in a GIS environment, using hydrological events with different return periods.

METHODOLOGY

Study Area

The area of the Rio Mundaú drainage basin is 4,126 km², and is situated between the states of Pernambuco and Alagoas. The study area for the hydrological model comprises the whole of the drainage basin (Figure 1) but the hydraulic model uses only one reach of the main river with length 4.64 km, within the urbanized area of the Rio Largo (AL) township (Figure 1).

The prevailing climate within the basin, according to the Köppen classification, is of type Bsh, with precipitation and mean annual temperature approximately 800 mm and 18ºC respectively (COTEC, 1999).

According to measurements taken at the Fazenda Boa Fortuna gauging station (Código 39770000 – ANA), nearest to the basin outfall and upstream of the Rio Largo, the mean flow is 25.78 m^3/s, with peak discharges greater than 1000 m^3/s and low flows less than 10 m^3/s (COTEC, 1999). The topography is steeply sloping, suggesting rapid surface flow. In the basin headwaters the altitude is near 1000 m; in the lower reaches, altitude reaches a minimum of 8 m (COTEC, 1999).

In the headwaters and middle reaches, the geology is determined by the Pernambuco-Alagoas Massif of crystalline rocks, igneous or metamorphic in origin, with low infiltration capacity; the basin's lower reaches are derived from the Sergipe -Alagoas sedimentary basin, which occupies only a small part of the basin where infiltration capacity is higher.

Soils within the drainage basin include: (a) Red-Yellow Argissols and their associations (51.80%), well- or moderately-drained, moderately porous, non-hydromorphic; (b) Red-Yellow Eutrophic Argissols and their associations, similar to those mentioned previously, but with greater depth (17.21%); (c) Litholic Eutrophic, Distrophic Neossols and their associations (10.96%), with low potential for surface runoff, porous; (d) Red-Yellow Distrophic Latossols and associations (17.25%), which are more porous; (e) Haplic Eutrophic Solodic Planossols and associations (1.53%); (f) Eutrophic Litholic Neossols

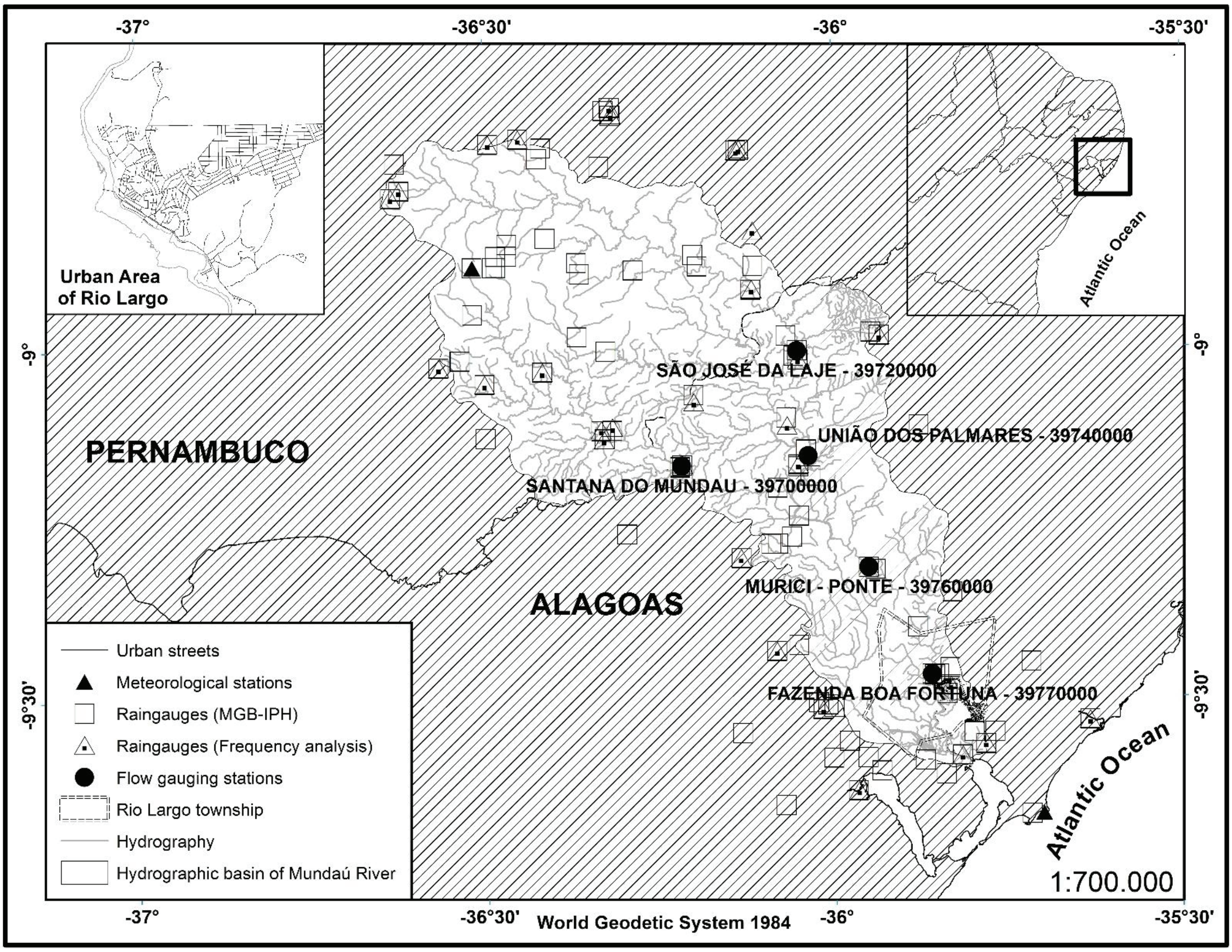

Figure 1 – Location of the hydrographic basin of the Rio Mundaú. Meteorological stations, flow-gauging stations and raingauge sites are also shown

and associations (0.14%), shallow soils; (g) Eutrophic Haplic Gleissols (0.34%), soils with excess water, and (h) Eutrophic and Distrophic Neossol Association (0.77%) (Adapted from COTEC, 1999).

Land use is divided among: areas showing effects of human activity, 75.68 % (urban areas, pasture and small- to large-scale agricultural systems, particularly for sugar-cane production) and only 22.76 % covered by forest, scrubland or original cover (COTEC, 1999).

The Rio Largo township is one of the last river-side towns lying on the Rio Mundaú, the oldest part lying on the Cachoeira do Meirim geological fault which separates crystalline from sedimentary rocks, causing a marked change in level of about 13 m. In addition, the township is sited on a narrow flood-plain. The town's urban perimeter corresponds to the study area to be mapped for liability to flooding, with a reach comprising 4.64 km of the Rio Mundaú, within an urban area of 18.55 km².

HYDROMETEOROLOGICAL DATA

For frequency analysis, data were used from raingauge sites maintained by the National Water Agency (ANA); by the Pernambuco Technological Institute (ITEP); by the Secretariat for the Environment and Water Resources of the State of Alagoas (SEMARH-AL); and from the flow-gauging station Fazenda Boa Fortuna on the Rio Largo, operated by ANA. These sites were selected by means of a Gantt graph which displayed the availability of data. The selected sites were those with fewest gaps in record (those with gaps occurring in months with low precipitation, with longest gap not exceeding 30 days) in a common period of 30 years at all sites (1962-1991); this gave a selection of 31 raingauge sites (Figure 1). The period January to December was used, with the criterion that at least 15 years of maximum annual rainfall were included, in order to reduce statistical uncertainty (SAF, 2010).

To use the MGB-IPH model, hydrological data at daily intervals were taken from the raingauge network (97 gauges) in the Rio Mundaú drainage basin by ANA, ITEP e SEMARH-AL, with 5 flow-gauging sites of ANA and meteorological stations (2 sites) on the National Institute for Meteorology (INMET) (Figure 1).

Frequency Analysis of Rainfall and Maximum Flows

The extreme rainfall events in each year of the selected period were analysed for consistency and the removal of outliers which may have occurred through recording errors. This procedure used the program Expert System for At-Site Frequency Analisys of Hydrologic Variables® (SEAF), based on methods of Grubbs and Beck (1972). One value in each of the historic series from two raingauge sites (Caetés - 0836008 (ANA); Jurema – 0836021 (ANA)) was discarded, because they looked like recording errors (values greater than 50% of the highest rainfall in the series without the outlier).

A non-parametric hypothesis test was then used to test for homogeneity in raingage and flow records using the Wilcoxon Sum of Ranks test for independent samples (equivalent to a Mann-Whitney test), with significance level $\alpha = 0.05$ for a two-tailed test. The test is based on the comparison of medians of two or more samples from a data-set. The null hypothesis is that the samples are from populations having the same median (TRIOLA, 2008). In a hydrological context, the Mann-Whitney test identifies whether the samples come from different events, ordinary rainfalls or unusual phenomena.

Normally the choice of distribution for maxima is open to some discussion, because each distribution has strengths and weaknesses. In this work, the Generalized Extreme Value (GEV) distribution was used, since it has extensively used in studies of extreme rainfalls and river flows (HOSKING; WALLIS; WOOD, 1985; KATZ; PARLANGE; NAVEAU, 2002; KOUTSOYIANNIS; BALOUTSOS, 2000; SAF, 2010; TRAMBLAY et al., 2012). The GEV distribution's three parameters include one for position, which avoids problems from smoothing the distribution when data series are short. This may occur, for example, when the Gumbel distribution is used (ROGGER et al., 2012). The method of Maximum Likelihood, which maximizes a function of the distribution's parameters, was used to estimate the GEV parameters. This method yields estimates of the parameters with least variance and which are consistent, sufficient and with greatest asymptotic efficiency. A Kolmogorov-Smirnov goodness-of-fit test was used with plotting positions of empirical data given by the Gringorten equation (appropriate for the GEV distribution). Extreme values of rainfall and flow were then obtained for return periods 2, 5, 10, 25, 50, 100, 200, 500 and 1000 years.

Hydrological Modelling

The transformation of rainfall to runoff was effected by using the MGB-IPH hydrological model developed by Collischonn et al (2007) and further refined by Paiva, Collischonn and Buarque (2013). It is a distributed model which simulates processes in the land phase of the hydrological cycle in terms of physical and conceptual relations. The model has been shown to be adequate in various applications to medium-size Brazilian drainage basins (between 2.000 km^2 and 10.000 km^2) (GAMA, 2011; CHAVES, 2013) and larger (> 10.000 km2, COLLISCHONN et al., 2007; PAIVA; COLLISCHONN; BUARQUE, 2013).

The model has four components: soil water balance, evapotranspiiration, flow (surface, sub-surface and subterranean), and propagation of flows through the drainage network. MGB-IPH is appropriate for Brazilian conditions, allowing easy use of of input data (remote-sensed images, digital terrain models, and hydrometeorological data) in formats produced by national agencies. A daily time-interval was used for simulations. Physiographic characteristics of the basin (division into sub-basins, river reaches, lengths and slopes of rivers) were obtained using ArcHydro, an extension of the ArcGIS software.

The basin was divided into 5 sub-basins and 95 mini-basins (i.e., elements draining to a single river reach) using the Digital Elevation Model (DEM) Shuttle Radar Topographic Mission (SRTM) of the National Aeronautics and Space Administration (NASA) provided with corrections for missing data given by the Consultative Group on International Agricultural Research-Consortium for Spatial Information (CGIAR-CSI). Each mini-basin had its characteristic type, use and soil cover that defined its HRU (Hydrological Response Unit) (KOUWEN et al., 1993). Following the grouping of Sartori, Genovez and Neto (2005a; 2005b) (Table 1), soils were classified as shallow or deep; soil cover was classified as exposed soil, short vegetation, and forest, resulting in 6 HRUs (blocks) for the basin. To define the HRUs for the Rio Mundaú basin, these were reclassified and processed using the digital soil map of the Empresa Brasileira de Pesquisa Agropecuária (EMBRAPA) (Published in 2001 at Scale 1:5.000.000) and originating in the Project RadamBrasil. Images from the Landsat 7 satellite (Thematic Mapper sensor) were used for classifying land-use and soil cover (Table 2 and Figure 2). Values of fixed and calibrated parameters were based on HRU characteristics, following recommendations given in the MGB-IPH manual.

Fixed parameter values were taken for albedo, leaf-area index, canopy cover and surface resistance. Calibrated parameters included soil moisture capacity (Wm); a parameter defining the shape of the storage-saturation relation (b); a parameter controlling flow during dry periods (Kbas); a parameter controlling quantity of soil water emerging as surface flow (Kint); a parameter controlling the shape of the reduction in intermediate or sub-surface drainage (XL); a parameter controlling flow from subterranian reservoir to the soil surface layer during a time-interval (CAP); residual storage (Wc); the coefficient for surface propogation in cells (CS); the coefficient for sub-surface propagation in cells (CI); and the delay for the subterranean reservoir (CB) (Table 3). A value 0.0100 m^3/ (s.km^2) was obtained for specific baseflow (QB).

The model was calibrated manually. The period chosen for model calibration was from January 1998 to December 2005 and the validation period from January 2006 to January 2008. The objective functions used to evaluate calibration were the Nash-Sutcliffe coefficient (NS), the Nash-Sutcliffe coefficient calculated using logarithms (NSlog) and the difference in volume (AV).

Table 1 - Grouping of soils in the Rio Mundaú basin in terms of their characteristics

Group	Depth	Permeability
A	Very deep (> 2 m) or Deep (1 m a 2 m)	Rapid/ Moderate
B	Deep (1 m to 2 m)	Rapid/ Moderate
C	Deep (1 m to 2 m) or Moderately Deep (0.5 m to 1.0 m)	Slow/Rapid
D	Moderately Deep (0.5 m to 1.0 m) or Shallow (0.25 m a 0.50 m)	Slow/ Moderate

Table 2 - Caracteristics of soil type and use in HRUs (Blocks) and their percentage area in the basin

RHU	Type and Soil Use	Area %
Block 1	Soil D + Bare soil	5.99
Block 2	Soil D + Short Vegetation	12.79
Block 3	Soil D + Forest	1.37
Block 4	Soil C + Short Vegetation	57.68
Block 5	Soil C + Bare soil	6.28
Block 6	Soil C + Forest	15.89

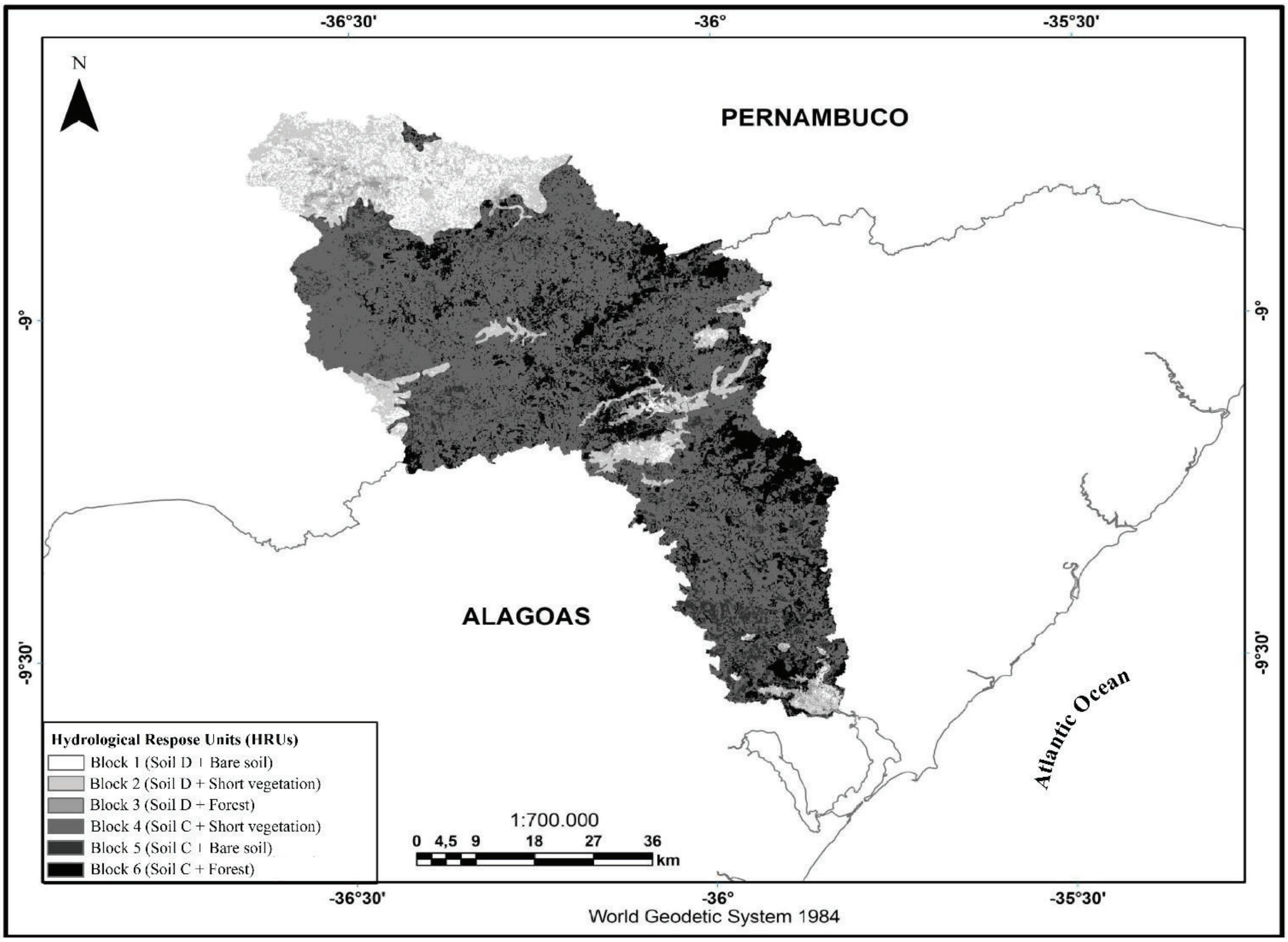

Figure 2 - HRUs in the Rio Mundaú hydrographic basin

Table 3 – Final values of calibrated parameters in the MGB-IPH model of the hydro-graphic basin of the Rio Mundaú

HRU	Wm	b	Kbas	Kint	XL	CAP	Wc
Block 1	60.1	0.50	3.80	14.27	0.00	0.00	0.90
Block 2	50.4	0.37	3.89	10.97	0.10	0.00	0.50
Block 3	60.2	0.38	5.84	14.70	0.10	0.00	0.03
Block 4	1370.9	0.26	3.77	52.60	0.70	0.00	0.60
Block 5	1363.8	0.28	3.88	48.00	0.70	0.00	0.60
Block 6	260.2	0.34	7.86	72.93	0.10	0.00	1.20

Hydraulic Modelling and Mapping of Flood-Prone Areas

To determine flood levels for different return periods, the hydraulic model HEC-RAS 4.1, developed by the Hydrologic Engineering Center (HEC) was used. HEC-RAS® is a mathematical model that simulates super-critical, sub-critical or mixed flows in natural or artificial channels (WARNER et al., 2010). It can be used to calculate and analyse one-dimensional hydraulic flows in permanent, quasi-permanent or no-permanent regimes. It can also be used to simulate river-bed erosion and sediment transport, and to model water quality in the simulated reach.

The model requires data on flow, localized change in flow (non-permanent regime), boundary conditions, topgraphic -bathymetric information at each transverse section, a roughness coefficient for each transverse section, and a post-processing DEM to spread the flood into a pseudo 2D, since velocities in the two-dimensional plane are not simulated.

A simplified configuration of the model was used in which flow regime was taken as permanent, since the input data consist of an average of two daily readings. This simplification gives results for the project which err on the conservative side.

To ensure that estimates of flooded areas were fully representative, topographic-bathymetric sections were needed (i.e., sections which integrate channel bathymetry with flood-plain topography) that were representative of flow conditions. The locations of topographic-bathymetric sections were defined by field visits to the river reach, and sought to identify sites where river hydrulic conditions varied, while taking into account the viability of survey at the section. Variation in hydraulic conditions can result from changes in river-bed slope, the presence of bridges, islands or other obstructions, widening or narrowing of the transverse section, or from other causes.

Five such sections were defined in the Rio Largo township (Figure 3). The topographic survey of the flood-plain used a Total Station (Topcom model). The margins of bathymetric sections were geo-referenced using a GPS (model Garmin Etrex H, accuracy < 10 m). The bathymetric survey of two of the sections used an Acoustic Doppler Current Profiler (ADCP, model M9 SonTek®).

In the direction upstream-downstream, bathymetry of the transverse secction at Fazenda Boa Fortuna (4.64 km distant from the final section), and of the penultimate section (at distance 0.52 km from the third section and 0.95 km from the last section downstream) and of the last section downstream, were surveyed by ADCP. The section at Fazenda Boa Fortuna set the boundary conditions for the hydraulic model, where maximum flows were estimated by statistical distribution and the hydrological model. Being located 1.98 km from the section at Fazenda Boa Fortuna and at 2.66 km from the final downstream section, the second transverse section was defined by bathymetric measurement because of rocks in the river bed. The third section (distant 1.19 km from the second section and 1.47 km from the last downstream section) has an old run-of-river barrage used for hydropower production; its dimensions were obtained from the dam design plans (Figure 3).

The topography of the study area (Figure 3) was obtained by combining two sources of data: (a) topographic maps supplied by the Companhia de Saneamento de Alagoas (CASAL) with equidistant contours at 1 m interval (scale 1:2000) in the flood-prone area; and (b) altimetry given by the Digital Elevation Model (DEM) TOPODATA, provided by the Instituto Nacional de Pesquisas Espaciais (INPE), with interpolated spatial resolution 30 m and data corrected by the DEM SRTM (spatial resolution 90 m). The DEM data were used only for sites distant from the flood-plain, where no CASAL topographic data were available.

The topographic-bathymetric sections were extended beyond the flood-plain using the DEM information. Some difference could be seen between the data resulting from field survey and those derived from DEM, mainly for the river-bed. The average difference was about 12%. Combining DEM data with topographic and bathymetric data improves the quality of results (CASAS et al., 2006).

All pre-processing for HEC-RAS (definition of transverse sections, channel and margens, geometric data) used the ArcGIS software extension HEC-GeoRAS 4.3.

The roughness coefficient was the only parameter calibrated in the model HEC-GeoRAS, because of its sensitivity to hydraulic conditions. The Manning roughness coefficient was fitted manually, using as a starting point the reference values given by Chow (1959). Brunner (2010) recommended measurements or satellite images which define the flooded area for use when calibrating this parameter. In this paper, flood marks from the June 2010 flood were used (36 marks surveyed in the field using GPS) to calibrate the hydraulic model. This survey was restricted to the river's left bank in the city of Rio Largo, because there is

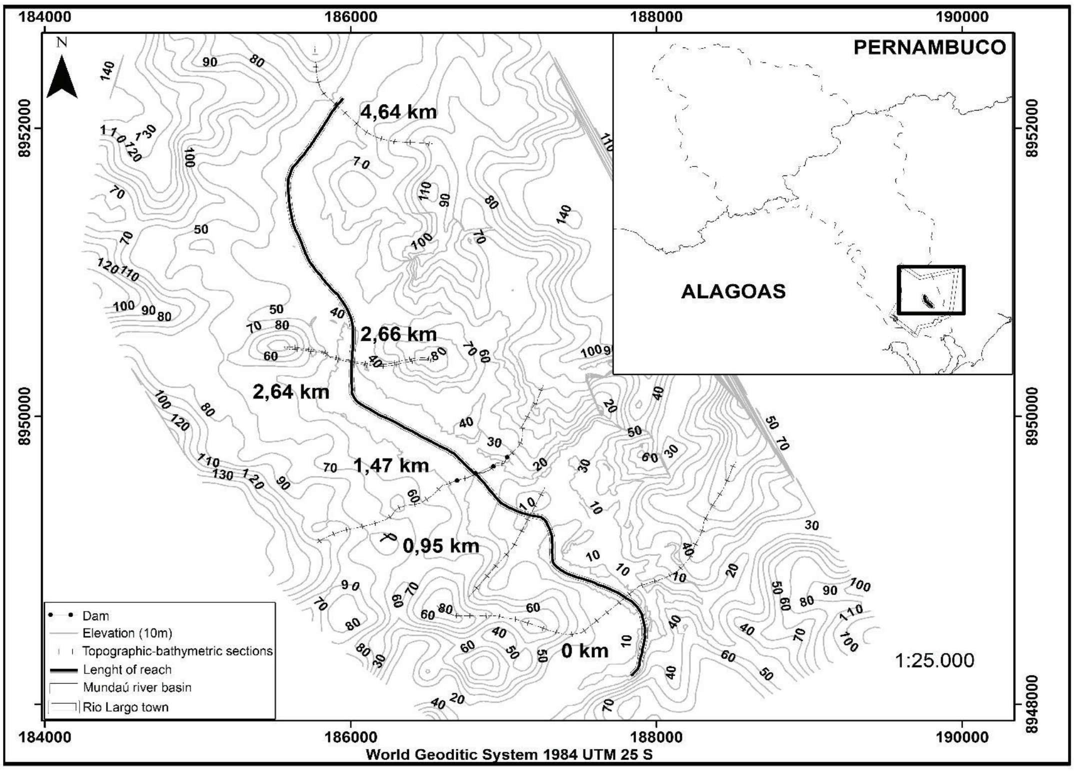

Figure 3 - Topographic-bathymetric sections used in the hydraulic model

no urbanisation on the opposite bank. The upstream boundary condition was the flow estimated from the stage-discharge curve for the event of June 2010. The downstream boundary condition was the flow estimated from Manning's equation, where the channel slope was obtained using the resulting DEM. The quality of the hydraulic model's calibration was assessed using the coefficient of determination (R^2), the root mean squared error (RMSE) and the coefficient of variation of mean squared error (CV (RMSE)) between observed and simulated water-levels. It was not possible to use the indicators of calibration quality recommended by Sarhadi, Soltani and Modarres (2012) because the limits of the flooded area could not be defined using the flood marks surveyed in the field.

Maps of flooded areas for different return periods were generated for two conditions of estimated upstream flow: (a) maximum flows generated by fitting the GEV distribution; and (b) maximum flows generated by the hydrological model using estimated maximum rainfalls for different return periods (TR). Thus possible differences were explored that might have resulted from different methods of defining maximum flows (ROGGER et al., 2012). The return periods for maximum flows are the same as those for maximum rainfalls. Agreements between flooded areas given by different flow estimates (determimistic and stochastic) were evaluated by comparing them and by means of the equation Fit (1) (BATES et al., 2006; BATES; DE ROO, 2000; SARHADI; SOLTANI; MODARRES, 2012):

$$Fit(\%) = \left(\frac{A_{om}}{A_o + A_m - A_{om}}\right) \times 100 \qquad (1)$$

where: *Fit* is the percentage of convergence between two generated areas, A_o is the area of flooding generated using stochastic flows (the GEV distribution) and A_m is the area of flooding generated using deterministic flows (from the hydrological model), A_{om} is the intersection of of flooded areas from the two boundary conditions. Values near 100% indicate good correspondence between the areas, and values near 0% low correspondence between them.

RESULTS

Frequency Analyses of Flows and Maximum Rainfalls

The non-parametric Mann-Whitney test for homogeneity of medians showed that the rainfall series and the series of flows at Fazenda Boa Fortuna bore no evidence of trends arising from local climate changes and/or extreme clmatic events, indicating that the series came from the same population.

The results from the Kologorov-Smirnov test showed that all 31 raingauge sites were well represented by the GEV distribution, at the 0.05 significance level.

Having used the tests for homogeneity and adherence, return periods were estimated for each rainfall record and for the flow record from Fazenda Boa Fortuna (Figure 4). At the flow-gauging site, flow estimated from the stage-discharge curve for the flood of June 2010 was 1233 m^3/s (recorded water level 11.50 m), which corresponds to a return period of roughly 200 years (Figure 4).

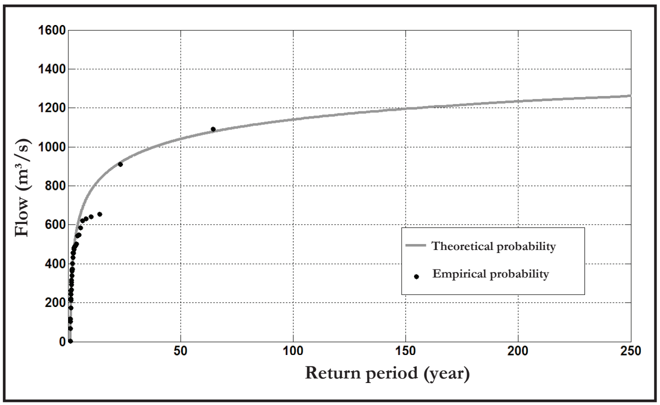

Figure 4 - Estimated flows for different return periods using the GEV distribution at Fazenda Boa Fortuna, Rio Largo (AL)

Hydrological Modeling

Values of goodness-of-fit criteria in calibration and validation periods of the hydrological model are given in Tables 4 and 5 respectively. The model performed best at downstream sites in the basin (397400000, 397600000 and 397700000). The poorest results were in the basin headwaters (397000000 and 397200000). The best fit was obtained at Fazenda Boa Fortuna (397700000), the section used as upstream boundary condition for the hydraulic model. For this site, the fit to the time-series for the year 2000 (a year when flooding occurred) and for the whole series, is shown in Figures 5 e 6 respectively.

After model had been calibrated and validated, maximum flows were estimated for different return periods at the cross-section Fazenda Boa Fortuna for comparison with flows estimated from the GEV distribution (Table 6). Comparison between the two methods shows that their values were similar up to a return period of 200 years (maximum difference 16%), with values estimated from the GEV distribution being greater than flows estimated from the hydrological model. This pattern was reversed at higher return periods. It is emphasized that in this region the uncertainties in the stochastic estimates are greater because they lie in the extrapolated part of the frequency distri-

Table 4 - Values of objective functions for the hydrological model calibration period (NS – Nash-Sutcliffe, NSlog – Nash-Sutcliffe using logs, ΔV – Difference in volume)

Code	Site	NS	NS_{log}	ΔV(%)
397000000	Santana do Mundaú	0.65	0.94	-19
397200000	São José da Laje	-1.55	0.92	118
397400000	União dos Palmares	0.68	1.00	73
397600000	Murici-Ponte	0.76	1.00	20
397700000	Fazenda Boa Fortuna	0.81	0.45	12

Table 5 - Values of objective functions for the hydrological model validation period (NS – Nash-Sutcliffe, NSlog – Nash-Sutcliffe using logs, ΔV – Difference in volume)

Code	Site	NS	NS_{log}	ΔV (%)
397000000	Santana do Mundaú	0.48	0.89	-48
397200000	São José da Laje	-1.73	0.91	96
397400000	União dos Palmares	0.75	1.00	0
397600000	Murici-Ponte	0.87	1.00	-1
397700000	Fazenda Boa Fortuna	0.74	0.47	3

Table 6 - Comparison of flows estimated from the GEV distribution and from the hydrological model.

TR	Flow (GEV) (m³/s)	Flow from model (m³/s)	% difference
2 years	403.9	367.12	9.11
5 years	634.8	537.13	13.38
10 years	773.1	650.24	15.89
25 years	932.7	801.89	14.02
50 years	1041	926.86	10.96
100 years	1141	1066.19	6.56
200 years	1233	1236.78	-0.31
500 years	1345	1593.09	-18.45
1000 years	1422	1864.29	-31.10

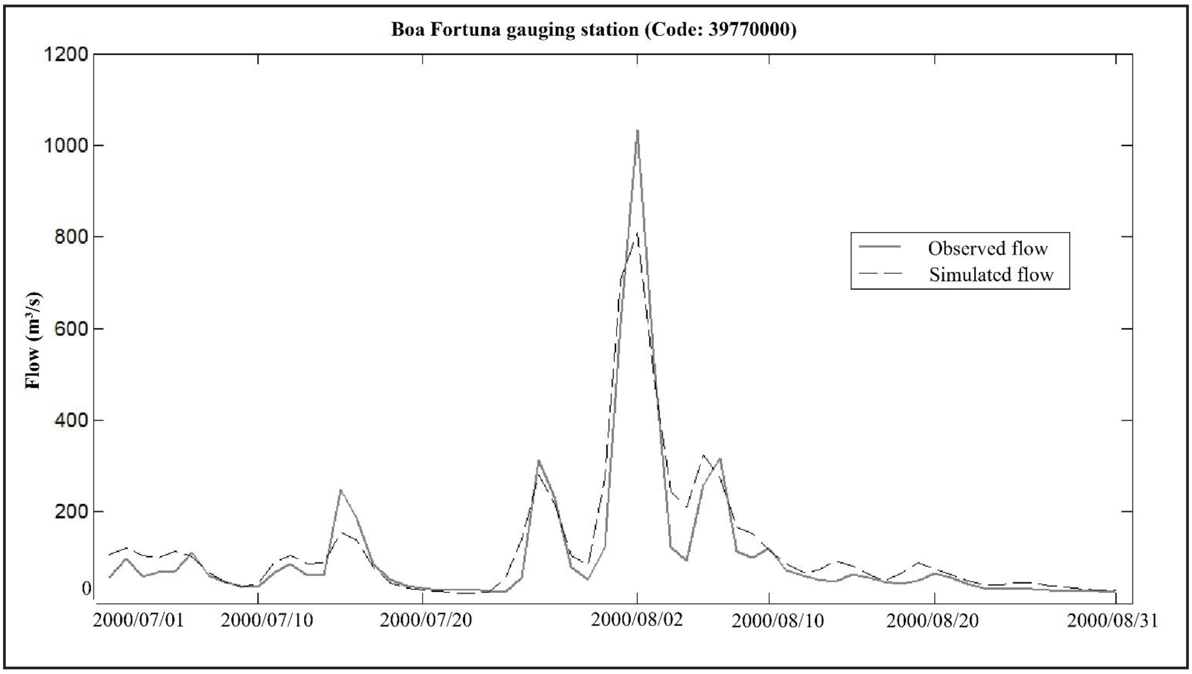

Figure 5 – Comparison of observed and simulated flows for the year 2000, when a flood event occurred

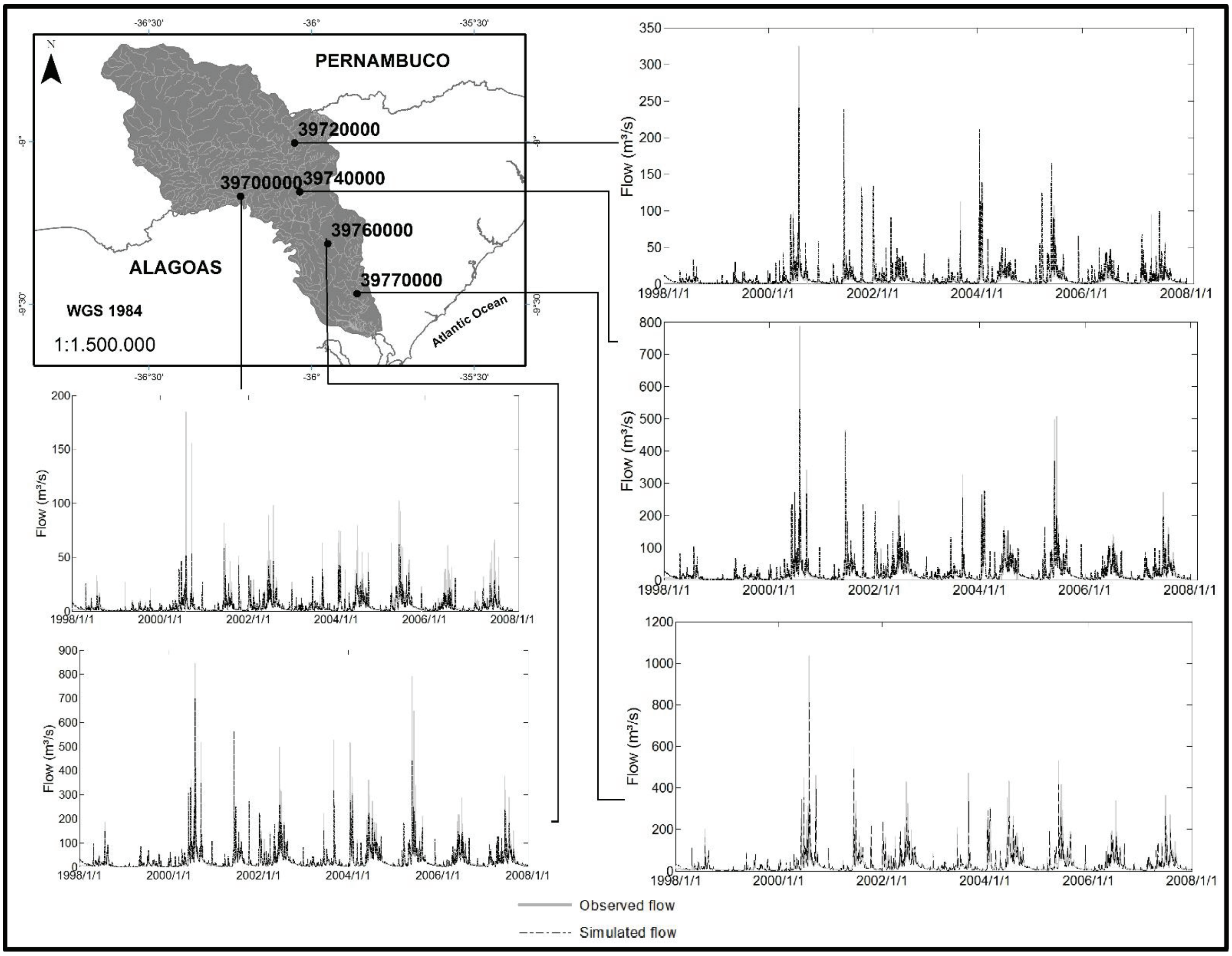

Figure 6 - Comparison between observed and calculated flows at each flow-gauging station

bution, so that estimates derived from physical considerations are to be preferred.

Hydraulic Modelling

The simulated flooded area and the flood marks surveyed in the field for the June 2010 event are shown in Table 7. In general, the hydraulic model performed well ($R^2 = 0.99$, RMSE = 1.41 m and CV (RMSE) = 0.04), as shown by comparison of observed and simulated water-levels. However there were some points of divergence at sites near where the city begins, in the central area and in the lower part (from upstream to downstream). The mean and median differences in location in the horizontal plane between flood marks and simulated flood

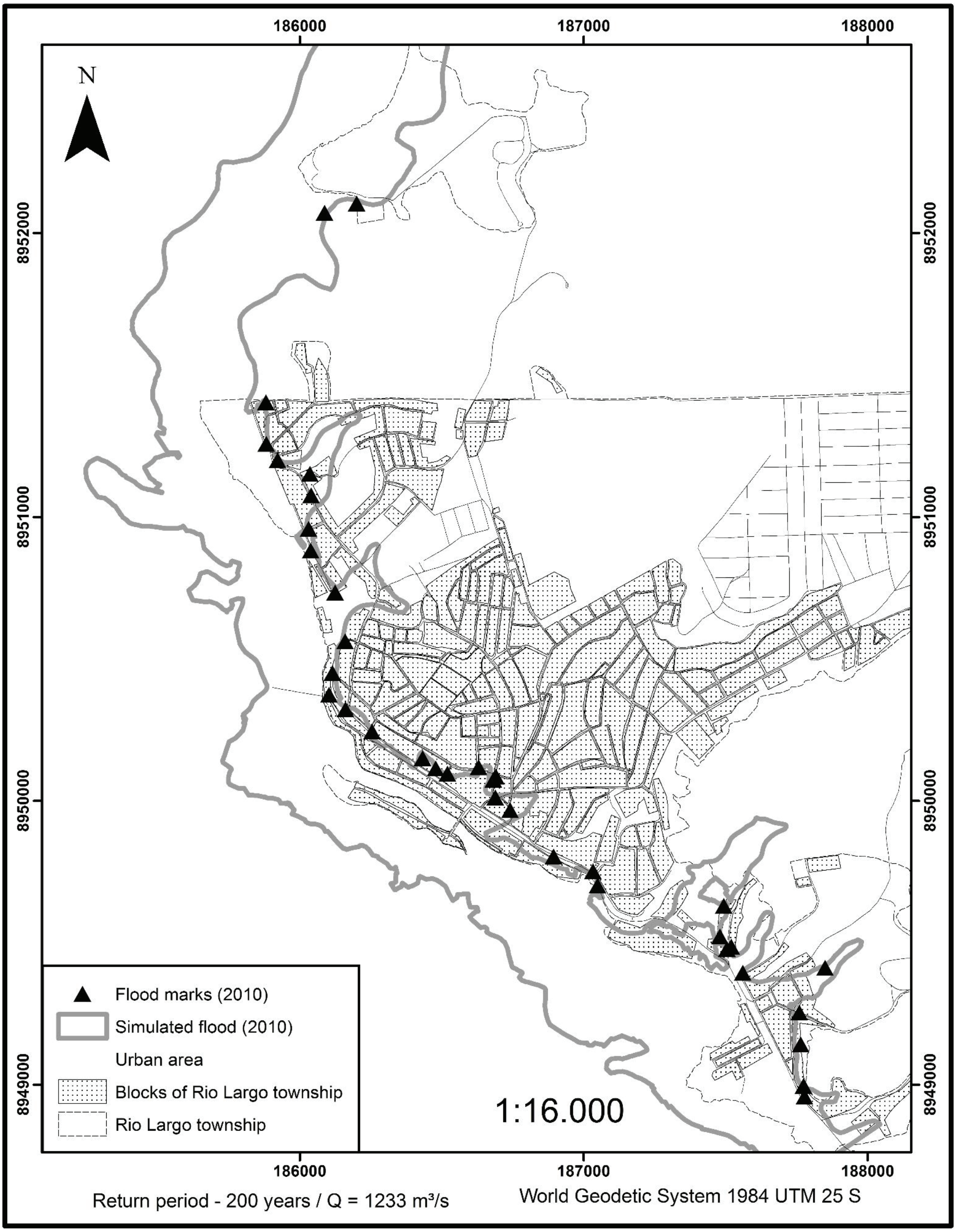

Figure 7 – Comparison of simulated flooded areas with field flood marks: June 2010 flood

Table 7 - Values of the Manning coefficient for the Rio Mundaú reach flowing through the Rio Largo township (sections from upstream to downstream).

Sections	Left bank	Channel	Right bank
Fazenda Boa Fortuna	0.14	0.14	0.14
Bridge	0.17	0.17	0.17
Pre-Barrage	0.17	0.17	0.17
Slope post-	0.15	0.07	0.15
Barrage	0.15	0.07	0.15

area were 1284 m and 9.34 m respectively. The mean and median differences between observed and simulated water-levels were around 1.22 m and 0.93 m, respectively.

Mapping of flood-prone areas

Using the hydraulic model, flooded areas were obtained with flows generated by the hydrological model (Figure 8) and by the GEV distribution. Flows with return periods greater than 50 years gave rise to flooded areas mainly in the middle and lower parts of the reach. These areas are residential, commercial, or are used for the city's public and private services (Table 8).

Differences betwen flooded areas obtained using different types of flow (deterministic or stochastic) were measured by the statistic Fit. Good correspondence is seen (greater than 92%) between flooded areas found when different methods of estimating upstream flow are used (Table 9).

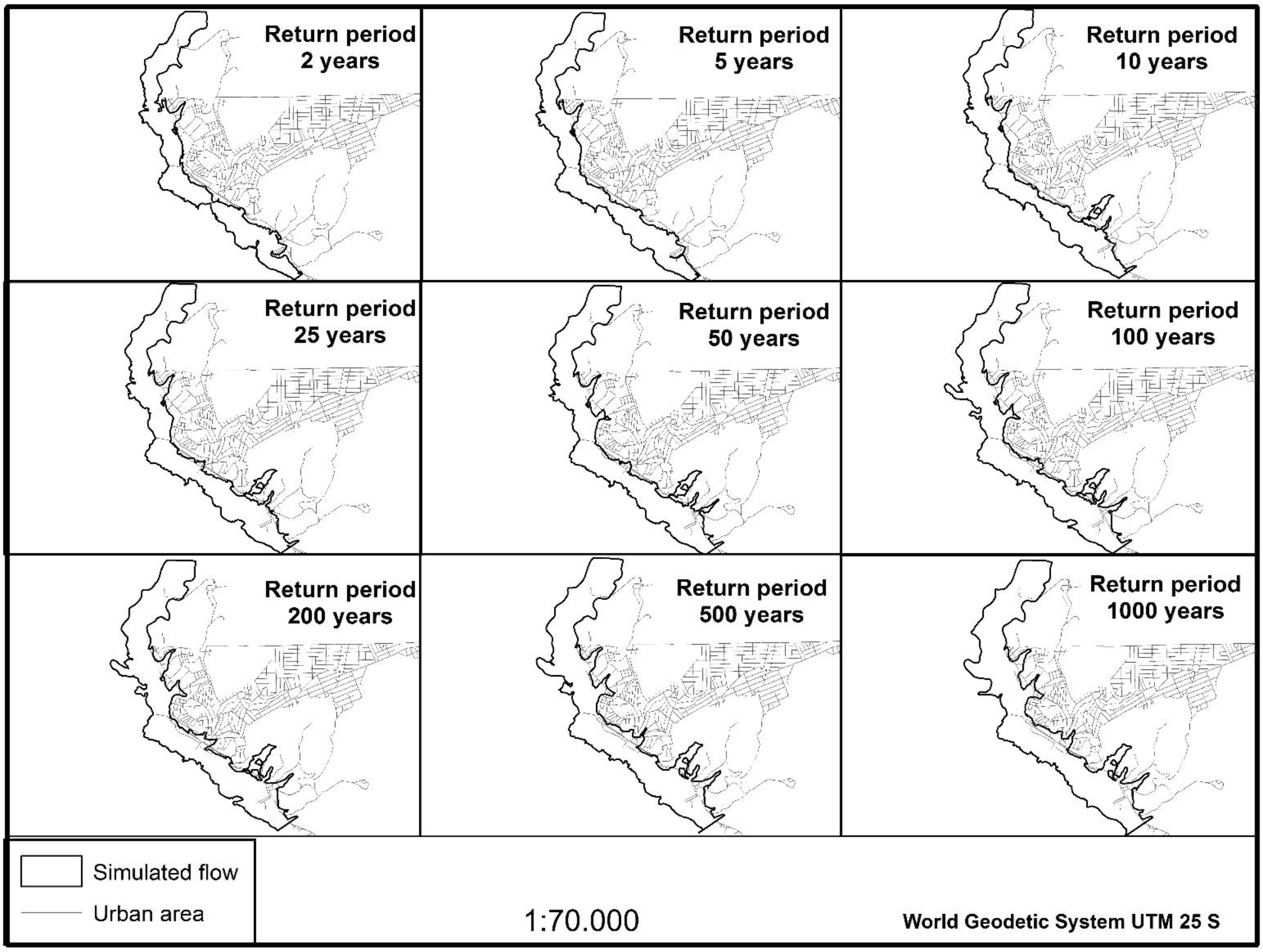

Figure 8 - Mapping of areas susceptible to flooding for different return times estimated through the coupling model Hydrological and Hydraulic

Table 8 - Flooded urban area for different return periods

TR	Flooded urban área (km²)	% Flooded urban area
2 years	0.25	1.42
5 years	0.29	1.65
10 years	0.35	1.99
25 years	0.39	2.21
50 years	0.46	2.61
100 years	0.51	2.89
200 years	0.55	3.12
500 years	0.63	3.58
1000 years	0.65	3.69

Note: urban area of Rio Largo: 18,55 km²

Table 9 - Goodness of fit between flooded areas generated by flows from the GEV distribution, and from the hydrological model

TR	Area, GEV-estimated flow (km²)	Area, flow estimated from model (km²)	Statistic *Fit* (%)
2 years	1.58	1.55	97.57
5 years	1.75	1.69	95.88
10 years	1.88	1.81	95.20
25 years	2.02	1.91	93.35
50 years	2.11	2.01	94.86
100 years	2.19	2.14	96.76
200 years	2.23	2.24	99.46
500 years	2.28	2.41	94.61
1000 years	2.33	2.51	92.19

DISCUSSION

Analyses of Extreme Statistics

The GEV probability distribution fitted to rainfall and flow data was found to be robust and applicable to the region, with good agreement with the empirical distribution shown by goodness-of-fit and non-parametric tests. This is confirmed by other hydrometeorological and hydrological studies that used the GEV for the distribution of maxima (KATZ; PARLANGE; NAVEAU, 2002; NAUMANN; LLANO; VARGAS, 2012; NORBIATO et al., 2007; TRAMBLAY et al., 2012). The Mann-Whitney test did not detect any change in rainfall characteristics. However, it is difficult to identify trends when historic records are short (< 30 years), as in the present study (NAGHETTINI; PINTO, 2007). Estimates of flow obtained by probability distribution also have limitations resulting from the shortness of historic record. For return periods of 500 years or more, estimates of flow given by the GEV distribution differ from flow estimates given by the hydrological model which used maximum design rainfalls as input. A number of studies have shown that estimates generated from probability distributions are of limited reliability when estimated by extrapolation of the frequency curve (KATZ; PARLANGE; NAVEAU, 2002; ROGGER et al., 2012). On the other hand, flows estimated from the model may be over-estimated, particularly for large return periods, when it is recalled that in design conditions the intense rainfall is assumed to fall over the entire drainage basin (GRIMALDI et al., 2013) whilst the relation between return periods for rainfall and for flow was not explored (VIGLIONE; BLÖSCHL, 2009; VIGLIONE; MERZ; BLÖSCHL, 2009). Even so, the areas flooded by different flows were not markedly different, probably as a consequence of the region's topography (the flood-plain is narrow), which does not result in large changes to the flooded area when flows are increased.

Hydrological Modelling

The hydrological model did not simulate flows very well at upstream sites in the basin, probably because areas upstream of such sites were small (the gauging station 397000000 drains an area 762.70 km² with perimeter 74.27 km; the station 397200000 drains an area 1182.86 km² with perimeter 117.87 km), and the hydrological responses to intense rainfall are more rapid at these locations because the geology consists of crystalline rocks overlain by shallow soils, with limited capacity to retain infiltrated water. Furthermore, the upper and middle part of the basin is a climatic transition zone between the semi-arid and tropical litoral. This may explain the unsatisfactory values of objective functions at these gauging stations.

Earlier studies have shown that the MGB model does not simulate mean daily flows well in basins with area less than1500 km² (COLLISCHONN; COLLISCHONN; TUCCI, 2008; COLLISCHONN et al., 2007; PAIVA; COLLISCHONN; BUARQUE, 2013; PAZ et al., 2011; RAJE; KRISHNAN, 2012). However calibration and validation of the hydrological model at Fazenda Boa Fortuna (drained area more than 3.000 km²), above the Rio Largo township, was saisfactory and served the purpose of the present study. At this gauging site, the model did not give a good fit for low flows in the dry season (tending to over-estimate them), since the fitting procedure was concentrated on the period of maximum flows, giving an explanation of the low-flow result (ROGGER et al., 2012). However, giving priority to a period during fitting may have contributed to a reduction in performance measures. Thus the hydrological model should be used with caution in upstream sections of Rio Largo and when modelling low-flow conditions when calibration for an appropriate low-flow period is to be recommended (PAIVA; COLLISCHONN; BUARQUE, 2013).

Regarding the calibrated parameters, b, Wm, kbas were the most sensitive in calibration. The parameter b controlled the shape of hydrograph peaks, giving better fit to flood peaks. The parameter Wm adequately represented the soil characteristics in the middle and lower parts of the basin (soils with greater infiltration capacity). As the parameter Wc is associated with soil saturation capacity, it has an important role in representing flood events that are strongly influenced by large volumes of surface runoff such as, for example, those occurring in the flood of June 2010 (OLIVEIRA; SOUZA; FRAGOSO JÚNIOR, 2014).

Hydraulic Modelling and the Mapping of Flood -Prone Areas.

Despite some limitations, calibration of the hydraulic model was satisfactory for the aims of the study. Although the exact boundary of the area flooded in June 2010 was not known, the field survey of flood marks gave a viable alternative in the absence of more exact information such as, for example, Synthetic Aperture Radar (SAR) images, Airborne Synthetic Aperture Radar (ASAR) (BATES et al., 2006; BATES; DE ROO, 2000; SARHADI; SOLTANI; MODARRES, 2012), or aerial images or field surveys on the day of the event.The calibration resulted in values for the Manning roughness coefficient within the ranges cited by CHOW (1959) and recommended by WARNER et al. (2010), and which were based on approximate values for the stream-bed and its margins. The mean and median differences in the horizontal and vertical, and the statistical results in the vertical, show some discrepancies which can nevertheless be considered reasonable in the light of of the other uncertainties in the study: such as, for example, the age of the topographical maps, the absence of a Digital Surface Model (DSM) to better interpret results in the urbanised area, small errors inherent in map digitization, and the accuracy of GPS for defining points of the 2010 flood. It is also important to note that the section at Fazenda Boa Fortuna was subject to two major changes in its geometry over 10 years, mainly during the floods of 2000 and 2010. Alterations to the hydraulic characteristics of a transverse section when a flood passes modifies flow characteristics in the reach being simulated (DI BALDASSARRE; MONTANARI, 2009). It is recommended that the input data to the hydraulic model be updated whenever a flood passes or when artificial alterations occur (reservoir construction, canalization). The topography of the urban area of the city of Rio Largo was based on topographic maps provided by CASAL and which may give rise to two problems: (a) information could be out of date (the survey was dated 1978) and not representative of topographic changes that have occurred since; and (b) some areas do not have levels, which may give rise to uncertainties in the survey value at some locations. For a better description of flood areas at the building-lot scale, a more detailed information set would need a DSM capable of identifying the tops of constructions and of trees, at spatial resolution not greater than 1 m (for example, a surface generated by LiDAR), together with information on building-lots and a dense network of topographic-bathymetric sections (CASAS et al., 2006). Because of the absence of such refined data, modelling did not represent the flood of 2010 particularly well in some areas at the outskirts and centre of the city; this could result in technical and financial costs if the modelling system were to be used operationally (BORGA et al., 2010). In general, no large differences in flooded area were observed for floods of different return periods, because of steeply sloping land which constrained floods topographically in the reach that was studied. Despite the various limitations of data and the simplifications adopted, such as the small number of topgraphic-bathymetric sections available, the difficulty of integrating topographic maps of the region with the DEM TOPODATA, the limited information available on flood extent and the effect of building-lots (areas with greatly modified runoff) on flood extent, the statistical estimates suggest that the hydraulic model was not greatly in error as a representation of the 2010 flood.

CONCLUSIONS

To apply frequency analysis to records of local daily rainfall as input data to the rainfall-runoff model, it was necessary for the hydrological model's parameterization to be derived from extreme flows. The hydrological model showed that it could represent well the flood events in the city of Rio Largo. Results showed that the model experienced some difficulty when maximum flows were simulated in drainage areas less than 1500 km², even with attempts to improve parameterization through calibration based on maximum flows. Flow from such areas responds rapidly with time of concentration less than a day, and they lie in a region with but one soil horizon and a geology of crystalline rock. Hence, it is recommended that simulations of such areas use a time-interval of one hour, whilst recognizing that the rainfall and flow records required as input data are not always available at an hourly time-scale.

Coupling the models allowed the estimated flooded area to be mapped, thus providing a channel of information for mitigating actions to limit flood damage or to provide flood warnings in circumstances where there is sufficient lead-time for forecasting to be useful (knowledge of future rainfall, or data-collection in real time) and for comparing the extent of flooded zones with their estimated extent, thus reducing possible socio-economic damage. It should also be noted that coupling models can be considered a promising methodology in locations where data sequences are short and/or not long enough for a local frequency analysis, needing at least one event in the calibration period and another in the validation period. Locations in the Rio Largo township where floods recur more frequently include agricultural areas gowing sugar-cane, old residential areas, areas of new construction and the city's main commercial area.

Calibration of the hydraulic model used flood marks from the 2010 event which may neverthless be subject to errors, being in effect no more than a qualitative survey of the location; however they were found to be useful and indeed necessary in the absence of anything better. However, aerial or satellite images are recommended as a better alternative for defining an area under flood. The use of a more detailed DSM would also result in improved maps of urban flooded areas.

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Mahelvson Bazilio Chaves: Acquisition of data, Hydrological Simulation and Hydraulic Simulation.

Cintia B. Uvo: Analysis and interpretation of data, Drafting of manuscript and Critical revision.