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HYDROLOGIC AND HYDRAULIC MODELLING INTEGRATED WITH GIS: A STUDY OF THE ACARAÚ RIVER BASIN – CE

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Abstract: The paper presents a case study integrating hydrologic models, hydraulic models and a geographic information system (GIS) to delineate flooded areas in the medium-sized Acaraú River Basin in Ceará State, Brazil. The computational tools used were HEC-HMS for hydrologic modelling, HEC-RAS for hydraulic modelling and HEC-GeoRAS for the GIS. The results showed that a substantial portion of the riverine populations of the cities of Sobral, Santana do Acaraú and Groairas were affected by floods. Overall, the flood model satisfactorily represents the affected areas and shows the locations with the greatest flooding.

Keywords: urban flooding; flood zones; hydrological modelling

INTRODUCTION

The estimation of flooded areas is important for flood risk management. Inundations are recurrent problems in several densely populated Brazilian cities and frequently result in considerable damage and, sometimes, in loss of life (Suleiman & Barbassa, 2005).

Floods have significantly affected the cities neighbouring the Acaraú riverbed in the northern state of Ceará. From 2000 to 2010, floods intensified and affected larger areas due to the urbanisation of the river flood plain.

Two factors increase the floods in the middle Acaraú Valley: the contribution of large discharges generated by intense rainfall in the Ibiapaba Mountains and the roughly circular shape of the tributary basin, which increases the potential for flood formation.

The problem is more serious in large cities, such as Sobral and Groaíras, near the confluence of the Groaíras, Jacurutu, Macacos, Jaibaras, and Acaraú Rivers (**Fig. 1**). In these areas, the Acaraú River becomes narrower, with a lower hydraulic capacity; thus, the inundation potential in nearby urban areas increases.

Further, vegetation cover removal reduces the infiltration capacity and substantially increases the basin runoff coefficient, and riverbed sedimentation reduces the river hydraulic capacity. The combination of these two factors accelerates the water transport to the main course of the canal, causing flooding at several points where there are section bottlenecks or bed obstructions (Oliveira & Guasseli, 2011).

Flood warning systems are used by society to reduce the impacts of major floods. These systems are a combination of meteorological, hydrological and hydraulic models. Therefore, the modelling and simulation of these events, which occur in natural or artificial drainage channels, and assessing their interaction with adjacent plains are considered highly important for urban planning (Ribeiro & Lima, 2011).

According to Oliveira & Guasseli (2011), mapping of areas susceptible to flooding is a very important resource for understanding flood events and assists in making decisions to mitigate associated impacts. With the high storage capacity of computers and facilities to analyse and cross-reference information, geoprocessing emerges as a dynamic tool capable of adding precision to mapping and spatial analysis. The use of this tool enables the implementation of a geographic information system (GIS), which includes a set of digital databases and databanks that can be manipulated to promote spatial analysis according to the user goals.

Several authors (Abushandi & Merkel, 2013; Gichamo *et al.*, 2012; Ali *et al.*, 2012; Martin *et al.*, 2012; Oliveira & Guasselli, 2011; Oliveira *et al.*, 2010; Ribeiro & Lima, 2011, Wahid *et al.*, 2009) used hydrological and hydraulic models and GIS for determining flooding locations in urban rivers and canals to facilitate actions by government agencies to reduce the losses of riverine populations.

This article aims to examine the wetlands in the Middle Acaraú that are fed by centennial occurrence of rain using hydrologic and hydraulic modelling nested within GIS. The resulting maps can help formulate plans for flood prevention by the state government and civil defence.

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DESCRIPTION OF THE AREA

The Acaraú Basin is located in the northwestern region of the state of Ceará (**Fig. 1**) at 40° 54′ and 39° 44′ West and 2° 49′ and 4° 59′ South. The basin has an area of 14 423.00 km² and comprises 11 entire districts and parts of 17 municipalities.

The Acaraú River has a declivity of approximately 960 m along a 320 km length. The basin has high compactness index (1.85) and low form factor (0.15). The drainage has a dendritic pattern in the upper and middle river courses. **Figure 2** shows the hypsometric curve of the Acaraú Basin.

The average annual rainfall ranges from 500 to 1300 mm, with a well-defined rainy season between February and May. This rainy period is a result of the southern-most position of the intertropical convergence zone (ITCZ) and squall lines.

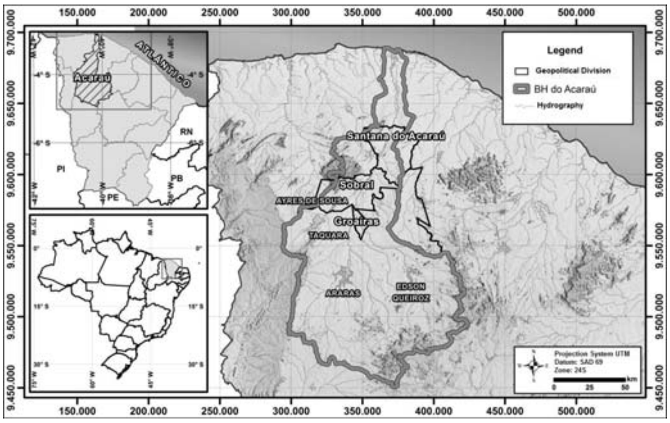


Fig. 1 Location of the Acaraú River Basin.

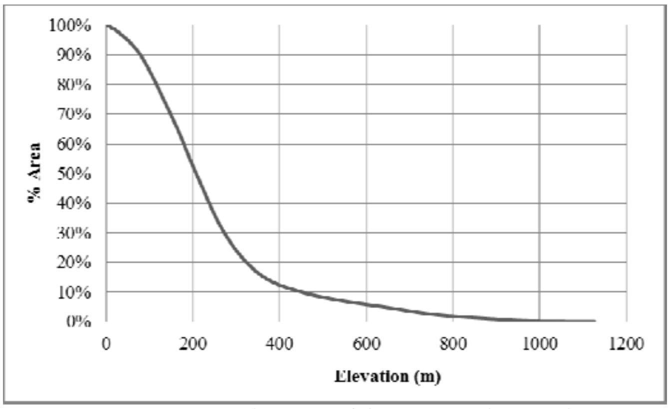


Fig. 2 Hypsometric curve of the Acaraú River Basin.

Table 1. Characteristics of the rainfall stations used in the study

Code	Begin	End	Station	Municipal	Latitude	Longitude
2	1974	2013	Acaraú	Acaraú	-2,88	-40,12
24	1981	2013	Bela cruz	Bela Cruz	-3,05	-40,17
32	1974	2013	Cariré	Cariré	-3,95	-40,47
44	1989	2013	Cruz	Cruz	-2,93	-40,18
46	1980	2013	Forquilha	Forquilha	-3,80	-40,25
52	1981	2013	Groairas	Groairas	-3,92	-40,38
55	1979	2013	Hidrolândia	Hidrolândia	-4,42	-40,40
62	1974	2013	Ipu	Ipu	-4,32	-40,70
63	1974	2013	Ipueiras	Ipueiras	-4,53	-40,72
84	1980	2013	Marco	Marco	-3,15	-40,15
86	1974	2013	Massapê	Massapê	-3,53	-40,33
88	1979	2013	Meruoca	Meruoca	-3,55	-40,45
96	1984	2013	Morrinhos	Morrinhos	-3,23	-40,12
97	1974	2013	Mucambo	Mucambo	-3,90	-40,77
100	1974	2013	Nova russas	Nova Russas	-4,72	-40,57
106	1981	2013	Pacujá	Pacujá	-3,98	-40,70
126	1974	2013	Reriutaba	Reriutaba	-4,15	-40,58
129	1974	2013	Santa Quitéria	Santa Quitéria	-4,33	-40,15
130	1974	2013	Santana do Acaraú	Santana do Acaraú	-3,47	-40,20
138	1974	2013	Sobral	Sobral	-3,70	-40,35
141	1979	2013	Tamboril	Tamboril	-4,83	-40,33
150	1988	2013	Varjota	Varjota	-4,18	-40,48
252	1989	2013	Pires Ferreira	Pires Ferreira	-4,25	-40,65
276	1974	2013	Amanaiara	Reriutaba	-4,05	-40,52
277	1983	2013	Graça	Graça	-4,05	-40,75
287	1988	2013	Catunda	Catunda	-4,67	-40,20

DATA AND METHODS

Rainfall data

The rainfall data used in this study were obtained from the database of the Ceará Foundation of Meteorology and Water Management (FUNCEME) at http://www.funceme.br. Twenty-seven series of maximum daily rainfall, with durations ranging from 21 to 36 years, were used (**Table 1**).

To calculate the average rainfall in the sub-basins, we used the Thiessen polygon method, which consists of a weighted average of the areas of influence of the rainfall stations, according to **Eq. 1**.

$$\overline{P} = \frac{\sum P_i . A_i}{A} \quad (1)$$

where P_i is the precipitation at position ***i***, A_i denotes the area of influence of the station ***i*** and A refers to the total area of the sub-basin.

The mean values of the annual maximum precipitation were used, with a return time of 100 years, for each sub-basin studied.

Hydrological modelling: Hydrologic Modelling System (HMS)

The *Hydrologic Engineering Center - Hydrologic Modeling System* (*HEC-HMS*) software developed by the Hydrologic Engineering Center of the Army Corps of Engineers, United States of America, was used to estimate the flows generated by the centenary rain.

The contribution areas were calculated using the cartographic base of the Company of Management of Water Resources (COGERH) of Ceará and data from the *Shuttle Radar Topography Mission* (SRTM) to extrapolate the basin topography; the ArcGIS 9.3 3D Analyst extension was used for this purpose.

Hyetograms were constructed using the alternating blocks method, and the data were added to the HMS by the “Specified Hyetograph” option with rainfall data from the user (Campos, 2009). To determine the effective rainfall and hydrological process *Loss*, we applied the method of the curve number (CN) developed by the *Natural Resources Conservation Service* (NRCS) of the United States. The SCS-CN method accounts for most of the characteristics of the basins to produce flow, such as soil type, land use, hydrologic conditions, and antecedent moisture (Mishra & Singh, 2004). **Equation 2** is applied:

$$P_e = \frac{(P - I_a)^2}{P - I_a + S} \text{ for } P > I_a\text{; otherwise, it is 0} \quad (2)$$

where P_e is the effective rainfall, P is the total precipitation, I_a is the initial abstraction and S is the maximum potential for soil retention.

To estimate S, the NRCS recommendation of I_a = 0.2S was adopted. Thus, **Eq. 2** can be rewritten in the form of **Eq. 3**:

$$P_e = \frac{(P - 0.2S)^2}{P + 0.8S} \quad (3)$$

where the S parameter is given by the curve number (CN) table as:

$$S = \frac{(1000)}{CN} - 10 \quad (4)$$

The CN parameter is a function of the type of soil, land use and soil antecedent moisture. For the study area, we adopted soil type B for all basins. To estimate the CN, we used aerial images of the main urban centres combined with images from Google Earth for the rest of the basin. Notably, the CN value was estimated from the table values as determined by the NRCS (1975) according to the soil type of the study area.

For the *Transform* process that generates the flow hydrograph from the rain hyetogram, the NRCS's dimensionless unit hydrograph method was applied. The method is based on measuring the time delay (T_{lag}). The T_{lag} value is obtained by **Eq. 5**.

$$T_{lag} = 0.6T_c \quad (5)$$

where T_c denotes the concentration time. In turn, T_c is estimated by Kirpich (**Eq. 6**):

$$T_c = 0.0078x\left(\frac{L^{0.77}}{S^{0.385}}\right) \quad (6)$$

where *L* is the river length in metres and *S* is the river slope as a percentage.

The basin model design in the HMS

The Acaraú Basin was divided into four sub-basins: Goairas, Jaibaras, low Acaraú and middle Acaraú, as shown in **Fig. 3**. In the study area, there are two uncontrolled sub-basins (highlighted in **Fig. 3**), and one sub-basin is controlled by a reservoir.

Table 2 shows physical and hydraulic parameters of the sub-basins, such as area, CN value, river length, lag time, time of concentration and average slope of the river. The *S* value was obtained from the hypsometric curve by dividing the difference between the maximum elevation of the watercourse and its elevation in the control section by the river length. The river length (*L*) was obtained by measuring the horizontal distance of the drainage from the source to the control sections

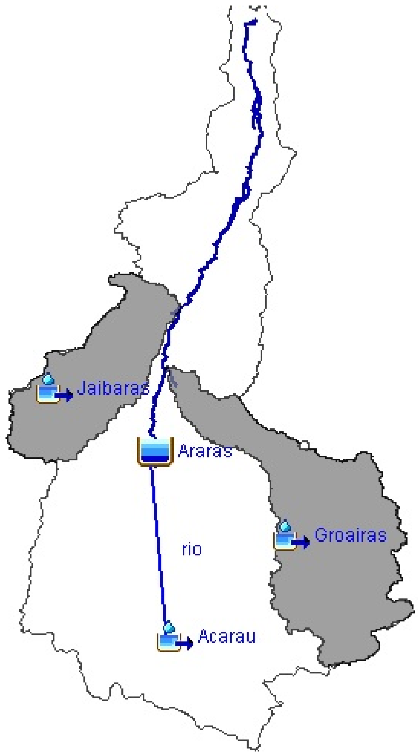


Fig. 3 HEC-HMS program layout.

Table 2. Physical and hydraulic information of the sub-basins.

Sub-basin	Area (km²)	CN	L (m)	Lag Time	Tc (min)	S (m/m)
Jaibaras	1582	80.11	4300	82.29	137	0.0016
Groairas	2816	82.61	5500	263.89	439	0.0011
Acaraú	3128	84.55	4678	370.26	618	0.0004

Hydraulic Modelling and GIS

For the flooding simulation in the study area, the *Hydrologic Engineering Center's River Analysis System* (HEC-RAS) software, which was developed by the U.S. Army Corps of Engineers, was used.

The maximum flow rates that were achieved by the hydrological model, as well as the hydraulic elements (drainage network, cross sections and gutter limits) were added as input data in the HEC-RAS model.

Because it is a zoning study, the system of permanent disposal was adopted. The value of the Manning roughness coefficient (**n**) was selected using satellite images and a field study. For the flow in the river channel, we used the initial value of **n** = 0.40. For the runoff in the flood plain, **n** = 0.45 was used on both banks.

After calculating the water surface profiles, the results were converted to a GIS format. The water levels in each section were superimposed on a SRTM to estimate the heights of the floods and inundation areas.

Fig. 4 RAS screen with the locations of the cross sections along the Acaraú River.

The cross sections along the river were three kilometres outside the urban area and one kilometre along the urban area. **Figure 4** shows the RAS screen with the Acaraú River sections.

RESULTS AND DISCUSSION

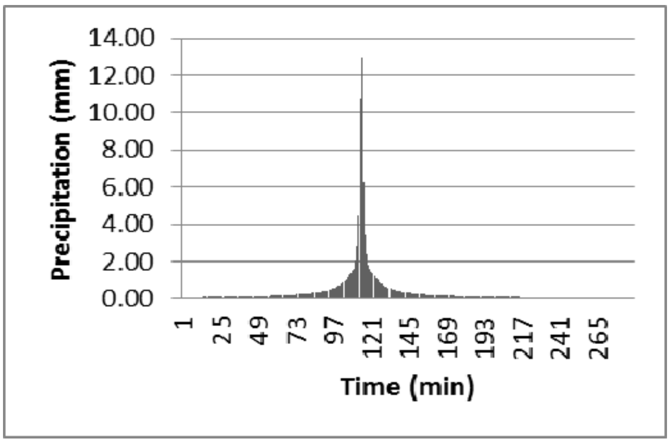
The rain project

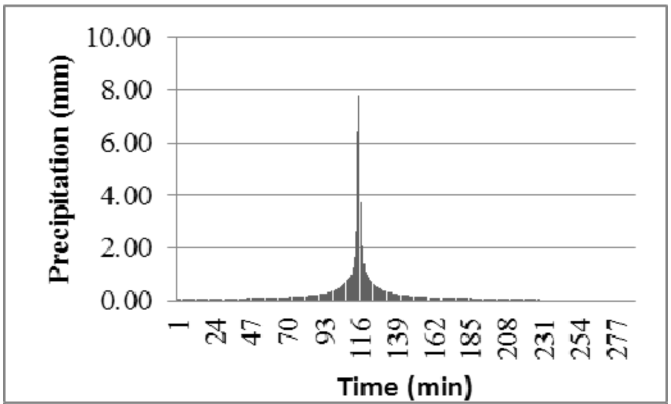
Based on the statistical analysis of the rainfall stations within the Acaraú Basin and testing the functions of the probability distributions and compliance tests, the maximum rainfall was 166.1 mm in the Jaibaras sub-basin, 129.5 mm in Groaíras sub-basin and 160 mm in the Acaraú sub-basin with a return period of 100 years, as shown in **Table 3**.

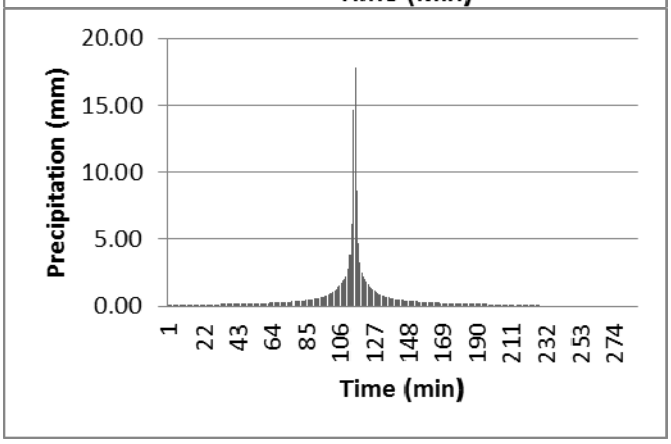
Figures 4a, **4b** and **4c** show the hyetograms of the sub-basins of Jaibaras, Groaíras and Acaraú, respectively. It is noted that the hyetograms of the sub-basins are directly related to their T_c values and are dependent on the river basin area.

Table 3. Daily maximum precipitation with a return time of 100 years.

Sub-basin	Jaibaras	Groairas	Acaraú
$P_{Tr\ 100\ (years)}$ (mm)	166.1	129.5	160







The Jaibaras sub-basin presents a hyetogram with a peak intensity of approximately 18 mm/min at a maximum annual rainfall at T_r = 100 years, while the Groairas sub-basin has a hyetogram with a peak intensity of approximately 13 mm/min at a maximum annual rainfall at T_r = 100 years.

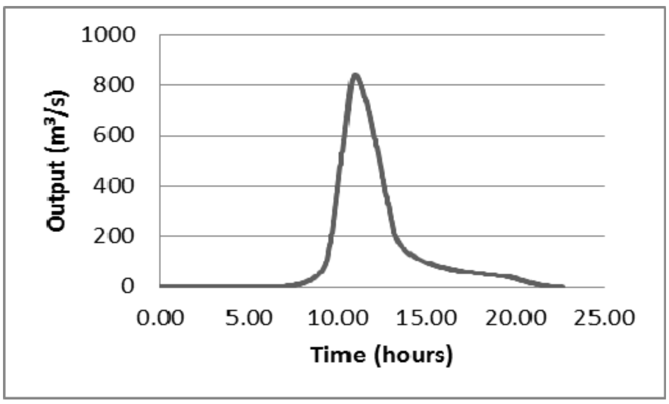
The flooding project

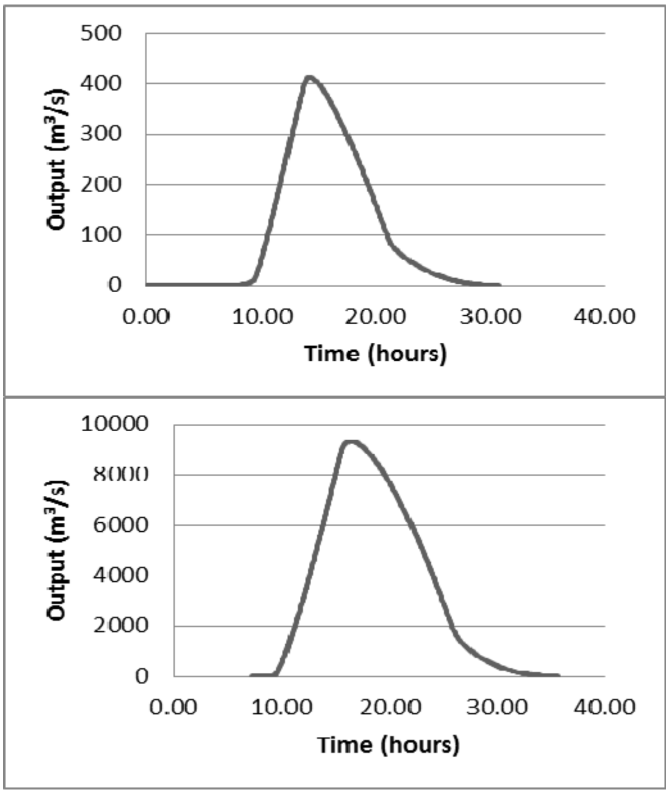
Table 4 presents the values of the peak flows obtained by the HEC-HMS program for the sub-basins.

Table 4. Flows for rains with a return time of 100 years.

Sub-basins	Jaibaras	Groairas	Acaraú
$Q_{(peak)}$ (m³/s)	830.6	421.5	902.7

Figures 5a, **5b** and **5c** show the hyetograms resulting from the peak flows as generated by the centenary rain of the sub-basins.





The results show that the hydrograph design depends on several variables, such as precipitation, use and soil type, soil infiltration capacity, and the response time of the watershed to the same rainfall input, among others.

The flood areas

Table 5 shows the relationship between the areas of the studied cities (total and urban) and the percentage of urban areas affected by flooding due to centennial rains in the Acaraú River Basin, Ceará.

All of the analysed municipalities are affected by urban flooding. Sobral and Santana do Acaraú are the most affected: approximately 39% and 79%, respectively, of their urban areas are affected by Acaraú River floods.

Table 5. Relationship between the urban area and the percentage of flooded urban areas.

Cities	Total Area (km²)	Urban Area (km²)	Flooded Area (km²)	Flooded Urban Area (%)
Sobral	2184.32	12.36	4.8	38.9
Groairas	128.78	1.35	0.5	30
Santana do Acaraú	968.74	1.14	0.9	78.9

Figure 6 shows the spatial distribution of the flooded area in Sobral for a precipitation of return time of 100 years and a flow of 1600 m³/s. The map also shows that most of the flooded areas are located along the left bank of the main river as a result of the unplanned urbanisation processes in the municipality.

The most affected areas are riparian. The flood extent of these areas is approximately five km² at an approximate distance of 500 m from the Acaraú River to an elevation of 51 m.

Generally, upstream from the stations, there is a large flood area that is possibly associated with the water impoundment. Nearly the entire length of the flooded area is concentrated near the main stream due to the basin's steep topography and overflow tendency.

From the flood map of Sobral, it is possible to verify that the simulated levels were well represented in areas on the margins of the Acaraú River. These areas are the most flood prone and are characterised by a very high degree of risk.

Figure 7 shows the flooded areas of the municipality of Groaíras; this municipality has the most pristine riverine areas and a high percentage of vegetation on its riverbanks, which minimises the effects on the population. Although the urban areas are relatively less affected by the simulated floods, these areas are the most vulnerable due to social and economic factors. Thus, some places where residences and urban structures reach 81 m are considered critical for flood occurrence.

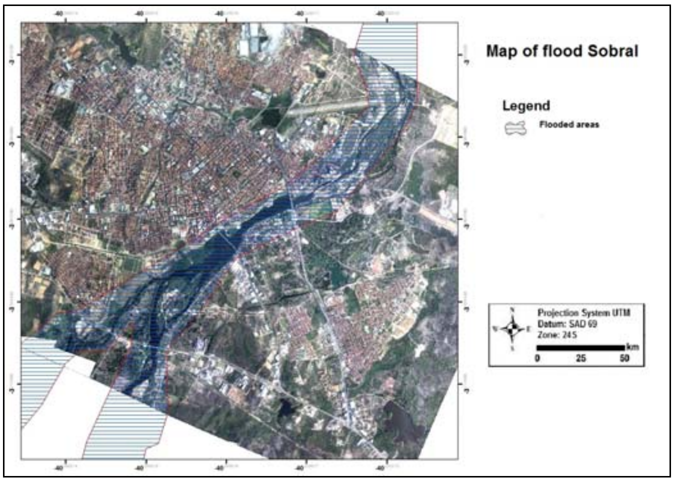


Fig. 6 Flooded areas in the city of Sobral.

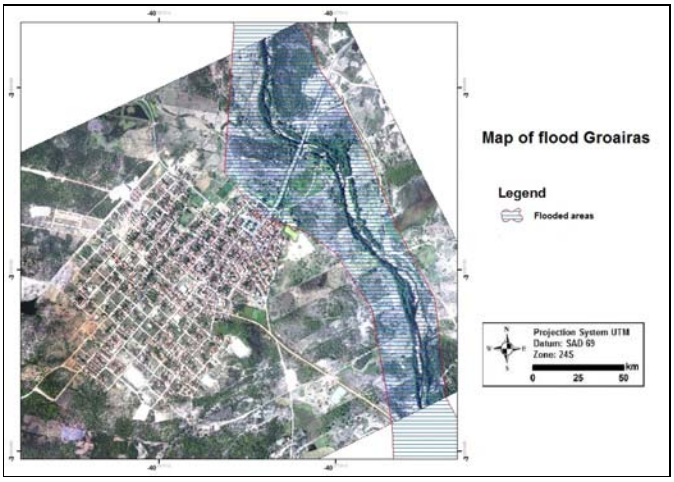


Fig. 7 Flooded areas in the city of Groaíras.

Figure 8 shows the spatial distribution of flooding at T_r = 100 years in the municipality of Santana do Acaraú; a large urban area is affected by flooding, up to 43.5 m.

The predominant disorderly use of riparian areas leaves all of the cities vulnerable to flooding throughout the basin.

Another flood-conducive factor is the lack of vegetated areas along the Acaraú River. The lack of riparian vegetation, as well as soil sealing due to unplanned urbanisation of the municipalities, increases the peak flow across most of the basin.

Notably, the study area lacks reservoirs with the capacity to handle the expected flood volume. The expected reservoir volume is intended to dampen flood peaks and reduce downstream impacts of these events; thus, continuous monitoring during the rainy season is necessary for flood warnings in Acaraú Valley.

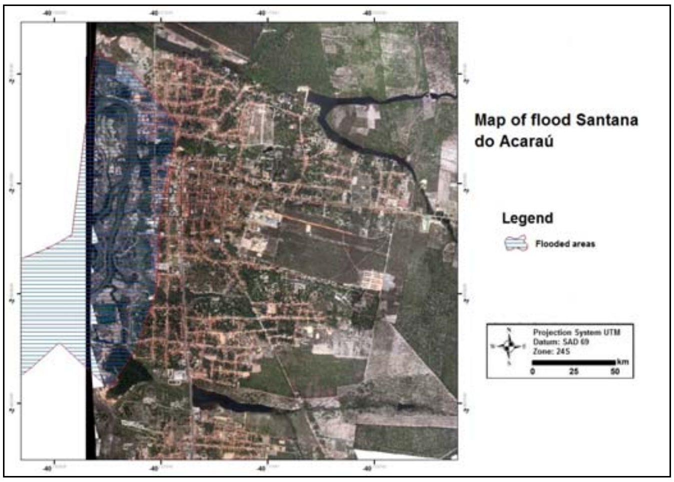


Fig. 8 Flooded areas of the municipality of Santana do Acaraú.

CONCLUSIONS

The integration of hydrologic and hydraulic modelling and GIS showed that it is possible to develop a reliable flood assessment in urban basins based on digital data, satellite imagery and a good network of field observations. The hydraulic model satisfactorily represented the flood areas using 100-year rains in the middle Acaraú municipalities, and it could be a promising tool to support urban planning and to warn and protect the city against floods.

The hydraulic model calibration was successful when relating the Manning coefficient and flood extents in urban centres. The calibration is a reliable method to check for other flood events.

The results highlighted the vulnerability of the study area, especially heavily urbanised areas, to the occurrence of floods, which represent a serious risk to the safety of the population and infrastructure.

REFERENCES

Abushandi, E. & Merkel, B. (2013) Modelling rainfall runoff relations using HEC-HMS and IHACRES for a single rain event in an arid region of Jordan. *Water Resour. Management* **27**(7), 2391–2409. doi: 10.1007/s11269-013-0293-4.

Ali, H., Lee Teang, S., Majid, M. & Hadi, M. (2012) Incorporation of GIS based program into hydraulic model for water level modeling on river basin. *J. Water Resour. Protect.* **4**(1), 25–31. doi:10.4236/jwarp.2012.41004.

Campos, J.B. (2009) *Lições em Modelos e Simulação Hidrológica*. ASTEF/EXPRESSÃO GRÁFICA, Fortaleza, Brasil.

Gichamo, T.Z., Popescu, I., Jonoski, A. & Solomatine, D. (2012) River cross-section extraction from the ASTER global DEM for flood modeling. *Environ. Modell. Softw.* **31**(5), 37–46. doi: 10.1016/j.envsoft.2011.12.003.

Martin, O., Rugumayo, A. & Ovcharovichova, J. (2012) Application of HEC HMS/RAS and GIS tools in flood modeling: a case study for River Sironko – Uganda. *Global J. Eng. Design Technol.* **1**(2), 19–31.

Mishra, S.K. & Singh, V.P. (2004) Long-term hydrological simulation based on the Soil Conservation Service curve number. *J. Hydrol. Process.* **18**(7), 1291–1313.

Oliveira, G.G. & Guasselli, L.A. (2011) Relação entre a suscetibilidade a inundações e a falta de capacidade nos condutos da sub-bacia do arroio da areia, em Porto Alegre/RS. *Rev. Bras. Recur. Hídr.* **16**(1), 5–15.

Oliveira, G.G., Saldanha, D.L. & Guassellil, A. (2010) Espacialização e análise das inundações na bacia hidrográfica do rio caí/rs. *Geociências* **29**(3), 413–427.

Ribeiro, C.B.M. & Lima, R.N.S. (2011) Simulação de inundações urbanas a partir da integração de técnicas de geoprocessamento à modelagem hidráulica e hidrológica. *Rev. Geogr.* **2**(1), 1–9.

Suleiman, H.C. & Ademir Paceli Barbassa.A.P. (2005) Mapeamento preliminar de áreas urbanas de inundação. *Ciência & Engenharia* **15**(2), 51–58.

Wahid, A.M., Madden. M.M., Khalaf. F., Fathy. I. (2009) Land suitability scenarios for arid coastal plains using GIS modeling: southwestern sinai coastal plain, Egypt. *J. Urb. Environ. Engng*, **3**(2), 1−8. doi: 10.4090/juee.2009.v3n2.073083