Flooding Susceptibility Identification Using the HAND Algorithm Tool Supported by Land Use/Land Cover Data

José Augusto de Lollo, Alice N. Marteli, and Reinaldo Lorandi

Abstract

In Brazilian urban areas, the increases in human activities and extreme climatic event frequencies have resulted in an increase in floods and flooding. Despite Brazilian laws, risk analyses and management are still rare in Brazilian towns due to poor financial and human resources. Hydrological dynamic surveying coupled with land use information can result in quick and low-cost predictions of flood risks, allowing for the identification of critical areas and the design of intervention proposals. In this paper, this methodology is applied to the Caçula stream watershed using the HAND algorithm combined with land use/cover surveys to identify flood and flooding susceptibility. Imagery classification was developed in IDRISI Selva using OLI sensor bands from the Landsat 8 mission with a supervised classification. The HAND calculations resulted in a DEM for the surface flow analysis, including flooding, based on a normalized 3D model. The adopted method provides an understanding of surface process dynamics and the delineation of critical areas and their hierarchy. The results indicate a strong relationship between flooding susceptibility and land changes in the Caçula watershed.

Keywords

Natural hazards • Urban planning • Watershed

1 Introduction

Areas close to rivers are conducive for human settlement, motivating their habitation. Due to human activities, the hydrological cycle has altered, which has increased runoff and reduced water infiltration and groundwater recharge (Tucci and Orsini 2005).

Floods and flooding expose the fragility of the manmade hydrological system, where small local changes can lead to big changes (Montenegro and Tucci 2005). Several Brazilian cities have experienced a large increase in the number of events, which has resulted in material losses and, above all, human death (Carvalho et al. 2007). According to the National Risk and Disaster Management Center, in Brazil in 2012, 376 natural disasters were recorded, involving 3781 municipalities. In the same year, floods and flooding affected 5,492,618 people (CENAD 2013).

Current challenges for cities related to floods, flooding, erosions and landslides during heavy rainfall periods are mainly consequences of past decisions without proper planning (Silva et al. 2014).

Thus, studies that consider the identification and spatial analysis of geodynamic processes related to land changes have increased by organizations that perform urban planning and environmental management in watersheds and municipalities. Considering this context and the lack of relevant information in small Brazilian municipalities, we verified the response of floods and flooding potential to natural conditions and their relationship with human activities in the area.

2 Study Area

Ilha Solteira is located in the extreme northwest of São Paulo (Fig. 1) on the border of Mato Grosso do Sul between meridians 51º00′ and 51º30′W and parallels 20º15′ and 20º45′S, with an area of 652.45 km^2 (IBGE 2014).

The local terrain is comprised of rounded/slightly rounded hill that are medium to large in size, with gradual slopes and wide valleys. Fine sandy soils are prevalent, and the regional climate is tropical, with rainy summers and dry and mild winters. The original semi-deciduous forest vegetation has been almost completely eliminated by human activities.

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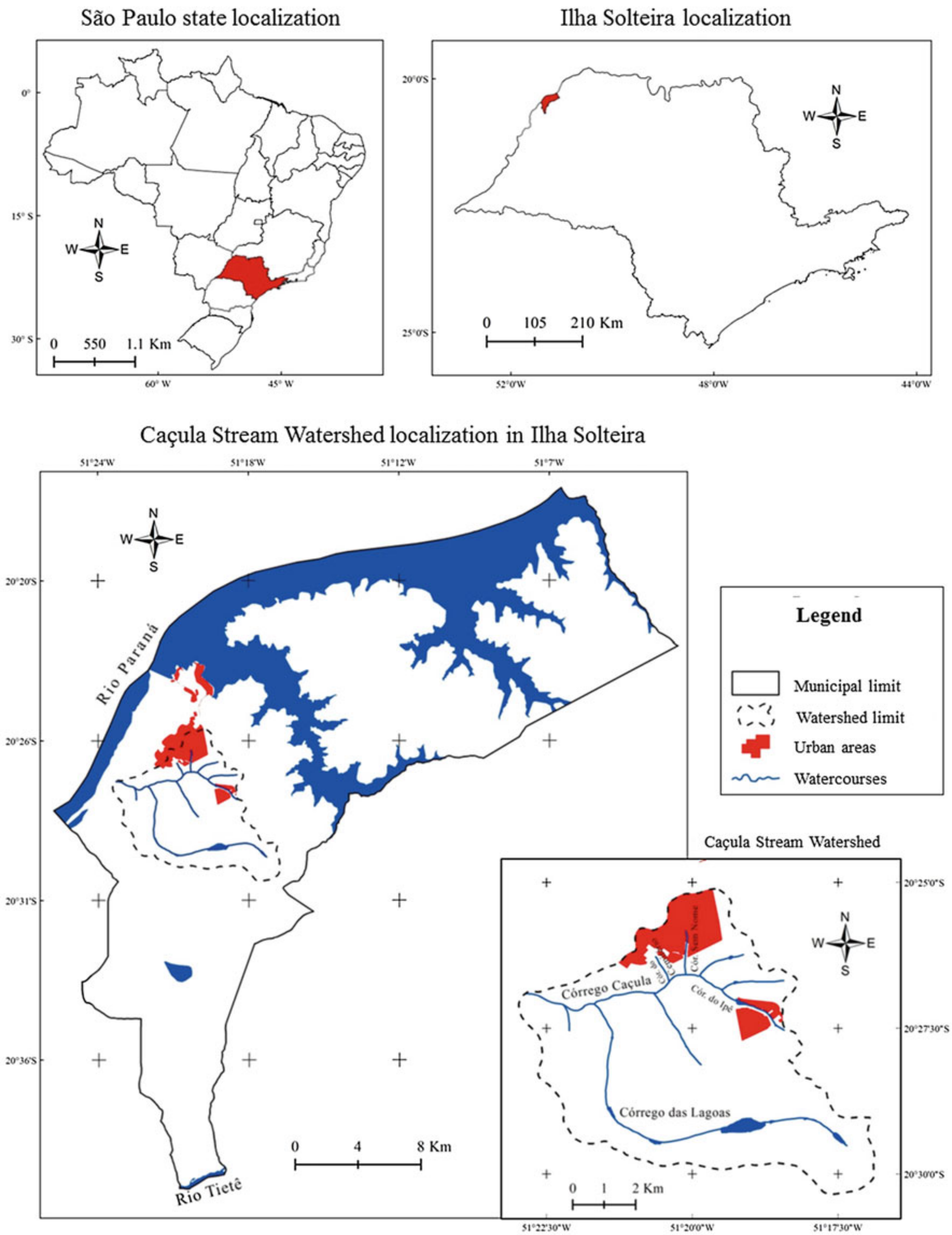

Fig. 1 Caçula stream watershed localization

Even as a planned city, Ilha Solteira exhibits reoccurring floods and flooding events, most of which occur in the Caçula watershed (Marteli 2015). During intense precipitation events, there are serious impacts on many buildings and the urban infrastructure, and the reactivation of former erosive processes also occurs.

3 Data Survey

Data and information surveys were conducted using land use/cover classifications and application of the HAND (Height Above the Nearest Drainage) module. The land use/cover classification was developed in IDRISI Selva (Eastman E2012) using Landsat 8 imagery, which is available on the USGS website (USGS 2015).

HAND is an algorithm developed by INPE (National Institute for Space Research) (INPE 2013). According to Rennó et al. (2008), it calculates the altitude of each point related to the following drainage outlet using SRTM (Shuttle Radar Topographic Mission) data.

HAND results in a DEM (digital elevation model), which facilitates a hydrological analysis from the normalized topographic data (Nobre et al. 2011) and provides predictions of water levels in soil profiles (Rodrigues et al. 2013). The sequence of procedures used for the HAND calculation and analysis in this paper are summarized in Fig. 2.

For HAND processing, SRTM elevation data with a 1 arc-second (~30 m) horizontal resolution were used, with a latitude/longitude projection and datum of WGS84 (USGS 2015). From the SRTM elevation data, a DEM was created using TerraView Hydro software (http://www.dpi.inpe.br/terraview).

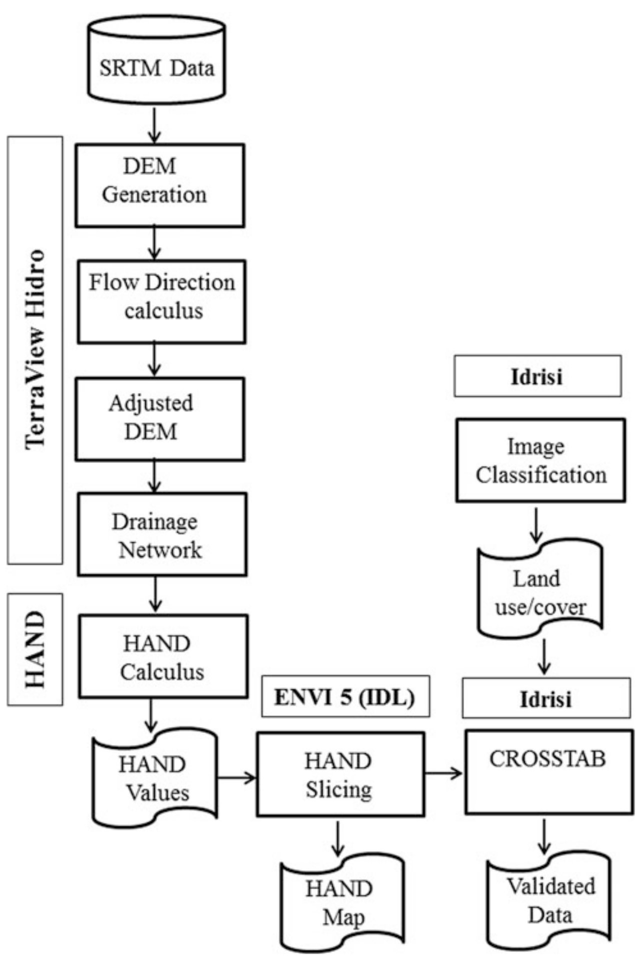

Fig. 2 Procedures used for the HAND calculation and the interpretation of results

From this DEM, TerraView allows us to calculate the flow direction for each point on the grid. The flow direction was defined as the maximum steepness value among eight neighboring points.

Because the flow direction grid can present sinks (i.e., discontinuities), the next step is to provide grid adjustments in order to fill these depressions and summits. From the adjusted grid for flow direction, it is possible to obtain flow accumulation grid values, which provide a drainage network based on the local base level.

After these tests, we observe that a HAND threshold of 2300 calculation interactions provides a better agreement between the HAND drainage network and the local drainage network depicted in the official maps. Therefore, we used this threshold to obtain the drainage network.

From this set of data, HAND calculates the values of relative elevation by considering flow directions and drainage network connections, which results in HAND values.

Therefore, the elevation values are good indicators of flooding susceptibility at each point (Nobre et al. 2011), which can be used to select scenarios for territorial planning in areas prone to flooding (Rodrigues, G.O., Nobre, A.D., Silveira, A.C., Cuartas, L.A.: Effects of SRTM data spatial resolution in terrain description in HAND (height above the nearest drainage)—case study in Manaus/AM. In: Remote sensing brazilian symposium on electronic annals, pp. 5568–5575, INPE, Foz do Iguaçu 2013).

The resulting HAND grid image was so processed with ENVI 5 in IDL (the Interactive Data Language, which is the original language of HAND), where class slicing was performed, and three classes of flooding potential were obtained.

For land use/cover classification, we used the R5G4B3 composition from OLI sensor bands (Landsat 8). Land use was obtained using a supervised classification, which uses typical spectral signature training samples for each land use/cover class. After training, classification was conducted using a maximum likelihood algorithm. Map calculations between HAND and the land use/cover classes were operated in Idris Selva.

After the map calculations, we applied a non-parametric test (chi-square) using two independent samples (i.e., groups of pixels) to assess the relationship between land use/cover and HAND classes. This was implemented to test independence, which was calculated from the sum of observed and expected frequencies, according to Eq. (1). Independence was applied at 200 randomly selected points using the standardized CROSSTAB grid.

$$\sum_{i}\binom{l}{1}\sum_{j}\binom{c}{1}\frac{(FAObs_{ij}-FAEsp_{ij})^2}{FAEsp_{ij}}\sim X^2_? \qquad (1)$$

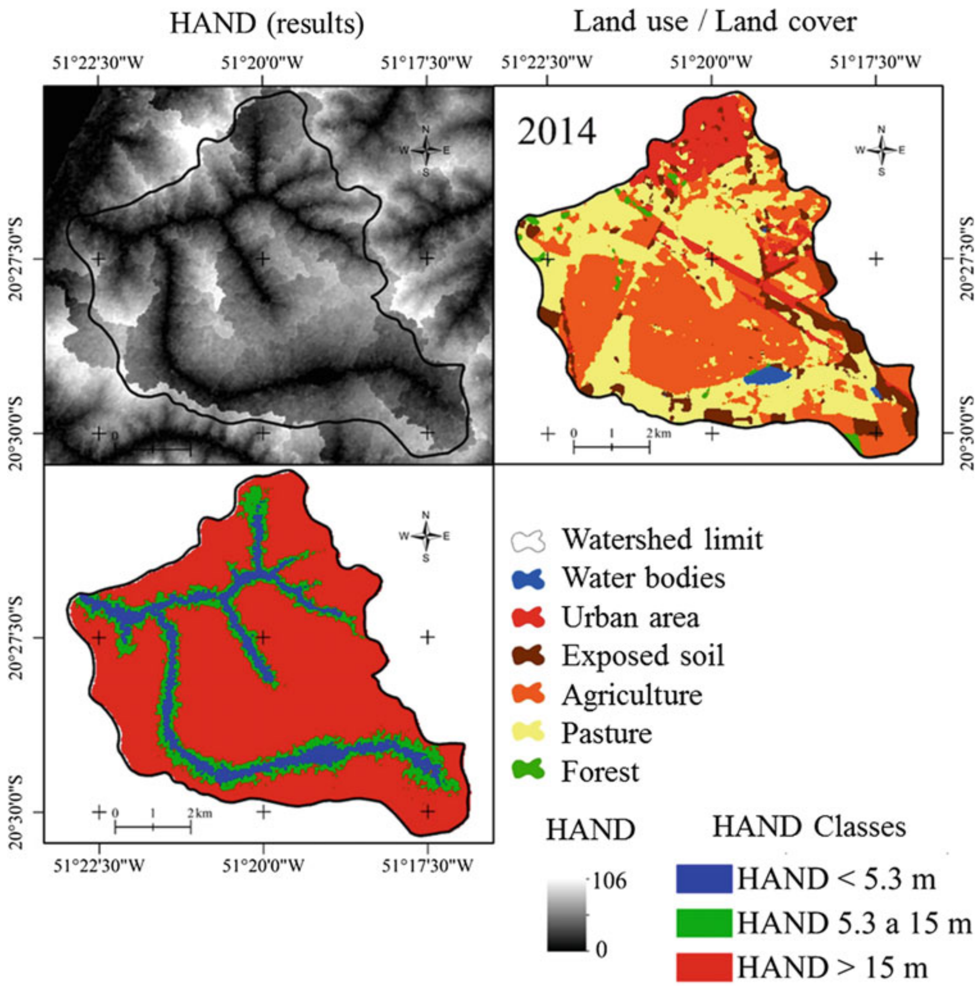

Fig. 3 HAND and land use/land cover classes in the Caçula watershed

4 Results and Discussion

Spatial land use/cover classes in the Caçula watershed and the HAND results are presented in Fig. 3. Low HAND value areas (near zero) represent shallow groundwater levels, with soil profiles that are nearly saturated. Areas with high HAND values are related to deep groundwater levels in well-drained soils (Rennó et al. 2008; Pires and Borma 2013).

In the northern portion of the basin, excessive waterproofing due to urban use was observed. In this area, HAND values were lower than 5.3 m for 3.2% of the urban area. According to Rennó et al. (2008), these results indicate areas with a very low groundwater level. The results also show that 14.8% of the urban area has HAND values varying from 5.3 to 15 m, and 82% of areas have HAND values higher than 15 m.

Using the grid of 200 sample points and the results from Fig. 2, we obtain the class frequencies used for the independence test calculation. From the independence test, the null hypothesis was rejected with 5% significance (i.e., classes are more favorable to occur in areas where HAND values are higher than 15 m).

This preference (classes occurring in areas where HAND values are higher than 15 m) is expected because it occurs in a much larger area in relation to other classes. Despite this observation, sample frequencies increased when the susceptibility to flooding decreased, which is a result of an increase in HAND value.

The urban area data do not show high HAND potential values (classes less than 5.3 m) once these areas exhibit fewer dimensions than other HAND classes areas. However, for the analysis of data observed in the urban area, sampling points with the potential for flooding and overflow occur (HAND < 5.3 m). This was due to the small size of the area in relation to other areas. However, this area presents high susceptibility due to its urban use.

From the land use/cover and HAND class calculations, we obtain flooding susceptibility according the following classes: Class A—very low floods and flooding potential; Class B—low floods and flooding potential; and Class

Table 1 HAND classes versus land use/land cover classes in the study area

Land use/land cover	HAND classes		
	<5.3	5.3–15	>15
Water	C	C	B
Urban	C	C	B
Exposed soil	B	A	A
Agriculture	A	A	A
Pasture	C	B	A
Forest	A	A	A

C—high floods and flooding potential. HAND classes were associated with land use/cover classes according to Table 1, which resulted in the potential for floods and flooding in the Caçula stream watershed.

The main contribution of the HAND results was the floods and flooding analysis, where HAND values indicated that only the surface geometry controls surface water flow, and surface roughness was disregarded due to its irregularity and runoff/infiltration balance caused by surface recovery from land use/cover.

We can observe that land use/cover can heighten flooding processes. In natural vegetation and agricultural areas, the application of proper management techniques reduces this potential because they result in well drained areas. In urban areas with low HAND values, the flooding potential increases depending on the low permeability of the surface and the decrease in surface roughness.

Potential for floods and flooding results are presented in Fig. 4. In this figure, we also present the places with long historical records of floods and flooding over the past twenty years in the Caçula watershed.

We can observe that most of these records are related to areas that are classified as "high potential for floods and flooding" in the watershed. The only two records that do not belong to this class are local, which have serious problems in the urban drainage system due to improper engineering.

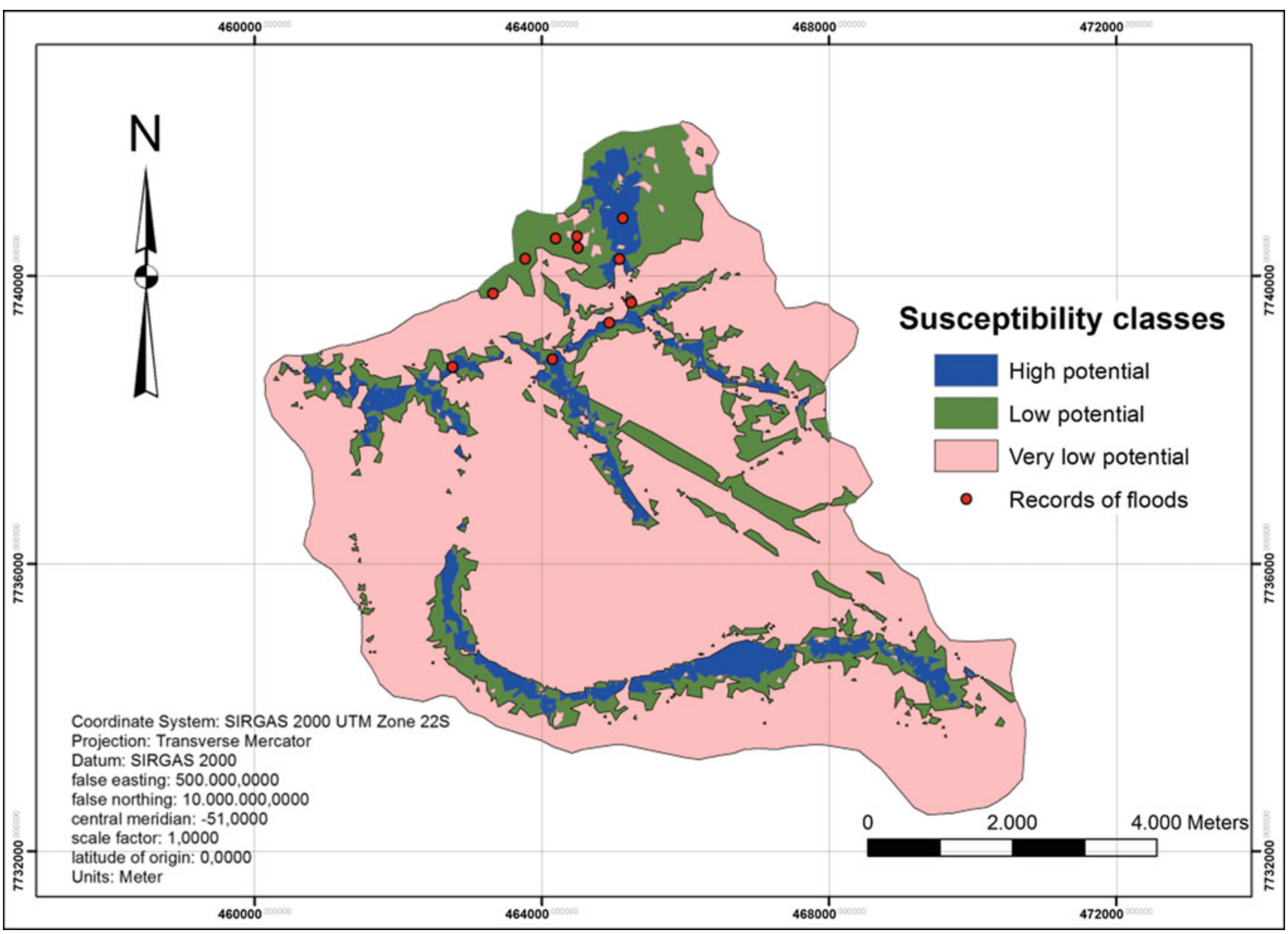

Fig. 4 Susceptibility chart based on flood and flooding classes

5 Conclusions

Low HAND values obtained in the study area coincide with depressed terrain areas in the Caçula stream watershed, indicating that the usage of SRTM data in the HAND algorithm results in an effective characterization of natural conditions in the area and its potential use in studies for physical environment mitigation.

Despite these results, HAND values alone were not sufficient to diagnose potentials for floods and flooding because they do not consider variations in roughness and infiltration conditions. The land use/cover classification provides an additional set of data for floods and flooding potential identification. The existence of persistent floods and flooding records shows that the association of land use/cover data with HAND results allows for the improved and precise analysis of flooding potential areas in the Caçula watershed.

Urban areas where flood records did not coincide with the high potential for floods and flooding require special attention in the review of drainage networks.

The chi-square test proved (with 98% confidence) that the dependence between land use/cover and flooding potential in this area was confirmed by historical flood and flooding records in the area. All the evidence shows that urban expansion was the main trigger for floods and flooding, indicating the need for the protection and recovery of natural vegetation areas.

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