Influence of drainage network and compensatory techniques on urban flooding susceptibility

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ABSTRACT

Urban flooding due to accelerated urbanization and the resulting drainage problems have become a worldwide issue and the subject of several studies in recent decades. Alternative and holistic approaches such as sustainable drainage systems have been gaining prominence. Compensatory techniques represent one of these promising alternatives for managing flooding risk in the transition to regenerative urban environments. The goal of this study is to assess the effect of a drainage network together with compensatory techniques on the susceptibility to urban flooding in Campeche District. This study applies the analytical hierarchy process together with a consistency analysis, using overlapping influential parameters in three scenarios. The results show that introducing a drainage system decreases the susceptibility to urban flooding in approximately 27% of Campeche District. In general, considering the absence of a drainage network, it is concluded that its implementation together with compensatory structures provides a reduction of approximately 32% in the susceptibility to urban flooding. It should be noted that, although costly, interventions for the implementation of a drainage infrastructure associated with compensatory techniques are extremely important for disaster reduction and sustainable development.

Key words | analytic hierarchy process, flooding susceptibility, urban drainage

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INTRODUCTION

Flooding resulting from accelerated urbanization has gained notoriety in the last 30 years. Due to the influence of climate change and accelerated urbanization, extreme rainfall events have been intensifying the problem of urban flooding worldwide (Tucci 2004; Duan *et al.* 2016). According to Duan *et al.* (2016) the United Nations Office for Disaster Risk Reduction (UNISDR) reported more than 100 urban flooding events worldwide between 1980 and 2008, resulting in approximately 6,700 deaths. In an analysis carried out by Jonkman (2005), in the set of global flooding events from 1975 to 2001, for each serious flooding event approximately 12 deaths are associated with urban drainage problems, which is due to the lack of infrastructural capacity or even the lack of infrastructure. Although there are many different concepts of flooding, most authors agree that urban flooding is due to extrapolation of capacity of drainage systems and watercourses, thereby accumulating water in backyards, streets, sidewalks or other urban infrastructures.

In the specific case of urban drainage, downstream effects go far beyond political-administrative territorial units. Actions in the upstream of the watersheds affect all water resources and transfer environmental problems to downstream municipalities (Todeschini *et al.* 2014). Urban drainage planning and management based only on the road system is a misconception, but it is still carried out in many cities around the world, causing great problems of urban flooding (Maidment 1993; Tucci 2001).

These problems become more critical in developing countries, where flooding disaster management is mostly reactive; that is, planning for flooding often receives greater attention by local authorities after the occurrence of these events (Fadel *et al.* 2018). This planning tends to fade with time, compromising stormwater management. In these countries, management activities are handled by the government without integration with the stakeholders: non-governmental and private agencies, and citizens (Tingsanchali 2012). In Brazil, the fifth largest country in the

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world in territorial extension and population, the situation is no different.

Urban drainage systems in Brazil are mostly based on the assumption that 'draining is necessary': draining runoff through conduits, as quickly as possible, increasing the magnitude and frequency of downstream flooding (Souza et al. 2013). Thus, the traditional urban drainage (grey infrastructure) predominates in most cities, the absolute separator system being adopted. Garcia & Paiva (2006) mention that a large number of Brazilian municipalities face problems due to a lack of planning and investment in drainage.

Particularly in urban areas, the management and drainage of stormwater is a great challenge. Drainage infrastructure often no longer has the capacity to keep pace with the ongoing urbanisation and the increasing rate of stormwater. In these cases, changes in the climate and increasing soil sealing can lead to increased runoff and a higher risk of urban flooding (Zhou 2014; Perales-Momparler et al. 2016). In addition, managing urban drainage by grey infrastructure approaches usually entails high construction, maintenance and repair costs (Hair et al. 2014).

Although traditional urban drainage has reduced flooding damage over the past two centuries and it will still be needed for extreme flooding events in the future, alternative approaches that accomplish these aims while offering additional benefits are being progressively pursued (Perales-Momparler et al. 2016). Compensatory techniques represent a promising alternative for managing flooding risk in the transition to regenerative urban environments. These techniques are a range of drainage devices allowing for runoff volume attenuation and mitigation, peak flows, and more generally reducing the vulnerability of urban areas to flooding, and to a somewhat lesser extent, pollutant reduction and amenity construction (Fletcher et al. 2014). The filter and infiltration trenches, permeable surfaces, water storage areas, swales, water harvesting, detention basins, wetlands and ponds are the most popular compensatory techniques that have been used (Srishantha & Rathnayake 2017).

A successful application of compensatory techniques to mitigate rainwater runoff was reported by Perales-Momparler et al. (2014), which show the potential of infiltration basins, swales and green roofs in flow mitigation, with reductions exceeding 63% of the volume. Bressy et al. (2014) demonstrated a case study using compensatory techniques (vegetated roof, underground pipeline or tank, swale, grassed detention pond) for peak flow mitigation in a suburban area near Paris (France). The results showed the promising compensatory techniques' performance in providing storage capacity reduces water discharges at a rate of about 50% and contributes to a significant reduction of runoff pollutant discharges, by 20% to 80%. Another good example of the use of compensatory techniques is introduced by Jato-Espino et al. (2016) showing the effects on surface runoff through the inclusion of green roofs (37% reduction) and pervious pavement (68% reduction) in the layout of the urbanized landscape in Donostia (Spain).

In this context, there has arisen the concept of the resilience of an urban drainage system, interpreted as the ability of the system to minimize urban flooding; that is, the excess runoff volume that overflows from the drainage network to the surrounding urban area, resulting from extreme rainfall events. Building the resilience of urban drainage to extreme rainfall events is therefore vital to maintaining acceptable levels of flooding protection in urban areas (Mugume et al. 2014).

In Brazil, as in most developing countries, the use of compensatory techniques, such as the resilience/flexibilisation of the drainage system, is not yet widespread, mainly due to the resistance to their application on the part of public managers, in addition to a natural opposition to innovation. However, the few studies performed have demonstrated their efficiency in solving problems, as well as low costs of implementation and maintenance (Tucci & Genz 1995).

By integrating natural elements as compensatory techniques into the design of an urban drainage system, an alternative solution is provided to reduce flooding damage, improve management and water quality, and protect the environment, while offering a wide range of benefits complementary to those provided by purely 'grey' solutions (Zhou 2014). For this to happen and be applied by decision-makers, it is necessary to determine the influence that a resilient drainage system has on susceptibility to flooding. This recognition can be useful and lead to some changes in the framework for the integration of flooding and stormwater management. Therefore, the goal of this study is to explore the influence of the parameters of drainage networks and compensatory techniques on the susceptibility to the occurrence of flooding in urban regions, integrating the analytic hierarchy process (AHP) with spatial modelling. This method was applied in a Brazilian district where all the complexities of the scenarios of the urban drainage of developing countries can be observed. Among the main characteristics observed in the study area are: the lack of maintenance of the drainage structures (pipe cleaning and replacement of broken pipes), improper disposal of organic sweepings, and municipal solid waste, besides the non-existent or poorly sized drainage networks in a few areas of the system coverage. In addition, there have been illegal discharges of sewer (a drainage system characterized as an absolute separator) and a lack of integrated planning of the drainage system and urban paving, reducing the capacity for infiltration of rainfall (Caprario *et al.* 2017).

MATERIALS AND METHODS

Study area

This study was applied to the Campeche District, located in Santa Catarina State, in the southern region of Brazil (Figure 1). This area faces many problems in stormwater management and has been the object of conflicts related to the use of the land and natural resources. With an area of 34.91 km^2, the district is located in a sedimentary plain, considered the largest flooding area on the Santa Catarina Island, rich in marshy ecosystems such as lagoons, ponds, marshes, streams and mangroves. In addition, the area stands out due to the presence of a superficial free aquifer (Campeche) used for water supply and has numerous compensatory techniques installed, such as swale and well infiltration. At the same time, it receives effluents from urban drainage and from individual sewage treatment systems; that is, septic tanks. The drainage network was deployed over the years, beginning in the 1970s, without complying with more technical criteria. Most of the network was constructed with pipes ranging from 40 to 50 cm, which should be able to withstand a precipitation of 112.52 mm/h with a 10-year recurrence interval (PMISB 2009). However, this intensity was estimated with an old time series (1975–2001) from a station distant from the region. Another

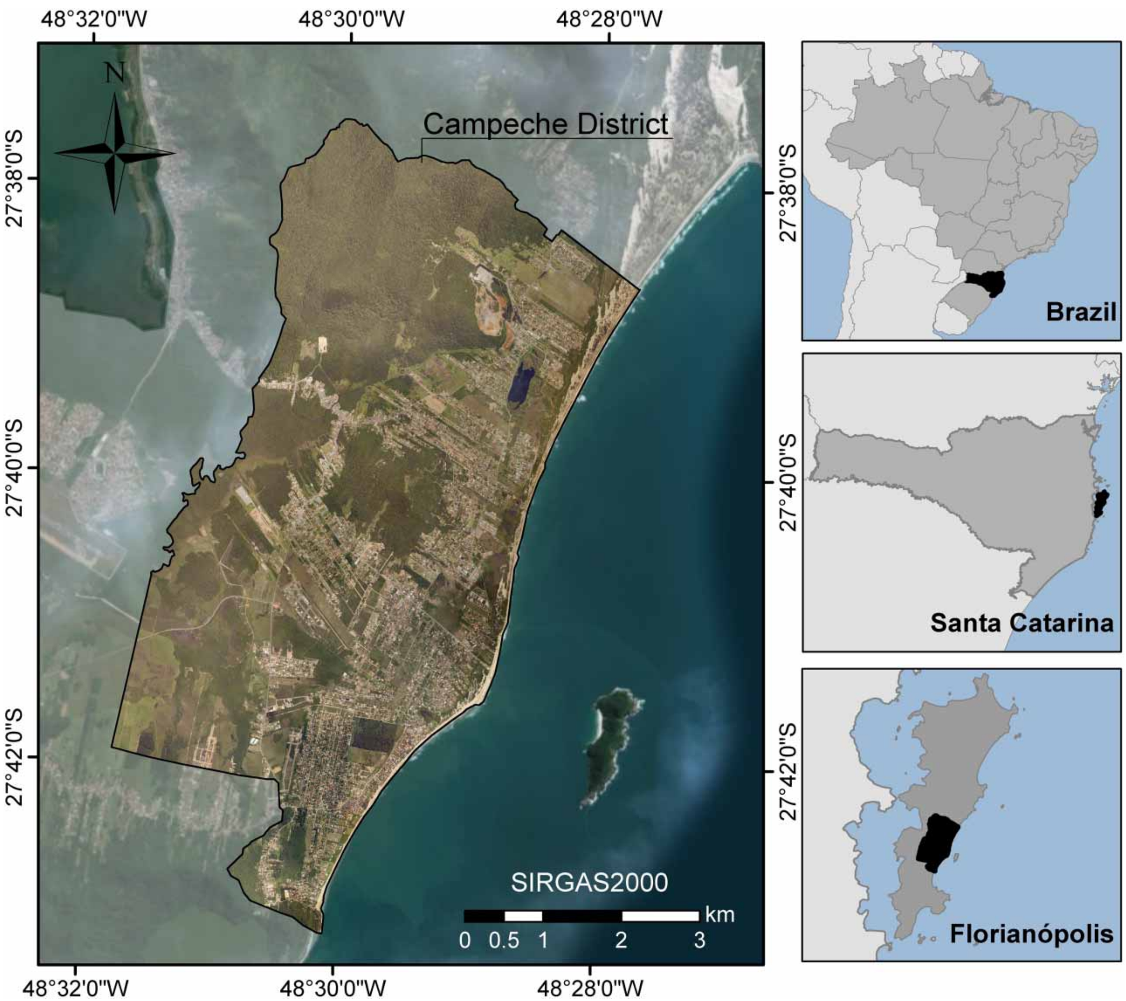

Figure 1 | Location of Campeche District.

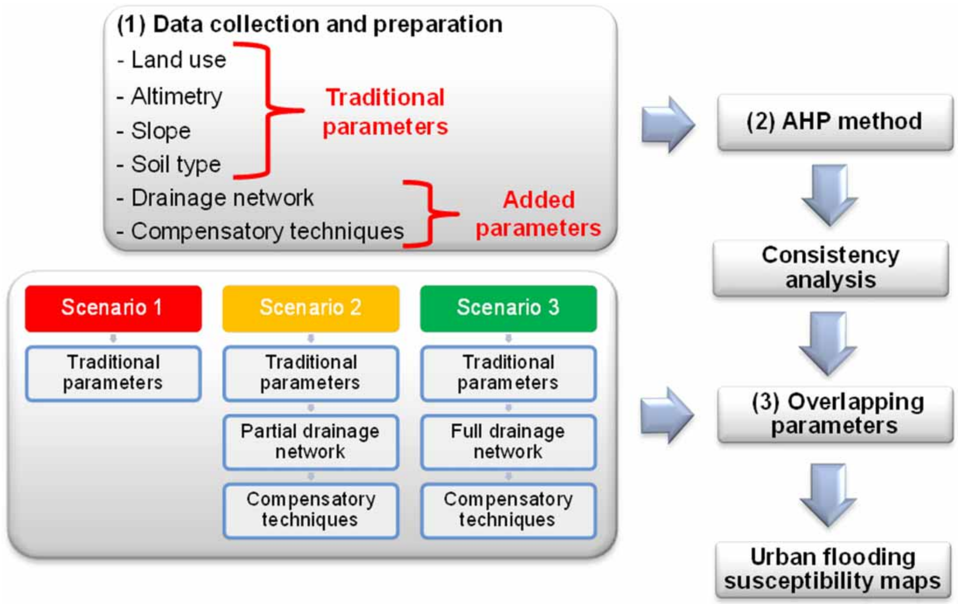

Figure 2 | Steps of the method.

aggravating feature is the fact that there are no manholes in the rainwater drainage system, which makes it difficult to carry out maintenance work that occurs only in a remediate way. In this way, there was never a concern on the part of the public administration to reconcile the drainage system with the global context of the contribution area, resulting in a sub-dimensioned system, where punctual solutions prevail (PMISB 2009). A wastewater collection system is being installed, but there is no sewage treatment plant yet. Currently, treatment is performed in the individual septic systems. However, increased groundwater saturation and widespread flooding after frequent rainfalls, natural characteristics of the Campeche plain, have led to reflux of the septic tanks in many houses in the region (Pacheco & Finotti 2015).

Table 1 | Data used for creation of influencing parameters

Data type	Source	Data	Produced parameter
Aerial photography	SDS	2010	Land use *(U)*
Topographical curves	IPUF	2000	Altimetry *(A)*
Topographical curves	IPUF	2000	Slope *(S)*
Drainage network design	PMF	2013	Drainage network $(D_{p,f})$
Drainage network design	PMF	2013	Compensatory techniques *(C)*
Soil type map	EMBRAPA	2011	Soil type *(T)*

SDS, Secretaria de Estado do Desenvolvimento Sustentável (State Secretary for Sustainable Development); IPUF, Instituto de Planejamento Urbano de Florianópolis (Urban Planning Institute of Florianópolis); PMF, Prefeitura Municipal de Florianópolis (Department of Public Works of the Municipality of Florianópolis); EMBRAPA, Empresa Brasileira de Pesquisas Agropecuárias (Brazilian Agricultural Research Corporation).

Methods and input data

This study is organized in three major steps (Figure 2): (1) data collection and preparation; (2) application of the AHP and consistency analysis; and (3) overlapping parameters for each scenario. Three distinct scenarios were adopted: (1) absence of drainage system; (2) partial existence of a drainage network associated with compensatory techniques; and (3) complete drainage system.

In the first step, data referring to six influential parameters of the study area were collected and prepared for geographic information system (GIS) input as displayed in Table 1. The input parameters produced are: land use U, altimetry A, slope S, drainage network $D_{p,f}$, compensatory techniques C, and soil type T. For the classes of each parameter, a rate i is assigned, varying between 1 and 10, representing the relative importance in terms of the susceptibility to flooding and the contribution to runoff.

Soil type. Soil texture has a great impact on flooding. Sandy soils absorb water quickly and few flows occur, characteristics that are the opposite to those of clay soils. This implies that areas characterized by clay soils are more affected by flooding. Structure and infiltration capacity also have an important impact on soil efficiency, due to its acting as a sponge and soaking up water (Ouma & Tateishi 2014). For this study, the soil type parameter was reclassified into two categories based on the water absorption conditions of depth and texture. The Red-Yellow Argisol class was considered more susceptible to flooding than the Quartzarenic Neosol class, since its composition normally has a greater amount of clay, making it difficult to infiltrate, which favours a quick runoff.

Land use. Land use parameter classes were reclassified respecting the condition that the lower the human interference, the lower the degree of susceptibility to flooding, as well as a lesser contribution to runoff. In this way, areas covered by forest or even undergrowth were considered as having great infiltration capacity, delaying possible flood spikes. Vegetation cover density is the factor of differentiation between rates. Rainwater runoff is more likely in bare fields than in those with good vegetation cover. The presence of dense vegetation cover intercepts precipitation and reduces the amount of runoff. For areas covered by sand, a medium rate was adopted because although these areas do not have vegetation cover, they have good infiltration capacity due to the high sand content present in the soil composition. Conversely, urbanized areas received a high rate, because the higher the impermeability, the higher the surface runoff, and consequently the higher the flooding susceptibility. It is important to emphasize that for areas covered by a body of water, the maximum degree of susceptibility was adopted, since these were naturally flooded.

Altimetry. Altimetry is relevant to the analysis of superficial hydric flow behaviour, indicating conditions more favourable to runoff in higher altitude areas and water accumulation for lower altitude areas. Therefore, the altimetry parameter was reclassified into two categories (0–250 m, 250–500 m) considering that the susceptibility to flooding is inversely proportional to the elevation of the terrain.

Slope. Slope has a dominant effect on the contribution of rainfall to the flooding process. It controls the duration of overland flow, infiltration, and subsurface flow. The combination of the slope angles basically defines the shape of the slope and its relation with the lithology, structure, soil type, and drainage. A flat surface that allows water to flow quickly is a disadvantage and causes flooding, whereas a higher surface roughness can slow down the flooding response (Ouma & Tateishi 2014). Thus, physical characteristics such as greater slope, greater runoff, and lower infiltration contribute to the accumulation of water in flat areas, consequently increasing flooding susceptibility. In this study, the reclassification was made considering that the degree of susceptibility to flooding is inversely proportional to the slope.

Drainage network. The urban drainage network is considered an essential system for the prevention of urban flooding, as well as for reducing risk and the damage caused to the population. Disorganized urban expansion, associated with the nonexistence or inefficiency of micro drainage systems, resulting from under-sizing of catchment structures and of the conduction of runoff, are decisive factors in the occurrence of flooding. Based on this information, the drainage network parameter was made an indicator of two classes, one representing the areas where a network exists (full or partial), completely separate from the sewer, and the other where no network is present. Since this is the first study that has approached the urban drainage network, the assignment of rates to parameter classes was performed considering only the existence or lack of a drainage network, with extreme rates being assigned. The question of flow acceleration and possible flooding downstream from the drainage system was not considered, due to system integration with compensatory techniques that attenuate the flow.

Compensatory techniques. Compensatory techniques are devices that enable the attenuation of runoff, reduction of pollutants, and provide more landscape amenities. These techniques have a considerable impact on water flows; however, the reduction of water volume is very limited in extreme events and sensitive to local conditions, such as the size and duration of the rainfall event, as well as the material and texture of the soil (Hamel *et al.* 2013). Based on this information, rate assignment to classes of the parameter compensatory techniques was performed considering only storage capacity, whether for retention, infiltration or evaporation, it did not consider the cost of implantation, maintenance or integration of the structure with the urban area. Thus, the greater the storage capacity of the device, the lower its flooding susceptibility, so the lower the rate assigned to it.

In the second step, the AHP, developed by Saaty (1977), was used to determine the statistical weights of these parameters and generate mathematical models of flooding susceptibility. This method was selected based on three considerations. First, the method uses a hierarchical structure, allowing the systematic definition of high-level objectives and strategies, where the judgment scale is well defined. Additionally, a consistency analysis ensures better prediction for hypothetical scenarios. Finally, the method is simple and versatile, being in widespread use. Figure 3 shows the general AHP method scheme.

The parameters of each scenario were organized hierarchically and pairwise compared, thus producing a

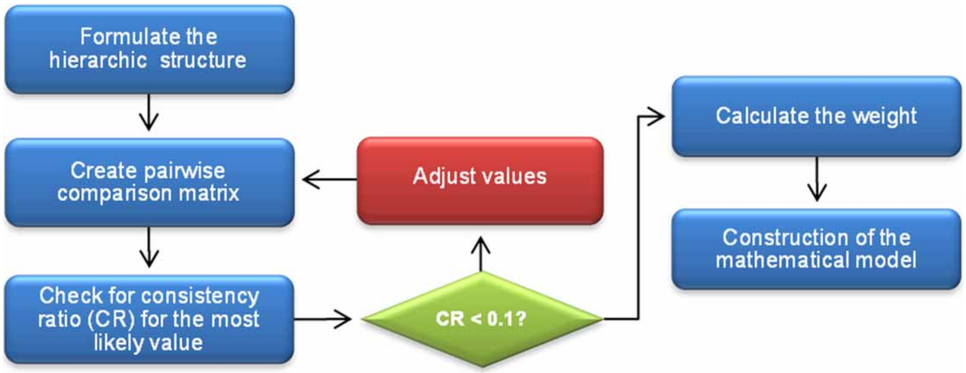

Figure 3 | Analytic hierarchy process (AHP) scheme. *Source*: Adapted from Siddayao *et al.* (2014).

comparison matrix, indicating by how much one parameter is more important than another. Judging the degree of importance of each parameter is the main objective of multicriteria decision making, it being considered one of the most important parts of the entire process of constructing a flooding mapping model. The quality of this prioritization directly influences the effectiveness of the available resources, which are, in most cases, the main judgment of the decision maker. In this study, to determine the objectives and formulate the decision making process, we have chosen to join a bibliographical survey with on-site observations, with the idea that this is sufficient to obtain satisfactory results. Thus, the judgment of the degree of importance of each parameter for the susceptibility to urban flooding was performed according to Fushita *et al.* (2011), Silva *et al.* (2016), and Seejata *et al.* (2018), besides the knowledge of natural conditions observed on site. The importance of each parameter is judged using a scale of 1 to 9 predefined by Saaty (1977), with 1 representing equality of importance and 9 extreme importance (Table 2).

In order to ensure the consistency of the judgments made during this comparison, the Consistency Ratio, CR, of the judgments was calculated by the following equations:

$$CR = CI/RI \quad (1)$$

$$CI = \frac{(\lambda_{max} - n)}{(n-1)} \quad (2)$$

where CI is the Consistency Index, RI is the Random Index, which is dependent on the sample size (refer to Table 3), n is the number of parameters and λ_{max} is the largest eigenvalue. A reasonable level of consistency in pairwise comparisons is assumed if $CR < 0.10$, while $CR \geq 0.10$ indicates inconsistent judgments.

After verifying the consistency of the judgments, the parameter comparison matrix was normalized A_w, and the eigenvector w representing the parameter's statistical weight for each scenario, and its corresponding biggest eigenvalue was extracted according to Equation (3).

Table 2 | Predefined criteria trial scale (Saaty 1977)

Intensity or importance	Definition
1	Equally important
3	Moderately important
5	Strongly most important
7	Very strongly more important
9	Extremely important
2, 4, 6, 8	Intermediate values

Table 3 | *RI* values for square matrices of order *n* (Saaty 1987)

Random Index (*RI*)									
n	2	3	4	5	6	7	8	9	10
RI	0	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49

$$A_w = \lambda_{max}.w \quad (3)$$

At the end of this stage, two mathematical models were constructed. They describe the susceptibility to urban flooding in three proposed scenarios.

These models were constructed based on the following generic model.

$$Susceptibility\ index = W_1(T) + W_2(U) + W_3(A) + W_4(S) + W_5(D_{p;f}) + W_6(C) \quad (4)$$

where W_1, W_2, W_3, W_4, W_5 and W_6 refer to the statistical weights of the parameters adopted in each scenario. For detailed information on how to apply the AHP method see Saaty (1977).

Finally, in the third step of this study, an urban flooding susceptibility map was generated for each scenario. For this step, the parameters of influence of each scenario were overlapped according to the mathematical model constructed by the AHP. For the factors, drainage network and compensatory techniques were considered beyond the road surface areas, all the runoff contribution areas, these being defined by a planialtimetric survey. The preparation and overlapping of the parameters were performed using the ArcGIS® 10.1 software package. After overlapping the parameters, the results were classified, using the natural breaks Jenks standard classification method, into four classes of urban flooding susceptibility: Low, Moderate, High, and Extremely High.

RESULTS

A graphical representation and the rates assigned for each class of parameters used to obtain urban flooding susceptibility maps are displayed in Figure 4. Most of the Campeche District is formed of Quartzarenic Neosol, where areas of low elevation (0–250 m) and flat slopes (0–3%) predominate. Regarding social characteristics, there are many green areas (forest or low vegetation),

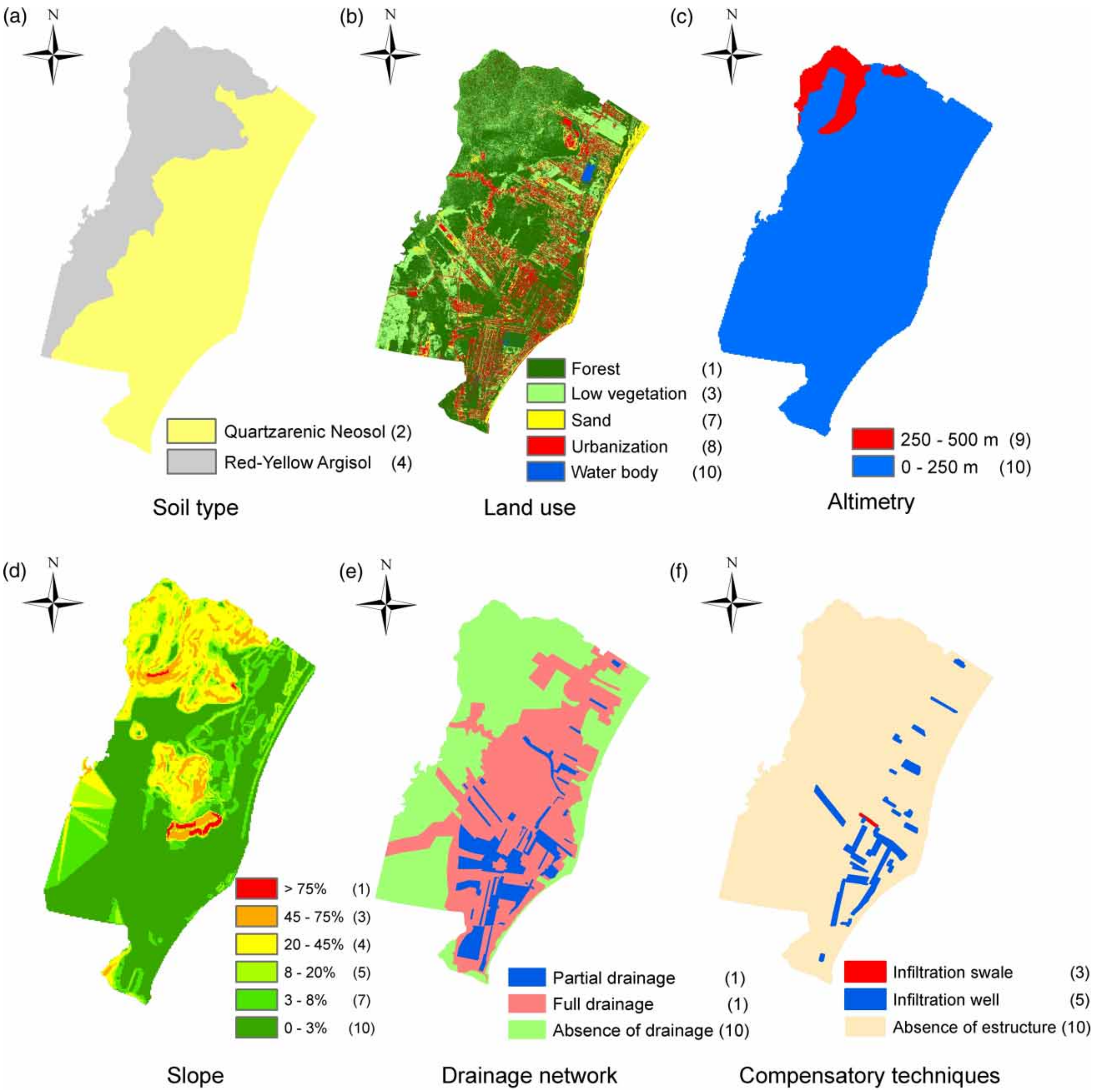

Figure 4 | Parameters of influence and rates assigned.

which face increasing urbanisation pressure. In the occupied area there is poor drainage network coverage (only 13%); however, there is a large amount of compensatory techniques (swale or well infiltration).

Results of the pair-wise comparison and judgment of the degree of importance among parameters for three scenarios are shown in Tables 4 and 5.

As a result of applying the AHP to the influential parameters for each scenario, two consistent mathematical models were obtained. The first model describes scenario 1 using four factors, ensuring 97% confidence in the results. This model is traditionally used and doesn't consider the urban drainage system. The second model describes scenarios 2 and 3 using six factors, ensuring 95% confidence in the results. The weights of the influential parameters for each scenario, as well as the consistency ratios of the models constructed by the AHP, are provided in Table 6.

Once the mathematical models reached consistency, the mapping of the flooding susceptibility in each scenario was performed. The influential parameters of each scenario were overlapping by linear combination (LC) of weights presented in Table 1. The results are shown in Figure 5 and Table 7.

Table 4 | Pairwise comparison matrix for scenario 1

Comparison matrix				
Parameter	**Soil type**	**Land use**	**Altimetry**	**Slope**
Soil type	1	1/3	1/5	1/7
Land use	3	1	1/2	1/3
Altimetry	5	2	1	1/3
Slope	7	3	3	1
Total	16	6.33	4.70	1.81

Table 5 | Pairwise comparison matrix for scenarios 2 and 3

Comparison matrix						
Parameter	**Soil type**	**Land use**	**Altimetry**	**Slope**	**Drainage**	**C. techniques**
Soil type	1	1/3	1/5	1/7	1/8	1/8
Land use	3	1	1/2	1/3	1/3	1/3
Altimetry	5	2	1	1/3	1/2	1/2
Slope	7	3	3	1	1/2	1/2
Drainage	8	3	2	2	1	1
C. techniques	8	3	2	2	1	1
Total	32	12.33	8.70	5.81	3.46	3.46

DISCUSSION

Scenario 1 (absence of drainage system). The results show that nearly two-thirds of the total district area is prone to high or extremely high flooding. These areas occupy basically the entire Campeche plain and are generally associated with low altitudes, urbanized areas, water bodies, and exposed soil regions. One-third of the study area is prone to low and moderate levels of flooding. Most of these areas tend to be at the tops of hills, where declivity and altimetry are high.

Scenario 2 (partial existence of drainage network associated with compensatory techniques). Analysing the results of the overlapping, it is possible to verify that the low susceptibility range remained the lowest in Campeche District, covering only 12.83% of the total area. These areas are evidenced mainly at the tops of hills and where there is an association between a drainage network and the presence of compensatory structures. The range of the average

Table 6 | Weights of the parameters, as determined by AHP

	Statistical weights (W_i)		
Influence parameter	**Scenario 1**	**Scenario 2**	**Scenario 3**
Soil type *(T)*	0.0592	0.0297	0.0297
Land use *(U)*	0.1590	0.0804	0.0804
Altimetry *(A)*	0.2563	0.1300	0.1300
Slope *(S)*	0.5255	0.2114	0.2114
Partial drainage network (D_p)	–	0.2743	–
Full drainage network (D_f)	–	–	0.2743
Compensatory techniques *(C)*	–	0.2743	0.2743
CR	0.0271	0.0252	0.0252

CR stands for consistency ratio.

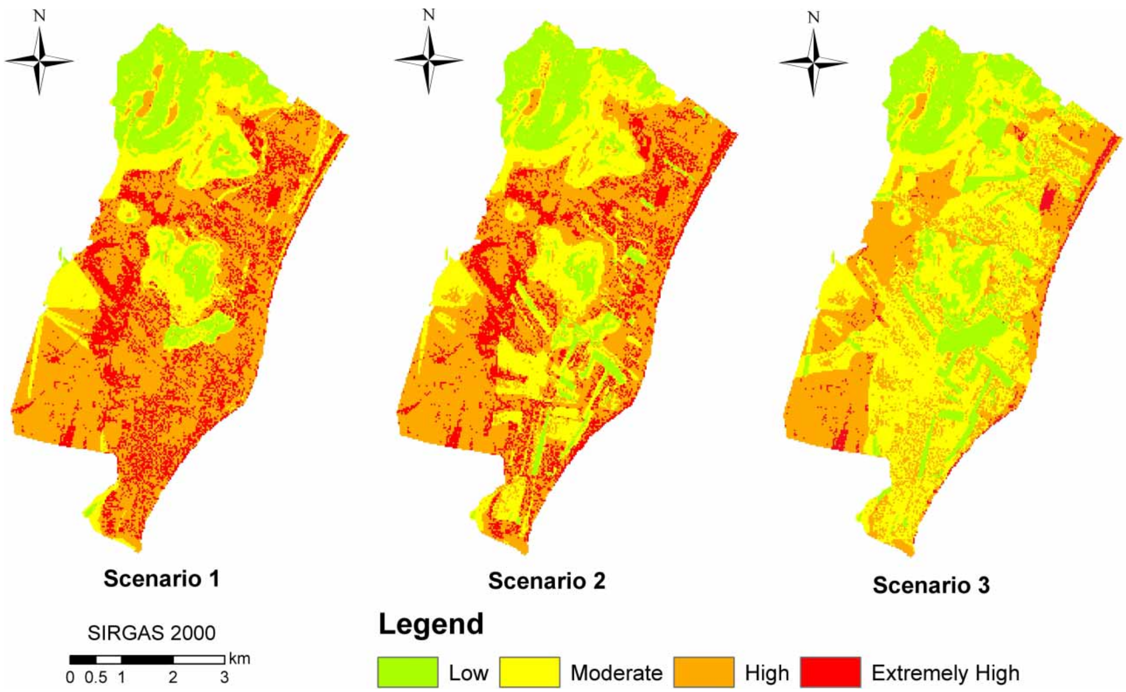

Figure 5 | Urban flooding susceptibility map for each scenario.

Table 7 | Flooding susceptibility class for each scenario

		Area					
		Scenario 1		**Scenario 2**		**Scenario 3**	
	Susceptibility	**km²**	**%**	**km²**	**%**	**km²**	**%**
	Low	4.98	14.00	4.48	12.83	7.12	20.39
	Moderate	6.2	0	8.70	24.94	15.57	44.61
	High	16.60	47.54	15.88	45.48	11.39	32.64
	Extremely high	6.65	19.04	5.85	16.76	0.82	2.36

susceptibility increased by 5.52%, a fact justified by the presence of a drainage network, even if it is present in only 13% of the streets. Significantly, the results showed a reduction in areas with high and extremely high flooding susceptibility. Although the reduction was in the order of only 4%, the affected areas are densely urbanized; thus, they were taken into account for further analysis of environmental damage as well as social and economic risks.

Scenario 3 (full drainage system). The results show that areas extremely susceptible to flooding have reduced to the point of being considered insignificant (only 2.36%). These areas are those close to a body of water, as well as areas of dune/exposed soil.

When comparing the results of scenarios 1 and 3, it is possible to identify a reduction of areas with high and extremely high flooding susceptibility (14.90% and 16.69%, respectively). This reduction contributes directly to an increase of areas with moderate susceptibility (25.19%). However, when comparing the results obtained by overlapping of the influential parameters of scenarios 2 and 3, it can be observed that an increase by 87% in the drainage network would lead to a 27.24% decrease in susceptibilities classified as high and extremely high, which would provide a reduction by 14.40% of the susceptibility. Considering the current situation of the Campeche District infrastructure, where only 13% of the roads are integrated into a drainage network, it is estimated that, although costly, interventions for the implementation of a drainage infrastructure associated with compensatory techniques are extremely important for sustainable development. Moreover, these interventions can contribute to reducing environmental, social, and economic damage. The worldwide tendency of the application of compensatory techniques observed over the last decades proves that, even in developed countries, integration of the drainage infrastructure with these techniques is still not evident, and there is a need to make a change in stormwater management principles.

In general, comparing all scenarios, one concludes that implementing a drainage network associated with compensatory structures will provide a reduction of approximately 32% of the susceptibility to urban flooding. This value could be even greater, since the study area presents environmental conditions naturally prone to flooding. In addition, despite the frequent use of compensatory techniques in this region, the urban drainage of the study area has been, and continues to be projected as a result of street paving, this not being linked to a Stormwater Management Master Plan.

The mapping of flooding susceptibility, as performed in this study, is extremely important for decision making in urban planning and management. Commonly, modelling and mapping methods are used to assess the flooding potential of riverine areas. In essence, these methods are based on physical characteristics of the watershed (its topography and morphology) and channels (hydraulics) under study. In addition to such physical characteristics, the flooding susceptibility mapping applied in this study also considers the drainage system (drainage network and compensatory techniques). In this way, the results are extended to determine the flooding susceptibility of different urban areas. Such an approach may be more useful than that commonly used, and the integration of methods that evaluate multiple parameters is recommended.

The consideration of pluvial drainage system parameters showed promising results in the mapping of urban flooding susceptibility. Both the drainage network and compensatory techniques presented the potential to reduce the high susceptibility level generated by urbanization. Integrating these parameters with those traditionally adopted allows going beyond susceptibility mapping, identifying the areas and characteristics that allow a choice of structure type to be implanted, minimizing and/or preventing flooding problems in urban zones. The new approach has the potential to be used by developing countries, focusing on stormwater drainage planning and management, and by developed countries, focusing on flooding prevention by adapting the drainage system so as to approach a holistic view involving the quantity and quality of the water, biodiversity, and amenity. However, the adjustment of the rates assigned to these parameters is of fundamental importance, since extreme values have been adopted due to the absence of any standards in the literature for use in this first application.

From the study results, it can be seen that the AHP offers a flexible and transparent manner of analysing complex problems, taking into account the knowledge and judgment of specialists and/or the end user. Due to its ability to readily incorporate multiple judgments, AHP and its combination with other tools, such as GIS, provides a potential decision support tool, finding solutions to complex problems where multi-parametric geospatial analysis is involved.

The AHP-GIS approach, as applied in this study, has proven to be relatively simple, inexpensive, quick and, more importantly, easily reapplied in any area or city. AHP can be easily adapted according to local peculiarities. The rates assigned to the classes of influential parameters are mostly to be found in the literature and can be adapted at any time. Flooding susceptibility in urban areas can be monitored over time as an important environmental indicator, becoming a reference for urban development and continuous improvement.

CONCLUSIONS

Campeche District is a region characterized by a series of unintended effects resulting from uncontrolled population growth and the consequent unplanned urbanization, favouring the occurrence of waterlogging and flooding in its urban environments. The lack of drainage systems and/or the disposal of domestic waste and effluents in existing networks has increased the susceptibility of this region, leading to the depletion of water resources and the degradation of the environment. This study evaluated the influence of the drainage network associated with compensatory techniques on the susceptibility to urban flooding in this district, identifying a reduction of approximately 27% in susceptibility when drainage is linked to a Stormwater Management Master Plan. Considering the current state of infrastructure, where only 13% of streets are included in a stormwater drainage system, interventions for resilient drainage infrastructure implementation are, although costly, extremely important for regional development.

The present study contributes to the advancement of sustainable urban drainage systems, focusing on the capacity to improve the resilience of green and grey infrastructure options in the face of potential disturbances of the system induced by urbanization and climate change. Therefore, the need for public managers to rethink urban zoning, integrating it into a Sustainable Stormwater Management Master Plan, encouraging the reduction of impermeable areas and the implementation of compensatory techniques appropriate to the site, further aiming at the prevention and control of urban flooding resulting from extreme events, ensuring the quality of the received waters and urban public safety. The proposed approach can assist decision and policy makers in the quick assessment and management of flooding in urban municipalities. This perspective ranges from simple flooding control to broader and more integrated management, which includes land use management by urban zoning, determining areas of potential flooding damage and regulating their development.

The study results confirm that the integration of AHP and the GIS method provides a powerful tool for decision making procedures for urban planning and management, allowing the efficient use of spatial data for mapping the areas susceptible to urban flooding. The multicriteria evaluation provided by the AHP can also be useful in defining the degree of importance of each of these parameters, making it possible to predict urban flooding susceptibility using a mathematical model. Overall, the study results show that the AHP-GIS approach is effective in zoning susceptibility areas, assisting in urban drainage planning, as well as in identifying the areas and types of structures that can be built.

For further studies, and to take further advantage of the versatility of AHP-GIS integration in urban flooding susceptibility studies, research efforts could be focussed on adjusting the rates assigned to the classes of parameters for drainage networks and compensatory techniques. In addition, judgments of the degree of importance of the parameters should be constantly investigated.

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