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Hydrometeorological disasters in urban areas of Costa Rica, Central America

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ABSTRACT

Tropical countries are subjected to natural disasters which cause substantial human and economic losses. Coping with disasters in tropics requires to improve our understanding of the frequency and distribution of hydrometeorological disaster events. These assessments are scarce in many developing countries, despite rapid urban expansion and lacking efficient public policies. Costa Rica's location over the Intertropical Convergence Zone, its mountainous landscapes, and vulnerability generate risks conditions for urbans centers. Here, we analyze the Greater Metropolitan Area of Costa Rica (GAM in Spanish), a region that concentrates 65% of the national population. We analyze the hydrometeorological disasters occurrence and distribution in the GAM as well as a population and social indicators analysis to identify spatial patterns of demographic growth. Our results indicate that 5987 hydrometeorological disasters events were reported in the GAM between 1970 and 2018. From this total, 63.7% were floods, 35.3% landslides, 0.9% droughts and 0.1% storms. Coupling historical natural disasters and public policies to an urban sprawl continuous process in the GAM is a critical tool for land use planning and disaster risk reduction decision makers. Results from this study can enhance our understanding on the spatiotemporal characteristics of natural disasters in developing and/or tropical countries urban areas.

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Developing countries; land use planning; disaster risk reduction; cascading disasters; urban sprawl; Central America

Introduction

Over 80% of global Gross Domestic Product (GDP) is generated in cities, nonetheless annual direct loss from natural disasters in cities is estimated to be over USD 314 billion (Sharifi, 2019). One key element of developing countries urban areas is rapid urbanisation resulting in increased vulnerability (Mitchell et al., 2015). Natural disasters occur worldwide but their impact in developing countries is greater due to their limited coping and

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adaptive capacity (Alcántara-Ayala, 2002). Recently, Rus et al. (2018) found that only a few studies deal with the resilience assessment of an urban system. The lack of foresight and failures in decision making contribute to absence of preparedness for increasing cascading disasters (Cutter, 2018).

The World Bank (2018) reports that 54% of the population lived in urban spaces. Within the last three decades the population of Costa Rica has shifted from a marked rurality to a clear urban trend. By 2011, 75% of its population were in urban areas (Quesada-Román, 2015). Historically, rural-urban migration was not controlled, generating an urban sprawl around a historical center (Pérez, 2012). The beginning of the Second Republic in Costa Rica in 1948 marked a period of the first approaches to formal territorial management (Rankin, 2012). It was not until 1968 that the urban planning law was enacted. It was aimed at defining general guidelines for the implementation of the National Urban Development Plan, the Regional Plans and the Cantonal Regulatory Plans. In addition, granted specific competences to the National Institute of Housing and Urbanism (INVU) in relation to urban planning (INVU, 2011). In 1982 the first plan of territorial management of the GAM was designed entitled GAM82. However, according with the Ministry of Housing and Human Settlements (MIVAH, 2012), the execution of this plan was not respected in its entirety and did not generate the expected territorial management. The Plan was used for more than thirty years with few updates regarding the development model, the population and environmental demands.

The Environment Organic Law and the Forestry Law were enacted in 1995 and 1997. The State provides instruments to the population to have a balanced environment. These laws were complemented with the creation of the Municipal Code of 1998, establishing territorial jurisdiction to the municipalities. In 2000, the National Council for Urban Planning (CNPU) and the Technical Secretary of the National Plan for Urban Development (STPNDU) were created to support the Urban Planning Department of the INVU in the preparation of the National Plan for Urban Development. These entities were tasked to coordinate and resolve the political aspects in the planning process of urbanisation. The MIVAH between 2004 and 2009 designed the project entitled the Urban Regional Planning of the Greater Metropolitan Area (PRUGAM). Its objective was to generate greater functional and spatial integration of population centers. However, this was discontinued in 2014 to start the National Plan of Urban Development for the GAM and the project called PlanGAM. The objective was once again to reorder cities using an articulated network scheme of dense integral centralities. It looked for the regeneration of urban centers and the reversion of expansive growth (MIVAH, 2013). Since 1968, Costa Rica have developed several territorial management institutions, plans and strategies. Nonetheless, without a visible positive impact on the development and urban planning (Barrantes-Sotela, 2018). Lack of territorial management policies has generated a process where market has setting the standard (Peck, 2015). Urban sprawl clearly describes the GAM development over the last decades. This urbanisation system commonly has some of the following characteristics: (1) commercial strip development, (2) low-density or single-use development, (3) scattered development, and (4) poor accessibility to open spaces, a result from unplanned growth (Ewing & Hamidi, 2015; Zhou et al., 2019).

Tropical climatic conditions favour that over 90% of the disasters in Costa Rica are hydrometeorological in nature. Among the disasters total 60% are related to floods and 30% to landslides (LA RED, 2018). The other 10% are earthquakes, volcanic activity, and anthropogenic disasters. The study of landslide and flood processes has been extensive in Costa Rica. However, the hazard maps' output scale and its integration with vulnerability and risk analysis has been limited (Quesada-Román, 2017; Quesada-Román et al., 2018). Due to the combination of its natural and anthropogenic climate variability and change conditions and the lack of efficient territorial management in the GAM, hydrometeorological disaster risks are likely to increase. For instance, we develop (i) a spatial and temporal distribution of hydrometeorological disasters during the last five decades, and (ii) a correlation between disasters events and municipalities Social Development Index according to population density to understand the GAM vulnerability.

Materials and methods

The GAM comprises an area of 1779 km^2 with 35 municipalities (called cantons in Costa Rica; Table 1). It contains approximately 65% of the population of the country with ~1300 inh/km^2 (INEC, 2011) (Figure 1). The GAM comprises four historic cities (San José, Heredia, Alajuela and Cartago) and their peripheries, which in recent decades have started growing rapidly in an unorganised combination of urban, suburban and rural typologies (Van Lidth de Jeude et al., 2016).

We used the disaster database DesInventar to develop the disaster incidence analysis in the GAM during the period of 1970–2018 (LA RED, 2018; Velásquez & Rosales, 1999). This database provides the greatest spatial detail at provincial, municipal and district levels. The information in DesInventar is provided by the National Commission for Risk Prevention and Emergency Attention (CNE) reports, as well as newspaper news, and the 9-1-1 emergency system. This database can be accessed on the site http://www.desinventar.org, is public and has data since 1968. DesInventar shows nine types of hydrometeorological events; to simplify the analysis we merged into four classes (landslides, floods, storms, and droughts). The number of disasters were analyzed considering the El Niño South Oscillation (ENSO) variations during the last five decades based on the 3-Month above/below 0.5 Standard Deviations of the Oceanic Niño Index (ONI; Huang et al., 2017; NOAA, 2018). The international efforts from UNDRR determining the International Decade for Natural Disaster Reduction (1990–2000), and in 1999 the National Emergency Law in Costa Rica was reformed, and the National System of Risks Prevention and Emergencies Attention was created, thereby empowering all the national actors and encouraged the studies of

Table 1. Municipalities names and codes of the GAM.

Municipality	Code	Municipality	Code	Municipality	Code
San José	101	Alajuela	201	Heredia	401
Escazú	102	Grecia	203	Barva	402
Desamparados	103	Atenas	205	Santo Domingo	403
Aserrí	106	Naranjo	206	Santa Bárbara	404
Mora	107	Palmares	207	San Rafael	405
Goicoechea	108	Poás	208	San Isidro	406
Santa Ana	109	Valverde Vega	212	Belén	407
Alajuelita	110	Cartago	301	Flores	408
Vázquez de Coronado	111	Paraíso	302	San Pablo	409
Tibás	113	La Unión	303		
Moravia	114	Alvarado	306		
Montes de Oca	115	Oreamuno	307		
Curridabat	118	El Guarco	308		

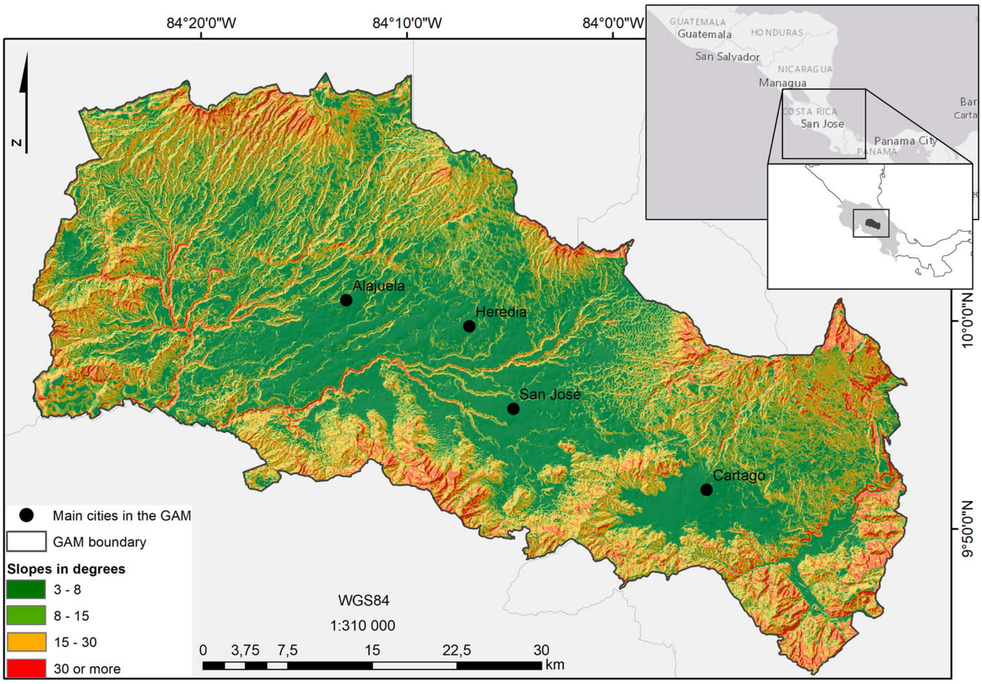

Figure 1. Location of Greater Metropolitan Area of Costa Rica.

disasters (Brenes & Bonilla, 2005). The temporal and spatial variability of rainfall or droughts in the GAM is heavily influenced by ENSO (Méndez et al., 2019). In the GAM, during the warm phase of ENSO or El Niño (La Niña or cold phase of ENSO) years it is common to observe precipitation reductions (increases) associated with the phenomenon. We also used climate change projections for Central America during the next decades (Alvarado et al., 2011; Giorgi, 2006; Imbach et al., 2018). All the events in the present study that were reported between 1970 and 2018 were called disasters. It should be noted that not all of them have caused major socioeconomic impacts, they correspond mainly to specific events and annual/monthly recurrence. They mainly are extensive manifestations of risk or small-scale disasters, whose occurrence over time has had a cumulative economic impact.

In addition, we used the social development index (IDS 2017) made by the Ministry of National Planning and Economic Policy of Costa Rica (MIDEPLAN). With this index, we made direct relationships between the disaster incidence and the social characteristics of the GAM population. The index gathers and evaluates economic, educational, public health, civic participation, and security variables of the municipalities of the GAM (MIDEPLAN, 2017). The demographic information comes from the last national census (INEC, 2011), and population projections for 2020 of the National Institute of Statistics and Census (INEC). Finally, the number of disaster events and the IDS for each municipality were plotted according to its population density. This analysis identifies relationships among them in order to depict the spatial distribution of hydrometeorological disasters and the risk conditions of each municipality. All statistical analysis was performed in R version 3.5.1. (R Core Team, 2018), and the cartography with the software Arc GIS 10.3.

Results

Between 1970 and 2018, 5987 hydrometeorological disasters events were registered and distributed in 35 municipalities of the GAM. The most impacted municipalities located in the first quintile for 48 years have been Desamparados with 719 reports, San José with 607 reports and Alajuela with 547 reports (Figure 2). Nonetheless, a reduced number of municipalities also compose the second quintiles, where Cartago, Aserrí, and La Unión combined reported 930 total disaster events. These six municipalities constitute approximately 50% of the total disaster occurrence in the GAM by hydrometeorological events for the period studied.

Floods were more recurrent in Desamparados (430 reports), San José (410 reports) and Alajuela (407 reports). Meanwhile minimum values were in Atenas, Alvarado, and San Isidro, which together reported 187 events. Regarding landslides, the municipalities that presented the most recurrence of events were Desamparados (287 reports), San José (193 reports) and Aserrí (170 reports). San Pablo, Belén, and Flores were the least affected by landslides with less than six reports (Figure 3). Droughts comprised only 49 reports in 21 municipalities, with San Isidro and Goicoechea reporting the highest number of incidents with four each. The reports in San Isidro were three in 1983 and one in 1998, and two in Goicoechea in 1973 and one in 1983 and 1998, respectively. Finally, storms with only six reports affected only Alajuela, Barva, Cartago, Heredia, Aserrí and San José. From the 5987 hydrometeorological disaster events recorded in the GAM a 63.7% were floods, 35.3% landslides, 0.9% droughts, and 0.1% storms.

The occurrence of hydrometeorological disasters events is concentrated on the two rainfall maxima between May and November, typical climate conditions of the Pacific

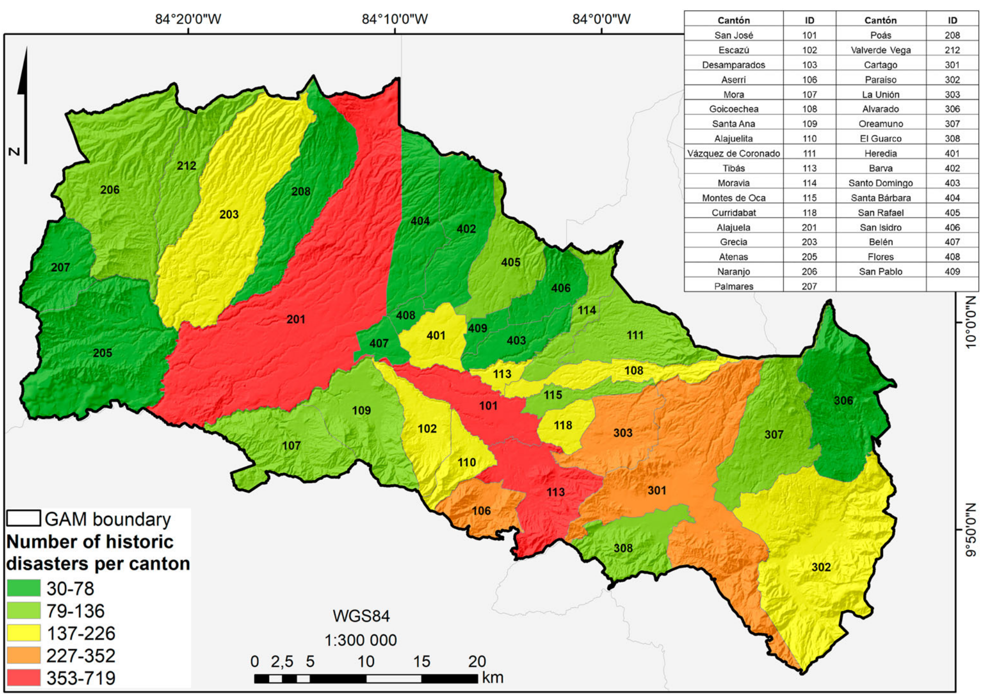

Figure 2. Spatial distribution of disaster events per municipality in the GAM during 1970 to 2018.

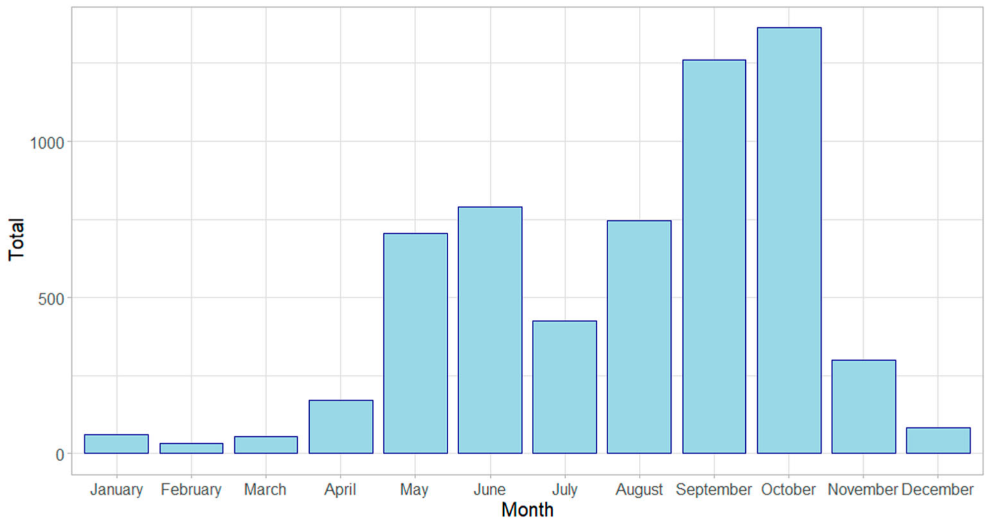

Figure 3. Number of disaster events by month since 1970 until 2018 in the GAM.

basin of Costa Rica. There is a clear peak of reports on the rainy season beginning and an impasse during the Midsummer Drought (Magaña et al., 1999). Finally, an intensification occurred during the allocation of the Intertropical Convergence Zone over the country and the influence of the tropical cyclones (Figure 3). In addition, five municipalities are located in the Caribbean basin (Cartago, El Guarco, Oreamuno, Paraíso and Alvarado), and their precipitation behaviour is similar than the Pacific basin.

On the other hand, the Social Development Index (IDS) of 2017 classified the municipalities on a scale from 0 to 100 and divided it in quintiles. In the case of the GAM (Figure 4), most of the municipalities are located between the IV and V quintile, with some exceptions in the III quintile (Aserrí, Mora, Paraíso, Oreamuno, and El Guarco). Higher IDS is associated with major development opportunities for the population due to the centralisation of public and private services in the GAM.

As state in the IDS 2017, the highest numbers of population density of Costa Rica are in the GAM (Figure 5). According to the Jenks natural breaks classification method of the population projection for 2020 (Jiang, 2013), some municipalities have more than 4914 inh/km^2 (San José and Tibás), and others more than 2153 inh/km^2 (Goicoechea, Alajuelita, Montes de Oca, Curridabat, Flores and San Pablo). Other representative cases between 2028 and 2152 inh/km^2 are Escazú, Desamparados, Moravia, La Unión, Santo Domingo, and Belén. The rest of the municipalities have less than 2028 inh/km^2 but with a continuous growth trend. These distributions are consistent with topographical characteristics of the GAM (plain and subhorizontal surfaces intersected by rivers and canyons). These conditions favour or limit the natural urban sprawl, but in the last decades, the scarcity of options of properties close to the workplaces have moved the population to floodplains and mountainous spaces. This urban densification phenomenon are also linked with a services centralisation in the GAM.

The number of disaster events that occurred in the GAM during the last five decades are the result of natural and anthropogenic climate change and variability through more severe storms over time and the lack of inefficient public policies in different social

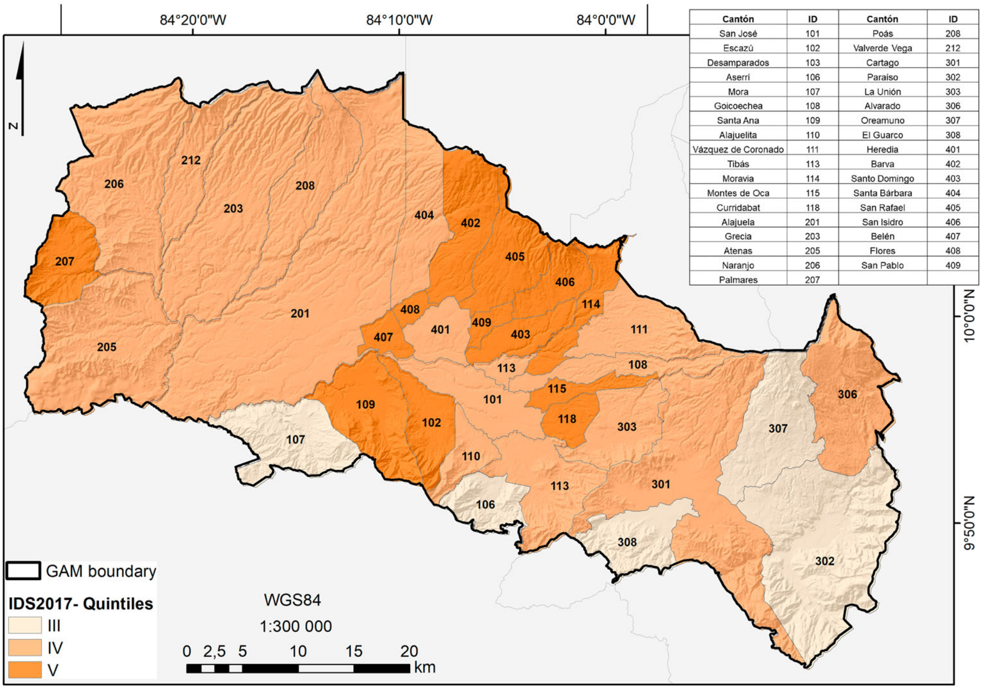

Figure 4. Spatial distribution of the IDS 2017 in the municipalities of GAM.

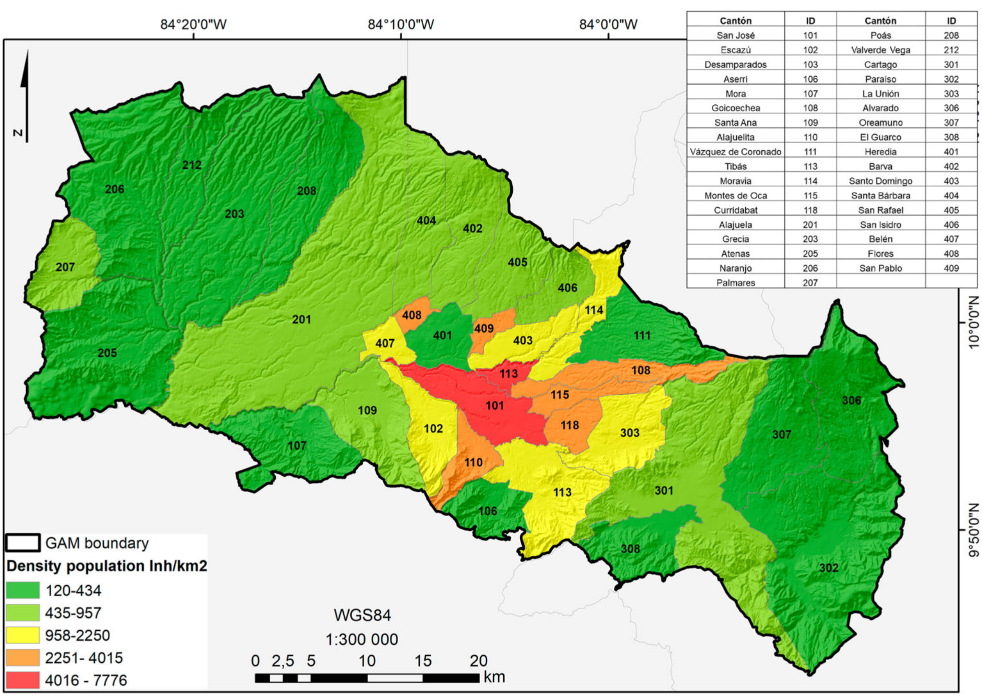

Figure 5. Spatial distribution of population density in the municipalities of GAM.

aspects. Especially in education, health, infrastructure, transportation, and the limited territorial management plans coupled with risk assessment strategies. Some municipalities have a direct relationship with their social development, the population density and the number of disasters presented during the last five decades (Figure 6). This is the case of Desamparados, San José, Alajuela, Alajuelita, Heredia, Cartago, La Unión, and Goicoechea with more than 200 disasters events, in the IV and V quintile 3of the IDS 2017, with population densities over 2000 inh/km^2. Other municipalities to beware in the future are Aserrí, Paraíso, El Guarco, Mora, and Oreamuno in the III quintile of IDS 2017, with a growing population density due to the increasing of housing complexes.

Discussion

Hydrometeorological hazards impacts in the GAM

The GAM is affected by a clear rainy season from April to November and the impact of cold breaks between December and March (Alfaro & Pérez-Briceño, 2014; Campos-Durán & Quesada-Román, 2017a; Retana, 2012) and El Niño-Southern Oscillation, Atlantic climatic variations, the influence of the Intertropical Convergence Zone, East waves, the Caribbean Low Level Jet, and tropical cyclones from June to November (Alfaro et al., 2010; Alfaro & Quesada-Román, 2010; Hidalgo et al., 2015; Pérez-Briceño et al., 2016). Despite of the presence of five municipalities that belong to the Caribbean basin (Cartago, El Guarco, Paraíso, Oreamuno and Alvarado) their climographs reported very similar behaviour that the Pacific basin (Méndez et al., 2019). These climatological characteristics favour the occurrence of floods in the river floodplains and landslides in the inclined slopes in the urban areas as well as in the mountain zones with agricultural or forest land uses (Barrantes &

Figure 6. Number of hydrometeorological disaster reports by municipality (R), its distribution according with its IDS 2017 (IDS), and its population density (PD).

Quesada-Román, 2016; Quesada-Román & Barrantes, 2016, 2017; Quesada-Román & Feoli-Boraschi, 2018; Quesada-Román & Mata-Cambronero, 2020). This climatic condition responds to its location in the Pacific side of Costa Rica (Maldonado et al., 2018). During La Niña years the conditions favoured the occurrence of storms, floods, and landslides, meanwhile during El Niño years the droughts are common (Hidalgo et al., 2019; Méndez et al., 2019; NOAA, 2018; Quesada-Román, Ballesteros-Cánovas, Guillet et al., 2020).

Desamparados, San José, Alajuela, Cartago, Aserrí, and La Unión show the highest number of disaster events in the GAM and Costa Rica (~47%). These data are consistent with previous works (Barrantes et al., 2017; Campos-Durán & Quesada-Román, 2017a; Quesada-Román, 2015; Quesada-Román & Calderón-Ramírez, 2018). Many municipalities that already have a continued urban growth in mountainous landscapes will be more affected by landslides e.g. Desamparados, Alajuela, Alajuelita, and Aserrí (Quesada-Román, 2015). Meanwhile, the municipalities located in the vicinities of the river valleys could be impacted by an increased number of floods, not only by the hydrometeorological conditions, but also by the huge amounts of domestic wastes and water conflicts along the river flows (Esquivel-Hernández et al., 2018). Urban areas had an increase of impervious surfaces in association with the inefficient pluvial sewer system (Quesada-Román & Calderón-Ramírez, 2018). These are two factors that significantly contributed to the annual recurrence of urban floods. On average, between 1970 and 2018 a total of 3816 flood reports were reported, of which 20% occurred due to overflow of sewers (Brenes & Girot, 2018). The cause of these events includes the poor inter-institutional coordination for the prevention of emergencies, mainly in the rainy season (Quesada-Román, 2015).

For northern Central America the future climatic high-resolution projections indicate warming of extreme temperatures and less precipitation (Giorgi, 2006; Hidalgo et al., 2013; Nissan et al., 2019). Nonetheless, an increase of heavy rains is predicted for the Caribbean of Costa Rica (Imbach et al., 2018). In the GAM, precipitation will fall in the lower areas, meanwhile in the mountains the rainfall will increase (Alvarado et al., 2011; Nissan et al., 2019). Likewise, a greater number of tropical cyclone occurrence in the Atlantic basin have been predicted (Lavender et al., 2018), as well as more major hurricanes recurrence (Bender et al., 2010). The increase of the hydrometeorological disaster events coupled with the climatic projections forces the consideration of the potential economic impacts in the GAM. Since 2010 the impact of hydrometeorological phenomena has produced huge economic impacts in Costa Rica. Recent disaster impacts in Costa Rica, due to the tropical cyclones, are clear examples of the increasing vulnerability. The cost of recovery from Hurricane Otto (2016) represented 0.394% of the national GDP, while tropical storm Nate (2017) totalled 1.283% of the GDP. The impacts of these processes were predominantly in road infrastructure (bridges and roads) where Costa Rica has a clear development lag (Brenes & Girot, 2018; Quesada-Román, Ballesteros-Cánovas, Granados-Bolaños et al., 2020). The impact of a physical event or the development of an initial technological or human failure generates a sequence of processes in human subsystems that result in physical, social or economic disruption (Alexander, 2018). The increasing vulnerability conditions within the GAM due to the inefficient territorial management lead to the occurrence of cascading disasters (Quesada-Román et al., 2019).

Baseline information for disasters in Costa Rica should be enhanced and the cartography of natural hazards must be improved (Quesada-Román, 2017). In addition, the number of investigations on vulnerability and risk in the country should increase in order to decrease the probability of disasters in the most populated areas like the GAM (Quesada-Román et al., 2018). Economic asymmetries show greater impacts in lower development municipalities due to their higher vulnerability (Campos-Durán & Quesada-Román, 2017b). Therefore, it is essential to create a land use management law that integrates all the planning elements of the municipalities, from the national, regional and local scales, considering the hydrographic basins (Quesada-Román & Calderón-Ramírez, 2018).

Urban policies evolution in the GAM

The lack of updates to the policies led to the uncontrolled growth of the urban expansion of the GAM. The urban centers of San José, Cartago, Heredia, and Alajuela became a single urban sprawl. GAM area is bigger than other urban cities areas as London, Los Angeles, Barcelona, and Manhattan (Van Lidth de Jeude et al., 2016). This has expanded transportation and service infrastructure towards unmanageable limits and creating a world of fragments that is neither urban nor rural (Van Lidth de Jeude & Schütte, 2010). Moreover, a dispersed lineal (in low densities) urban growth model domain the GAM. It is one of the great factors that increases travel times of the population to their places of work, recreation and consumption. Despite the slow population growth, this collapse of the urban mobility is associated with the increase of housing, offices and industry construction. Along the GAM the constructed area has grown 600% in the last three decades (Sánchez, 2018). Then, the horizontal urban growth model is maintained for a large amount of the population. Housing growing trends are located away from the city leading to a loss in the quality of the habitat and favouring the disorganised urban sprawl. This has led to a progressive increase in social housing in rural areas and areas in urban-rural transition (Quirós-Arias, 2018). In rapidly developing urban centers, most zoning regulations promote expansion and linear development. This is often in direct conflict with the objectives and goals of an urban regulatory plan, which seeks to consolidate the existing centers and preserve the rural landscapes (Barrantes-Sotela, 2018).

Population density is higher in the municipalities near the urban centers of the four provinces that comprise the GAM. This shows a dependence on essential services existing in these areas, such as education, access to health care, greater connectivity between different sectors, as well as the variety of businesses and better options for activities related to leisure. The existing conurbation process in the GAM means that more remote municipalities have become dormitories. These segregation processes have historically existed in Latin American countries, including Costa Rica. Segregation in urban areas is associated with actors that in one way or another tend to separate members from other socio-economic categories and where access to public resources (education, health, decent housing) for vulnerable people is limited (Murphy & Stepick, 1991). The symbol of progress in different countries is found in the idea of the city (de Sousa-Santos, 2014) and, as such, cities become the main destination of migrants. These generate limitations related to the distribution of space, putting pressure on the most vulnerable people of the social stratum to settle in marginalised places, which are often spatially located in risk areas (Séguin, 2006). This is the case of the main informal settlements of the GAM, e.g. La Carpio, Pavas, Alajuelita, and Los Guido. All of these are located in places considered by the National Emergency Commission as High-Risk Areas (Pérez, 2012).

The GAM conditions resemble other urban areas in developing countries, with an increasing population density, complex risk assessment, and lacking planning policies. An integral urban policy, planning and design process for the GAM should combine the entire urban population, the public and the private sector interests (Van Lidth de Jeude et al., 2016). Land use planning measures in parallel with engineering projects have been identified to prevent floods in Sao Paulo, Brazil (Haddad & Teixeira, 2015). In addition, a strong association between informal settlements with high hazard exposure in Puerto Montt, Chile (Paz-Castro et al., 2015). Fakhruddin et al. (2019) recommend the implementation of early warning systems and effective risk communication tools in Nuku'alofa, Tonga. The readiness of city governments to enhance resilience and create inclusive cities is a key factor in adapting to floods in Africa (Douglas, 2017). Disaster risk in Asian cities is highly dynamic and difficult to assess due to a national level dependence (Hochrainer & Mechler, 2011). Decentralisation of government and disaster management could improve disaster governance in small cities (or municipalities). This process could close the distance between citizens and their government and by improving local governance capacity (Rumbach, 2016). Hydrometeorological risk assessments, planning and implementation of risk management measures success depend on community participation (Froude & Petley, 2018; Tingsanchali, 2012).

Conclusions

We analyzed the impact of hydrometeorological events in the municipalities of the GAM from DesInventar reports between 1970 and 2018. The hydrometeorological events that have impacted the GAM correspond to localised events influenced by the annual rainy season and extraordinary climatological events such as ENSO or tropical cyclones. Such events accumulated over time can generate an impact that amounts to a large-scale disaster as a series of cascading processes. Urban expansion favour that much of the flooding registered is due to inefficient sewerage and stormwater management. An intense public centralisation of the main education and health facilities, and major job offerings without a clear counter plan of decentralisation of the country produced great population densities in the GAM. The creation of a land use planning law is critical. This policy should integrate all the municipalities planning elements, from national, regional and local scales. In addition, it must incorporate watersheds and Disaster Risk Management as main transversal axes is fundamental for Costa Rica and the GAM. Therefore, it is necessary to integrate risk management and climate change scenarios within the urban planning processes. Costa Rica and Central America resemble tropical/developing countries disaster risk reduction and urban planning problematics. Therefore, our results open the opportunity for further studies of natural disasters associated with urban growth of should be assessed in the future.

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Disclosure statement

No potential conflict of interest was reported by the author(s).

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