

Influence of solid waste and topography on urban floods: The case of Mexico City

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Abstract Floods in cities are increasingly common as a consequence of multifactor watershed dynamics, including geomorphology, land-use changes and land subsidence. However, urban managers have focused on infrastructure to address floods by reducing blocked sewage infrastructure, without significant success. Using Mexico City as a case study, we generated a spatial flood risk model with geomorphology and anthropogenic variables. The results helped contrast the implications of different public policies in land use and waste disposal, and correlating them with flood hazards. Waste disposal was only related to small floods. 58% of the city has a high risk of experiencing small floods, and 24% of the city has a risk for large floods. Half of the population with the lowest income is located in the high-risk areas for large floods. These models are easy to build, generate fast results and are able to help to flood policies, by understanding flood interactions in urban areas within the watershed.

Keywords Floods · Land subsidence · Waste disposal · Watershed

INTRODUCTION

Many cities have become increasingly vulnerable to floods, affecting a larger number of people every year (Balica et al. 2012; Hallegatte et al. 2013; Klomp 2015). These floods are the consequence of changes in watershed hydraulic dynamics, caused by the transformation of land uses to urban areas (Haddad and Teixeira 2015; Zambrano et al. 2017). For example, green areas reduce the speed of water moving to the lowlands and promote infiltration, reducing the possibility of inundation (Jyrkama and Sykes 2007). Other characteristics of watershed hydraulic dynamic

changes involving flood frequency are based on watershed morphology. Areas at high altitudes with large slopes are less susceptible to flooding (Bradshaw et al. 2007) than are flat areas at low altitudes (Pérez and Blanco 2010; Versini et al. 2010). Water connectivity among landscape units also affects the speed and the amount of water that flows to the lowlands (Kalantari et al. 2014). Additionally, it is necessary to consider variables such as precipitation intensity (Sankarasubramanian and Lall 2003; Field et al. 2012) as flash-flood events may increase river runoff and occurrences of floods (Versini 2012). In addition, the progressive overexploitation of aquifers accelerates the subsidence process, increasing flood risks as low lands become lower (Izazola 2001; Zambrano et al. 2017). As a consequence, the role of the heterogeneous landscape is important in adapting to flood occurrence (Lankao 2010; Pérez and Blanco 2010; Sosa-Rodriguez 2010; Reinoso et al. 2012). Coastal cities are particularly vulnerable to overflows caused by storms and sea level rise, both of which will increase with climate change (Balica et al. 2012) and may generate yearly global losses larger than US 60 billion by 2050 (Hallegatte et al. 2013).

These changes within watersheds have accelerated over the last century as consequence of population growth and have increased flood risks in cities such as Athens (Mazi and Koussis 2006), Mexico City (Zambrano et al. 2017), Sao Paulo (Haddad and Teixeira 2015) and Lagos among many Nigerian cities (Adeoye et al. 2009). These floods directly affect people and property, and the economy of urban areas decreases in terms of their GDP in the short term after the event (Hallegatte et al. 2013; Haddad and Teixeira 2015). This phenomenon is particularly important in developing countries where these hazards affect their economy (Klomp 2015). However, cities in developed countries, such as London and New Orleans, seem to be

affected by the increment of floods (Parker 1995; Dixon et al. 2006). Within cities, populations with lower incomes occupy the areas with a higher climate vulnerability (Sanderson 2000; Harland et al. 2006; Jenerette et al. 2007). This is partly explained by the fact that populations with different incomes are not distributed homogeneously within an urban area.

As floods in urban areas are the product of a multi-variable socio-ecosystem process with many drivers, it is easier for societies to look for those drivers of floods that can be observed such as sewage blockages (Holzer and Johnson 1985). Water flow from heavy rains is blocked in sewers by the presence of solid waste, when its carried by runoff to the sewer (Ricaño 2015; SPC 2016). This effect has been widely cited as one of the principal drivers of urban floods in some cities (Stevaux et al. 2010), and may be the reason many local authorities focus their policies around waste disposal. Strategies of waste disposal strategies are based mainly on removing trash and other debris from the sewage system and implementing large pumping systems to move the water to the sewage (SACMEX 2016).

However, city management is shifting from reactive actions in local areas to a watershed management approach for flood risk (Pielke 1999; Mostert and Junier 2009). Hence, in order to decrease risks to populations, it is recommended, as a first approach, to improve information on landscape characteristics (Pielke 1999) or land attributes (Zambrano et al. 2017) and the valuation of areas that are susceptible to floods (Mostert and Junier 2009).

By using these variables, it is possible to generate a flood hazard model to evaluate the hydrologic dynamics in urban watersheds and to translate the information into spatially explicit results. Here, we present a spatial model that uses public geographic information, available in many cities, to evaluate variables that drive urban flood hazards, using Mexico City as a case study. For this model, we used a landscape approach to evaluate the relation between the amount and size of floods with the amount of garbage disposal in different regions of the city. We also contrasted these results with the relation between the amount and size of floods within basins at different altitudes within the regions. We related this information to the social development index for the city to evaluate the effect of floods in regions with different income levels. The interpretation of the data can be useful for the implementation of policies to reduce vulnerability to new inundation events.

Study area

Mexico City is established on a system of five lakes, in the lower area of a natural endorreic watershed, which is present relative similarities to coastal cities, but it is an inland territory more than 2000 m above sea level. The

lowest areas of the city are located at approximately 2200 m a.s.l., and the highest urbanized areas are located at nearly 2800 m a.s.l. (Fig. 1). The average precipitations are 600 mm in the northern part of the city and 1200 mm in the southern part of the city (Soto Montes de Oca and Herrera 2009; Lankao 2010). The city covers 1495 km² and has a population of nearly 8.8 million inhabitants (INEGI 2010), but the total urbanized area has nearly 20 million people (INEGI 2014). The central and northern areas of the city are mostly urbanized, and some areas have a land subsidence a rate of 350 mm per year (Cabral-Cano et al. 2008). The southern areas are more conserved, where agricultural and protected forests, wetlands and grasslands are dominant, with almost no subsidence.

Since pre-Hispanic civilizations established on the edge of the lakes, most of the meteorological hazards in Mexico City have been related to inundation (Pérez and Blanco 2010; Romero-Lankao 2010). Aztec civilizations built dams the north of the city to contain overflows that destroyed the city repeatedly in rainy years (Legorreta 2006). The Spanish colony changed this infrastructure to a drainage strategy, which also allowed them to gain land over the lakes (Candiani 2014). The first attempts at a mega-sewage system that was capable of draining all the lakes started at the beginning of the seventeenth century (Romero-Lankao 2010). Since then, the draining system to control floods has been used for water management. Now, the nearly finished 7.5-m-wide and 62-km tunnel (Conagua 2008) is part of the largest and most expensive drainage system in the world (Legorreta 2006). However, this drainage infrastructure has been unable to stop the overflow occurrences in the city (Sosa-Rodriguez 2010). The risk of flood events has resulted in several economic losses and fatalities (Torres et al. 2013), affecting a considerable amount of the 20 million inhabitants (Vargas and Gourbesville 2014).

Mexico City produces 12 000 tons of solid waste every day (SEDEMA 2015). In the rainy season, authorities launched communication programmes on the reduction of waste disposal on the streets. However, rainy seasons are characterized by large storms that fill all the drainage systems in a few minutes (Jauregui and Romales 1996). The structural connectivity between landscape units in Mexico City increases the risk of flooding, given the geomorphological characteristics of the area, as well as the processes that drag sediment from the upper part of the basin to the low areas, where human settlements are located (Kalantari et al. 2017). The water flows through superficial rivers and aquifers from the highlands where the heaviest rain occurs (Ezcurra et al. 2006), discharging at the lowest part of the basin (Garrido et al. 2010), where floods are common. This infrastructure (roads and pipes) accelerates water runoff from the highlands, resulting in

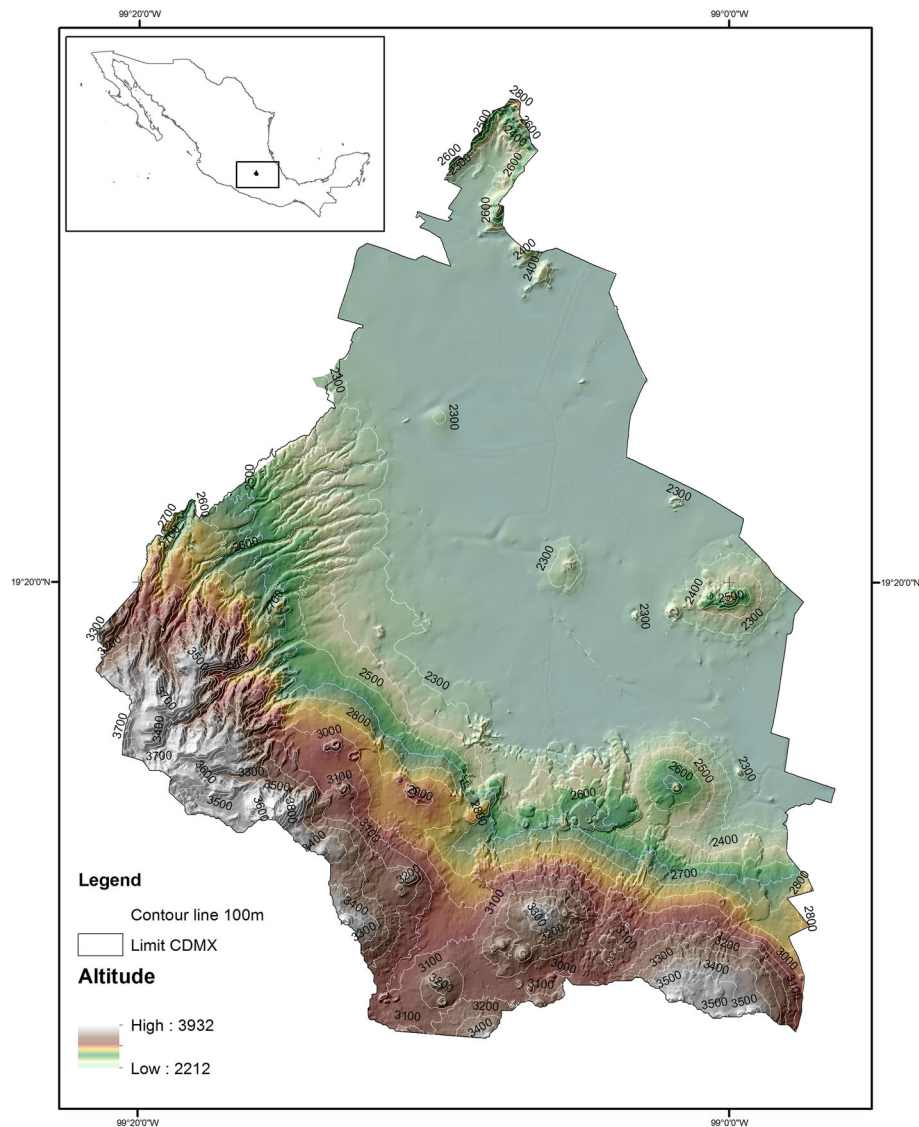


Fig. 1 Mexico City altitudes. Each line covers 100 m

rapid and large inundation events in the lowlands (Chen et al. 2009; Kalantari et al. 2014).

MATERIALS AND METHODS

There are different models and methods to estimate flood risk (Ward et al. 2015). From models able to describe flow hazards in roads (Mazi and Koussis 2006; Kalantari et al. 2014, 2017) to conceptual vulnerability index for coastal cities (Balica et al. 2012). The majority of these models applied complex hydrological modelling, generally using records of rainfall events, runoff and drainage networks (Vargas and Gourbesville 2014). Models predicting water runoff in roads and floods in cities have been generated

using types of soil, land uses, topography and precipitation (Mazi and Koussis 2006; Zambrano et al. 2017) and more recently connectivity of the watershed by water and sediments (Kalantari et al. 2017). In Mexico City, the required meteorological data are not available (Vargas and Gourbesville 2014) as appropriate recording of flood events started in 2005, which is considerably recent.

We used a qualitative method to generate a spatial model that produces areas with different flood risks. To generate this model, we used variables that have a direct influence on inundation dynamics. We corroborated those variables with other models such as the one generated by Pérez and Blanco (2010), who calculated flood risk at Iztapalapa, one of the 16 Mexico City counties; and the ones used by Kalantari et al. (2014, 2017), who developed

a flood probability affecting road infrastructure in Sweden. The variables used to build an algorithm that was translated into a raster map for the flood risk model include the following: (1) solid waste production density per counties (2) altitude, (3) slope, (4) average land subsidence rate, (5) precipitation, (6) green area and (7) flood occurrence. Since the city is a cluster of different administrations, information on some variables such as waste production or flood occurrence is not available for the whole urban area. Thus, the model used only the area named officially Mexico City, which is the capital of the country (previously named Distrito Federal).

Solid waste data were obtained from the Inventario de Residuos Sólidos de la Ciudad de México issued by the SEDEMA (2015) from the period of 2008–2012, which report the mean daily production rates per year for each county within the city. For the analysis, average solid waste daily production for all years and the average flood density of the same period at county level were used.

The altitude and land subsidence of Mexico City were obtained from the Sistema de Aguas de la Ciudad de Mexico (SACMEX) database from 2007, which had 2050 location heights only in Mexico City with a range of 2220–2795 m a.s.l. Kriging interpolations were applied to generate a digital elevation model, slope and average land subsidence rates per year. Altitude records of SACMEX from 1983 to 2007, with two-year intervals from each height location data, were used to calculate the average land subsidence rate per year for all the location heights. Not all stations had complete data for this period. There was no information for three-year intervals for the periods of 1989–1992 and 2002–2005. Precipitation data were obtained from WorldClim with a 30-s resolution (Hijmans et al. 2005).

Green areas were obtained from the Procuraduría Ambiental y Ordenamiento Territorial del Distrito Federal (PAOT 2010) database. The data are regionalized in local neighbourhood areas cluster called “colonias.” Trees per neighbourhood area were used to calculate green area

density. Flood events records from SACMEX for the period of 2005–2012 were used to calculate flood occurrences based on neighbourhood area. We used the flood classification from SACMEX for the data analysis. Since flood data contained information on event size, we categorized floods in two groups: small floods from 1 to 200 m³ (with 8019 events in the city) and large floods larger than 201 m³ (with 1558 events in the city). Categorization was based on the potential risk given by the magnitude of the event, since damage is related to the depth of the inundation. In floods with depths larger than 1 to 2.5 m, there is a substantial increment in the cost of the damage (Notarola et al. 2014). Small floods can occur in any area with small topographical depressions, for instance under bridges. Therefore, we generated two models to evaluate the area at risk by large and small floods. The algorithm for large floods did not use solid waste production density, since these variables were not related. Models and correlations of floods with key variables were made for both groups.

A relation between land subsidence and altitude was tested using an adaptation of the Michaelis–Menten equation. The correlation model was built using R V3.3, where $v = (V_{\max} \times [S]) / (K_M + [S])$. Here, V_{\max} is maximum average subsidence rate, $[S]$ is altitude, v is average subsidence rate and K_M is Half in metres of the highest subsidence rate.

Based on the seven variables described above, we built the model using the following algorithm:

$$FR = \sum (A_{C_i}, SW_{C_i}, P_{C_i}, T_{C_i}, SK_{C_i}, F_{C_i}, SL_{C_i}), \quad (1)$$

where FR is flood risk, A is altitude, SW is solid waste production density, P is precipitation, T is tree density, SK is average land subsidence rate, F is flood density (small or large), SL is slope degree, C is coefficient and i is the coefficient value of each group.

Each variable was divided into a maximum of five ranks, partitioning data into classes based on natural grouping in the data distribution. The standardization was based on a proportional relation between values and ranks,

Table 1 Coefficients based on ranks from each variable used on the flood risk model

Coefficient	Altitude (m.a.s.l.)	Solid waste production density (ton/km ²)	Precipitation (mm)	Tree density (trees/km ²)	Land subsidence (cm/year)	Flood density (flood/km ²)		Slope
						Small	Large	
1	2217–2236	26.8–41.5	1500–1800	5.5–24.3	– 6.8	17.9–46.2	18.4–54.9	0–1
0.8	2237–2256	20.5–26.8	1200–1500	2.6–5.5	– 0.9	9.4–17.9	6.5–18.4	1.1–2
0.6	2257–2275	7.1–20.5	1000–1200	1.2–2.6	– 0.8	4.8–9.4	2.1–6.5	2.1–3
0.4	2276–2300	2.4–7.1	800–1000	0.3–1.2	– 0.7	2.0–4.8	0.6–2.1	> 3.1
0.2	> 2300	0.4–2.4	500–800	0–0.3	0.3–3.8	0.03–2.0	0.00–0.5	N/D

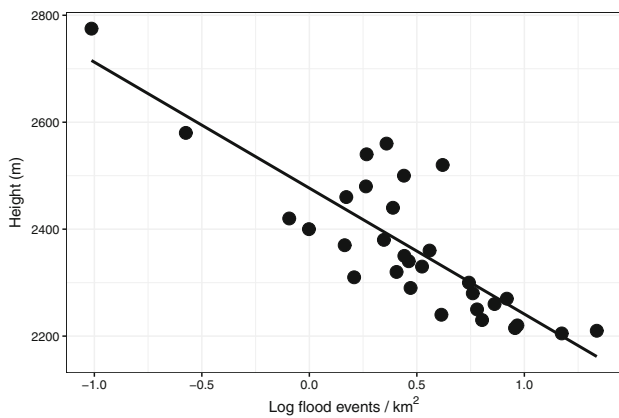


Fig. 2 Relation of altitude and flood events density (Log), which are the number of flood occurrence per unit of area (see text for statistic information)

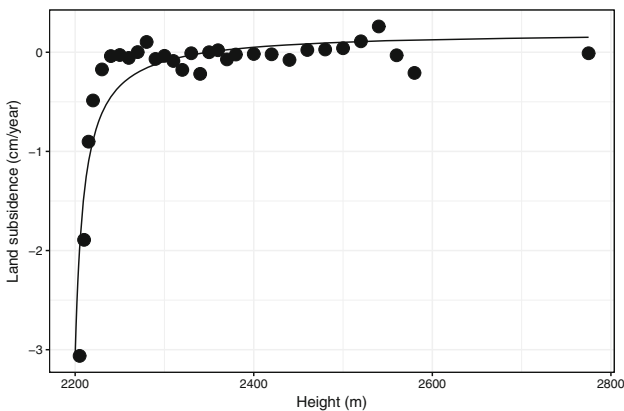


Fig. 3 Relation between altitude and subsidence rate average. Michaelis–Menten equation $v = (V_{\max} \times [S]) / (K_M + [S])$. Values are $V_{\max} = 0.2 \pm 0.08$ cm/year and $K_M = 10.72 \pm 1.98$ m (see text for statistic information)

using geographical information to rank each variable in the flooding process. This partitioning was not applied to altitude and slope, where the natural groupings are smaller in terms of their influence on the flooding process, because Mexico City has large areas with small differences in altitudes—the lowest areas—and small areas with drastic changes in altitude at the highest areas. The ranks were standardized with coefficients between 0.2 (smaller categories) and 1 (highest contribution to floods) (Table 1).

Each variable was transformed into a raster format and applied in the equation with its coefficient (1) to obtain flood risk areas, using map algebra with the software ArcGis 10.1v.

The flood risk value is unitless, and it has a spatial resolution of 100 metres per pixel. A higher value indicates a major flood occurrence. These values were used to generate flood models and were classified into five inherent groups, which were divided by natural breaks using ArcGis

10.1v software. The groups were reclassified into five categories in accordance with the flood risk value as follows: “very low-low-mid-high-very high”.

To evaluate the effect of the flood risk on different sectors of the population, we used the Social development index (SDI) issued by the Sistema de Información del Desarrollo Social (SIDESO 2010). The index categorizes population income as follows: high, mid, low and very low. The SDI was used to assess the population of each income category for each flood in both models.

RESULTS

Both sizes of flood events have a strong decreasing exponential relation with altitude ($r = -0.81$, $r^2 = 0.66$; (Fig. 2)). The lowest altitude range in the basin, between 2220 and 2240 m a.s.l., contained 70% of all flood events. Altitudes between 2360 and 2370 m a.s.l. and 2500–2580 m a.s.l. appear to have more floods than expected, according to the trend (Fig. 2). Four neighbourhoods occur at these altitudes and are next to each other in the south-western region of the city.

Lower altitudes have a higher subsidence rate than higher altitudes (Fig. 3). Additionally, altitudes above 2240 m a.s.l. have subsidence rates close to zero ($RSS = 2.51$, $RSE = 0.29$ and d.f. = 29). The amount of garbage only plays a role in small floods, where there is a strong correlation ($r^2 = 0.70$), compared to its relationship with large floods ($r^2 = 0.25$) (Fig. 4).

The model outcome, using small floods as an input, shows that more than half of the city area is under high or very high flood risks (32% high and 25% very high). In contrast, the category of low flood risk occupies the smallest area of the city at 6% (Fig. 5). In this model, higher flood risk areas are in the central, north-east and south-east sections of the city. These regions are populated counties with large solid waste production facilities at the lowest altitudes. The small flood risk areas are in the eastern and southern sections of the city, mainly at high altitudes (Fig. 6a). More than 67% of the population lives in areas considered as high and highest flood risk areas, and only 5% of the people live in the lowest flood risk areas (Table 2). Nearly half of the people in the high and mid categories on the SDI are living in higher flood risk areas, while the two lowest flood risk categories have a greater proportion of people considered in the low and very low SDI (Table 2).

These results contrast with the model using large floods as an input. In this case, high and very high flood risks occupy a quarter of the territory of the city (high flood risk 19, 9% and very high 5%). This amount is almost the same amount of territory that is occupied by the low and very

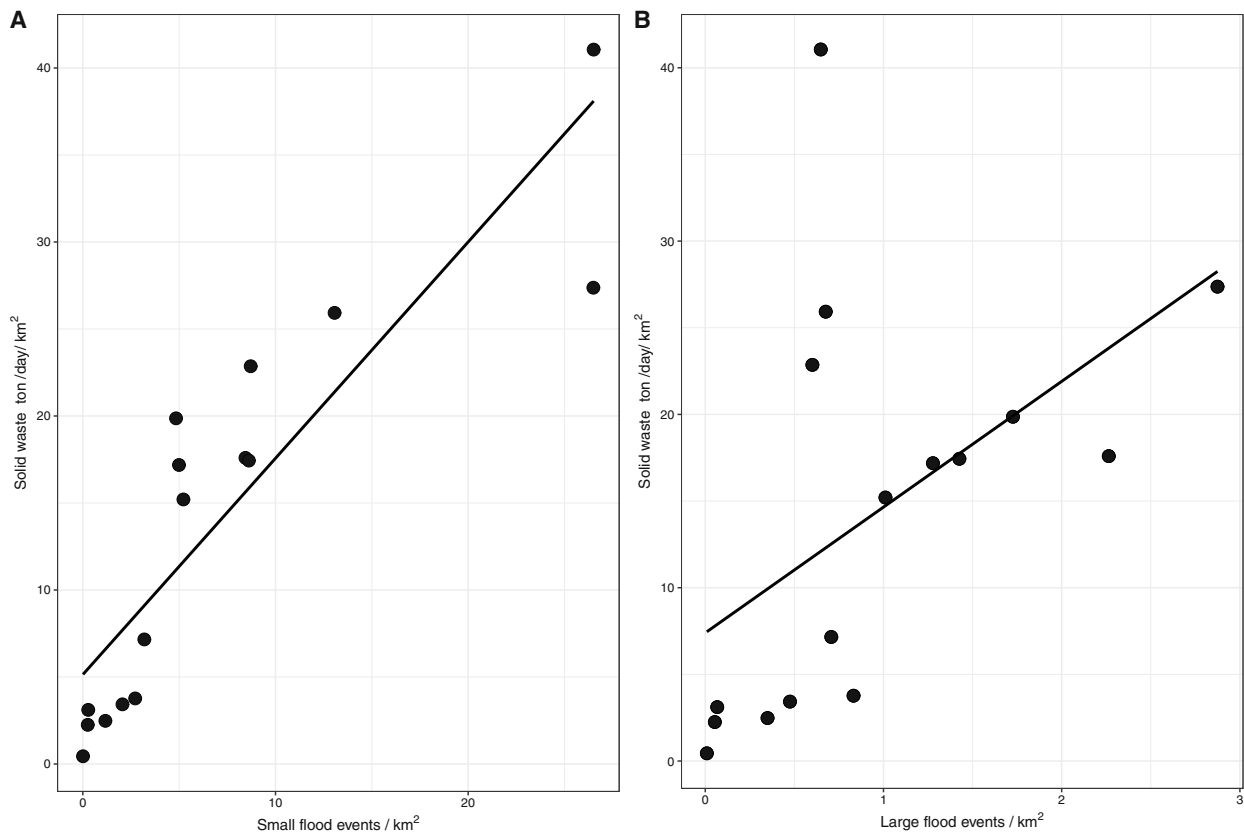


Fig. 4 Relation between solid waste production per day (tons) vs. small (a) and large floods (b) in Mexico City with linear regression (see text for statistic information)

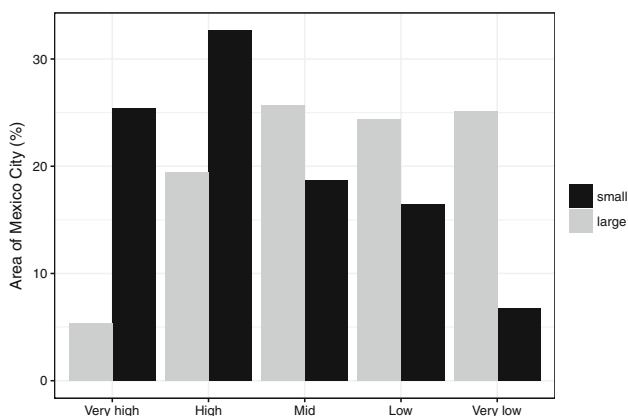


Fig. 5 Percentage of area of the city subjected to small and large flood risks

low flood risk categories (Fig. 5). The highest flood risk values in these models are concentrated in mainly three areas: (1) The south-east region covering the wetlands of Mexico City, (2) the central-west area, in the Pedregal ecosystem and (3) the north-east area, which mainly covers part of the city centre and other populated counties (Fig. 6b). Low-risk categories are almost exclusively in the high-altitude areas, which are common west and north of

the city, predominantly in high mountain western and southern counties. The population distribution along the risk areas susceptible to large floods suggests that very few people live in the highest risk area (2%), while almost one-third of the population (28.5%) lives in an area categorized as having a mid-range flood risk. Nevertheless, each of the remaining categories contain nearly 23% of the population. This model includes most of the flood categories with a greater proportion of mid and low SDI citizens. None of the very low SDI population lives in the highest flood risk areas (Table 2).

DISCUSSION

Results based on the presented model suggest that geomorphology and land use play an important role in urban flood vulnerability (Hallegatte et al. 2013; Klomp 2015), particularly for large floods, which significantly affect the economy of the city in the short term (Haddad and Teixeira 2015). The model, based on available public databases, is useful for evaluating changes in inundation areas across years and can be applied in many cities with similar basic data. More specific models capable of giving quantitative

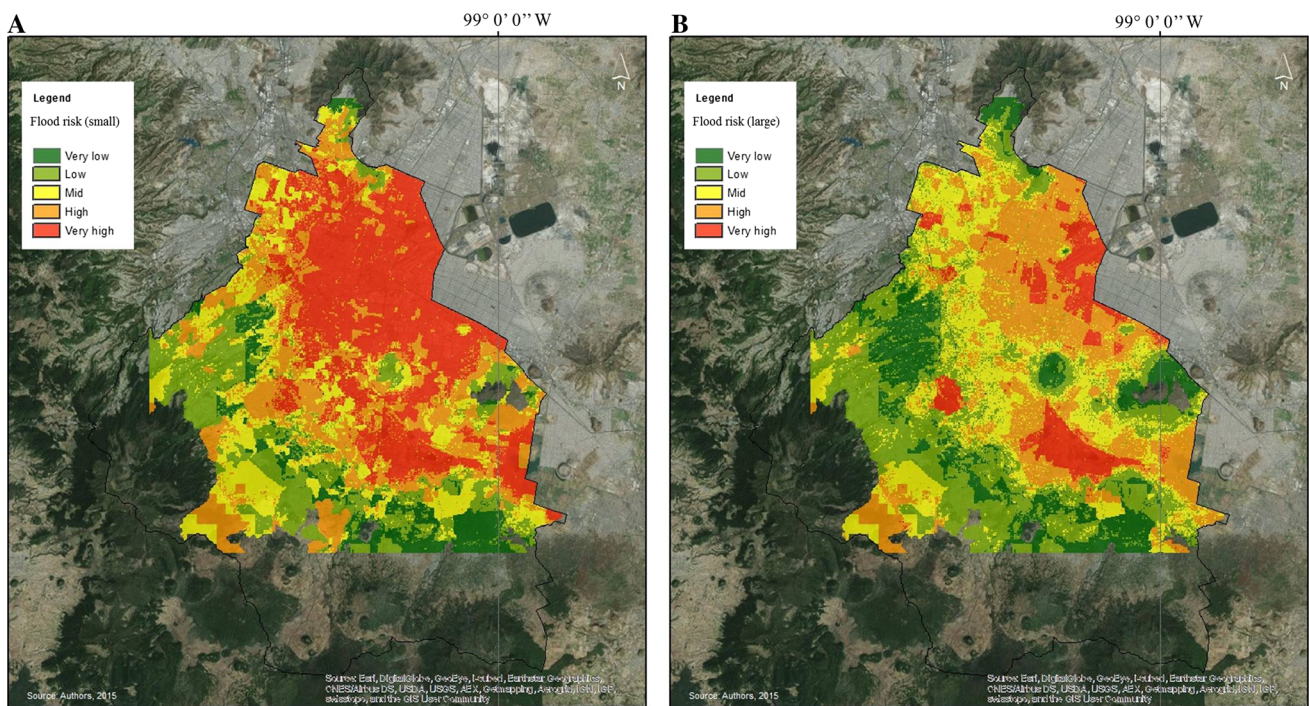


Fig. 6 Flood risk models on the city. Map a is the result from the model using small floods data, while Map b is the result of the model using large floods data

Table 2 Proportion of flood risk at areas with different Social Development Index (SDI) obtained from (Sistema de Información del Desarrollo Social (SIDESO) 2010). Where High SDI represents high wellness decreasing until very low SDI

Flood risk	SDI				Population (%)	Population
	High (%)	Mid (%)	Low (%)	Very low (%)		
Small						
Very high	24.1	36.8	34.1	5	35.3	2 748 933
High	25	26	35.4	13.7	31.5	2 453 550
Mid	25	26.7	38.1	10.2	15.6	1 214 900
Low	7	11.1	46.2	35.8	12.8	996 215
Very low	4.4	24.1	47.1	24.4	4.8	375 774
Large						
Very high	48.3	0.7	50.9	0	2.2	168 517
High	14.2	43	36	6.8	22.6	1 758 475
Mid	31.6	27.2	34.4	6.8	28.5	2 222 850
Low	26.7	40	21.4	12	23.2	1 809 016
Very low	8	44.8	16.7	30.5	23.5	1 830 514

information are difficult to build, since they require information that not all cities have. However, the model does not include drivers such as the runoff capacity of sewers and pipelines that run along the city, which generates a gap in the information obtained. Nevertheless, the watershed large-scale approach tries to minimize these gaps, and the information used is helpful to understanding watershed dynamics and flood risk areas. Thus, although this model

gives qualitative information, it helps provide an assessment for land-use management.

The altitude within the watershed is one of the most important drivers for all floods. Land subsidence has also become an important factor affecting flood occurrence. This factor is particularly important in coastal cities that are affected by floods that are caused by different factors depending on the watershed where the city is based. For

example, in New Orleans, land subsidence had increased before Hurricane Katrina, resulting in an increased vulnerability to this meteorological hazard (Dixon et al. 2006). In Semarang, Indonesia, aquifer overexploitation affects and modifies the soil structure, increasing subsidence rates (Marfai and Lorenz 2007). Mexico City appears similar to coastal cities that have highly complex geomorphology and meteorological dynamics (Balica et al. 2012), mostly because of similarities in land-use changes and land subsidence (Holzer and Johnson 1985). Areas with altitudes lower than 2240 m a.s.l. seem to have increased subsidence rates; as a result, they will be more susceptible to inundation in the future. Land subsidence generates other negative effects such as soil instability, which increases the vulnerability of a city to earthquakes, such as the buildings of Mexico City that have been affected by recent events.

Flood risk areas in Mexico City, such as the northeast of the city, have the lowest altitude and the fastest land subsidence rates and have the largest amount of solid waste in the area. Areas susceptible to high-risk inundation based on this model should be analysed more in-depth to reduce vulnerability. For instance, the international airport is located in the region that was occupied by the largest of the five lakes (Ruiz-Angulo and López-Espinoza 2012). As a consequence, the two highest flood risk categories for both flood models in this region occur there, increasing the vulnerability of the economy of the city. In contrast, the other large flood risk area in the southeastern region of Mexico City is a protected wetland that serves as a buffer for floods (GODF 2006), among other ecosystem services (Ibarra et al. 2013; Merlín-Uribe et al. 2013). Nonetheless, all wetlands in the city are threatened by urban sprawl (Merlín-Uribe et al. 2012).

Another example of the influence of land use on flood vulnerability is given by the model results for south of the city. This region with high altitudes is categorized as a high flood risk area by both models. This area has experienced changes to topography caused by volcanic lava runoff. The cracked volcanic rock should allow fast infiltration into the aquifer (Lot and Cano-Santana 2009). However, the increasing flood vulnerability is caused by urbanization soil sealing, as concrete reduces water infiltration capabilities of the region. However, within this area, there is a small (237 ha) ecological reserve that reduces the flood vulnerability of the surrounding areas (Scott et al. 2015). These results show the importance of naturally flooding or infiltrating areas to reduce vulnerability to flood events, and these areas can be seen as opportunities for cities to adapt to their local environment rather than to become urbanized.

Small floods in the city are related to solid waste production, which means that a proper solid waste disposal programme may be useful. However, as landscape characteristics also contribute to small floods, these will not

disappear, even if there is a reduction of waste blockages in the sewage systems. Therefore, a different management approach, where multiple stakeholders decide with models that describe and predict floods hazards, using geophysical and climate change information for watersheds, should be considered to reduce urban vulnerability (Tingsanchali 2012).

Economical differences within a city can be related to flood vulnerability (Sanderson 2000). Populations with a lower SDI are normally in higher risk areas (Tucker et al. 2015). However, the results show that both type of flood and size similarly affect lower and higher economic level SDI. Since Mexico City was settled near the lakes and its inshore areas have the highest population densities, the city is occupied by people with the range of rank SDI values (INEGI 2010). Therefore, 66% of the population lives in areas with a high risk of small floods, and almost a quarter of the population lives in areas with a high risk of larger floods. Peripheral areas, at high altitudes, are where new urban sprawl is occurring, including people with low and high income. This phenomenon can be explained because floods are not the only hazard in the city, earthquakes also affect urban development. Therefore, colonized areas of the city respond to complex social-economical dynamics partly shaped by different types of vulnerabilities.

CONCLUSION

Flood hazard vulnerabilities of cities are highly related to the hydraulic dynamics of the watershed based on its geomorphology, the land use and aquifer exploitation. A model, such as the one presented in this research, can help evaluate the most vulnerable urban areas for inundation; therefore, it is possible to take actions in terms of land use. This type of model does not look for the precise amount of water that generates flooding but to provide information about flood vulnerability for different regions within a city. The outcome of the model helps to initiate discussions about land-use management, water management and economic inequality in urban areas. To do this, it is necessary to shift perspectives of water management from protection to managing floods by considering the natural characteristics of the landscape, not only water infrastructure or solid waste disposal. Furthermore, city management must create proper land-use developments to reduce flood vulnerabilities in different areas.

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