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Methodological framework for territorial planning of urban areas: Analysis of socio-economic vulnerability and risk associated with flash flood hazards

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1. Introduction

Floods are complex natural hazards that result from an interaction among extreme hydrometeorological phenomena, geomorphological predisposition, and anthropic susceptibility. They are considered the most frequent phenomenon with the greatest destructive effects worldwide due to their recurrence and detrimental impact on the population (UNDRR and CRED, 2020). Specifically, flash floods are among the most significant socio-natural hazards to human life and economic activities on an urban and sub-urban scale (Shahabi et al., 2021). However, despite these phenomena being numerous, records of flash floods are scattered, local, and little known or understood in terms of the particularity of their characteristics and destructive effects. International statistics do not show specific systematic records, and flash floods are included in the category of floods in general (UNDRR and CRED, 2020).

Flash floods are water flows that invade low, concave, and sub-horizontal areas, caused by torrential rains in short periods, in areas generally smaller than 6 ha and basins smaller than 500 km^2 (Norbiato et al., 2008). Soil saturation and subsurface flow are not much involved in water circulation. Runoff depends almost exclusively on the surface water flow generated when rainfall intensity exceeds the soil's infiltration capacity (Camarasa, 1992). Although these phenomena are typical of semi-arid and arid areas, they also occur in urban areas in tropical and temperate regions associated with sub-basins where runoff, infiltration, and evapotranspiration patterns have been altered by urban growth (Hermas et al., 2021; Khosravi et al., 2019; Moore et al., 2005).

Flash floods are becoming more frequent, especially in medium-sized cities in underdeveloped countries without long-term urban planning (Kapović Solomun et al., 2021; Schroeder et al., 2016), and both natural and anthropic causes are involved in their origin and behavior (Khosravi et al., 2019). Due to inhibition of infiltration induced by the increase in impervious surfaces and shorter flow concentration time, runoff in cities increases rapidly in volume and speed after extraordinary rains (Xia et al., 2011). The disorderly human invasion in flood zones within urban areas and the relative increase in runoff produce higher volume flows that often exceed the capacity of the drainage network, whose maintenance is often inadequate or non-existent in developing countries (Bayazıt et al., 2020; Hofmann & Schüttrumpf, 2019). Despite this, a holistic analysis of flash flood processes at an urban scale is one of the challenges recognized by the scientific community (Aroca-Jimenez et al., 2020; Hermas et al., 2021; Hofmann & Schüttrumpf, 2019).

Flash floods can result in risk and disaster whose origin is not related only to the natural phenomenon per se, since disaster situations start with other latent or potential conditions that generate exponential damage. Risk and disaster analysis have multiple definitions, depending on the scientific discipline that proposes them. Recently, it has been a generalized perception that risk and disasters are not natural and result from the different response capacities of affected social groups (Romero & Maskrey, 1993). From this perspective, the conception of risk and disaster recognizes that a hazard differentially affects the normal functioning of a social system and its component subsystems.

Since the end of the 20th century, the view of natural risks and disaster management in Latin America has gradually changed, bringing an understanding that responses to the same natural hazard differ depending on the historical moment when it occurs (Lavell, 2005). The concept of local risk management has been incorporated, seeking to move from administration and remediation of risk to comprehensive prevention strategies based on a corrective and prospective vision (McDaniels et al., 1999).

The new conception of risk and disasters is understood as a dynamic social construction that can change territorial expression over a short time and where all the affected social groups must be involved in its management (Cardona Arboleda, 2005, p. 231; Maskrey, 1998). A minor

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hazard or risk, apparently harmless due to its intensity or duration, may have cumulative effects; its spatiotemporal expression changes depending on the territorial characteristics and socio-economic conditions. Hazards of different origins occurring in the same area may interact and exacerbate each other (Romero & Maskrey, 1993).

Therefore, an understanding of flash floods as a risk and potential disaster should be based on a holistic analysis of the relationship between the behavior of the natural phenomenon and anthropogenic effects on exposure degree, socio-economic fragility, and lack of resilience; i.e., a socio-natural perspective.

Efforts have been made to analyze risks and disasters from such a socio-natural perspective. One is a multicriteria evaluation based on the analytic hierarchy process (AHP) (Saaty, 1987; Saaty & Vargas, 2001). This methodology was designed to choose indicators within a system of weighting factors to calculate the overall value of all concurrent impacts in a measurement period based on three principles; decomposition, comparison, and integrating priorities (Malczewski, 1999).

Selecting parameters to construct indices starts with a dataset of urban socio-economic and socio-natural variables that can be expressed spatially and are related to the process under analysis (Cardona Arboleda, 2005, p. 231). The variables are classified into sub-indicators, indicators, and indices that can be combined in synthetic maps showing the spatial distribution of hazards and vulnerability to a process, such as flash floods in urban environments. Relevant indicators are selected through expert knowledge based on systematic and scientific observations (Saaty, 1987). This expert knowledge includes observations about the process's regularities, principles, and measurable behaviors.

Implementing the AHP methodology allows for integrated interpretations that facilitate strategy design that identifies risk elements and proposes policies that include microeconomic, social, and physical-geographical aspects to strengthen the capacity to face and recover from the negative impacts of hazardous phenomena (Kienberger et al., 2009).

Our approach was developed based on AHP, a conceptual and methodological Framework that enables flash floods to be analyzed from a socio-natural perspective through the following objectives: 1) to construct a flash flood hazard index (FfHi) that combines the magnitude intensity, frequency, and persistence of the natural process through fieldwork data collection and bibliographic revision; 2) to design the socio-economic vulnerability index (SVi) with statistical data that identify the socio-economic characteristics of the population affected by the natural process; 3) to territorially link natural and socio-economic characteristics through a risk index (Ri) that enables priority areas for attention to be identified through interpretable and systematically weighted data, strengthening local planning and efficient responses in emergency scenarios.

2. Materials and methods

2.1. Study area

The city and metropolitan area of San Luis Potosí (SLP) lie in the north-central part of Mexico at 100° 59′ W by 22° 09′ N (Fig. 1) at an average 1873 masl elevation in a semi-desert climate with summer rains (INEGI, 2002b). SLP is located within a graben with an irregular basement and a high geomorphological and sedimentological predisposition to flooding (Labarthe-Hernández et al., 1982, pp. 1–280). In hydrogeomorphological terms, most of the SLP is located on fluvio-palustrine plains within an endorheic basin fed by two rivers partially controlled by dams and canals, which are often exceeded in capacity when heavy rains occur.

The average annual accumulated precipitation amounts to 370 mm per year, which would not pose a flood hazard; however, the flash floods in study area are related with the torrential behavior of precipitation (INEGI, 2002). For SLP the most frequent maximum rainfall is around 38.3 mm/h in June and 44.6 mm/h in July, considered very heavy rainfall (Alhassan & Ben-Edigbe, 2010, p. 7; Gobierno de España, 2015).

2.2. Areas affected by flash floods

In SLP, the civil protection agency has characterized the various flood zones as "sites affected by runoff" and "flood zones" (CONAGUA, and UASLP 2009). The first are streets that are usually waterlogged, which mainly affects motor vehicle traffic within the city. The second are areas where water remains and damages homes, businesses, and other assets.

The sites that constituted the fieldwork areas were selected from "flood zones", and verified through reports from emergency measures, fire departments, newspaper articles, news, social media reports, and direct communication with the population, resulting in a list of 43 sites where recurrent floods have occurred. These sites were visited during fieldwork to verify and measure the magnitude, frequency, intensity, and persistence of flash floods through direct methods.

These direct methods consisted of measuring watermarks, mud, debris, and the amount of trash suspended in and on fixed objects.

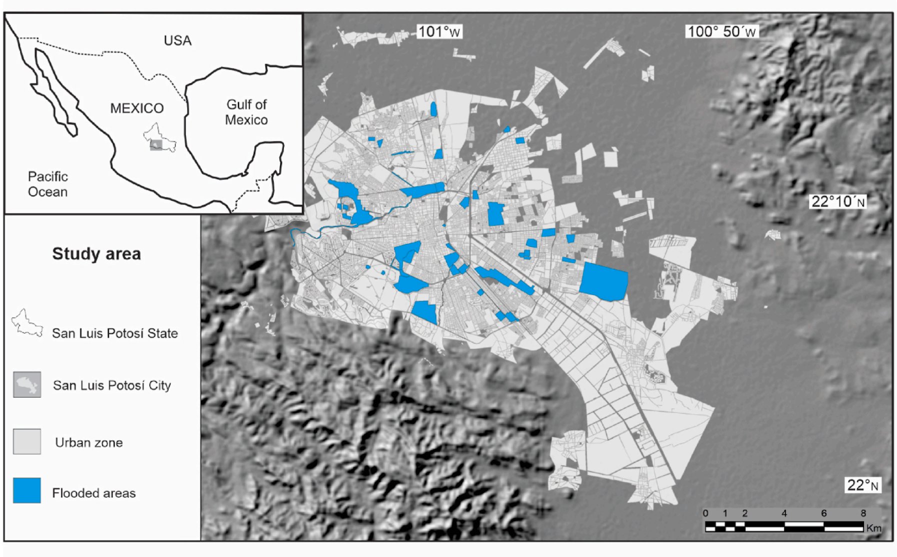

Fig. 1. Study area.

Interviews were also conducted with local inhabitants whose properties and homes have been affected to record their experiences and the strategies implemented to cope with flash floods in SLP.

2.3. Selection of indices and indicators to build the hierarchical analytical process

The indices are based on verifiable, reliable, easily accessible technical, empirical, documentary, historical, and statistical data collected directly and indirectly. The spatial interpretation was carried out through geographic information systems (GIS). The selected indicators were grouped into two indices; flash flood hazard (FfHi) and socio-economic vulnerability (SVi) (Table 1). The magnitude of the process was used to identify the flash flood's spatial patterns and select the sites to be analyzed and verified during fieldwork.

Each set of sub-indicators, indicators, and indices was organized in a model that transformed quantitative and qualitative values from a matrix to their spatial expression. Every index becomes a raster layer, and every analytic map eventually becomes a spatially differentiated response. The methodology (Fig. 2) was carried out with the Weighted Overlay and Map Algebra GIS-ArcMap modules.

2.4. Flash flood spatial patterns: magnitude of the process

Land use, particularly in urban environments, can impact and increase the severity of a flash flooding event (Castillo et al., 2003; Leopold, 1968; Martínez-Mena et al., 1998). The magnitude indicator explains the extended spatial pattern of flash floods, magnified by the increased impervious surfaces in SLP (Moreno Mata et al., 2016). This condition causes extraordinary flows from the adjacent hills with different speeds and dispersion, depending on the urban development of the neighborhoods.

The extent of floods was identified in official reports (CONAGUA and UASLP, 2009). This data was used as a magnitude indicator for selecting the 43 sites to be analyzed and verified during fieldwork. Magnitude is not part of the flash flood hazard index (FfHi); however, it is a parameter that enables us to understand the territorial patterns of the hazard in a given place.

2.5. Flash flood hazard index: frequency, intensity, and persistence of the process

The flash flood hazard index (FfHi) characterizes the behavior of minor flash floods that chronically affect an area at the local level. This index is based on the characterization and relative concentration of flash floods' destructive or modifying effects in urban settings. It is composed of normalized values of three process-related indicators; frequency, intensity, and persistence.

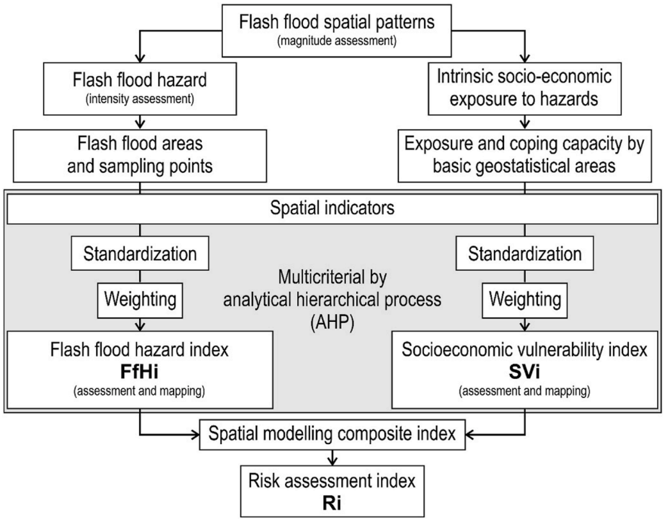

Fig. 2. Methodological Framework for mapping hazard, vulnerability, and risk of flash floods.

Frequency measures the number of events directly affecting each of the 43 analyzed sites in a given period. It reflects the incidence of flash floods associated with specific natural and artificial conditions that cause them. The frequency assessment enables the relative importance of flash floods to be assessed by comparing the repetition and fieldwork registers of the events. The frequency index (Fi) is calculated and normalized using the following equation:

$$Fi = \frac{[Fp - Fmin]}{[Fmax - Fmin]}$$

where:

Fi = frequency index
Fp = frequency of flooding at the measurement point
$Fmax$ = maximum frequency of floods
$Fmin$ = minimum frequency of floods

Intensity is the most prevalent indicator and identifier of floods. It measures the depth of the flood and its destructive effects in a proportional relationship. Various studies identify water depth as the flood characteristic that most significantly influences flood damage

Table 1
Selected indicators to build the flash flood hazard index (FfHi) and socio-economic vulnerability index (SVi).

Index	Indicators	Sub-indicators	Spatial unit	Methods/Data	
Flash flood spatial patterns	Magnitude		Flood zones and flood sample points	Analytical hierarchical process by matrix (AHP), Standardized and Ranking	*Direct*/Historical record of point sampling in the fieldwork and CONAGUA and UASLP (2009). *Indirect*/Interpolation of point samples weighted by inverse distance (IDW)
Flash flood hazard ***(FfHi)***	Normalized values of: Frequency Intensity Persistence		Flood zones and flood sample points		
Socio-economic vulnerability ***(SVi)***	Physical exposure	Average annual population growth Average annual occupancy of housing	Basic geostatistical areas (BGA)		*Indirect*/Interpolation of point samples weighted by inverse distance (IDW) *Indirect*/Official socio-economic statistics of the local population
	Socio-economic Fragility	Occupancy rate of the population Unemployment rate			
	Lack of resilience	Percentage of population covered by health services Population concentration of purchasing power			

(Penning-Rowsell et al., 1994). The intensity index is proposed to characterize the hazard of flash floods. Depth values recorded at the 43 analyzed sites are normalized to the overall data to identify the relative importance of individual data. The following equation yields the intensity index (Ii):

$$Ii = \frac{[Ip - Imin]}{[Imax - Imin]}$$

where:

Ii intensity index
Ip = depth of the flood recorded at the measurement point
Imax = maximum depth of floods
Imin = minimum depth of floods

Persistence refers to the average time that flash floods last and their relationship to the flood's direct and indirect destructive effects. Duration is a parameter related to flood intensity and the rate of rising water (Begum et al., 2007; Wind et al., 1999). The persistence index (Pi) was calculated by normalizing the residence time of the flood at each of the 43 analyzed sites based on the other recorded persistence values to account for the intrinsic importance of each record collected during fieldwork.

$$Pi = \frac{[Pp - Pmin]}{[Pmax - Pmin]}$$

where:

Pi = persistence index
Pp = duration of flooding at the recorded point
Pmax = maximum duration of flooding
Pmin = minimum duration of flooding

The flash flood hazard index (FfHi) summarizes the multiple characteristics of the hazard of flash floods in a single parameter based on the relative importance of the indices. It is a complex index formed by the harmonic mean $= \frac{1}{n}(x_1 + x_2 + \ldots + x_n)$ and is appropriate for situations when the average of data is desired. However, it aims to retain information from high values and not eliminate their influence on the harmonic mean. The three indicators included in the index are frequency, intensity, and persistence:

$$FfHi = 1 - [Fi * Ii * Pi]^{1/3}$$

The FfHi map is based on normalized and weighted indicators that contribute in different degrees of importance and spatially express three hazard levels; high, medium, and low.

2.6. Socio-economic vulnerability index

The socio-economic vulnerability index (SVi) (Birkmann et al., 2013; Cardona Arboleda, 2005, p. 231) was implemented to identify the condition of the population and their exposure to flash floods. The SVi consists of three indicators that use official information on the economy and state of the population at a given time. The three indicators were as follows:

1. Physical exposure indicator (I_{PE}): reflects the degree of physical exposure of economic assets and people through indicators of the susceptible population, investments, infrastructure, production, livelihoods, essential assets, etc. In this study, the following indicators were selected:

a. *Average annual population growth 2000–2010 (AAPG)*: Displays specific areas with the highest population growth. This indicator shows the historical trend in population growth, not at one particular moment. The following formula applies:

$$AAPG = \left[\left[\sqrt{TTP_2/TP_1})\right] - 1\right] * 100$$

where:

T: period between TP_1 and TP_2
TP_1: total population at the beginning of the period analyzed
TP2: total population at the end of the period analyzed

b. *Average annual housing occupancy 2000–2010 (AAOH):* This parameter shows the relative occupation of dwellings; that is, whether urban spaces have migrated from one residential use to another or if houses have been for various reasons abandoned. It is calculated with the following formula:

$$AAOH = \left[\left[\sqrt{TOH_2/OH_1})\right] - 1\right] * 100$$

where:

T: period between OH_1 and OH_2
TP_1: total occupied homes at the beginning of the period analyzed
TP2: total occupied houses at the end of the period analyzed

2. Socio-economic fragility indicator (I_{SF}): Reflects the weaknesses or deterioration of the socio-economic condition of the population, which can magnify the destructive effects of natural hazards. It comprises parameters of poverty, social security, economic dependency, illiteracy, social inequality, and unemployment, among others.

a. *Occupancy rate of the population (ORP):* This shows the percentage growth of the economically active population that works at least 33 h per week. If more people have paid jobs, the population is economically less vulnerable:

$$ORP = \frac{EAP_{(<33hs)}}{EAP_{(TOTAL)}}$$

where:

EAP $_{(<33hs)}$ = economically active population working at least 33 h a week.
EAP $_{(TOTAL)}$ = total economically active population.

b. *Unemployment rate (2010) (UR):* Defined as the proportion of the unemployed population within the economically active population. It is assumed that if the unemployment rate is lower, the level of economic development is higher. It is summarized in the following formula:

$$UR = (UP \,/\, EAP) * 100$$

where:

UR = unemployment rate
UP = unemployed population
EAP: economically active population

3. Lack-of-resilience indicator (ILR): Reflects the ability of a social group to recover from or absorb the impact of dangerous phenomena, regardless of their nature or severity. Its parameters are related to the level of human development, economic redistribution, governance, financial protection, and preparedness to deal with a crisis. These indicators are included in the overall vulnerability calculation with an inverse complementary treatment, which identifies reduction of vulnerability as an increase in resilience (Lavell et al., 2012).

a. *Percentage of population covered by health services (PPCHS):* The percentage relationship between the population entitled to health care services and the total population. Access to government health services increases the ability of a community to cope with and overcome a hazardous event.

$$PPCHS = \frac{PCHS}{TP}$$

where:

PCHS = population entitled to health services
TP = total population

b. Concentration of purchasing power of the population (*CPPP*): It indirectly shows the economic capacity of the people in a given territory; the higher the percentage of the population receiving higher income, the higher the level of economic development and their ability to respond to the hazard of a phenomenon.

$$CPPP = \frac{EAP_{(<2MW)}}{EAP_{(TOTAL)}}$$

where:

EAP $_{(<2MW)}$ = economically active population that earns more than twice the minimum wage
EAP $_{(TOTAL)}$ = total economically active population.

The socio-economic vulnerability index (SVi) is calculated using the harmonic mean so as not to lose information contributed by the highest values. In the following equation, the spatial expression of the socio-economic vulnerability is summarized holistically:

$$SVi = 1 - [I_{PE} * I_{SF} * I_{LR}]^{1/3}$$

All calculations are based on the corresponding basic geostatistical areas (BGAs) determined by the National Institute of Statistics and Geography (INEGI, for its initials in Spanish), the government agency responsible for providing official social and economic statistics for all regions of Mexico, including spatial information. The BGAs are georeferenced units with demographic, social, and economic statistical data generated by the INEGI from censuses and surveys.

The socio-economic vulnerability index (Svi) map shows the spatial expression of the distribution of urban development, social fragility, and the economic capacity of the population to cope with hazards in areas affected by flash floods. In practical terms, socio-economic vulnerability is evident indirectly through urban morphology and deterioration of the city infrastructure after extreme events. The Svi expresses the relationship between flash floods that generate damage and the economic capacity of the population and their coping strategies to improve recovery.

2.7. *Complex flash flood risk assessment index*

In this study, risk assessment is considered a socio-natural process resulting from the interrelationship between the detrimental effects of natural hazards and the differential capacity of social groups to cope with them.

Risk assessment can be synthesized from two parameters: the behavior and destructive effects of socio-natural hazards, and the historical accumulation of vulnerability (Birkmann & Wisner, 2006; Merz et al., 2010; Wisner et al., 2003). A normalized value of the potential damage resulting from the conceptual equation of the flash flood risk index (Ri) is composed of the arithmetic average of its two components:

$$\boldsymbol{Ri} = \frac{FfHi + SVi}{2}$$

3. Results

3.1. *Magnitude*

The spatial pattern of flash floods in SLP is concentrated or clustered. The highest values were found to be focused in the eastern part of the city (Fig. 3), where the elevation is lowest (1840 masl). In terms of hazard, it can be inferred that the conditions that favor deeper flooding are concentrated in small areas.

3.2. *Flash flood hazard index*

The FfHi map (Fig. 4) highlights areas where extraordinary flash floods cause frequent damage, affecting urban infrastructure and the local population. Of the 238 km^2 covered by the urban and suburban area of San Luis Potosí, 15.4 km^2 (Table 3) present some degree of hazard. That is, flash floods can potentially affect 6.5% of the territory. The weighting of the indicators enables 41 areas to be distinguished, with varying degrees of hazard, which reflects the high recombination of parameters and indirectly reflects the causes for the hazard at a specific level.

The largest proportion (57.8%) of the hazard area is in the lowest degree of hazard, where low intensities, low persistence, and low frequencies predominate. The persistence of flooding ranges from 10 to 20 min, with intensities of around 10 cm deep. Flows are turbulent on slopes steeper than 10°. The recurrence of the phenomenon is at least one flood every two years. It occurs in zones affected by torrential water flows, causing damage to road infrastructure and occasionally causing indirect injuries to the population due to traffic accidents or to mud, debris, and garbage carried by the water.

The zones with a medium degree of hazard are transition areas with a total area of 1.4 km^2, located at the feet of hills, where persistence begins to present larger values of between two and 4 h. Generally, these areas are fringes of topographic inflection between the hills and the plains that quickly reach the lower areas with a difference of 50 m of topographic elevation.

The highest-hazard zones cover 5.9 km^2 (32.9% of hazard areas). These areas are at the bottoms of the flood plains in the valley, with hydromorphic soils. Due to insufficient drainage and lack of maintenance, flood depths of up to 50 cm are reached with an hour of rain. The water is concentrated in less than 12 min and can remain for up to 48 h (Table 2). Extraordinary cases have occurred, such as in 2008 when neighborhoods in the suburban area were flooded for five days by persistent rain, with 46.5 mm accumulated in one day. These areas are where the most significant and most recurrent damage occurs, with up to 9 floods per year.

In practical terms of urban planning, it is necessary to know the probability that a phenomenon will be repeated, and its magnitude and intensity. This is known as the probability of occurrence or exceedance of a phenomenon, where the value "p" is the probability $p = 1-(1-p)^n$ that a phenomenon of specific intensity is repeated within n years.

The probability that a flood will exceed the maximum FfHi level (0.9), where all parameters are extreme, is 10% per year; this percentage implies that although these intensities are somewhat recurrent, there is always a possibility that it will occur at least once a year. For low FfHi levels (0.1), the probability is 90%, which means it is highly probable that most occurrences of floods will be of low intensity. For average hazard levels between 0.4 and 0.6, the annual occurrence probability ranges from 30% to 35%; at least three out of ten floods could reach this FfHi level.

3.3. *Socio-economic vulnerability index*

The SVi map (Fig. 5) shows that high values of SVi cover 34.5% of the affected areas, which means that more than a third of the hazard territory shows a high level of intrinsic exposure. These low-income housing

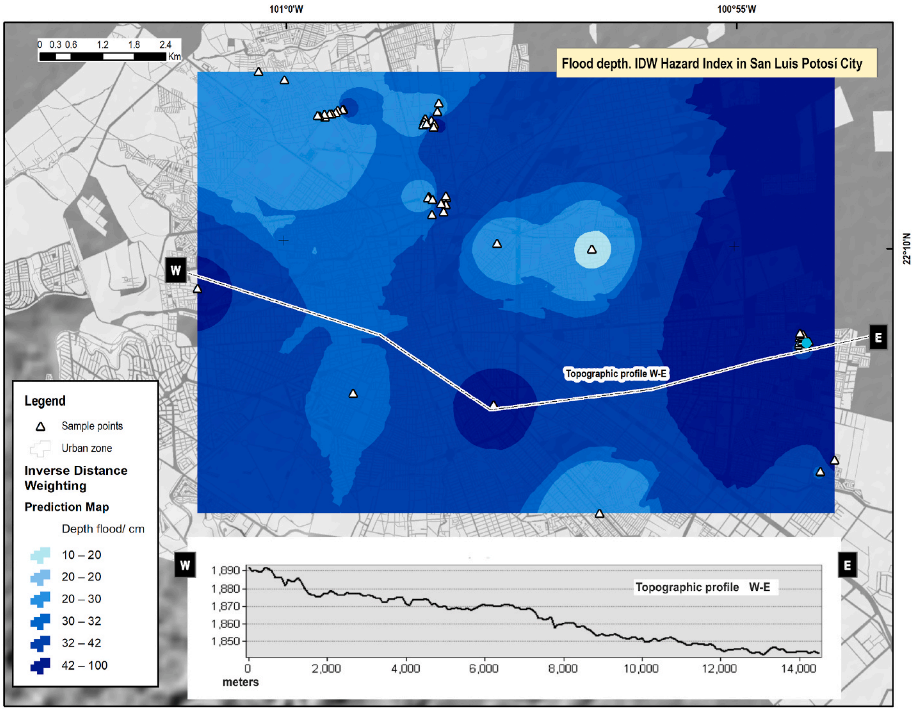

Fig. 3. Interpolated depth measurements (intensity-based magnitude) of flash flooding in San Luis Potosí.

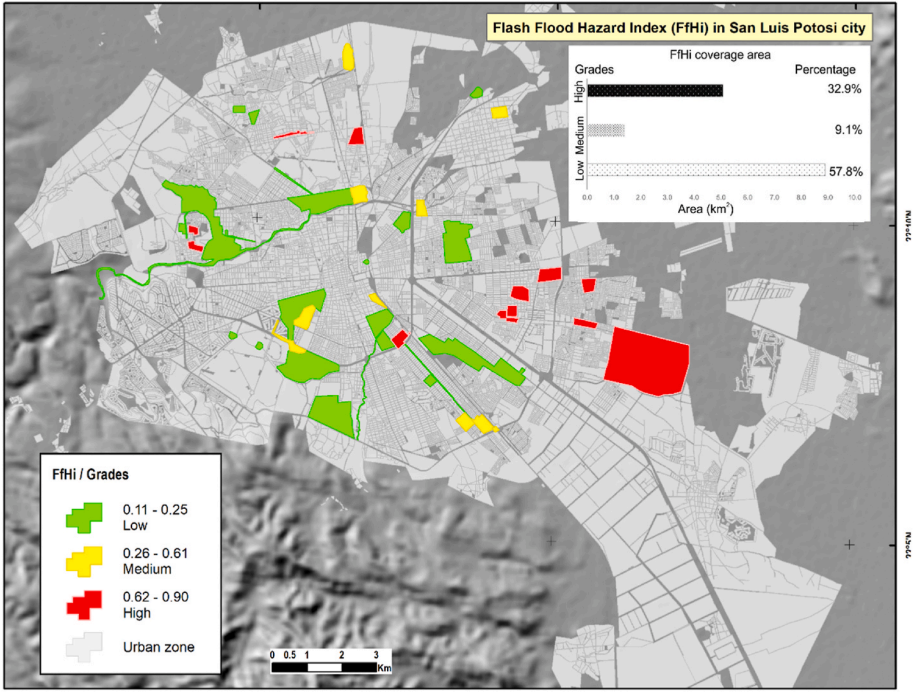

Fig. 4. Flash flood hazard index (FfHi) map.

areas should be equipped with a high-level emergency alert system with minimal urban infrastructure.

The zones with medium SVi values cover 28% of the affected territory and show a flexible economic response to coping with extreme events. Residents partially resolve the destructive effects of flash floods in their homes but require municipal support to restore the drainage system. Most of the population has middle-class housing, government health services, average population densities, and functional urban infrastructure, giving it a moderate degree of recovery capacity.

The areas with low SVi values cover 37.5% of the territory affected by flash floods and have greater chances of recovering from a disaster due to an extreme phenomenon because these are areas where there is lower population density, where the type of housing is medium and high income, the economic capacity for recovery is high, and urban infrastructure is functional.

The spatial variability of the socio-economic conditions of the population is evident in the 133 areas differentiated by degrees (Table 3) within the areas affected by flash floods. This spatial fragmentation

Table 2
Evaluation indicators and sub-indicators for flash flood hazard index (FfHi).

	Fd	Dr	Fi	Ii	Pi	EfHi	A
Total							**15.40**
Minimun	10.0	0.20	0.11	0.20	0.004	0.11	0.01
Maximum	50.0	48.00	1.00	1.00	1.000	0.90	3.51
Mean	24.4	4.96	0.29	0.49	0.100	0.28	0.15
Median	20.0	0.40	0.22	0.40	0.008	0.38	0.14
Standard deviation	14.7	9.97	0.25	0.29	0.208	0.30	0.71
Total areas for all degrees.							**41**

Fd = Flood depth (cm); Dr = Duration (hr); Fi = Frequency; Ii = Intensity; Pi = Persistence; FfHi = Flash flood Hazard Index; A = Area (km^2).

Table 3
Evaluation indicators for socio-economic vulnerability index (SVi).

	I_{PE}	I_{SF}	I_{LR}	*SVi*	Area (km^2)
Total					14.65
Minimun	0.55	0.10	0.54	0.48	0.01
Maximum	1	0.55	1	0.99	2.41
Mean	0.64	0.34	0.69	0.62	0.11
Median	0.59	0.36	0.69	0.59	0.04
Standard deviation	0.13	0.12	0.07	0.13	0.25
Total areas for all degrees		133			

shows the disorder in urban growth during the last three decades. The exposure patterns are random and diverse because of the absence of patterns in the urban structure.

The probability that a given area will be affected according to its vulnerability, particularly in highly vulnerable areas with indices between 0.7 and 1, does not exceed 10%. This implies a low probability of effects in these areas; however, if intrinsic exposure (SVi) is compared with the intensity of the phenomenon (FfHi), it will be seen that low vulnerability implies some degree of social fragility and coincides with an area of high levels of hazard, and therefore of risk. Hence the need to consider the importance of even low probabilities in the context of inclusive urban planning. Less vulnerable areas have a high probability (90%) of being affected in a given year, confirming that exposure is concentrated in small areas that are highly fragmented according to their socio-economic status.

3.4. *Risk index*

The map of Ri (Fig. 6) shows the areas where different socio-economic conditions of urban development combine with the differential impact of flash flood hazards. There is no overlap in the areas where the partial or analytical maps are not present, and they are outside the analysis of this index.

The areas with the highest Ri values cover 20.3% of the zones. These are areas where the probability of severe effects and high exposure are combined, making these priority areas for attention in the event of a flood. In these places, risk management is necessarily corrective to avoid high-impact destructive effects in the future.

The areas with medium Ri values cover 16.8% of the risk areas, occupying the low plains and areas of transition to hills. Here the risk has an important hazard component and a medium vulnerability component, resulting in a medium risk when combined in the index.

Low-risk areas occupy 62.9% of the affected areas, which does not mean an absence of hazard (FfHi) or vulnerability (SVi), but instead zones where the values of the partial or analytical maps compensate for the numerical weighting. In either case, corrective or preventive measures are required to deal with the hazard or vulnerability.

The area with the highest Ri values is in dense settlements of low-resource housing, where measures have been taken to deal with flash flood emergencies and their consequences. Among the measures are the construction of retaining walls that surround all the houses (Fig. 7a) or walls that protect the principal access (Fig. 7b) and elevation of the floor of the house above street level, among other examples.

The spatial units with Ri values cover 14.3 km^2 (Table 4). An area of this size could house up to two medium-sized residential developments, containing a total of 120 medium-low to medium–income dwellings.

It is important to note that there is a difference between the area with FfHi values (15.4 km^2), SVi values (14.65 km^2), and areas with some Ri

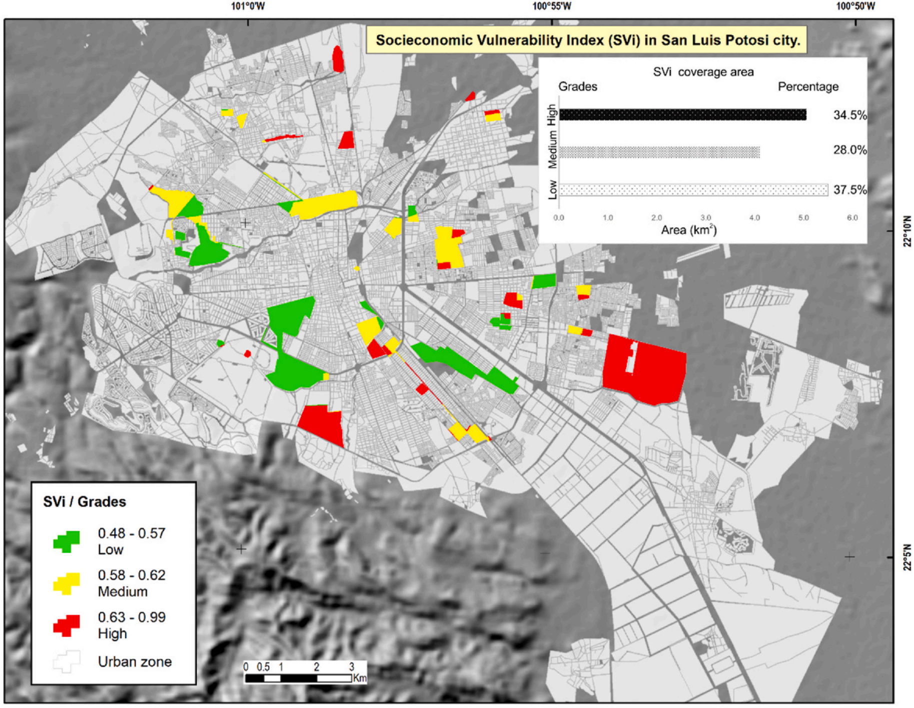

Fig. 5. Socio-economic vulnerability index (Svi) map.

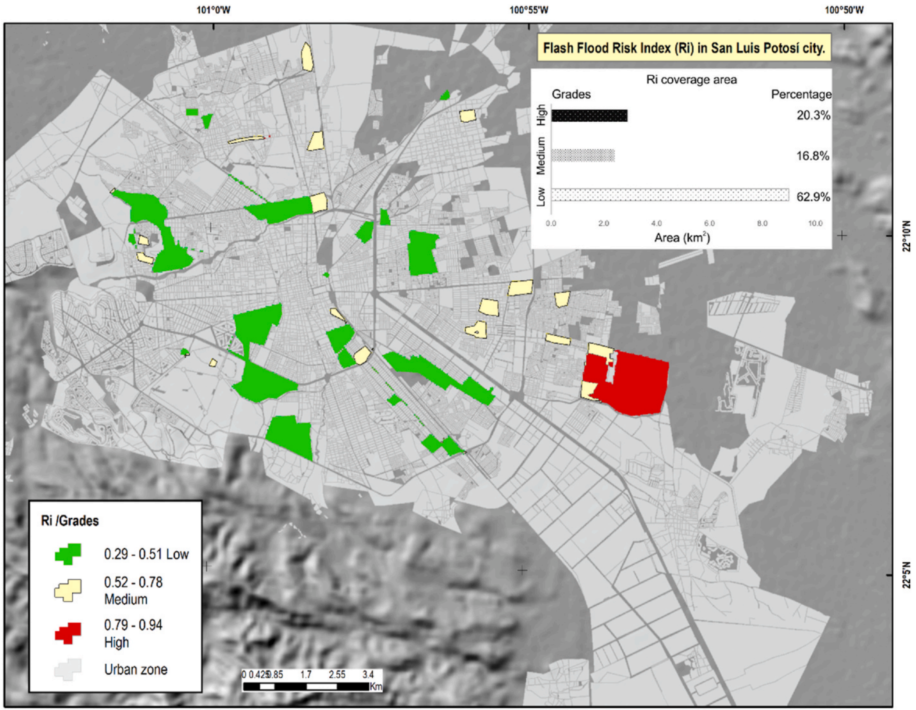

Fig. 6. Flash flood risk index map.

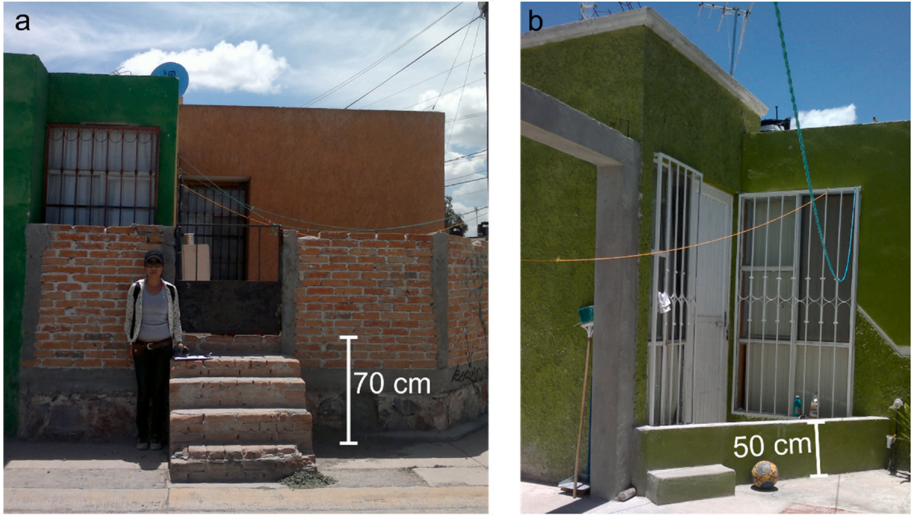

Fig. 7. Examples of modifications in houses to deal with flash floods.

Table 4
Evaluation for flash floods risk index (Ri).

	Flash Flood Risk Index Ri	Area (km^2)
Total	0.29	14.3
Lowest value	0.94	0.001
Highest value	0.94	2.91
Mean	0.52	0.012
Median	0.61	0.003
Standard deviation	0.46	0.446
Total areas for all degrees:		90

degree (14.3 km^2). Conceptually, the analysis of Ri requires the areas with analytical elements of hazard (FfHi) and socio-economic vulnerability (SVi) to coincide; spaces such as riverbanks, which do not present these combined characteristics, were not included in the risk analysis.

4. Discussion

4.1. *Problems in the study of flash floods*

Over time, the danger of floods, specifically flash floods, has been recognized because they cause material and human damage without prior warning (Shahabi et al., 2021). The short period that elapses between the start of the event and its climax limits the response capacity of both emergency forces and the population; hence, it is essential to develop methodologies that enable the triggers and the process behavior in multiple contexts to be identified (Khosravi et al., 2019).

One of the challenges faced in the study zone was the lack of detailed information about flash flood events. Lack of detailed or irregular information recording is a common problem in medium-sized cities in underdeveloped countries without long-term urban planning (Hermas et al., 2021; Kapović Solomun et al., 2021; Schroeder et al., 2016). This problem was compensated by fieldwork, reviews of print and electronic media, and visits to the affected sites to identify the strategies developed by the population. Modifications to buildings, watermarks, mud lines, data shared by the affected people, and other physical evidence made it possible to identify how flash floods evolved in the study area.

Purely hydrological models do not work in artificially modified environments in sub-basins limited by urban design (Khosravi et al., 2019). For this reason, deterministic methods are more helpful for understanding the behavior of floods based on real data (Pistrika & Tsakiris, 2007). The proposal in this paper is not a hydrological–topographic model for predicting flood-affected areas in cities with random or disorderly urban development patterns. Modifications to surface runoff lead to changes in the hydrogravitational behavior and magnitudes of flash floods because they alter and interrupt the natural stream patterns. Infrastructure and residential areas obstruct natural channels and alter infiltration; furthermore, infrastructure construction and maintenance for storm drainage are neglected because flash flood events are usually infrequent (Hermas et al., 2021). Therefore, the proposed methodology combines fieldwork, recording adaptation strategies, and interviews with residents affected by flash floods. These are only helpful at the local level and apply to the corrective or compensatory risk management phases.

4.2. *Integration of the social factor*

Fieldwork was conducted to verify flash flood behavior and its relationship with spatial heterogeneity of vulnerability. Despite considerable development in methodologies that analyze the natural processes per se, the inclusion of social factors related to vulnerability is still uncommon (Aroca-Jimenez et al., 2020). There are proposals for the analysis of territorial vulnerability that include measures of how goods, people, and activities suffer damages related to any natural or human process (Treu et al., 2004) or the economic cost of damages associated with a natural process (Lozoya et al., 2011). From both points of view, the population is a passive element of socio-natural processes (Wilches Chaux, 1993). Our proposal focuses on the population's capacity to cope with a hazardous situation, making the community a dynamic actor in a socio-natural process whose vulnerability will depend on its resilience capacity historically built and measured through socio-economic indexes and indicators (Lavell Thomas et al., 2003).

4.3. *Construction of indexes and indicators*

The use of indices and indicators allows analysis methodologies to be flexible enough to adapt the parameters that best evaluate the socio-economic conditions underlying hazardous processes (Cardona Arboleda, 2005, p. 231); however, these are usually considered on a national or regional scale (Aroca-Jimenez et al., 2020; Birkmann et al., 2013). Given the importance of analysis at the local level, methodologies cannot ignore each study area's environmental and socio-economic particularities (Xia et al., 2011). It is necessary to recognize and develop strategies for the study of local risk situations because it is on this scale where the population directly faces the effects of hazards (Othmer et al., 2020). The present work is an effort to analyze the problem of flash floods at the local level, including socio-economic information available at this scale. In addition, developing methodologies that recognize local heterogeneity is essential since flash floods occur in small basins, and their analysis requires detailed information (Hofmann & Schüttrumpf, 2019).

One of the most critical obstacles to carrying out studies that allow us to identify the heterogeneity of socio-natural processes at urban scales is the lack of access to information at this scale. For a comprehensive study at the local level, the availability of socio-economic details with a spatial distribution comparable to the extent of natural processes is also essential. In Mexico, the government agency in charge of the statistical registry of population and housing provides statistical information with a specific, consistent and systematic spatial distribution at the locality level. To select indicators to evaluate the socio-economic component of the analysis through the SVi, the availability of statistical information at the neighborhood level and whose spatial expression could be analyzed in conjunction with the spatial extent of flooding in the study area was considered. Indicators related to the employability and income of the affected people were selected to view vulnerability as the people's abilities to cope with and recover from a hazardous process (Pistrika & Tsakiris, 2007) and not consider vulnerability only as an economic loss (Lozoya et al., 2011).

The flash flood risk index (Ri) zone map is a risk management map that is a product of the interaction between semi-natural zones (FfHi) and socio-economic systems (SVi). This synthesis of variables, parameters, and systems of different origins enables an understanding of a complex reality with high spatial variability. The map can guide corrective or preventive actions based on calculated hazard levels, vulnerability, and risk (Lozoya et al., 2011). The more detailed and accurate the information used in risk management, the more realistic the models will be. Therefore, better decisions can be made regarding territorial planning and urban development. It is desirable to reduce the number of variables to avoid statistical dispersion of the results and to consider the characteristics of the buildings and houses that constitute an element of resilience for the population.

The comprehensive analysis of risk and vulnerability at the local scale helps in decision-making and in the development of specific actions to manage vulnerability and reduce the risk not only of flash floods but of a variety of hazards. Involvement by the population in the generation of local efforts favors the development of proactive measures that lead to positive impacts (Vázquez-Barquero, 2007) and the development of strategies that improve urban planning and social resilience (Guardiola-Albert et al., 2020) and therefore risk management. Strengthening social groups to face the problems associated with potentially dangerous natural processes promotes empowerment and social and political independence (Stough et al., 2011).

5. Conclusions

The indices applied here include numerous parameters and semi-quantitative indicators that are viable, applicable, and realistic for weighing the urban conditions that directly and indirectly underlie specific situations of flash flooding risk. However, it is essential to detect uncommon or random causes in the behavior and forecast of flash floods and their destructive effects. Some of the most important causes to consider are the management of urban waste, rubble, and mud; urban structures that hinder natural and artificial flows; and the hydraulic capacity of the drainage network to eliminate extraordinary flows and reduce the speed of increasing volumes of water.

The flash flood risk index (FfHi) and socio-economic vulnerability index (SVi) reflect, on the one hand, the magnitude and intensity of flash floods in specific urban conditions and on the other hand, the spatially differentiated degrees of underdevelopment in terms of urban development and extreme differences in the economic and coping capacity of the population. Therefore, these indices are useful for detecting priority areas for attention and highlighting the spatial heterogeneity of the relationship between hazards and socio-economic vulnerability.

CRediT authorship contribution statement

A.G. Palacio-Aponte: Resources, Conceptualization, Methodology, Investigation, Formal analysis, Writing – original draft, Visualization,

Funding acquisition. **A.J. Ortíz-Rodríguez:** Resources, Methodology, Investigation, Writing – review & editing, Visualization. **S. Sandoval-Solis:** Methodology, Formal analysis.

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