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Articles

Geospatial analysis of flood impact sites from a database compiled by the Guadalajara fire department during the rainy season of the 2010-2022 period

Análisis geoespacial de los sitios de afectación por inundación desde una base de datos recopilada por el cuerpo de bomberos de Guadalajara durante el temporal de lluvia del periodo 2010-2022

Maura González[1], ORCID: https://orcid.org/0000-0002-7201-2831

Boris Comi[2], ORCID: https://orcid.org/0009-0005-7964-9500

Jesús López-De la Cruz[3], ORCID: https://orcid.org/0000-0001-8230-6414

[1]Centro de Investigación en Alimentación y Desarrollo, A. C., Unidad CEIBAAS (Centro de Estudios e Investigación en Biocultura, Agroecología, Ambiente y Salud), Colima, México / Programa Investigadoras e Investigadores por México, Consejo Nacional de Humanidades, Ciencias y Tecnologías, México / Universidad de Colima, Facultad de Ingeniería Civil, Colima, México, maura.gonzalez@ciad.mx

[2]Coordinación Municipal de Protección Civil de Guadalajara, Guadalajara, México, bcomi@guadalajara.gob.mx

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[3]Universidad de Colima, Facultad de Ingeniería Civil, Colima, México, jlopez71@ucol.mx

Corresponding author: Maura González, maura.gonzalez@ciad.mx

Abstract

This paper analyzed Flood Impact Sites (SAI, abbreviated in Spanish) attended by the Coordination of Civil Protection of Guadalajara (CMPCG, abbreviated in Spanish) from a geospatial approach. It also addressed the distribution of how, when, and where floods affected during the last 12 years (2010-2022). The case study is the urban area of the municipality of Guadalajara. The frequency, distribution and intensity of floods are analyzed yearly and for the entire study period. We obtained a flow depth categorization map using neighborhoods' historical flood level height, where most range from medium to low. Subsequently, the services attended by CMPCG's operational area bases were analyzed, where the most affected sectors are the public roads and the residential sector. We worked with 3,676 SAI contained in the CMPCG flood inventory. The study allows to identify 63 Recurrent Flood Sites (SiRI, abbreviated in Spanish) with the information of the SAI. At the colony scale, they correspond to 65 Recurrent Flood Neigborhoods (CRI, abbreviated in Spanish). In addition, 20 Critical Flood Sites (SiCI, abbreviated in Spanish) are displayed, which, in addition to meeting the recurrence criteria, also consider the incidence criterion both in the domicile and crossing fields. We can highlight the daily work of the Municipal Coordination of Civil Protection of Guadalajara (CMPCG) and, specifically, the staff of the

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Operational Area since this study was carried out based on the information gathered by this staff during each rainy season. This study contributes to the first stage of Integrated Risk Management by analyzing and identifying flooding sites in Guadalajara.

Keywords: Flood, recurrence, hazard, civil protection, urban area.

Resumen

Se analizan los sitios de afectación por inundación (SAI) atendidos por la Coordinación de Protección Civil de Guadalajara (CMPCG) desde un enfoque geoespacial; se da a conocer la distribución de cómo, cuándo y dónde han afectado las inundaciones durante los últimos 12 años (2010-2022). El caso de estudio es la zona urbana del municipio de Guadalajara; se analiza la frecuencia, distribución e intensidad de las inundaciones año por año, y del total del periodo de estudio. Se obtuvo un mapa de categorización del tirante de agua, considerando la altura de nivel de inundación histórica presentada por colonias, donde la mayoría presenta un rango que va de medio a bajo. Posteriormente, se analizaron los servicios atendidos por bases del área operativa de la CMPCG, donde los mayores sectores afectados son la vía pública y el sector casa habitación. Se trabajó con un total de 3 676 SAI contenidos en el inventario de inundaciones de la CMPCG. El estudio permite identificar 63 sitios recurrentes de inundación (SiRI) con la información de los SAI. A escala de colonias, se corresponden a 65 colonias recurrentes de inundación (CRI). Se exhiben, además, 20 sitios críticos de inundación (SiCI), que cumplieron con los criterios de recurrencia, también se considera el criterio de incidencia tanto en el campo de domicilio como en el de cruce.

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Finalmente, se destaca la labor que se realiza día con día en la Coordinación Municipal de Protección Civil de Guadalajara (CMPCG) y específicamente del personal del Área Operativa, ya que este estudio se realizó a partir de la información recabada por dicho personal durante cada temporal de lluvias. Con el presente estudio se contribuye a la primera etapa de la gestión integral de riesgos al incluir el análisis e identificación de los sitios de inundación en el municipio de Guadalajara.

Palabras clave: inundación, recurrencia, peligro, protección civil, zona urbana.

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Introduction

There are two extreme hydrometeorological phenomena of great interest due to the impact they have on the economic, environmental and social spheres: floods and droughts. These phenomena are a clear demonstration that, although water is a vital liquid for the development of our daily activities and the permanence of humanity on this planet when they occur in excess or are drastically scarce, they generate innumerable damage (ONU, 2021).

Floods are events that can be defined as a phenomenon of natural or anthropogenic origin, in which precipitation, waves, storm surge, or

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failure of some hydraulic structure causes an increase in the level of the free surface of the water of rivers and seas, generating temporary flooding of areas that are not usually flooded. Salazar (2013) defines this process as the dialectical expression of water-territory, fundamental in the dynamic process of landscape modeling on planet Earth. Floods are a topic that researchers have positioned as one of the main lines of research for hydrologists (Kidson & Richards, 2005; Merz et al., 2019; Shaleen & Lall, 2001; Villarini, Smith, Serinaldi, Ntelekos, & Schwarz, 2012).

When a flood event occurs in an unpopulated area, damage to crops in agricultural areas and damage to nearby civil infrastructures may occur; however, it is well known that human settlements have developed along riverbanks (López & Francés, 2013). It is in this context that the importance of flood events is amplified when the flooded areas are densely populated urban centers that can claim the lives of many people.

Globally, floods are the most common disasters and the leading cause of mortality (Merz *et al*., 2019). Mishra *et al*. (2022), in their review of the current state of floods showed that floods continue to be the disasters that affect the largest number of people and experience the greatest growth. In addition, the International Disaster Database (EM-DAT) shows that in the last 40 years disasters have experienced a significant growth in frequency (EM-DAT, 2022).

Therefore, the general objective of this study is to perform a geospatial analysis of the areas historically affected by flooding in the municipality of Guadalajara during the period 2010 - 2022 from an emergency database compiled by the Guadalajara Fire Department. The study is focused on addressing the following specific objectives: a)

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Establish the recurrence criteria of flood impact sites attended from 2010 to 2022, b) Evaluate the flood services of the Municipal Coordination of Civil Protection of Guadalajara (CMPCG), c) Obtain a flood categorization map, d) Determine return periods from the flood inventory, e) Determine and define: Recurrent Flood Sites (SiRI), Recurrent Flood Neigborhoods (CRI), as well as Critical Flood Sites (SiCI).

Background

According to the World Disasters Report (IFRC, 2020), in the last ten years, severity weather and climate phenomena have triggered 83 % of disasters involving floods, storms, and heat waves causing the death of 410 000 people with one billion seven hundred million (1 700 000 000) people affected by this type of disasters worldwide. Floods are one of the most frequent and dangerous disasters in the world (Avila-Aceves, Rocha-Plata, Mojardin-Armenta, & Rangel-Peraza, 2023). Until now, the dominant conception of floods and climate change has been that of climate change as an active agent and society as a passive agent or recipient. However, it is well known that society is a complete actor in this process. In fact, it is society that, from various political, economic, socio-cultural and environmental causes, builds its own vulnerability.

In recent years, flooding caused by storms and hurricanes in Mexico has increased yearly, generating severe economic and infrastructure losses, with the most evident damage in the coastal areas of the Pacific Ocean and the Gulf of Mexico (Haer *et al.*, 2018). In this context, the country is investing many resources to restore the conditions of the

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affected regions, allowing the recovery of the population's activities. The significant vulnerability in large regions of the country is evident, as well as the absence of preventive measures (Salas & Jiménez, 2014). The Mexican institutional design to face the changes experienced by the climate and its effects on the frequency and magnitude of extreme hydrometeorological events "has focused more on the action of repair and assistance in the presence of extreme natural events, than on the prevention of their devastating effects"(Constantino & Dávila, 2011). The results have shown the failure of reactive interventions, which have generated a null risk reduction, and therefore maintaining the high probability of risk materialization in disasters with the corresponding negative effect they entail.

In this regard, different works address the issue of flooding from different perspectives according to the available information and the desired levels of accuracy, where most of them focus on flood assessment, which is essential for the design of infrastructure, planning of mitigation measures and policies focused on water resources (Vidrio-Sahagún & He, 2021). The geospatial modeling of floods, either hydrologically or hydraulically, in conjunction with Geographic Information Systems (GIS), provides significant advantages in identifying large-scale floods (Avila-Aceves *et al*., 2023), being the basis for the integrated management of water resources in all types of watersheds from high mountain (Ocampo & Vélez-Upegui, 2014) to pluvial floods in urban environments (Bulti & Abebe, 2020).

Other authors, such as Elkhrachy *et al*. (2021), obtained flood hazard maps as support before responses and designed emergency plans

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based on water depth and velocity obtained through simulations with the Hydrological Engineering Centers River Analysis System (HEC-RAS) software. Maranzoni, Dória and Rizzo (2023) addressed the issue of flooding through hydrodynamic modeling based on maximum water depth and flood extent to obtain hazard maps, which is considered a fundamental step in flood risk mapping. Another critical aspect is that, as part of risk management, it is necessary to identify flood zones with data on the extent and height of the water level, called non-structural measures of territorial resilience, which include evacuation and contingency plans (Avila-Aceves *et al*., 2023). Without data, multi-criteria and other probabilistic techniques and geographic information analysis have been used to obtain areas with flood potential (Vojtek, Vojteková, & Pham, 2021). Therefore, we can see the great advantage of the Coordination of Civil Protection of Guadalajara flood inventory.

Floods in the Guadalajara Metropolitan Zone (ZMG for its acronym in Spanish) have been addressed by different authors, among them the one presented by Ornelas, Castillo and Salazar (2005), in which he mentions that the increase in floods and the variables linked to this phenomenon have been influenced exclusively by the modifications in watershed regimes due to the anarchic urban process. They also point out that the new urbanizations were developed on high-risk sites in topographically low areas, riverbanks, canal margins, and edges, finally considering an arrangement by hydrological basin as a solution.

In a later study, Salazar, Juárez and Ramírez (2008) analyzed the intensity, duration, and recurrence period that rainfall can reach in the Metropolitan Zone of Guadalajara (ZMG); for this purpose, they

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integrated a database of maximum rainfall in 24 hours and used statistical and empirical procedures, finding that flooding in the ZMG has increased due to excessive population growth, invasion of natural watercourses, deficient urbanization and water channeling, which undoubtedly alters the natural soil conditions, decreasing the infiltration and moisture retention capacity and causing an increase in rainwater runoff.

The literature review shows that the flooding problem is an old one (GacetaUdeG, 2010) since it began in the 50's and has worsened over the years and that a scheme of the magnitude of the problem is needed, in addition to a master plan that includes collectors according to urban growth, avoiding urbanization in dangerous areas and greater micro-basins that avoid the replacement of natural collectors by artificial ones.

The vulnerability of sites within the ZMG, which are affected by floods and where the population loses its assets, has been reported by Torres, Franco, Souza and Lattuada (2019). Their study highlights the inadequate functioning of the Integrated Stormwater Management Program (PROMIAP for its acronym in Spanish) and the Integrated Flood Management Plan (PIMI for its acronym in Spanish), which were promoted as the solution to all flooding problems in the ZMG. The results show that the problem has not diminished year after year; on the contrary, the number of neighborhoods at risk of flooding during the rainy season has increased, together with the increase of flood risk points from 147 (between historical and recent recurrences) to about 380, according to records of the Institute of Statistical and Geographic Information and information from the risk inventory prepared by the State Unit of Civil Protection and Firefighters of Jalisco.

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The floods in Guadalajara are a social construction originating within external and internal processes of people's daily lives (Durán, 2019). Therefore, it is essential to use historical context to explain the processes that configure such disasters. The authorities of different Coordinations, Institutions, and Dependencies of the Government of Guadalajara, involved with some of the issues of the onset and preparation for the rainy season, make yearly efforts to be prepared. The main activities include field visits to the main SAI to detect needs such as tree pruning, preparation of shelters, cleaning of canals, rivers, streams and storm drains. We also have the eviction of homeless people due to the passage of streams, bridges, and channels, activities that contribute to the preparations by government agencies before the onset of the rainy season, being essential to implement more far-reaching solutions to reduce the risk of the population.

Each precipitation event in the municipality of Guadalajara and specifically, the first events of the season cause some damage; therefore, having an analysis of the flood inventory that corresponds to in situ data derived from emergency response or significant flooding events in the municipality of Guadalajara is very relevant information. The systematization of the flood inventory is the first step to start with a preventive scheme to reduce the number of services provided. This document can be used to reconstruct damages by implementing strategies and long-range programs focused on preventing and reducing the effects, thus making a municipality less vulnerable to extreme phenomena such as floods.

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Study area

The municipality of Guadalajara, located between the coordinates of 103.26°W and 103.40°W and 20.6° to 20.75°N, is the capital of the state of Jalisco. There are 126 million inhabitants in Mexico, of which Jalisco has 8,348,151 million, and Guadalajara has 1,385,629, according to the CENSUS of population and housing 2020 of the National Institute of Statistics and Geography (INEGI). The city of Guadalajara has played an indispensable role in the economy of the state of Jalisco; in the year 2000 it was home to 56 % of the state's population due to increased migration from the interior of the state and other states, creating a deficit in infrastructure needs (Herrera & Huizar, 2005), The process of urban sprawl began approximately 50 years ago, consuming space with profound modifications such as irregular subdivisions in the Guadalajara metropolitan area, irregular division of lots, and a drive towards industrialization, generating expansion towards ejido zones and the disappearance of agricultural zones. The Guadalajara area occupies the southern part of the Mexican Altiplanicie, known as the Anahuac plateau; it is bordered to the south by the volcanic axis, to the west by the Sierra Madre Occidental, and to the east by the Sierra Madre Oriental. The maximum accumulated precipitation in Guadalajara within the study period comprised 2010 with 1 025.4 mm, 2013 with 1 057.2 mm, 2015 with 1 252.1 mm, 2018 with 1 052.3 mm, and 2022 with 1 482.8 mm (IAM, 2023).

The Municipal Coordination of Civil Protection of Guadalajara has five stations, also called fire stations, distributed throughout the municipality of Guadalajara (Figure 1), which are responsible for covering

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different areas to have prompt and timely accessibility always at the service of the population because during the rainy season in the municipality of Guadalajara, which runs from June to October, increases the demand for services by the population of the municipality to the CMPCG.

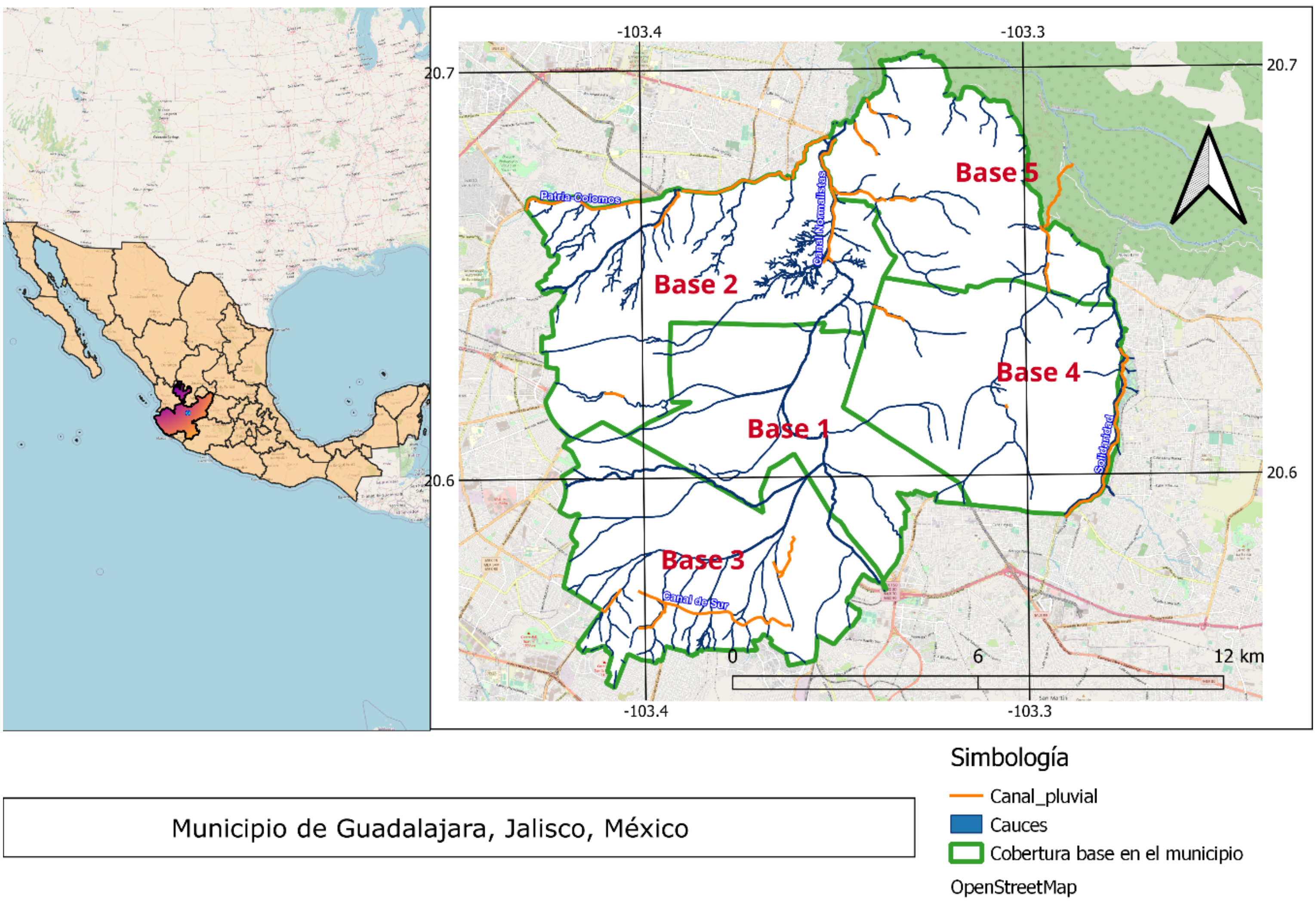

Figure 1. Spatial distribution of the CMPCG bases in Guadalajara, Jalisco, Mexico. Location of rivers and stormwater channels.

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Methodology

The CMPCG oversees safeguarding the life, goods, services, and environment of the population; it houses the Heroic Fire Department of Guadalajara, and as part of its activities, attention to fires, floods, automobile accidents, gas leaks, chemical spills, among others. In this case, the study focuses exclusively on analyzing flood depth as the first part of the prevention strategy.

Data collection and analysis

The CMPCG focuses year after year on addressing emergencies arising from the rainy season and, since 2010 to date, has created and stored within the emergency database an inventory of floods covering the period 2010 to 2022. The inventory is the product of the attention requested by the population to that institution. It contains information such as the address of the impact site that is equivalent to the service attended and the flood itself, since the firefighter goes to the site because there is damage derived from this phenomenon, reported to the communication booths of the CMPCG in addition to data on the height of the flood, neighborhood, intersection, number of firefighters attending, among others.

The flood inventory contains the Flood Impact Sites (SAI) that are collected in real time manually from a joint work, and the information is passed to other firefighters called "scribes", in charge of digitizing it, where it is stored and downloaded from a database called service capture,

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which is in a process of continuous improvement to transfer the information to a new platform called SPRINT, created in 2022 by staff of the Planning Directorate of that institution.

This flood inventory becomes a vital part of the CMPCG since authors, such as authors mention that flood data and specifically damages are scarce to find, being less frequent than hydrometric data and, in some cases, exist, but with privacy restrictions. An aspect of vital importance is the initial data analysis, where fundamental issues such as the spelling of the streets, neighborhoods, crossroads, and references to the flood site were detected in the first instance. In addition, the database needed to be of quality, and for this, cleaning and filtering of the database was applied using Excel pivot tables to eliminate spurious data such as very marked errors in the height of the flood or detection of locations that did not have consistency between neighborhoods, crossroads, references, and streets. This step was essential to transfer the information to a Geographic Information System, which used Google Earth Pro to obtain the georeferencing of the flood sites. Finally, 3,676 services attended were obtained, equivalent to Flood Impact Sites (SAI) (Figure 2).

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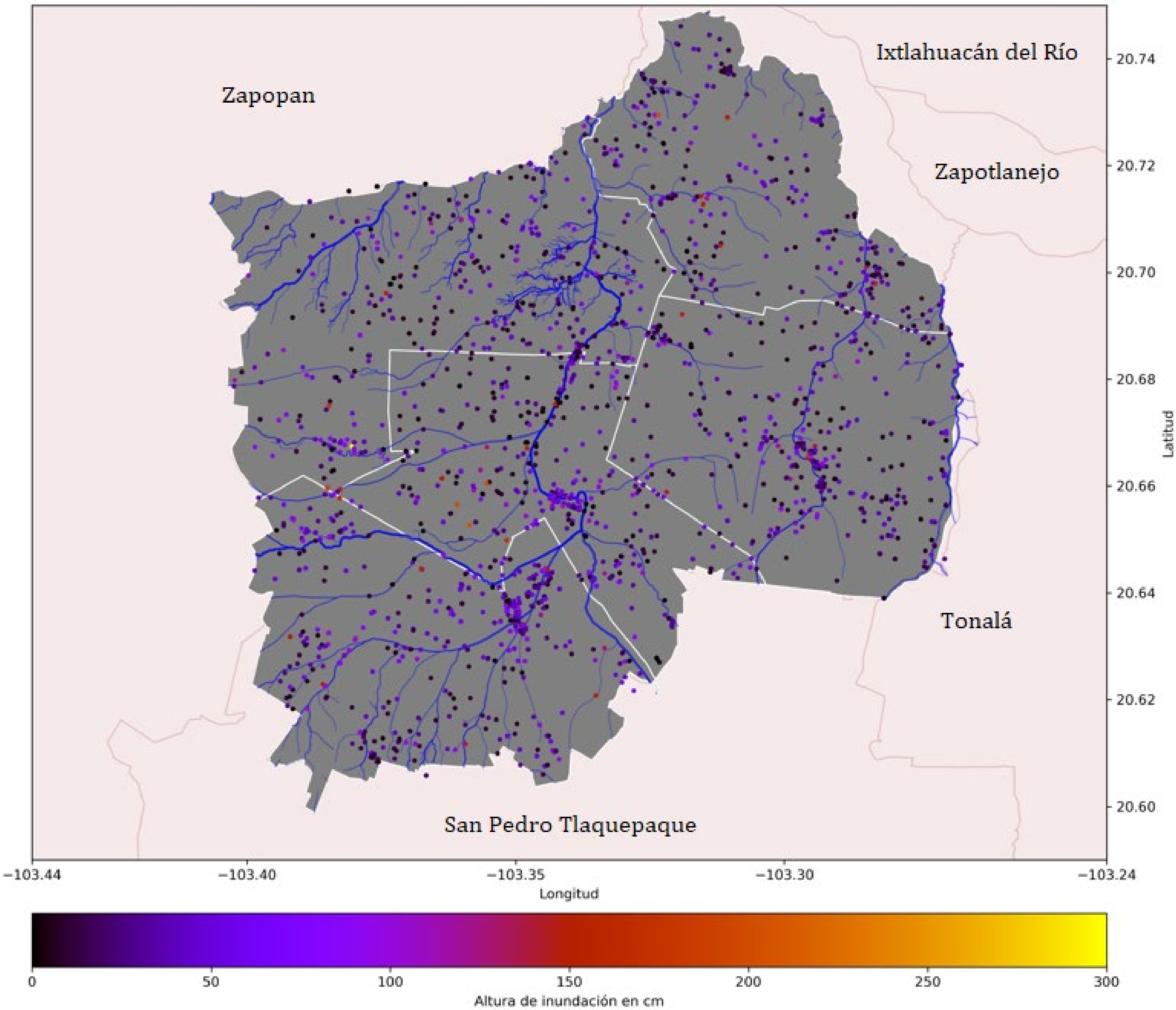

Figure 2. Flood Impact Sites (SAI) in Guadalajara in 2010-2022, where the color scale indicates the water depth recorded.

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The exhaustive review of the information allows for the generation of a robust and quality flood inventory that is the basis for ensuring the certainty and accuracy of the results derived from this study. The Qgis Geographic Information System in version 3.28.1, which is freely available, was the tool used to manipulate geographic information. The projection used for the vector and raster data generated was the WGS 84 geodetic coordinate system.

Once the SAI's are defined, descriptive statistical techniques, such as measures of central tendency, relative tendency, and box plots, which provide information on the data quality, are implemented.

Analysis of flood impact sites

In the first part of the analysis, the SAI attended from 2010-2022 are associated and accounted for yearly to a firebase or fire station. The second association was to identify the number of precipitation events based on the date of the services, which corresponds to an approximation of the incidence of the event. More than one precipitation event can occur in a day, but the database does not have time for service. An important aspect is that the results found are not evaluated with stations. The calculations were obtained with the help of the Python programming language and the Panda library, used to associate the historical flood impact sites with the CMPCG fire department stations, commonly called bases, obtaining. As a result, the percentages of services attended during the rainy season were identified.

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The flooding services provide an overview of the workloads present during the rainy season later and, if necessary, better organization in terms of equipment or personnel in these fire stations and thus improve the response of CMPCG personnel. Likewise, from the flood inventory, information was extracted regarding the impact on sectors, and those that have presented a greater vulnerability to flooding in the municipality of Guadalajara were identified, as well as those that have required greater attention from CMPCG's operations personnel year after year.

Within the framework of the geospatial analysis, interpolations are generated to observe those areas where the most significant number of flood impact sites tend to be concentrated or what is equivalent to the services served, using the inverse of the distance method. We use Python routines and the Geopandas library for analysis.

A descriptive statistical analysis of the flood depth reported in the flood inventory is also addressed, which allows us to observe their distribution and frequency.

Generation of flood depth categorization map

For this purpose, once the flooding points were georeferenced, they were located within the municipality of Guadalajara, the neighborhoods were added, and a union of attributes by location was made to associate the flooding levels to each neighborhood considering those flooding points that contain, fall within and overlap the neighborhood polygon using the Qgis software. The average flood depth of each point located within each neighborhood polygon was then averaged using the process tool add-in

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Qgis and assigned a category from low to the critical range. Although hazard criteria are used in various countries to evaluate floods (Alcocer-Yamanaka, Varela, Bourguett-Ortiz, Llaguno-Guilberto, & Góngora, 2016), transferring the criteria used to the municipality of Guadalajara would require different adjustments. In this sense and directed towards developing a more local study and research, we have proceeded to analyze the flood depths collected in the municipality of Guadalajara with a respective classification of local and more frequent ranges occurring from year to year. Other hazard maps have been made in the past, as mentioned in Durán's document (Durán, 2019).

The color ranges were selected according to the chromatic scale used to represent threat, vulnerability, risk, and hazard (Sedatu, 2016), and to determine the flood depth categorization ranges, a frequency analysis was applied. According to the analysis results, the low flood range corresponds to a level less than or equal to 25 cm, and the medium range corresponds to values greater than 25 and less than 70 cm. In contrast, in the high range, the values range between 70 to 100 cm, and the critical range will be those greater than 100 cm.

Obtaining Recurrent Flood Sites and Neighborhoods (SiRI and CRI) and Critical Flood Sites (SiCI)

A total of 3,676 SAI, equivalent to the services provided by CMPCG personnel. Recurrent Flood Sites were defined in this document as locations with a certain degree of affectation that meet the following recurrence criteria:

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- An annual accumulated flooding level greater than or equal to 25 cm.
- A historical frequency greater than or equal to 12 flood impact sites, considering all sectors such as public roads, commerce, and homes.

We define Recurrent Flood Neighborhoods (CRI) as with the highest historical accumulated flooding and the highest historical frequency combined with the application of recurrence criteria.

Finally, Critical Inundation Sites (SiCI) were defined as those that correspond to the highest frequency values recorded in the historical database and met the recurrence and incidence criteria in both the domicile and crossing fields.

Results

This section shows the results generated in the study and discusses them.

Analysis of Flood-Affecting Sites in Guadalajara

The results of the flood analysis are shown below. It should be emphasized that SAI's are equivalent to the services attended that are derived solely from the rainy season.

Figure 3a shows the number of services attended in the municipality of Guadalajara, where the highest number of services were attended in the years 2010 and 2014, with 470 services and a maximum of 500 flood services in the year 2015; in addition, it can be observed that from the year 2017, there has been a decrease in the services attended. On the

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other hand, Figure 3b shows the result of an approximate number of precipitation events, with a maximum of 67 precipitation events in 2010, observing an apparent decrease over the years from 57 events in 2018 to a minimum of 23 in 2022 and in general it is observed that each year there are several precipitation events above 40, except for the years 2019 and 2022.

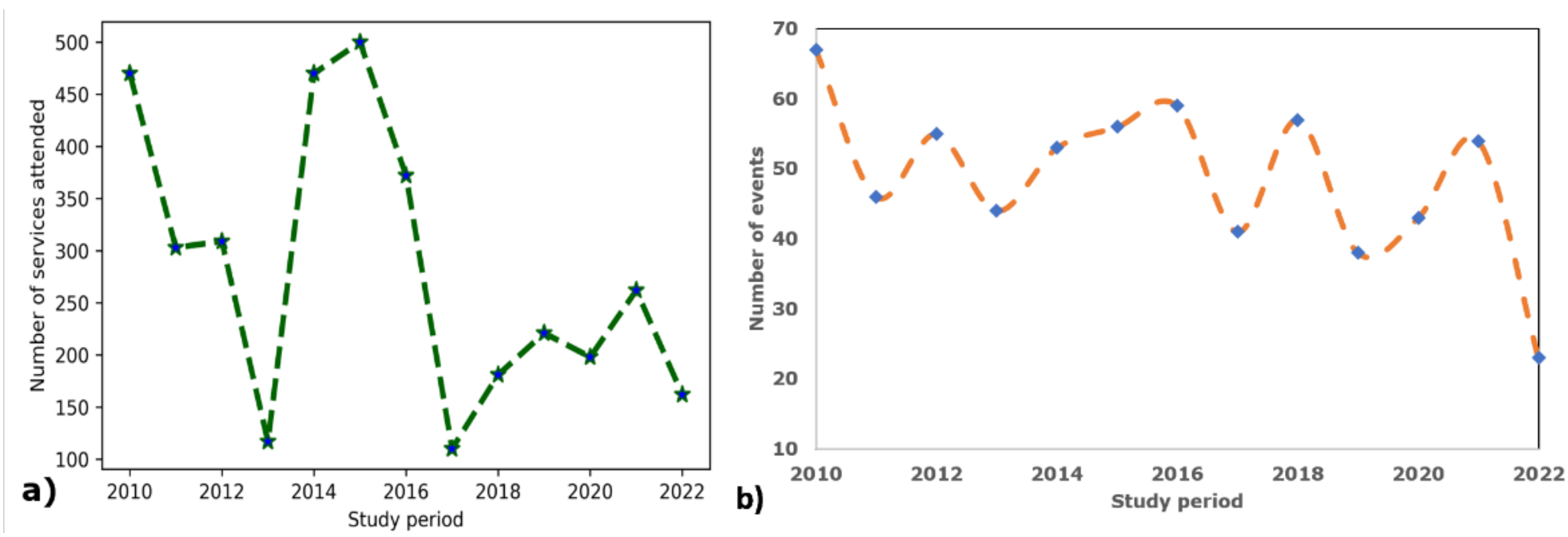

Figure 3. a) Number of services served per year in the CMPCG, associated with flood impact sites and b) approximate number of historical precipitation events in the municipality of Guadalajara.

Besides that, the 2015 hurricane season has been one of the most active recently, with 22 tropical cyclones in the Pacific Ocean. Hurricane Patricia is remembered as one of the most intense, given that in just 24 hours, it intensified to a category five hurricane, and of course, its effects

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reached the state of Jalisco (Conagua, 2015); the year 2014 also had an essential cyclogenetic activity (SMN, 2023).

Flood depth frequency analysis

Figure 4a shows the flood depth frequency distribution, which exhibits an asymmetric distribution with a bias to the left, and it can be seen that 83 % of the events are concentrated between 1 and 73 cm. The observed result aligns with those shown in records of extreme hydrological events. Figure 4b shows the behavior of the media, the 25 and 75 % quartiles, and the maximum and minimum of the records. The behavior of the median does not show a gradual change (trend) or abrupt change (break), as do the quartiles. However, there is a rate of decrease in the behavior of the maximum and the number of sites or services registered.

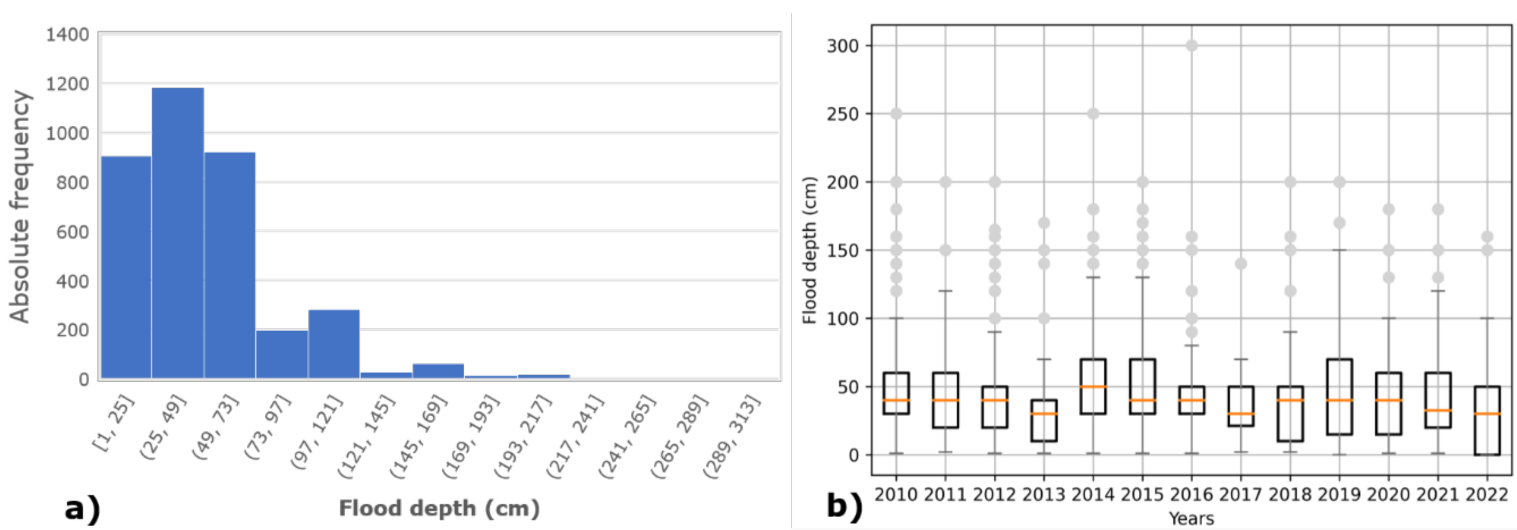

Figure 4. a) Frequency histogram of flood depth records; b) box plots showing the 25, 50 and 75 % quartiles and standard deviation.

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The frequency curve of the maximum annual flood depths is presented in Figure 5a, where the recurrence period of floods can be identified. Changes can be seen in points in two return periods, in floods with return periods greater than or equal to 2 and 5 years, where there are significant increases in flood heights. Figure 5b identifies the probability of non-exceedance associated with each event; floods below 200 cm are associated with probabilities of less than 40 %, while flood heights above 100 cm can occur every year and have a probability of occurrence or exceedance of more than 90 %. The systematization of flood depths and their association with return periods can be a tool to incorporate into the infrastructure design and the generation of contingency plans, in addition to taking this analysis to the colony level.

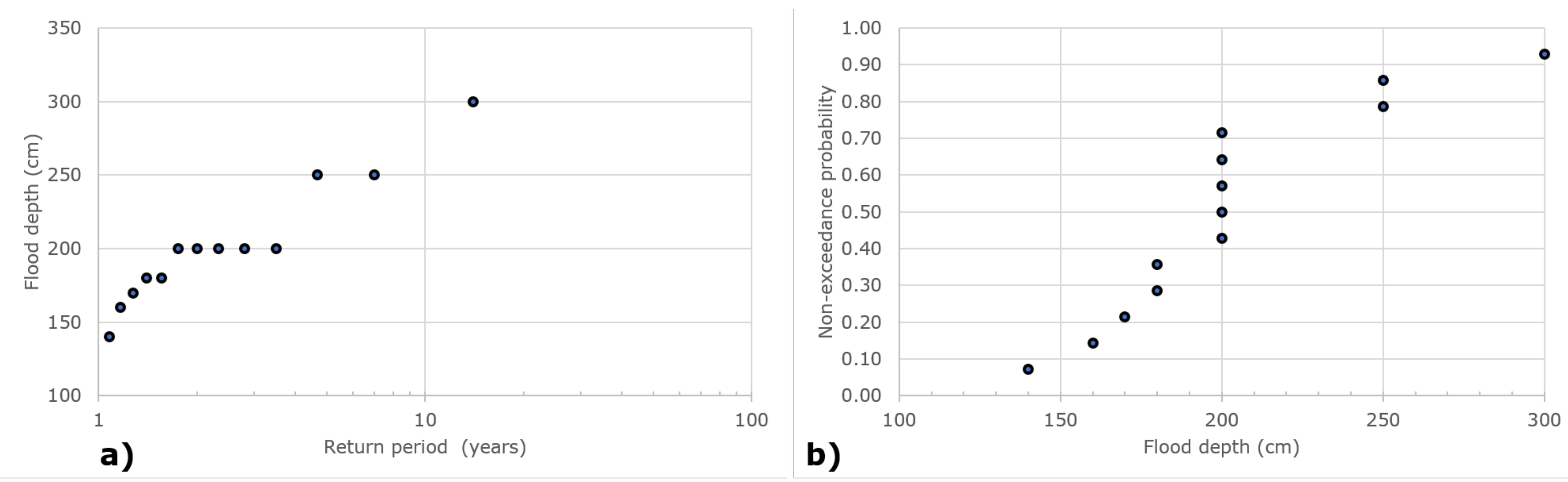

Figure 5. a) Maximum annual flood depths frequency curve; b) non-exceedance probability of the maximum annual flood depths.

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Evaluation of the CMPCG services provided

It is important to know the percentage of flooding services attended by fire stations, as it provides an overview of the workloads present during the rainy season, in order to subsequently and if necessary, have a better organization in terms of equipment or personnel in these fire stations and thus improve the response of CMPCG personnel. Figure 6 shows the percentage of historical services attended by each of the firebases, where base 3 is the one that has historically attended the highest number of services associated with flooding at 31.6 %, followed by base 1 at 20.6 % and base 2 at 18.6 %. Base 5 has historically had the most minor activity during the rainy season, with 11.6 %, while base 1 (Figure 7) has had the most activity in 2019 and 2022.

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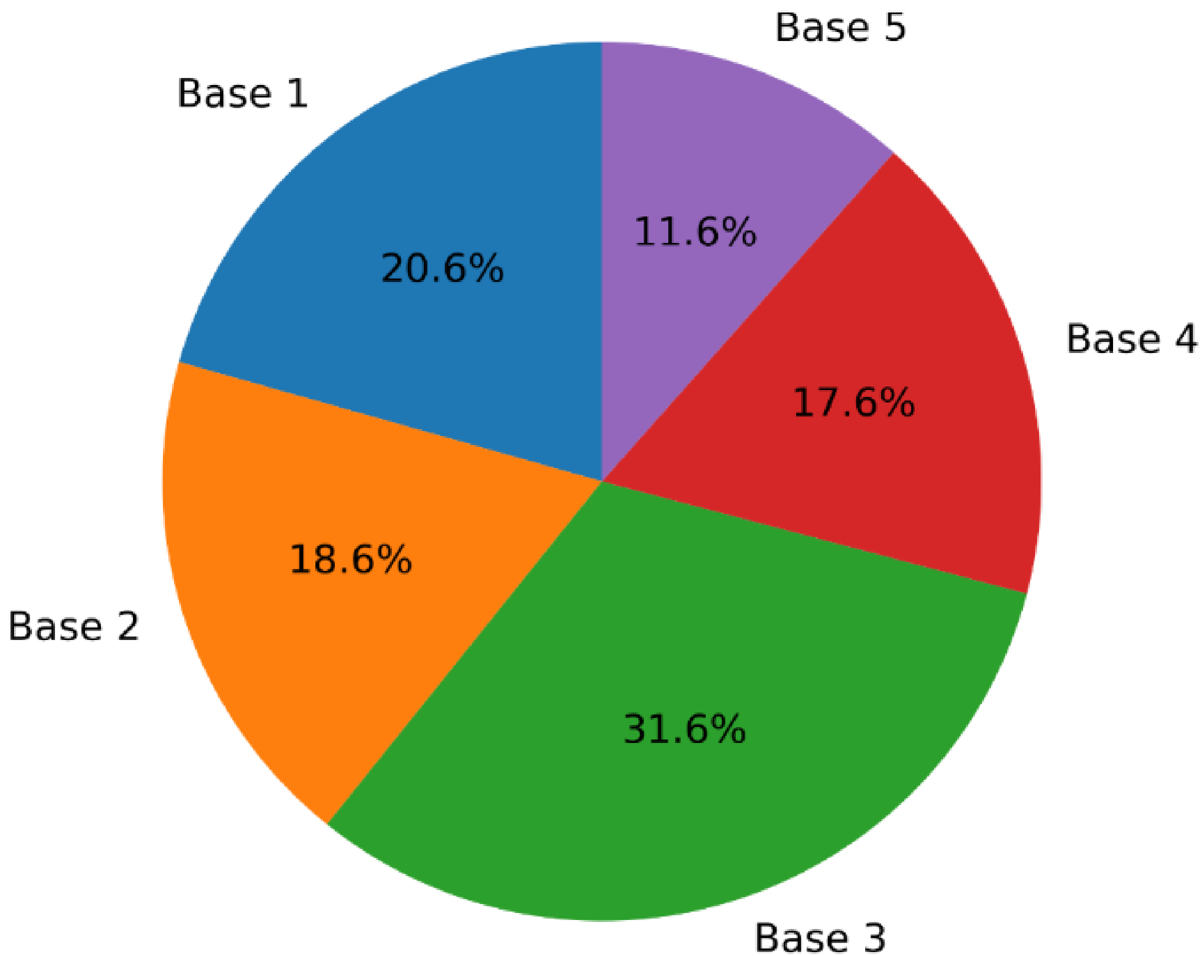

Figure 6. Historical percentage of flooding services attended by bases in the CMPCG.

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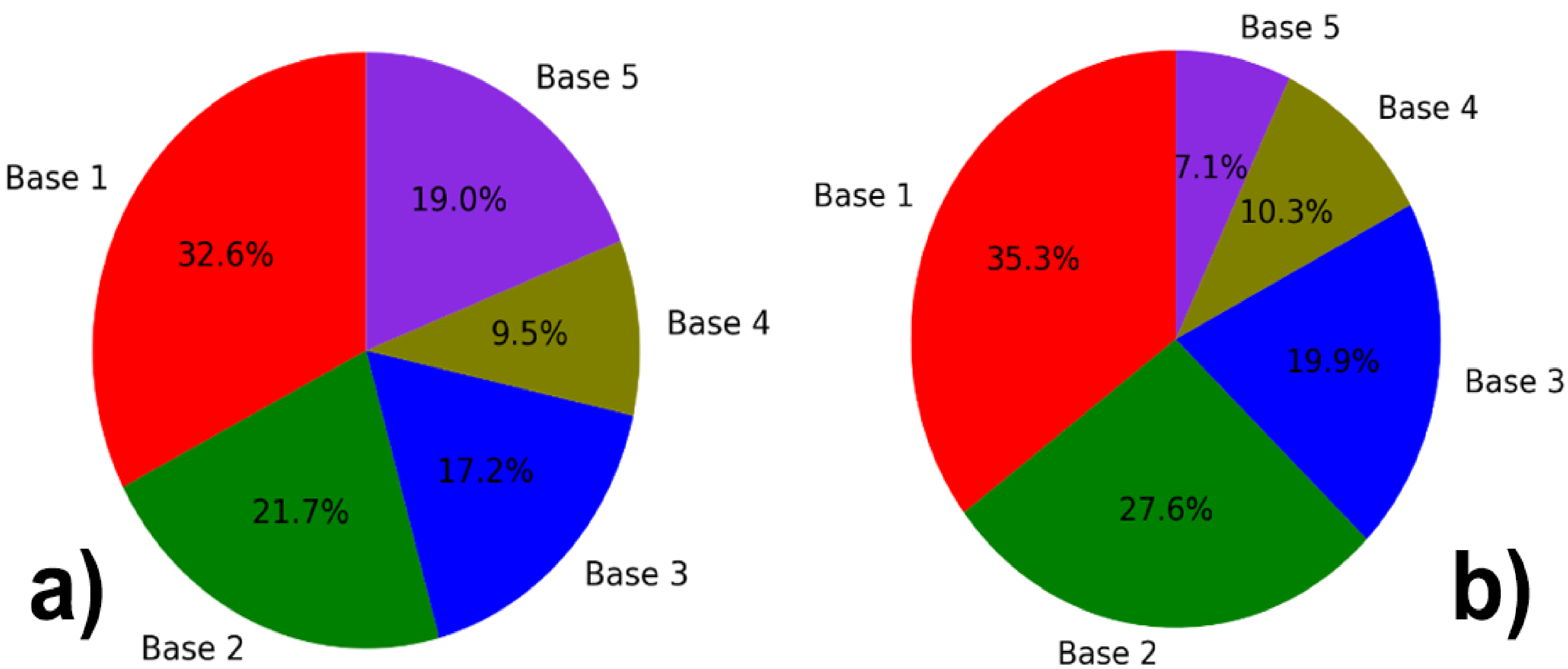

Figure 7. Historical percentage of flooding services attended by CMPCG staff in a) 2019 and b) 2022.

Figure 8 shows very clearly the sectors historically most affected by floods, among which are public roads with 2,369 historic number of firefighter services to the population, followed by homes with 954, service establishments with 170 services due to flooding emergencies, commercial establishments with 92 and overpasses with 27. Other sectors affected by less than 4 flood events are schools and canals, which have yet to be considered in the results of Figure 8.

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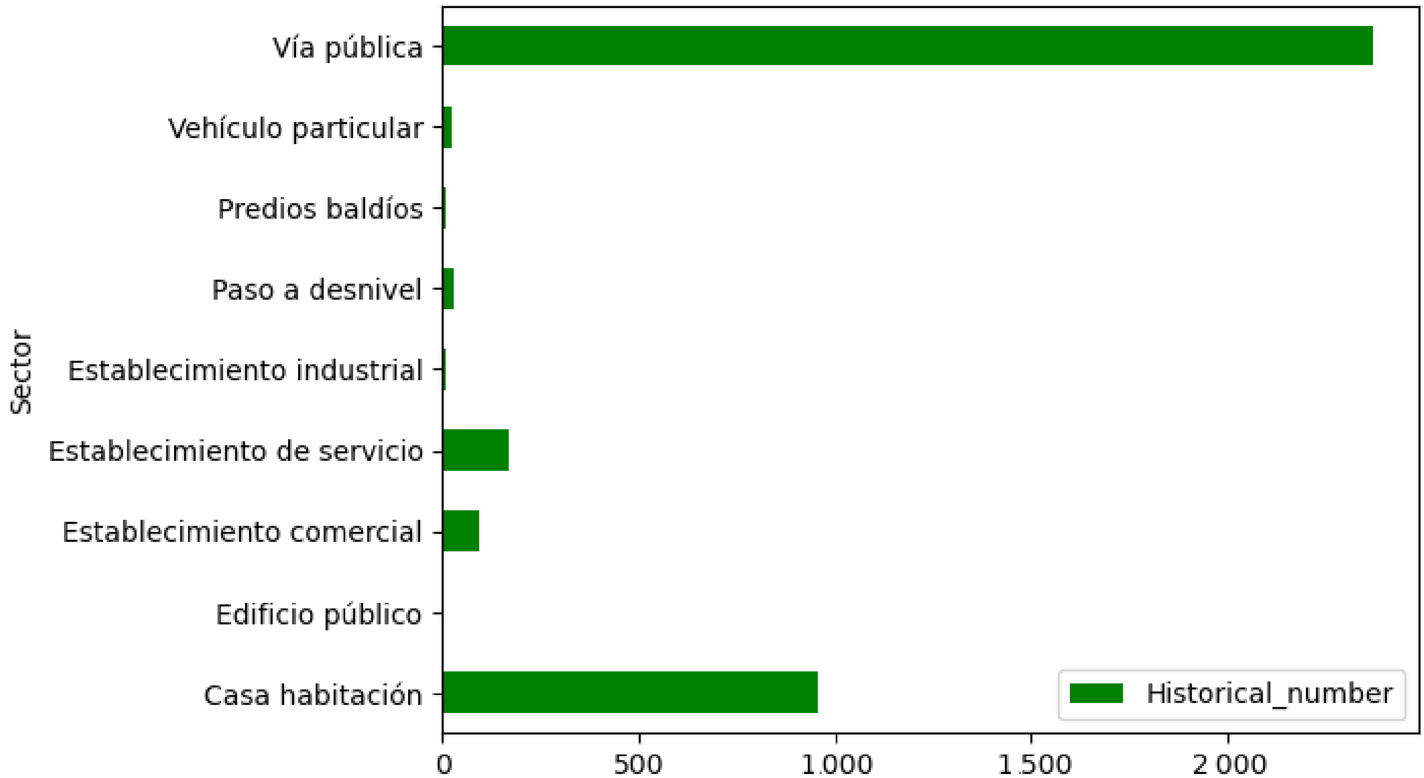

Figure 8. Sectors historically are most affected by the rainy season according to the number of services provided.

Flood Depth categorization map

Many of the irregular settlements, contamination, and invasion of canals, rivers, and streams in the municipality of Guadalajara are associated with a lack of knowledge of what this entails and a lack of interest in the basic concepts of conservation and quality of life. Figure 9 shows a categorization map according to the frequency ranges of flood levels, which range from a low level shown in green to a critical level in red, where the predominant range of categorization corresponds to the low to

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medium level with a greater tendency to a high level of flooding in the south-central part of the municipality. At this point, there are the most significant number of tributaries. With this map, it is possible to visualize the neighborhoods that year after year represent a medium and high level of flooding in the municipality of Guadalajara and the neighborhoods that so far have had less significant flooding and that indeed have been less frequent or with a flow rate below the parameter established in this flood height study.

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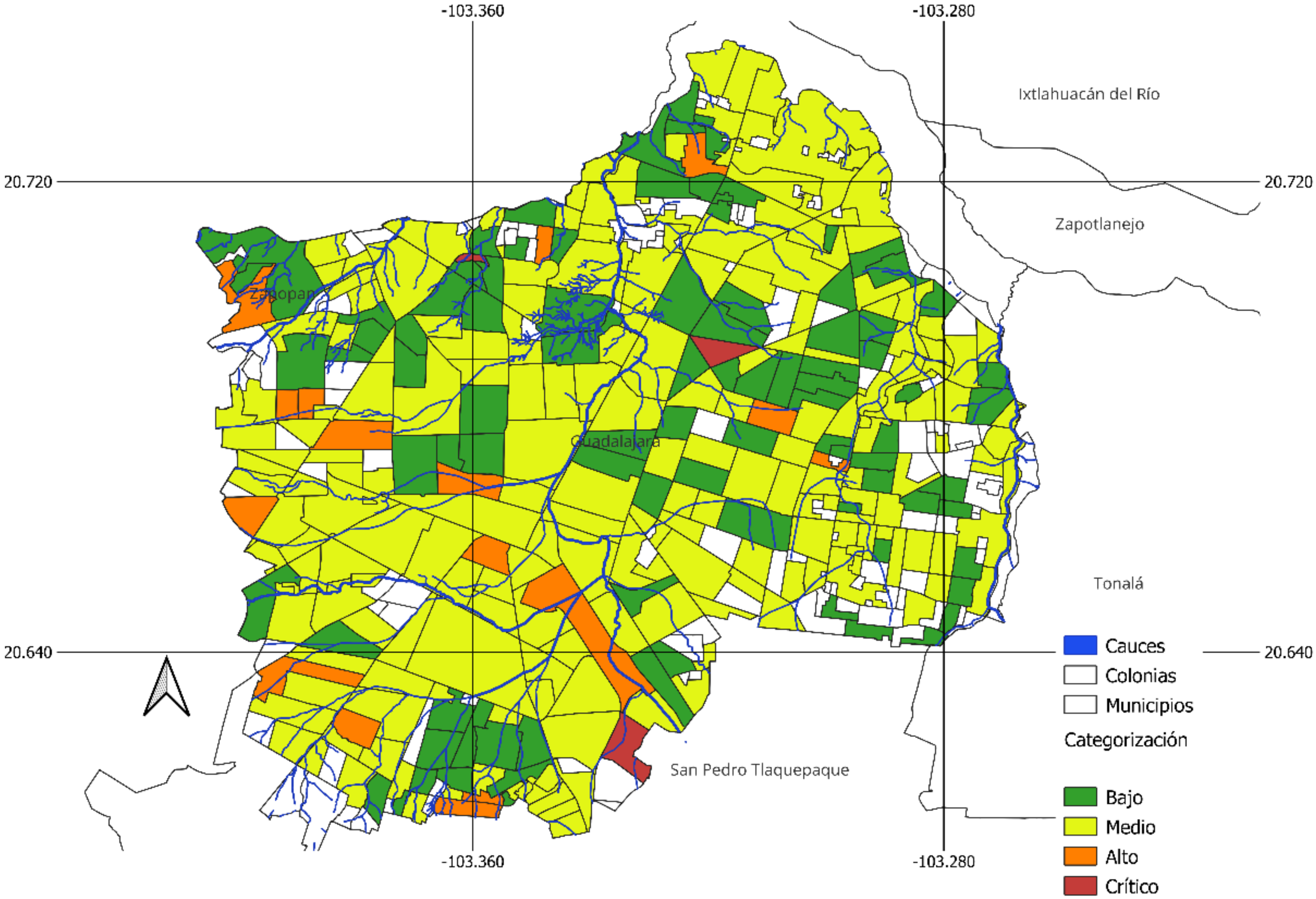

Figure 9. Flood depth categorization map at a neighborhood scale.

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Recurrent Flood Sites and Neighborhoods (SiRI and SiCI) and Critical Floos Sities (CiRI)

Once the recurrence criteria were applied, 63 SiRI were obtained. Table 1 shows the information from 20 SiRI of the 63 sites.

Table 1. SiRI with higher historical flooding and accumulative historical frequency (20 from 63 sites).

No.	Address	Accumulated level (cm)	Historical frequency
1	Av. Belisario Domínguez	2 566	54
2	C. Lope de Vega	2 750	43
3	Artes Plásticas	2 830	47
4	Av. Enrique Díaz de León	2 860	37
5	C. Las Conchas	3 015	48
6	Calz. Independencia Nte.	3 145	72
7	J. Salomé Pina	3 185	54
8	C. José Luis Verdia	3 940	64
9	Av. Niños Héroes	4 020	77
10	Av. Cvln. Division del Nte.	4 031	55
11	Av. Isla Pantenaria	4 620	49
12	Av. Inglaterra	4 810	69
13	Av. Washington	5 085	63
14	Av. Mariano Otero	5 596	64
15	Tuberosa	6 775	118
16	C. 32	6 790	137
17	Av. Miguel López de Legaspi	7 125	152
18	Calz. Lázaro Cárdenas	7 791	105
19	Av. Cristóbal Colón	8 968	130
20	Av. Gobernador Luis G. Curiel	11 700	208

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The analysis allowed the identification of 65 CRI, within which there are 1240 SAI, and performing the interpolation to observe where the most significant impacts are focused; Figure 10 shows that they occur in the central-southern part of Guadalajara, followed by the southwestern and eastern part of the municipality.

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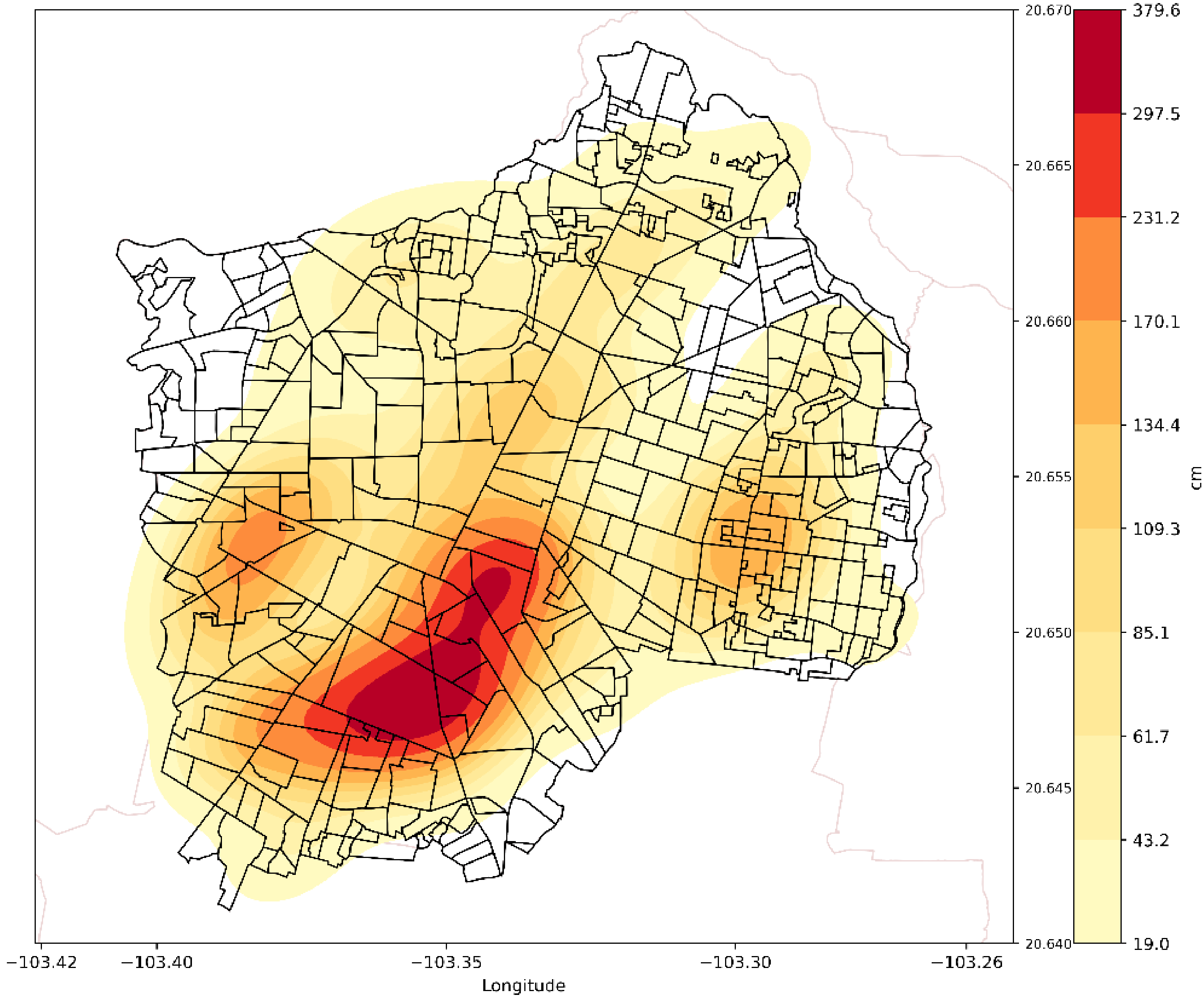

Figure 10. Spatial distribution map of SAI located within the CRI.

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Figure 11 shows the neighborhoods that have had the highest historical frequency (blue bars) and level of water flow (red bars), which could also be called critical flood colonies, and among which are: Colon Industrial, Miravalle, Jardines del Bosque, San Carlos and El Dean, mainly. A total of 65 neighborhoods were affected by significant flooding during the last 12 years out of 362 neighborhoods in the municipality.

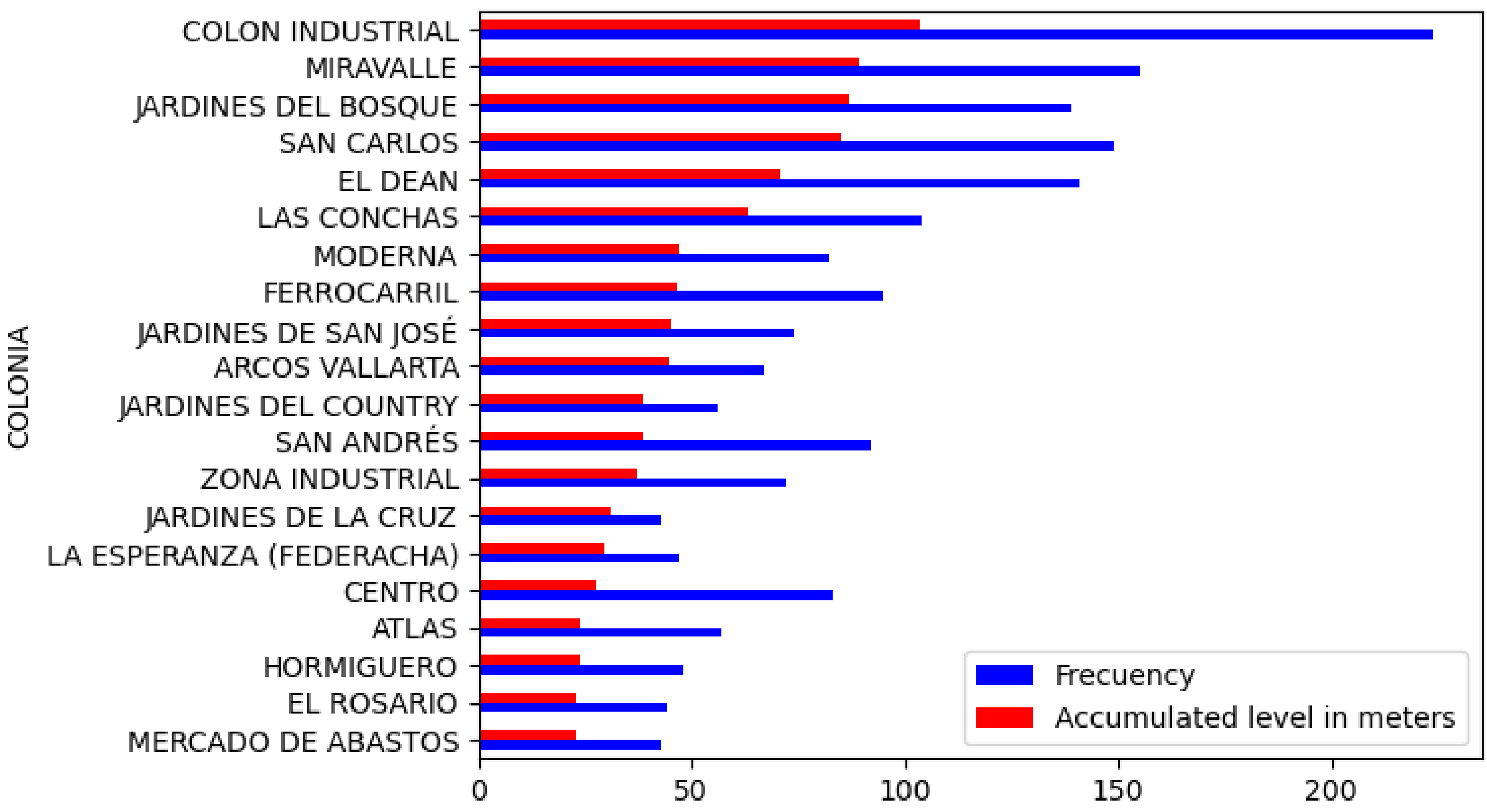

Figure 11. Main CRI with higher water depth (red bars) accumulated by neighborhood and frequency of historical flood impact sites in Guadalajara (blue bars).

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Finally, from Table 2, it can be seen the principal SiCI in Guadalajara. It is important to note that SiCI, apart from complying with the recurrence criteria, should have met the incidence criterion by having the same field of domicile and the same street crossing field, obtaining a total of 20 SiCI (Tabla 2), where the maximum value has a historical frequency of 120 and an accumulated level of 5, 835 cm.

Table 2. Principal SiCI that met the recurrence and incidence criteria at the address and street crossing.

No.	Address	Street crossing	Accumulaed level (cm)	Historical frequency
1	Hilaria Ríos	C. Manuel de Falla	440	12
2	Félix Palavicini	Av. Cvln. División del Nte.	610	12
3	Río Tuxcueca	Río Tizapán	670	13
4	Av. del Parque	C. Europa	740	15
5	C. 11	C. 14	827	16
6	Av. de la Pintura	Av. Gobernador Luis G. Curiel	880	13
7	C. 1	Av. Gobernador Luis G. Curiel	890	16
8	Av. Belisario Domínguez	C. Joaquín Romero	895	16
9	C. José Luis Verdia	Tuberosa	1 070	15
10	Av. Faro	Av. de las Rosas	1 310	24
11	Av. Ninos Heroes	Av. Inglaterra	1 320	20
12	Tuberosa	C. Las Conchas	1 450	27
13	Tuberosa	C. José Luis Verdia	1 470	25
14	Av. Niños Héroes	Av. de los Arcos	1 770	36
15	Artes Plásticas	Av. Gobernador Luis G. Curiel	1 960	33
16	C. Lope de Vega	Av. Inglaterra	2 620	41
17	J. Salomé Pina	Av. Gobernador Luis G. Curiel	2 665	47
18	Av. Isla Pantenaria	Av. Cristóbal Colón	4 620	49
19	Calz. Lázaro Cárdenas	Av. Mariano Otero	5 085	56
20	Av. Miguel Lopez de Legaspi	C. 32	5 835	120

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Discussions

A very important part of this study is the database with information that has been compiled by the CMPCG operations staff since many of the flood studies are based on hydraulic and hydrological modeling to obtain flood height data or through multi-criteria and other probabilistic techniques to obtain areas with flooding potential. (Avila-Aceves *et al*., 2023; Vojtek *et al*., 2021). Other authors (Pistrika *et al*., 2014) mention that flood data and, specifically, damages are very rare to find, much more significant than hydrometric data, and, in some cases, exist, but with privacy restrictions. Therefore, it is evident from the results that there is a great advantage of having a flood inventory in the CMPCG with data taken in situ at the moment of maximum intensity or the onset of precipitation, and they are practically in real-time. It is important to note that the database does not contain the time of service of the emergency services. It would be important to identify possible rainfall events since several services are often attended daily due to different rainfall events.

Another result to highlight is that when estimating the number of precipitation events, most are above 40, except for 2019 and 2022. according to what was discussed by López, Magaña and Pérez (2022), there has been an increase in vulnerability to heavy rains and the risk of flash floods in the municipality of Guadalajara, given the change in land use and the low capacity of the drainage network respectively and where year after year more than 30 rainfall events are expected.

On the other hand, an apparent decrease in the services attended by 4 CMPCG fire bases was observed starting in 2017, when a consultation

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of the public works in the municipality and year by year was made to observe the new works and their location, and starting in 2017 there was an increase of these, many located in the central and southern part of the municipality (Gobierno GDL, 2023). In fact, starting this same year, the number of precipitation events decreased.

Regarding the categorization of the flood level, the results show that most neighborhoods have a low to medium flood level, with some neighborhoods having a high range, just where the main channel that crosses the municipality branches off. It is important to remember that flooding is a social event. This phenomenon does not show a single face but is subject to multiple interpretations within the framework of a sociocultural fabric (Bartolomé, 2006). In this sense, hazard is a result of society's construction, which is why hazard assessment is fundamental for risk mapping (Bulti & Abebe, 2020; Maranzoni et al., 2023).

We worked with 3,676 SAI, corresponding to 63 SiRI, with 65 CRI y 20 SiCI that met the recurrence criterio. In the case of the SiCI, the incidence criteria for both at home and the crossroads are considered. According to the most recent information provided by the Instituto de Planeación y Gestión del Desarrollo del Área Metropolitana de Guadalajara (IMEPLAN), it manages 360 flooding points (Ortiz, 2023) at the year 2023 also began to name recurrent flooding sites, but at the metropolis level. Thus, identifying the main recurrent flood colonies is a basis for risk prevention since the criteria for obtaining these colonies and recurrent sites is a function of the frequency and height of significant flooding. On the other hand, the historically affected sectors are public roads, homes, and service establishments. In this sense, the academic sector and

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IMEPLAN agree on the urgency and need to regulate urban growth in the ZMG (Ortiz, 2023) to help reduce the risk of flooding at the metropolitan and municipal levels.

As part of future research, there is still much to be done, such as a study focused on direct damage, since the database describes the real impact of the service provided in greater depth, which needs to be addressed in future work.

Conclusions

This research focuses on the database analysis compiled during emergency responses by the operational area of the CMPCG, within which is the flood inventory that contains the Flood Impact Sites (SAI). The historical geospatial analysis of floods in Guadalajara municipality was carried out with the help of GIS tools. A flood categorization map was obtained, in addition to SiRI and CRI, among which are Colón Industrial, Miravalle, Jardines del Bosque, San Carlos and El Dean, whose colonies obtained a higher historical frequency of flooding and higher flood heights finally to obtain the SiCI. Based on these results, it is recommended to provide greater vigilance or, if necessary, to provide a solution to flooding.

The outcome of the discussion is expected to contribute directly to the support of emergency responses and plans and contribute to the quantification of damages, generation of warning systems and integrated risk management. An area of opportunity undoubtedly lies in the valuable systematization of information, such as linking flood heights to the

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concept of return period, an indispensable tool for the design of emergency plans or hydraulic infrastructure design.

Finally, it is important to mention that, within the CMPCG and the Integral Risk Management area, there is the Intelligence Office, which works on updating the Risk Atlas of the municipality of Guadalajara in order to have a relevant and updated tool to make more effective decisions and adequately plan urban growth in Guadalajara, support civil protection programs and studies in general. In addition, this Office constantly monitors atmospheric, geological and environmental phenomena, supporting the transition from a reactive to a preventive scheme.

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