Original Paper

Adaptation and mitigation actions for flood management.

Application of the analytic hierarchical process in geographic information systems for flood risk assessment

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Abstract. *In order to generate information that facilitates decision-making concerning adaptation and mitigation actions related to planning for flood management, this study assessed the risk of flooding in the Garrapata* *microbasin, located in Chone, Ecuador, using a multi-criteria analysis based on GIS modelling. The technique involved choosing conditioning factors, which included secondary data and satellite photos. These were then processed using QGIS to produce theme maps of isohyets, river distance, elevation, slope, soil texture, and land use and cover. These maps were weighted using the Analytical Hierarchy Process (AHP) to give distinct weights to each factor, producing a flood risk map that was validated with Google Earth Engine. The findings indicated that low plains spanning 12.64 km² close to the Garrapata River are at high risk of flooding as a result of heavy rainfall or overflows. This analysis shows that the use of AHP and GIS together is a useful technique for determining flood risk and providing essential data for decision-making, which helps build more resilient communities that are better equipped to handle flood-related disasters.*

1. Introduction

Profound planetary transformations, undermining the sustainability of the ecosystems on which all life depends and involving features such as climate change, loss of biodiversity, toxic pollution and land degradation, are causing increasing instability and insecurity together with greater frequency and intensity of disasters which affect ever larger numbers of human populations together with innumerable other species. This requires adopting strategies based on a complex interaction between adaptation and mitigation actions based on trade-offs and synergies that can enhance the combined effect of both.

Floods are a particularly common type of natural catastrophe, accounting for 47% of all climatic disasters that occurred globally between 1995 and 2015 (Gran & Ramos 2019). Furthermore, flooding is one of the most difficult issues that mankind is currently experiencing due to climate change and growing urbanization (Qi et al., 2021; Rosales, 2018). Nonetheless, there are clear constraints in research, economics, and policy framework that restrict how floods are seen in underdeveloped nations (Nkwunonwo et al., 2020).

Within the limits of a drainage division, the watershed is a geohydrological unit made up of land, water, and biota (Kumar et al., 2022). Because microwatersheds are the main component of watersheds, they are therefore crucial units for planning and management on a global scale. This is because managing a region requires a thorough understanding of its social, economic, and environmental aspects, which is necessary to ensure the sustainable use of its resources and to help decision-makers in the event of natural or man-made disasters (Fenta et al., 2023; Mirzaei et al., 2023).

Floods are a relevant problem among the many studies that may be conducted at the microbasin level since surface channel overflow brought on by excessive precipitation has several negative impacts that can even result in fatalities (Mercado et al., 2020). Studies that have already been done on flood risk management in developing nations contend that not enough is known about floods, they are not well studied, and there are either no management strategies in place or they are being used insufficiently (Salman & Li 2018). Furthermore, the variables that affect a basin's or microbasin's ability to increase floods, such as land use changes, urbanization, deforestation, and climate change, must be considered (Mirzaei et al., 2023).

The severe floods of 2012 in Ecuador were estimated to have cost $238 million in economic damages (Pinos & Timbe, 2020). Subsequently, 2,268 floods were reported in the country between 2015 and 2020, with losses including fatalities, harm to crops and infrastructure, interruptions to business and education, and detrimental effects on long-term human health and well-being. Lowlands along the shore often experience flooding (Galarza et al., 2018). The province of Manabí is one of the most afflicted areas in the above-described environment; in particular, the Chone canton experiences this recurring event, which poses a serious risk of flooding. The Mosquito, Río Grande, and Garrapata microbasins comprise the Chone River sub-basin.

While this kind of event happens suddenly, Ecuador lacks a well-defined procedure for monitoring floods. While most river basins have flood early warning systems in place using basic data, only four river basins have access to detailed hydrometeorological data. Despite the importance of this data to the national system, it is well known that its operational capacity has been hampered by a lack of funding (Tauzer et al., 2019). One of the main challenges in this country is monitoring floods in order to assess the effectiveness of the safeguards put in place and pinpoint places that require further action. At the moment, floods are being tracked using satellite photos and other data, and impacted towns are collaborating to help people in need of humanitarian aid.

In light of this situation, Geographic Information Systems (GIS), which Cedeño et al. (2017) define as a collection of software and technological tools for obtaining new kinds of real-world information, have advanced to the point where multi-criteria analysis based on GIS and the hierarchical analytical process method allow for the organization and control of parameters for making complex decisions (Drawish, 2023).

The assessment of flood hazards and risk assessment has been carried out globally through the integration of GIS and multi-criteria analysis, incorporating criteria such as rainfall (isohyets), land cover, soil types, slope map, and drainage density. The primary research studies of this kind have been conducted in Greece (Karymbalis et al., 2021), Iran (Allafta and Opp, 2021), Saudi Arabia (Abdelkarim et al., 2020), India (Das, 2020), Ethiopia (Hagos et al., 2022), Egypt (Abu El-Magd et al., 2020), and Ecuador (Reyna-Bowen et al., 2017).

From the standpoint of sustainability, this study supports long-term sustainable development, fosters community resilience, and encourages responsible territorial planning in addition to enhancing flood response capabilities, thereby bringing together adaptation and mitigation actions. With the background information in mind, the goal of this study was to assess the risk of flooding in the Garrapata microbasin using a multi-criteria analysis based on GIS modelling. This was done in order to produce data that would help decision-makers plan ahead and manage the risk of this kind of event.

2. Methodology

2.1. Study area

In the Ecuadorian province of Manabí, the Garrapata River microbasin is a place of significant natural and socioeconomic value. With a total size of 147.64 km 2, this microbasin is home to a range of habitats, including tropical forests, agricultural land, and populated regions. The research area is classified as an ecological region of tropical dry forest type (Holdrigde classification) and has tropical climate features, according to Ecuador's bioclimatic map. This region is characterized by variations in the Pacific Ocean and regional mobility. According to Aveiga et al. (2023), intertropical convergence has an impact. Reyna et al. (2018) describe the yearly average meteorological parameters in the Carrizal-Chone valley: temperature of 25.6 °C, potential evapotranspiration of 1365.2 mm, and precipitation of 838.7 mm. These parameters indicate a dry season from June to December and a rainy season from January to May. The Garrapata microbasin's location is illustrated in Figure 1.

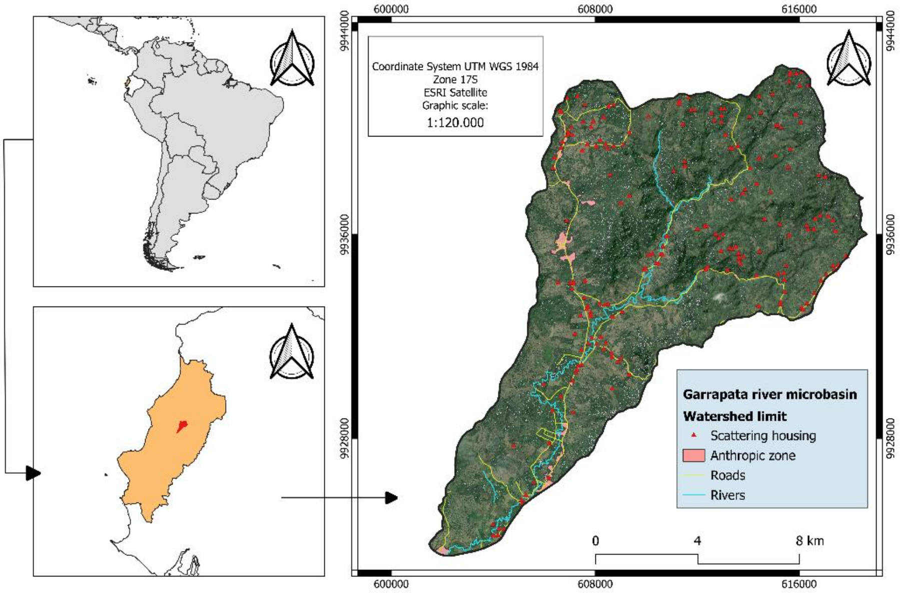

Figure 1. Geographic location of the Garrapata River microbasin, Chone canton, Manabí Province – Ecuador, specifically in Zone 17S of the Universal Transverse Mercator Coordinate System (UTM).

2.2. Selection of the conditioning factors of floods

By examining secondary data from government sources and pertinent agencies as well as satellite image data, thematic factors employed in this work to map flood-prone regions were identified. The Sentinel-1 satellite provided the digital elevation model (DEM), which was acquired from the website EARTHDATA (https://search.asf.alaska.edu/#/) at a resolution of 10 m. QGIS 3.36.0-1 software was utilized to analyse the DEM data in order to ascertain isohyet maps, river distance, elevation, slope, soil texture, land use, and land cover. Table 1 lists each variable's rationale, past research using it that is relevant to this study, and previous uses of the variable.

Table 1. Factors selected to represent flood hazard.

Factor	Justification	Reference
Rain	Because it increases the flow of rivers and streams, this is one of the primary causes of the overflow of bodies of water and the rise in river flow. Overflows and floods happen when the flow is greater than the channels' carrying capacity.	Darwish et al. (2023); Hagos et al. (2022); Swain et al. (2020); Cabrera & Lee (2019); Rincon et al. (2018)
Distance to the river	This is a major factor in how severe floods are since being next to a river raises the danger of flooding because riparian regions have higher water levels, are lower in elevation, and require less time to evacuate.	Swain et al. (2020); Abu et al. (2019);
Elevation	This is a crucial component to consider when assessing the danger of flooding since it affects how vulnerable towns are to flooding as well as how well the ground drains during periods of intense precipitation.	Karymbalis et al. (2021); Cabrera & Lee (2019)
Slope	This may have an impact on how water naturally drains during periods of intense rain. Water can collect in ponds and puddles on gently sloping terrain, raising the possibility of local floods. On the other hand, steeper slopes make it easier for water to flow into rivers and streams, which raises the possibility of floods later.	Hagos et al. (2022); Karymbalis et al. (2021)
Soil texture	This relates to the relative amounts of sand, silt, and clay in the soil, which greatly impacts how the soil takes in, holds onto, and releases water—all of which can impact the likelihood of floods.	Hagos et al. (2022); Cabrera & Lee (2019)
Coverage and land use	Flooding is more likely because of the altered soil's propensity to both infiltrate and hold onto water.	Nsangou et al. (2022); Hagos et al. (2022); Karymbalis et al. (2021)

By definition, floods are the outcome of several meteorological and topographic elements coming together across time and place. Consequently, every component that contributes to the occurrence of this phenomena has a distinct effect that enables the creation of a comprehensive landscape with varying degrees of flood risk sensitivity. Six parameters were considered in this study and were modelled in accordance with the AHP methodology's criteria (Figure 2).

2.3. Weighting of each factor using the AHP process

Once the thematic maps were prepared and classified, the AHP process was applied to assign different weights to each parameter. The relevance of each thematic layer in relation to the others was established by assigning weights, using the Saaty scale from 1 to 9 where 1 indicates that both elements are equally important and 9 indicates that one component is more important than the other. as detailed in table 2 (Saaty, 1980; Saaty & Vargas 1991).

Table 2. Definition of weights using AHP.

Numerical scale	Verbal scale	Description
1	Equal importance	Two activities contribute equally to the objective.
3	Moderate importance of one factor over another.	Experience and judgment slightly favour one activity over another.
5	Strong or essential importance	Experience and judgment strongly favour one activity over another.
7	Very strong importance	An activity is strongly favoured, and its mastery is demonstrated in practice.
9	Extreme importance	The evidence favouring one activity over another is of the highest order of affirmation possible.
2,4,6,8	Intermediate values between two adjacent judgments	When a commitment is necessary
1/2, 1/3, 1/4, 1/5, 1/6, 1/7, 1/8, 1/9	Inverses	This is used when the second element is greater in the criterion to be compared

Source: Adapted from (Mendoza et al., 2019)

In this research, the AHP method's first step is to compare two variables pairwise using a 6 x 6 matrix. Each theme layer's weighting was determined by the value obtained after normalizing the comparison results. A weighted sum was calculated for each row of the comparison matrix by multiplying the amount of each element by the priority assigned to each criterion. The weighted sum was then divided by the priority of the relevant criterion. Next, the mean ($\lambda_{máx}$) of the prior step's results was determined. The consistency index (CI) was calculated for each criterion, where n is equal to the number of criteria (equation 1). Subsequently, the random index (RI) was calculated as the average CI of a large sample of randomly generated comparison matrices (equation 2). Finally, the consistency ratio (CR) was established (equation 3) (Mendoza et al., 2019). The subjective evaluation is considered acceptable if the CR value is equal to or less than 0.10. However, if the CR value exceeds 0.10, the subjective evaluation is considered inconsistent and should be revised to ensure realistic results (Swain et al., 2020).

$$CI = \frac{\lambda_{máx} - n}{n-1} \qquad [1]$$

$$RI = \frac{1.98(n-2)}{n} \qquad [2]$$

$$CR = \frac{CI}{IA} \qquad [3]$$

In the second stage, each parameter was classified into subcategories and weighted using a 6x6 AHP matrix in Microsoft Excel 2016. The maximum and minimum values for each class vary from 1 to 4. In addition, normalization was utilized to calculate the weight of each class, which was then used to map flood hazard in QGIS 3.36.0-1. Isohyets, elevation, distance to river, slope, cover, and land usage are classified into four categories, whilst soil texture is classified into two. Furthermore, the flood danger index (Equation 4) is calculated by adding the weight values of all classes in each parameter to the weight values of all components. The weight of each component is multiplied by each class of the same factor to determine its overall weighting value (Hagos et al., 2022).

$$Risk\ of\ flooding = W_i X_i \qquad [4]$$

2.4. Flood risk map validation

The flood risk map generated by the AHP process was validated in a GIS environment using Google Earth Engine and Sentinel-1 data to obtain VV reference values. This allows detecting potentially flooded areas using a specific threshold (-3) (Johary et al., 2023; Singh & Rawat, 2024). The imaging period was from February 15 to February 28, 2024, since the latest flood in Chone occurred on February 22, 2024.

3. Results and discussion

The microbasin has a geographical distribution of moderate precipitation with four primary ranges: 1061 - 1076 mm/year (17.21 km^2); 1045 - 1061 mm/year (54.62 km^2); 1029 - 1045 mm/year (55.90 km^2); and 1013 - 1029 mm/year (19.83 km^2). According to Horton-Strahler, the water network consists of several channels that are categorized into two orders. The principal channel, the Garrapata River (order 2), spans 25.29 kilometres and distributes the microbasin's drainage (letter an in figure 2). The distance to the river variable illustrates that the regions most prone to flooding are those closest to the river, located in flood plains and low areas (shown in turquoise), making them vulnerable to heavy rain or overflow occurrences. Flooding is less likely in regions further from the river (in brown), as well as in mountainous and elevation areas (letter b in Figure 2).

The microbasin ranges in altitude from 29 to 794 meters above sea level. The range with the biggest size (51.78 km^2) corresponds to heights ranging from 29 to 794 meters, followed by the range of 29 to 82 meters (37.38 km^2). 36.55 km^2 have elevations ranging from 82 to 208 meters, whereas the smallest extension (21.93 km^2) ranges from 29 to 82 meters (letter c in figure 2). In terms of slope, the microbasin exhibits a wide range of terrain inclinations. The surface with a slope of less than or equal to 25% covers 143.80 km^2. The slope range of 25 to 50% covers 1.36 km^2, whereas a surface of 0.98 km^2 is within the range of 50 to 75%. The sections with a slope higher than 75% cover 2.25 km^2 of the microbasin (letter d in figure 2).

The microbasin's soil texture is mostly fine, covering 89.87 km^2 of the surface. However, near the river's banks, a medium texture (57.77 km^2) is detected, indicating bigger particles and loam-type soil (letter e in figure 2). In terms of land use, agricultural activity occupies the biggest area (114.19 km^2), with concentrations in the lowest and least sloping areas. Higher altitude regions contain remains of native forest (15.03 km^2) and secondary forests (15.79 km^2). In addition, there is a body of water and a small area (0.81 km^2) of shrub and herbaceous vegetation. The anthropic zone covers 1.79 km^2 of the microbasin (letter f in figure 2).

The first step of the AHP computations evaluates the weights and comparisons of all components using a 6 × 6 matrix with diagonal elements equal to 1 (Table 3). Furthermore, the result of the paired comparison (factor vs. factor) was adjusted to get a weighted value (Table 4).

Using the weighting in Table 4, the relative importance of each element was given to produce the flood risk map of the Garrapata River microbasin (letter a in Figure 3), which reveals interesting trends about the area's sensitivity to flooding. In this scenario, flood-prone regions (level 4) span 12.64 km^2 and are mostly located in the plains and lowlands near the Garrapata River's overflow discharge. These places are especially susceptible to flooding following heavy rain or river overflow occurrences. An area of 84.34 km^2 is distinguished as runoff plains; another 49.54 km^2 is located in level 2 (mountainous areas), and the remaining

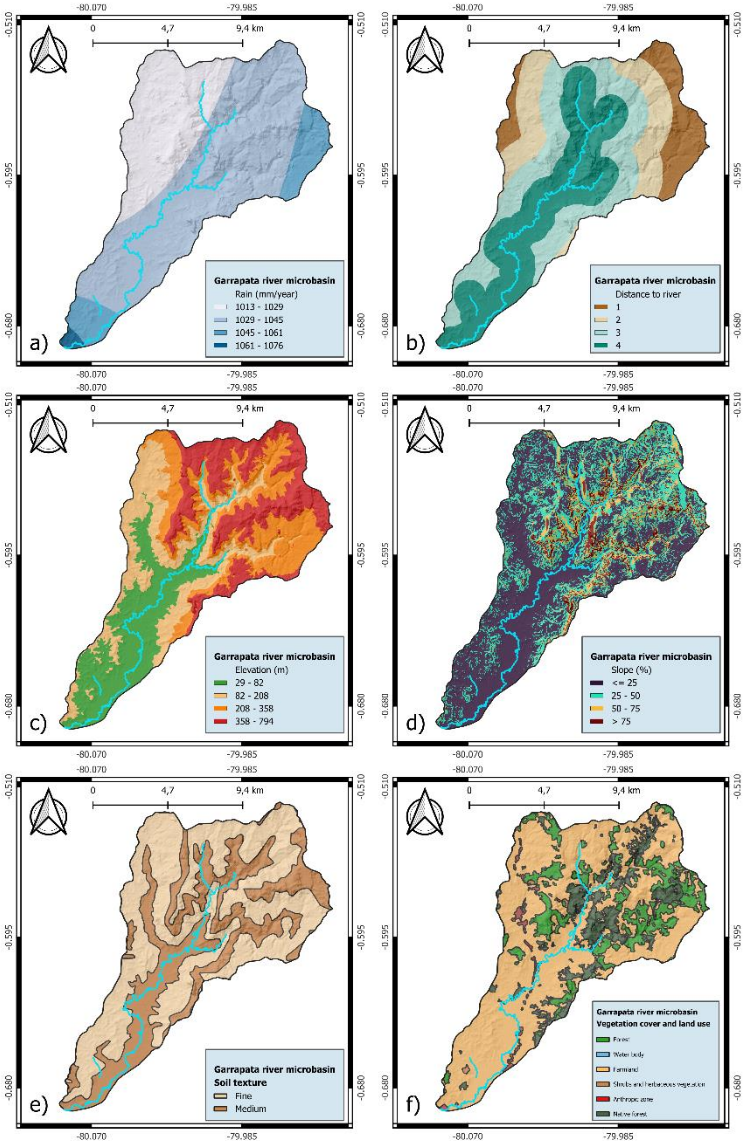

Figure 2. Factors for flood hazard mapping: a) Isohyets; b) Distance to the river; c) Elevation; d) Slope; e) Soil texture; f) Coverage and land use.

1.13 km² belongs to the most mountainous and elevated areas, which are not susceptible to flooding due to their topography and distance from the riverbed.

Table 3. Comparison matrix and relative score of factors related to flood risk.

Factor	Isoh yets	Distance to the river	Elevation	Earring	Soil texture	Coverage and land use
Isohyets	1.00	0.20	5.00	5.00	7.00	7.00
Distance to the river	5.00	1.00	5.00	5.00	7.00	7.00
Elevation	0.20	0.20	1.00	3.00	7.00	7.00
Slope	0.20	0.20	0.33	1.00	3.00	3.00
Soil texture	0.14	0.14	0.14	0.33	1.00	3.00
Coverage and land use	0.14	0.14	0.33	0.33	0.33	1.00

Table 4. Normalized values and weight of each factor according to the comparison matrix.

Factor	Pw	Weight (%)
Distance to the river	0.45	45.00
Isohyets	0.26	26.00
Elevation	0.14	14.00
Slope	0.07	7.00
Soil texture	0.04	4.00
Coverage and land use	0.03	3.00

Letter b in Figure 3 depicts the validation of the flood risk map; by superimposing the DEM derived from Google Earth Engine, a significant resemblance between the two maps is obvious; the validation flood surface measures 9.07 km², verifying the created model's accuracy. This validation confirms that the risk map created using the AHP approach and GIS accurately depicts flood-prone regions, highlighting the model's use for disaster risk planning and management.

Floods represent a danger to the built environment's economic, social, and environmental sustainability (Ekmekcioğlu et al., 2020). As a result, flood risk assessment is critical for managing this type of catastrophe, enabling the deployment of preventative, mitigation, and preparedness measures (Ma et al., 2021), as well as the integration of the AHP process with GIS. They enable for the creation of a model to assess the geographical distribution of flood-prone areas. The Garrapata River microbasin experiences more precipitation due to the

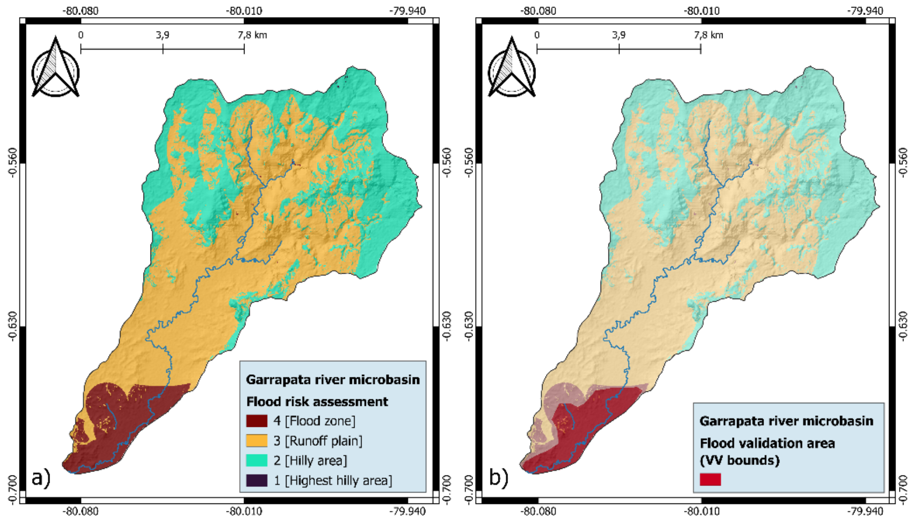

Figure 3. (a) Flood risk map of the Garrapata microbasin; (b) Validation map.

El Niño phenomenon. For example, the maximum annual precipitation level in the Chone River basin was recorded in 1982-1983, with 2855 mm, and 1997-1998, with 3352 mm, while the average annual precipitation reaches 903 mm (Rivadeneira et al., 2020). This dramatic increase in precipitation significantly raises the danger of flooding in the Garrapata River microbasin, a phenomenon that has also been identified as a critical concern posed by climate change (Rajkhowa & Sarma, 2021; Rivadeneira et al., 2020).

Recent studies have focused on areas in other parts of the world where flood management is of equal importance. Flood risk has increased significantly in Vietnam due to, among other reasons, the effect of climate change, but there is still limited research on flood risk assessment at the local level (Pham et al., 2021). In Turkey, Ekmekcioğlu et al. (2020) found that the highest flood risk districts are mainly located in the centre and highly populated areas of Istanbul, applying the AHP process to weight criteria. In China, flood risk maps were generated using the XGBoost algorithm. At the district level, it has been assessed that

40.3% of the districts are at high risk of flash floods, concentrating primarily in southern Yunnan (Ma et al., 2021).

Mujib et al. (2021) classified floodplain mapping results into five categories: poor 0.02%, low 4.26%, medium 37.11%, high 51.89%, and very high 6.72%, concluding that the AHP-GIS model's prediction is ideal for mapping flood-prone areas in Kencong district, Indonesia. Zhang et al. (2020) created a GIS-based multi-index spatial model for flood risk assessment and said that the development of this sort of study adds to future scientific efforts on flood prediction and mitigation. Similarly, Cai et al. (2021) suggest that by modifying the AHP procedure, flood risk may be properly assessed, and the results successfully applied to urban development strategy.

4. Conclusions

Flooding remains as a substantial hazard to community development over the long term and integrating adaptation and mitigation actions is essential. In this context, combining the Analytic Hierarchy Process (AHP) with Geographic Information Systems (GIS) is a potential technique to creating an accurate flood risk assessment map. This method was used in this study to determine the regions of the Garrapata microbasin that are most likely to flood. The major findings suggest that an expansion of 12.64 km² of the low parts of the microbasin and next to the bank of the Garrapata River has flooding risk (level 4). This information makes it easier to identify priority regions for the deployment of adaption measures and make educated disaster risk reduction decisions. Finally, this technology can help communities become more robust to floods and other catastrophic hydrometeorological phenomena. Several studies have demonstrated that the AHP approach is an effective technique for assessing flood risk. However, the efficacy of AHP is dependent on the quality of the expert judgment used to give weights to certain criteria. Furthermore than the validation presented in this research, other studies might compare the AHP-based map to other current flood risk maps for the Garrapata microbasin to determine its accuracy. It would be useful to know whether the study compared the AHP-based map to historical flood data for the Garrapata microbasin. Furthermore, comparing the map to flood risk maps made using other approaches may increase the validity of the results.

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