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Research article

Flood susceptibility in rural settlements in remote zones: The case of a mountainous basin in the Sierra-Costa region of Michoacán, Mexico

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A R T I C L E I N F O

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A B S T R A C T

Maps of natural hazards are essential for the prevention or mitigation of disasters. The Nexpa River mountainous basin is in the Sierra-Costa region of the state of Michoacán, Mexico. The dispersed rural settlements in the basin, accessed through a network of mainly minor roads and tracks, are highly vulnerable in cases of catastrophic hydrometeorological events. Our study aimed to map flood zones and assess flood susceptibility in the basin on the basis of geopedology, topography, land cover and land use, to assess the vulnerability of local rural settlements and their network of roads and tracks. The land morphology was mapped and the weighted overlay technique was applied in a geographic information system to generate maps of susceptibility to flooding. Our results showed that 13% of settlements and 7% of the communication network are within flood zones. Maps based on environmental factors showed low to medium susceptibility to flooding. These methods are useful and effective for zones with little or no hydrometeorological information, and they can provide a robust source of information for decision makers regarding land planning to mitigate flood vulnerability.

1. Introduction

Floods are one of the most common and devastating hydrometeorological hazards in Mexico and worldwide, causing both economic losses and human fatalities (Adhikari et al., 2010; Alcántara-Ayala, 2002). The main predisposing factors are of meteorological and geomorphological origin, both directly affecting surface runoff (Costa, 1987) by the combination of topographic, geological, and soil characteristics present in basins (Modrick and Georgakakos, 2015). Flood risk can also be increased by another hydrometeorological hazard represented by landslides, which also occur under conditions of excessive and high-intensity precipitations; landslides, in turn, intensify the occurrence of flash floods and flow accumulation, consequently increasing flood risk (Alcántara-Ayala, 2002).

Efforts have been made to evaluate flood hazards with the purpose of prevention or mitigation (Gallina et al., 2016; Kellens et al., 2013; Rufat et al., 2015; Teng et al., 2017; Wenger et al., 2013). Frequently these studies are preceded by flood risk study use hydrologic/hydraulic modeling to understand flood extend and peak discharge which later related to flood risk. Unfortunately, the lack of appropriate data availability (type and resolution) in the region prevents the application of standard engineering flood models which a common problem in developing countries (Komi et al., 2017; Mendoza et al., 2002). In particular, Perucca and Angilieri (2011) analyzed morphometric properties for assessing hazards of flash floods, and they suggested the implementation of mitigation measures. Characterization of terrain morphology and mapping of landforms is an essential, low-cost tool for evaluating vulnerability to floods (Cunha et al., 2017), and this can be used by decision makers for land use planning (Scheuer et al., 2013). Another advantage of the geomorphological approach to flood risk evaluation is that it can be applied at several scales, given that landforms can be mapped at large or small scales. In our study case we tackle a regional flood hazard evaluation because there has been a relatively limited research on this area (Azmeri et al., 2016).

Geomorphological mapping is essential for flood risk evaluation (Alcántara-Ayala, 2002) because the topography of a basin determines its hydrological responses and the flows generated (Saharia et al., 2017). The geomorphological approach allows landforms to be mapped

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and characterized in terms of terrain parameters that are directly related to surface water flows, soil erosion, sediment accumulation, and vegetation (Cunha et al., 2017; Mendoza et al., 2002).

A common alternative approach to flood susceptibility assessment is the weighted overlay technique (Bathrellos et al., 2017; Elsheikh et al., 2015; Fernández and Lutz, 2010; Siddayao et al., 2014), in our case defined as a complex multicriteria evaluation combining factors and objectives for classifying and evaluating flood susceptibility. This assesses the influence of each factor, and assigns values within a defined range of classes of the factors (Mayfield, 2015), thereby determining the environmental susceptibility to a specific hydrometeorological hazard. This technique is highly suitable for any kind of hazard evaluation because is a decision-making technique utilized for solving complex problems, with many parameters of interrelated objectives or concerned criteria. The level of each parameter is not equal; some parameters are dominant over others. Different weights can generate the difference in the level of susceptibility (Ahmed, 2015).

The Sierra-Costa region of Michoacán is susceptible to flooding due to the coincidence of several unfavorable factors: a high incidence of tropical storms with intense precipitations, and the distribution of its small population mainly in dispersed rural settlements accessed chiefly via unpaved roads and paths that receive limited maintenance. The resultant high vulnerability is exacerbated by the lack of a regional early-warning system regarding hydrometeorological hazards (Ferreira Silva et al., 2017; Ntajal et al., 2017; Ribera Masgrau, 2004).

With the ultimate goal of providing updated, efficient, and accessible information essential for creating an early-warning system in remote zones, our work had as objectives: (i) to identify flood zones in the Nexpa River basin of the Sierra-Costa region of Michoacán by means of geomorphological mapping; (ii) to characterize the factors involved in flood-susceptible zones in the basin; (iii) to evaluate the factors that increase flood susceptibility by means of weighted multiple criteria; and (iv) to analyze the results from the perspective of the vulnerability of the rural settlements and communication routes in the basin.

2. Material and methods

2.1. Study area

The Nexpa River basin (Fig. 1) is part of the Sierra-Costa region, Michoacán, Mexico, and is between the western part of the Sierra Madre del Sur physiographical province and the northwestern sector of the Cordillera Costera del Sur subprovince (INEGI, 2008). The basin consists of mountains with elevations of up to 2600 m a.s.l. and valleys defined by mainstream channel called Nexpa, and called Aguililla upstream. The climate is tropical dry, with an annual average temperature of about 20 °C, varying according to the altitude. Precipitation is associated with western winds and tropical cyclones, commonly occurring between May and October (Segundo-Métay and Bocco, 2015).

The vegetation includes coniferous and broadleaf forests at elevations between 600 and 2800 m a.s.l. on 39% of the total surface, low tropical deciduous forests on the upwind hillslopes of the Sierra Madre del Sur on 31%, grasslands associated with livestock on 27%, and rainfed and irrigated croplands on 10% of the total surface (Aguirre López, 2015).

The Nexpa River basin includes 459 rural communities dispersed throughout the territory and the town of Aguililla, which has the highest and densest population within the basin. The transportation network in the basin is 1438 km long and consists mainly of unpaved roads and tracks, except for the open federal highway (MEX-200) in the south communicating the coastal rural settlement of Nexpa, and the Apatzingán-Aguililla open state highway in the north of the basin.

2.2. Primary data

Primary data were obtained from government sources (Table 1). A spatial database was created in the geographical information system (GIS) ArcGIS 10.1 ESRI® and data were processed to create the following layers with a pixel size of 25 m: 1) Digital Terrain Model, 2) terrain steepness, 3) terrain curvature, 4) distance from streams, 5) flow accumulation, 5) landforms, and 6) ridgelines.

2.3. Land morphology mapping method

Land morphology mapping uses three input files: terrain steepness, streams, and ridgelines. The intersection of the defined criteria classifies the terrain into the following landforms (Cunha et al., 2017):

- Steep hillslopes, slope values > 25%
- Hillslopes, slope values 7–25%, and slope values < 7% without streams or ridgelines
- Hilltops, slope values < 7% containing ridgelines
- Valley bottoms, slope values < 7% containing streams

Because the basin has very steep hillslopes near the streams, normally in narrow valleys, a 7% steepness value was arbitrarily used as a threshold level for distinguishing valley bottoms and hilltops (Fig. 2, steepness). The resulting landform map was overlaid with the settlements and transportation network (roads/tracks) layers in order to identify settlements and roadways located within valley bottom landforms.

2.4. Weighted overlay technique in GIS

When data are limited, and there is decision making-problem, modeling, especially spatial modeling must be based on sound conceptual models that require a limited number of parameters and data, but with high spatial quality and precision. Weighted overlay is a suitable technique for spatial data integration and analysis. This technique enables the generation of reliable results, useful in the decision-making; even in the current case, when data is scarce and assignment of weight factors is complex. The weighted overlay technique has been applied for identifying flood susceptibility areas. However, it is the first time that land morphology mapping and the weighted overlay technique were integrated for evaluating flood susceptibility in remote areas with rural settlements; which is a frequent feature in inter-tropical countries.

Areas with higher flooding susceptibility based on input factors can be defined by means of the weighted overlay technique in GIS. This quantitative method also allows inclusion of qualitative considerations for establishing relationships between relevant factors and, after preliminary trials, assigns a weight to each factor for measuring its relative importance (Mayfield, 2015, Table 2).

Factors were selected by the working group through direct assignation on the basis of the literature (Guevara Ortiz et al., 2004; Rahmati et al., 2016; Salas Salinas, and Jiménez Espinosa, 2004), the availability of input data, and experience. The weights used in this study area are suitable because were defined by the experts based on revision of previous studies, characteristics of the selected factors, and as a result of previous preliminary tests with different weights. Weighting of topographic included 5 factors, non-topographic included 3 factors, and all included 7 factors, as the sum of the factors is 100%, different weights were assigned for the factors in every simulation. Despite this, the ratio of the factors was kept (i.e. steepness to landform is 20:25 in topographic, and 15:20 in all).

The values of the factors included in the study were incorporated in eight input files: 1) steepness; 2) curvature; 3) distance from a stream; 4) flow accumulation; and 5) landforms (created from morphological mapping of terrain), all these five determining flow accumulation and direction of water; 6) land use determining land cover; 7) soil surface texture, which together with other factors determines soil porosity that in turn establishes water infiltration into the soil; and 8) rock permeability (normally underlying the soil) determining infiltration of water