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Multi-criteria approach to develop flood susceptibility maps in arid regions of Middle East

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ABSTRACT

Flood susceptibility and risk assessment are very important for suitable urban development. The present study introduces a methodology for identifying flood susceptibility zones using a multi-criteria analysis. The methodology was applied in the Riyadh Province, the central region of Saudi Arabia, validated using historical flood records and re-applied in the Riyadh city to assess the effect of scale on the results. The methodology incorporates 10 susceptibility factors: flow accumulation, annual rainfall, slope, runoff, land use/cover, elevation, geology, soil type, distance from the drainage network, and drainage density. An analytical hierarchy process was employed to derive the weight of each susceptibility factor, and sensitivity analysis was done to test how sensitive are the results to changes in the weights of susceptibility factors, and to evaluate the contribution of different susceptibility factors in developing the flood susceptibility maps. These maps were found to be in good agreement with historical flood events in the Riyadh province and Riyadh city and so they should be useful to assist flood mitigation and for future land use planning in both Riyadh province and Riyadh city. The proposed methodology is useful for general planning and assessment purposes, since it has been shown to be independent of scale, given similar flood susceptibility zones for the Riyadh region were obtained from both large-scale and small-scale models. The highest flood susceptibility areas are found in northern, northeastern, and northwestern parts of the Riyadh Province. Key contributing factors to flood susceptibility are surface runoff, flow accumulation, soil type, elevation, distance to drainage network, drainage density, land use, slope, and geology. Based on results obtained from the sensitivity analysis, it is advisable to consider six or more susceptibility factors in developing flood susceptibility maps, especially factors related to surface runoff and flow accumulation.

1. Introduction

Millions of people are affected by flooding every year worldwide. Therefore, it is critical to control floods through proper land use management. Owing to their magnitude and sudden arrival often with minimal warning, floods usually lead to serious disasters locally. In other words, effective flood prevention has been a significant challenge in many countries. The frequent occurrences of extreme weather have caused flooding to be one of the most destructive natural hazards in arid regions. Many studies show that the rising number of major flood events is mainly due to the rapid increase in artificial surfaces, extensive urbanization and deforestation (Bronstert, 2003; Christensen and Christensen, 2003). Therefore, representative maps of flood-prone areas should be developed to prepare a fast and effective response under flooding circumstances. In the Arabian Peninsula, surface runoff from high latitude regions tend to post a threat to its urban residents, facilities, and infrastructure. Recent flooding events that occurred in Mecca, Jizan, Al-Baha, Riyadh, Jeddah, and Abha regions among others in the Kingdom of Saudi Arabia (KSA) show that arid/semi-arid regions in the Middle East region are susceptible to floods. Therefore, developing flood warning systems in any of these regions could be one of the most effective ways to reduce the loss of life and property damage due to flooding (Negri et al., 2005).

Conjunctive applications of GIS (Geographic Information System), and multiple criteria decision support system (MCDSS) helps researchers to manage large amounts of data in solving complex problems. The Analytic Hierarchy Process (AHP) developed by Saaty (1980) is one of the most popular methods in applying a multi-criteria decision support system to optimize decision making

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under a set of qualitative, quantitative, and sometimes conflicting factors. Saaty (2008) proposed a procedure that involves arranging variables in a hierarchy from which the best possible solution is determined via a pairwise comparison. The application of AHP and GIS in an integrated manner has been successful in various studies such as flood susceptibility mapping (Kazakis et al., 2015), landfall delineation, natural hazard (Fernandez and Lutz, 2010; Ahn and Merwade, 2015; Singh et al., 2017) and geo-environmental studies (Ju et al., 2012; Mahmoud and Tang, 2015; Singh et al., 2017; Patra et al., 2018). For example, Mahmoud and Tang (2015) applied AHP for managing the stormwater of the United Kingdom using five factors: rainfall excess, slope, curve number, land cover/use, and soil texture. To control flooding in UK, they developed a stormwater management map for UK that shows areas ranging from very high to low stormwater harvesting potential. They also identified locations for constructing flood control facilities based on a weighted combination of such factors, in which soil type and runoff depth contributed about 70% in developing maps for stormwater management, which is expected surface runoff is closely linked to flood occurrences (Nouh, 2006).

Other factors used in flood susceptibility mapping are such as flow accumulation, annual rainfall, elevation, distance from the drainage network, geology, slope, runoff, land use/cover, soil type, and drainage density. Fernandez and Lutz (2010) attempted to map urban flood susceptibility zones in the Tucumán Province, Argentina, using AHP. Due to a lack of spatial data, he only used five factors which are the distance to the drainage channels, topography, groundwater table depths, and urban land use. There is a lack of test on the effect of scale in flood susceptibility mapping, say from large to small scales, or vice versa, e.g. (Fernandez and Lutz, 2010; Kazakis et al., 2015). To improve our understanding of the effect of scale, testing the effect can be achieved by comparing results obtained from flood susceptibility maps for large-scale to small-scale areas located in the same region.

In the past few decades, AHP has been applied to many diverse applications of Decision Support Systems (DSS), such as applying an AHP-DSS in flood susceptibility mapping. For example, Chen et al. (2011) integrated AHP and GIS to delineate flood susceptibility zones in two cities of Taiwan. Tehrany et al. (2013) identified flood susceptibility areas in the Kelantan River basin using an advanced rule-based decision tree and ensemble statistical method and 10 susceptibility factors: DEM, curvature, geology, river, SPI, rainfall, land use/cover, soil type, TWI, and slope. Kazakis et al. (2015) delineated flood susceptibility zones in the Rhodope–Evros region of Greece using seven factors which were weighted according to their contribution to flood occurrences based on AHP. The factors with the highest weights of influence identified were elevation, slope, and distance from the drainage network. The flood susceptibility map developed was validated against observed flood records. Elkhrachy (2015) also used AHP to generate flood susceptibility map for the Najran city, KSA. AHP was used to determine relative weights of flood susceptibility factors, of which runoff and soil type were the dominant factors that contributed 35.5% to surface runoff in the flood susceptibility map, while less important factors were surface slope, surface roughness, drainage density, and land use.

Hsu et al. (2017) employed AHP and GIS to map flood susceptibility zones in the Fangshan District, China, using nine susceptibility factors such as rainstorm intensity and frequency, elevation, slope, river network density, and others. The flood susceptibility maps they developed agree well with historical flood records. In another study, Trail et al. (2017) integrated five factors into an AHP to map flood susceptibility zones in coastal lowland areas of central Vietnam, of which h they showed that elevation and distance to drainage network play a major role in the development of flood susceptibility zones. It seems common for many studies to miss factors such as surface runoff and drainage density in flood susceptibility mapping, in which important factors to be considered are such as surface runoff, drainage density, annual rainfall, distance to drainage network, soil type, and land use. Using a limited number of factors in flood susceptibility mapping will increase the possibility of getting some over-rated factors.

It is important to develop flood susceptibility maps in Riyadh province, the central region of Saudi Arabia (18% of KSA total area) where recurring flood events have occurred, for possible rescue operations and for including migration procedures in future land use planning in both the Riyadh province and Riyadh city. A multi-criteria approach is introduced to identify flood susceptibility zones and then a sensitivity analysis was done to examine how sensitive are the results to changes in weights applied to susceptibility factors and the relative importance of these susceptibility factors. The methodology was applied in Riyadh Province, and the result was validated against historical flood records. To test the effect of scale in the proposed methodology, it was applied again in the Riyadh City which is only 4.85% in area of the Riyadh Province, and 0.89% of the total area of KSA.

2. Study area

The Riyadh Province (24°38″ N and longitude 46°43′ E) (Fig. 1(a)), located in central Arabia, was selected as the study site because the entire study area has no flood susceptibility maps. Similar to most arid regions in the Middle East, where rainfall is scarce, there is a general lack of proper drainage system which tends to cause catastrophic flooding when extreme weather occurs. In the last 30 years, KSA constructed many rainwater harvesting dams in the mountainous region for agriculture development (Mahmoud and Alazba, 2015). Furthermore, floods could occur because of rugged topography and geological structures. Fig. 1(b) shows that a flood event in the northern Riyadh province had caused severe damages to infrastructure and private properties.

3. Materials and methods

3.1. Selection of susceptibility factors and data processing

Information from different data sources was collected and a database was developed in a geospatial environment. Ten susceptibility factors were selected based on literature reviews, which are flow accumulation, distance from the drainage network, elevation, LULC, annual rainfall, geology, slope, runoff, soil type, and drainage density. These factors were then characterized based on field survey and long-term flood records in KSA. Based on earlier studies (Fernandez and Lutz, 2010; Elkhrachy, 2015; Bathrellos et al., 2016; Hong et al., 2018), the importance of each flood susceptibility class such as flow accumulation, annual rainfall, geology, distance from the drainage network, slope, runoff, soil type, elevation, LULC, and drainage density. Because the susceptibility factors were measured on different scales, certain reclassifications were necessary to convert susceptibility factors to five comparable units or susceptibility classes: 5 (very high susceptibility), 4 (high susceptibility), 3 (medium susceptibility), 2 (low susceptibility), and 1 (very low susceptibility) as shown in Table 1, based on their contributions to flooding probability. For instance, based on historical flood records, the elevation of the study area was divided into five categories. An area with low elevation (0–250 m) falls under very high susceptibility category, while an area at a high elevation falls under a very low susceptibility category (Jacinto et al., 2014).

Similarly, the raster slope map was classified into five classes. Areas with 0–2% slope was assigned a very high susceptibility to