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Urbanization and climate change implications in flood risk management: Developing an efficient decision support system for flood susceptibility mapping

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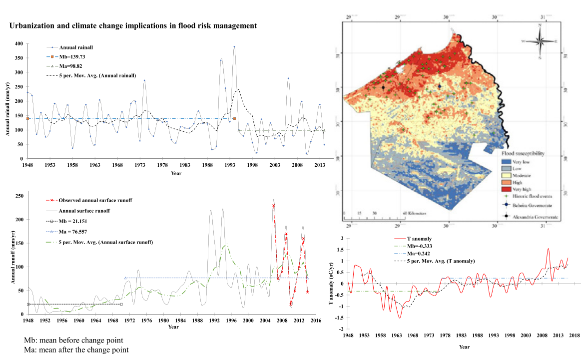
HIGHLIGHTS

- Investigating climate change implication in flood risk in arid regions
- Investigating rapid urbanization implication in flood risk
- Runoff curve number method to develop surface runoff between 1948 and 2014
- Illustrate the influence of urbanization rate in surface runoff through change point trend detection
- Develop susceptibility model to delineate flood susceptibility zones

GRAPHICAL ABSTRACT



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ABSTRACT

The effects of urbanization and climate change impact to the flood risk of two governorates in Egypt were analyzed. Non-parametric change point and trend detection algorithms were applied to the annual rainfall, rainfall anomaly, and temperature anomaly of both study sites. Next, change points and trends of the annual and monthly surface runoff data generated by the Curve Number method over 1948–2014 were also analyzed to detect the effects of urbanization on the surface runoff. Lastly, a GIS decision support system was developed to delineate flood susceptibility zones for the two governorates. The significant decline in annual rainfall and rainfall anomaly after 1994 at 8.96 and 15.3 mm/decade respectively was likely due to climate change impact, especially significant warming trend since 1976 at 0.16 °C/decade, though that could partly be attributed to rapid urbanization. Since 1970, effects of urbanization to flood risk are clear, because despite a decline in rainfall, the annual surface runoff and runoff anomaly show positive trends of 12.7 and of 14.39 mm/decade, respectively. Eleven flood contributing factors have been identified and used in mapping flood susceptibility zones of both sites. In the El-Beheira governorate, 9.2%, 17.9%, 32.3%, 28.3% and 12.3% of its area are categorized as very high, high, moderate, low and very low susceptibility to flooding, respectively. Similarly, in Alexandria governorate, 15.9%, 33.5%, 41%, 8.8% and 0.8% of its area are categorized as very high, high, moderate, low and very low susceptibility to flooding, respectively. Very high and high susceptible zones are located in the northern, northwestern and northeastern parts of the Beheira governorates, and in the northeastern and northwestern parts of Alexandria. The flood related information obtained in this study will be useful to assist mitigating potential flood damages and future land use planning of both governorates of Egypt.

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1. Introduction

In recent years, because of urbanization, there is an increase in flood risk even in arid regions with a limited amount of annual rainfall. Various flood risk studies reported the effect of urbanization in surface runoff (Satterthwaite, 2008; Zhang et al., 2008a; Fernández and Lutz, 2010). These studies reported that increase in urban areas and impervious surfaces have led to an increase in surface runoff because less water is lost by soil infiltration. On the other hand, there are studies that attributed the rising frequency of flood occurrences to the impact of climate change (Gizaw and Gan, 2015; Jiang et al., 2015). Precipitation in arid regions tends to be more variable in time than in humid regions (Pilgrim et al., 1988), and so are more vulnerable to hydrologic extremes such as flood and droughts. In the driest continent of Africa, climate change has been linked to more frequent occurrences of severe droughts, rising temperature and altered precipitation patterns (Ramanathan et al., 2001; Shanahan et al., 2009; Williams and Funk, 2011). In countries such as Egypt, floods have been occurring more frequently and in greater severity in recent decades. A hypothesis is herein investigated, whether increasing flood events in Egypt are due to rapid urbanization or the effect of climate change.

Therefore, we will investigate the implications of urbanization and climate change in the flood risk of Egypt, which is representative of the climate of other arid regions in the Middle East. The recurrent occurrences of flooding in Egypt, especially in its coastal regions have led to catastrophic and costly damage to properties and threat to human life, which may be because of rapid urbanization along the Nile River. In northern, coastal regions of Egypt's Nile Delta and coastal areas along the Mediterranean Sea, flood discharge from wadi basins can be a threat to coastal cities, towns, and villages. Since 1990, more than seven hundred people in Egypt had lost their life because of flash floods, and about 250,000 people were affected (Guha-Sapir et al., 2014). Therefore, flood-susceptible areas should be identified so that responses to flooding emergencies can be executed quickly and effectively. Historically, Egypt's most affected regions are El-Beheira, Alexandria, Sinai, Matruh, Cairo, and Giza, which are vulnerable to the potential threat of increased surface runoff, particularly in arid regions where people tend to be ill-prepared against flood hazards.

An analysis of long-term surface runoff data of urban areas can generally reveal the effects of urbanization. A limited number of studies have used the runoff curve number method to compute surface runoff and its effects to urban communities (Lim et al., 2006; Shi et al., 2007; Banasik et al., 2014). However, most studies have not considered the effects of both urbanization and climate change impact to urban surface runoff and the development of flood susceptibility maps, e.g., (Cherqui et al., 2015; Chen et al., 2015; Xiao et al., 2017; Hong et al., 2017; Termeh et al., 2018; Zhao et al., 2018). Methods such as Multi-criteria decision support system and analytic hierarchy process have proven to be effective tools in developing flood susceptibility maps (Ouma and Tateishi, 2014; Kazakis et al., 2015; Melesse and Abtew, 2016). Researchers have used various hydrologic and climatic data that contribute to floodings, such as precipitation, runoff, digital elevation model (DEM), curvature, geology, land use/cover (urbanization), soil type, topographic wetness index and slope (Şen, 2004; Nouh, 2006). However, because of a lack of data, only a limited number of studies have used comprehensive datasets in delineating flood-prone areas of river basins. For instance, Fernández and Lutz (2010) used five flood contributing factors to analyze flood-prone areas in the Tucumán Province of Argentina: distance to the drainage channels, topography, groundwater table depths, and land use. Kazakis et al. (2015) mapped flood hazard areas of the Rhodope–Evros region of Greece based on seven factors, namely, flow accumulation, distance from the drainage network, elevation, land use, rainfall intensity and geology. Tehrany et al. (2015) did that for Malaysia using ten factors: altitude, slope, curvature, stream power index (SPI), topographic wetness index (TWI), distance from the river, geology, land use/cover (LULC), soil, and annual surface runoff, but they used a different set of factors in an earlier study (Tehrany et al., 2013).

We expect that a systematic analysis of a comprehensive dataset will lead to a representative delineation of flood susceptibility areas, which can later be validated against ground observations of past flood events. Elkhrachy (2015) used an AHP approach to map flood hazards zones in Najran city of Saudi Arabia. Among the conditions considered, annual surface runoff, soil type, surface slope, surface roughness, drainage density, distance to the main channel and land use, Elkhrachy (2015) assigned a weighting factor of 35.5% to the annual surface runoff, making it one of the most important factors in flood susceptibility mapping. Many past studies derived the relative contribution of each factor to floods based on authors' experience, literature review and weighting methods and validate final flood susceptibility maps developed against historical flood records. Flash floods occur periodically in El-Beheira and Alexandria governorates due to a lack of proper drainage systems and rapid urbanization. In 2013, surface runoff destroyed about 121 km^2 of agricultural land in El-Beheira governorate. Alexandria governorate also suffered from increased surface runoff that badly flooded streets of the coastal city and damaged many private properties. Residents of Alexandria expressed their outrage at the former government of Alexandria that failed to efficiently flood-proof the city against foreseeable events. In recent years, floods in El-Beheira had caused twenty-five deaths, forced hundreds of schools to shut down, dozens of people were forced to evacuate from their homes, and large swathes of buildings in the region were destroyed. Therefore, the objective of this study was to investigate the effects of urbanization and climate change in the flood risk management of arid regions, in addition, to developing flood susceptibility maps to support decision making in the rescue operation.

To achieve our objectives, we first analyzed the variability and trends of the annual precipitation and temperature of the two governorates to estimate the possible impact of climate change. Next, to estimate the effects of urbanization to the flood risk of the two governorates, we applied the runoff curve number method to develop the time series of surface runoff for the two governorates between 1948 and 2014. Change point detections and trend analysis techniques were then applied to the surface runoff data to find the change points and trend. Surface runoff anomalies were also analyzed to assess the influence of urbanization in surface runoff. Finally, we developed a GIS decision support system to delineate flood susceptibility zones in the Beheira and Alexandria governorates of Egypt. The accuracy of the flood susceptibility maps developed was verified with historical flood records.

This study is necessary given there is generally a lack of flood susceptibility maps in Egypt and information related to the influence of climate change and urbanization in the surface runoff of Egypt. Similar situations are found in many if not all Middle Eastern countries of arid climate. Other than useful for flood risk management, flood susceptibility maps we have developed will also benefit planners and governments in choosing suitable locations for future developments and in mitigating potential flood damages and future land use planning in Beheira and Alexandria governorates. Furthermore, the surface runoff time series developed could be used in other hydrological studies in the two governorates of Egypt.

2. Study area

This study was conducted in two governorates of Egypt. The first is the El-Beheira governorate (Fig. 1) is located in the north coastal region of Egypt's Nile Delta (30.61°N, 30.43°E) with an area of about 10,130 km^2. El-Beheira's annual rainfall ranges from 29 mm/year in the south to 190 mm/yr in the north. The second is the Alexandria governorate (31.20°N, 29.92°E) which lies along the Mediterranean coast, at about 70 km northwest of the Nile Delta (Fig. 1) occupying an area of 2818 km^2 and an average annual rainfall of about 169 mm/yr.