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Factors controlling the spatial distribution of flash flooding in the complex environment of a metropolitan urban area. The case of Athens 2013 flash flood event

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ABSTRACT

This work studies the influence of various factors on the spatial distribution of flash flooding in urban areas. It examines an extreme precipitation event that occurred in 2013, in Athens, Greece, causing flooding and damages in various parts of the city. GIS was used to determine the values of potentially flood-influencing parameters, while logistic regression was used to examine the statistical correlation between their values and the respective values at the locations of 1138 flooded buildings. Statistical significance and other metrics were used to measure the influence of these factors on the distribution of flooding. Results showed that certain factors, including the degree of soil sealing, accumulated rainfall, slope and others, influence the distribution of flooding to significantly different degrees. Incorporation of building characteristics into the regression model increased further its coherence. The study showed a strong relationship between a combination of factors and flood occurrence with R^2 reaching 0.63 and a prediction accuracy of 82.9%. The degree of soil sealing and slope were the most influential in determining the distribution of flooding. However, when building parameters were incorporated, the level of a building's lower opening in comparison with ground level was by a significant margin the most important parameter.

1. Introduction

Floods in urban environment caused by high intensity storms are one of the most common natural hazards in the Mediterranean region, posing a significant threat to human life and causing extensive damages on property and infrastructure. Given the expected increase in the frequency of intense storms in the region [1] and the projected rise of urban population [2], their importance is expected to grow even more.

Particularly in urban environments, vulnerability is increased as higher concentration of population and assets leads to a higher exposure. The complexity of urban hydrology together with the influence of the multiple and continuously changing factors lead to significant difficulties when trying to predict the susceptibility of different parts of a city to flooding and to determine the vulnerability of individual structures [3–6].

Previous works have highlighted the influence of a variety of factors in controlling the manifestation of flooding, including meteorological parameters, inherent basin hydrological characteristics and parameters of individual buildings. Fowler and Hennessy [7], Bracken et al. [8], Cannon et al. [9] and others suggest that meteorological characteristics of storms influence flood occurrence, especially in small flash flood prone catchments, where flooding occurs usually after high-intensity storms. In these cases, rainfall intensity and distribution have been shown to have an important effect on flood triggering [8–13]. It has been also shown that the dynamics of hydrological processes, including flooding, are influenced significantly by the catchment's morphometry, including slope, catchment area and hydrogeological parameters [14–24].

Previous works acknowledge that building resilience in urban areas is related to specific elements of the built environment that could lead to a higher propensity to experience flooding [25,26]. Literature suggests that distinct building components can be critical to their susceptibility [27–30] including the construction material [26,28,30], the position of the building in relation to the ground level [28], openings (e.g. windows) under ground level [31] and other properties such as the number of open sides and the overall condition of a structure [29,32,33]. The issue of building vulnerability has been systematically discussed in recent studies

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(e.g. the SMARTeST project [34]) and has been accompanied with testing of different technologies designed to increase flood resilience.

Previous works have studied variables that have an effect on the spatial distribution of flooding and other risks, in order to predict the areas with increased propensity to experience harm [35–37]. Lee et al. [38] used a bivariate statistical analysis that explored the spatial relationship between influencing factors and flood occurrence. Pradhan et al. [39] used multivariate regression models to examine the relationship between multiple variables and flood spatial distribution. Tehrany et al. [40,41] combined the two approaches to predict flood susceptibility in space, examining in comparison the characteristics of known flooded and not-flooded locations. In the above works, flood influencing parameters were considered independent predictor variables in regression models, investigated for their correlation to the dependent (flood occurrence).

Furthermore, GIS has been used for the representation of the values of flood-influencing parameters in the form of thematic maps as raster datasets [36,41].

This work proposes a method that uses logistic regression tests to compare meteorological, geomorphological and building factors at known flooded locations with their variations across the study area. As a case study, this work applies the method to the case of Athens flood on February 2013 and aims to:

- investigate which factors influence and to what extent the distribution of flooding, for the first time to the authors' knowledge, within a metropolitan area, addressing the difficulty of predicting flood susceptibility in the complexity of urban environments,
- approach the problem by examining possible statistical relationships between influencing factors and flood occurrence at known flooded locations, incorporating, unlike the existing literature, individual buildings characteristics together with geomorphological and meteorological parameters,
- quantify and compare the influence of the examined factors,
- examine the efficiency of this approach in predicting areas susceptible to flooding within the complex environment of a metropolitan area.

2. Proposed method

The proposed approach explores the influence of the 12 factors (Table 1) on flooding across a study area, by examining their possible statistical correlation with flood occurrence.

These factors are chosen on the basis of relevant literature regarding parameters affecting flood processes in an urban area [42] and their values across the study area are represented through raster datasets in GIS.

To represent the spatial distribution of flooding in an objective way, the study area can be divided using grids of custom cell size. In this study we used 500 m × 500 m and 1 km × 1 km cell-sizes for two different tests.

By representing the actual flooded locations as points on GIS and then overlaying them on these grids, each cell is then given two values, describing:

a. Whether or not any flooded locations are situated within the cell (yes = 1, no = 0).
b. The number of flooded locations (points) within each cell (0, 1,…,n).

These two values are used as proxy indicators of flood occurrence in space, representing in essence the spatial distribution of flooding across the study area, on the basis of a grid.

Each cell of the two grids is also assigned a value for each one of the 12 influencing factors. This value is given by averaging the respective values of the raster that fall within each cell of the grid.

In order to study the potential influence of each parameter, it was assumed that the higher statistical correlation between flood distribution and a factor's value, the higher the influence (positive or negative) it has on flood occurrence. This assumption has been used systematically in previous works [38,39,41,47,48].

The statistical correlation between these 12 factors and flood occurrence can be explored using:

A Binary logistic regression (BLR) test, assuming:

a. The 12 influencing factors as independent variables (predictors).
b. The dichotomous value of whether or not any flooded locations are situated within a cell (yes = 1, no = 0) as the dependent variable. This value is used as a proxy indicator of the spatial distribution of the flood.

A Generalized Linear Regression Model (GLM) test, assuming:

a. The 12 potentially influencing factors as independent variables (predictors).
b. The number of flooded locations in a cell as dependent variable.

To examine the influence of building characteristics in urban flooding, an additional third binary logistic regression test has to be carried out between flooded and not flooded buildings (Table 2).

Table 1
Brief description of datasets used and the sources they derived from.

Group	Dataset	Source for this case study
Geomorphology-related factors	Altitude	Aster GDEM Version 2, (30 m resolution)
	Slope	Derived from digital elevation model (Altitude)
	Drainage network	1:5000 scale contour maps of the HMGS [43] containing drainage network lines.
	Distance to rivers	Raster dataset derived from drainage network vector data
	Degree of soil sealing with artificial surfaces	Raster dataset [44]
	Flow accumulation (contributing area)	Raster dataset derived from digital elevation model in GIS environment
Meteorological factors	Storm rainfall and maximum rainfall intensity of different durations	National Observatory of Athens Network rain gauges [45]
Building-related factors	Position of the building's lower opening	Based on imaging captured via Google Street View tool [46]