Exploring the Relationships between Impervious Surface Percentage and Frequency of Urban Waterlogging: A Case Study in Hanoi, Vietnam

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Abstract. In developing countries, rapid urbanization reduces the natural land area and increases the impervious surface. At the same time, urban rainstorm waterlogging is also becoming more frequent and serious. Therefore, one of the important works to be done is to elucidate the relationship between impervious surface expansion and waterlogging frequency (WF) causes of urban waterlogging. To move forward, we used ENVI to classify land cover types and applied the spatial analysis methods integrated in ArcGIS with internet open data to explore these relationships in Hanoi, Vietnam in 2018. The results show that waterlogging frequency was positively related to impervious surface percentage (ISP), indicating that if the median values of ISP increased then the waterlogging frequency would increase as well with a confidence level of 63.2%. This study demonstrates the importance for controlling the impervious surface expansion in urban waterlogging risk management and urban planning.

1. Introduction

Urban waterlogging refers to the phenomenon in which a rainstorm or a short-term period of heavy rain surpasses the capacity of the urban drainage system, which results in a waterlogging disaster [1]. Especially in the context of climate change, urban rainstorm waterlogging is becoming more frequent and serious in developing countries, causing losses to the social economy and personal property, accordingly hindering the sustainable development of a city [2, 3]. Urbanization rate in Vietnam reached 35.21% in 2017 [4], and the spatial expansion of urban will increasingly be the main characteristic of land use change in the future in Vietnam [5]. Hanoi is a center of national politics in Vietnam, it is characterized by rapid urbanization, as well as the most representative city suffering from serious urban waterlogging. Therefore, resolving urban waterlogging has been an urgent problem for Hanoi’s municipal government.

A number of urban waterlogging mitigation concepts and approaches were proposed such as Low impact development (LID) and Green infrastructure (GI) in USA, Water sensitive urban design (WSUD) in Australia, Sponge City (SC) in China, etc. [6]. However, exploring the roles played by the spatial factors of urban surface that cause urban waterlogging have not yet been fully researched. Previous studies found that impervious surface expansion was one of the important causes of urban waterlogging [2, 3, 7]. A few studies found that the spatial configuration of the impervious surface influenced surface
runoff and increased the potential urban flood risk [8-11]. In addition, several studies have been conducted to explore the relationship between impervious surface area and hydrological response, which are closely associated with urban waterlogging from the local scale to the watershed scale [12, 13]. However, most previous studies primarily highlighted the importance of the location of the impervious surface in an urban watershed or catchment to define the influence of the spatial configuration of the impervious surface [7]. This may not be sufficient considering the high spatial heterogeneity in the urban context [14, 15]. Internet open data can be defined as the various types of data generating or existing in the web, which can be developed, processed, stored, organized according to the specific needs of users and the corresponding internet protocol, rule and frame [16, 17]. Internet open data can make up for field investigation data, and more and more researches have made remarkable achievements in the application of open data and big data to urban research [18].

Taking Hanoi, Vietnam, as a case study, we aimed to explore the relationships between impervious surface percentage and frequency of urban waterlogging in 2018 base on the spatial analysis methods integrated in ArcGIS and ENVI with internet open data sources.

2. Study area and methods

2.1. Study area

Hanoi is located in the northwest of the center of the Red river Delta, with coordinates from 20°53' to 21°23' North latitude and 105°44' to 106°02' East longitude. In 2018, Hanoi has a population of 7.78 million and an area of 3358.9 km² and becomes second largest city in Vietnam. The study area is located in the inner city of Hanoi spans 454.9 km² and including 12 districts and 2 rural districts (Figure 1). Hanoi lies on the plain and is far from the sea, it belongs to a tropical region and is greatly affected by the monsoon. The climate in Hanoi is very comfortable and where four common seasons are discernible, sunshine of 1562h per year and annual precipitation of 1.900mm. Hanoi is being a city experiencing rapid urbanization and extensive urban waterlogging.

Figure 1. Location of the study area.
2.2. Methods
Integrated framework for exploring the relationships between impervious surface percentage and frequency of urban waterlogging in this study includes three modules: acquiring data, data processing and data analyzing (Figure 2).

2.2.1. Acquiring data. We searched the urban waterlogging news reports by Google’s search engine (http://google.com.vn) in 2018. We selected the useful reports through rapid reading, and eliminate duplicate reports, 6 rainstorms and 38 reports in 2018 were found with the specific location and occurrence frequency of waterlogging spots. In addition, we used 30m resolution Landsat satellite data by USGS (https://glovis.usgs.gov) from 7 June 2018 (path/row 127/45) as the remote sensing imagery for this study, the selected image has less than 10% cloud cover.

2.2.2. Data processing. The waterlogging spot was regarded as the risk resource and the area distant from the risk source boundary 0.5km which was influenced the most significantly was regarded as the risk area [18]. The spatial Buffer technique of ArcGIS was employed to analyze waterlogging risk area, which is considered to be a data class for statistical the value of the rasters. In addition, the waterlogging spots were handled as points, it is difficult to directly express the waterlogging situation of the neighbourhood. Therefore, Kernel Density Estimation (KDE) in ArcGIS is used to obtain the degree of urban rainstorm waterlogging of these neighbourhood areas. The aim is to construct a smooth surface that represents the density of the waterlogging spot group [3] (Figure 2, Figure 4c).

In this study, the Maximum likelihood method in the ENVI software is used to classify land cover types. In contrast to other impervious surface extraction studies (e.g. Yu et al. 2018) [3] where only regards construction land as an impervious surface for analysis. Our study investigated the use of multiple land cover classes [19], each being assigned a coefficient of imperviousness (Figure 3, Figure 4d).

![Figure 2. Integrated framework for the study.](image)

![Figure 3. Land cover categories and their associated coefficients of imperviousness [19](image)
2.2.3. Data analyzing. Both two the maps of waterlogging spots density and impervious surface percentage were converted to two rasters with a cell size value of 30x30 and were clipped by the boundaries of the study area (Figure 4c-d). The attribute values of these raster extracted through class of waterlogging risk area in order to form a dataset for analyzing the relationships between impervious surface percentage and frequency of urban waterlogging.

3. Results and Discussion

3.1. Waterlogging frequency and density of waterlogging spots in 2018
Among the 111 waterlogging spots, the range of waterlogging occurrence frequency was 1–6 times, most of which was 3–4 time (50 spots), followed by 1–2 times (46 spots). But there were 15 high frequency spots, the top of which reached 5–6 times. The majority of high frequency waterlogging spots was located in Hoang Mai (5 spots), Dong Da (3 spots), Cau Giay (2 spots), Hoan Kiem (2 spots), Thanh Xuan (2 spots), and Hai Ba Trung (1 spots) District. Compared to Hanoi center, the frequencies in the suburban districts was lower (Table 1, Figure 4a).

Table 1. Waterlogging frequency in the study area in 2018

| District      | Ba Dinh | Bac Tu Liem | Cau Giay | Dong Da | Ha Dong | Hai Ba Trung | Hoan Duc | Hoan Kiem | Hoang Mai | Long Bien | Nam Tu Liem | Thanh Tri | Thanh Xuan | Total |
|--------------|---------|-------------|----------|---------|---------|--------------|----------|-----------|-----------|-----------|------------|-----------|------------|-------|
| 1-2 times    | 4       | 3           | 8        | 5       | 9       | 0            | 1        | 4         | 2         | 3         | 4          | 1         | 2          | 46    |
| 3-4 times    | 8       | 1           | 7        | 9       | 3       | 3            | 0        | 4         | 5         | 2         | 1          | 2         | 5          | 50    |
| 5-6 times    | 0       | 0           | 2        | 3       | 0       | 1            | 0        | 2         | 5         | 0         | 0          | 2         | 15         |       |
| Total spots  | 12      | 4           | 17       | 17      | 12      | 4            | 1        | 10        | 5         | 5         | 3          | 9         | 111        |       |

Figure 4. Data processing in the study area
(a) Waterlogging frequency in 2018; (b) The relationships between ISP and WF; (c) Waterlogging spots density; (d) Impervious surface percentage (ISP)
Average density distribution of waterlogging in the study area was calculated using the KDE method (Figure 4c). The results show that the high density of waterlogging spots was concentrated in Hanoi center (located in Hoan Kiem, Dong Da, Hoang Mai and Cau Giay District) with the tendency of density value continuing to decrease into the northeast, northwest, west and southwest of the city, similar to the impervious surface expansion affected by urbanization.

### 3.2. Impervious surface percentage in 2018

The Maximum likelihood method in the ENVI software has been used to classify land cover types with the overall accuracy of classification greater than 97%, and the kappa coefficient is greater than 0.96. Then, land cover classes assigned a coefficient of imperviousness to form an ISP map (Figure 3, Figure 4d). The percentage distribution of ISP in the study area has been cross-checked with high-resolution Google images and the Hanoi map of master plan. We observed that the low range of ISP less than 40% is mainly associated with agricultural fields, green land and parks. The areas with more than 60% of ISP belong to the construction land of the city.

Based on the spatial distribution of the impervious surface, it can be concluded that the impervious surface in Hanoi expanded around the city centre to the north, south, northeast, west and southwest around the ring roads, with dense layers. After the expansion of administrative boundaries in August 2008, Hanoi has rapid rates of urbanization and a changing spatial structure of land use with agricultural and bare land converted mainly into construction land, creating strong environmental impacts, especially urban waterlogging problem.

### 3.3. The relationships between impervious surface percentage and frequency of urban waterlogging

The values of waterlogging spots density and impervious surface percentage were extracted and integrated into waterlogging risk areas (Figure 2) to form a dataset for analyzing the relationships between impervious surface percentage and frequency of urban waterlogging. Figure 4b shows that the increase in impervious surface percentage in an area is related to higher waterlogging risk with a confidence level of 63.2%. This result agreed with a large number of studies by Tang, X., et al., 2018 and Yu, H., et al., 2018 [2, 3], which concluded that an increase in the impervious surface area may be one of the most common causes of urban waterlogging.

Urbanization is an inevitable process that reflects the economic development of a country. However, frenzied urbanization in Hanoi took hold in the “Doi Moi” period, along with urban planning and management did not seriously consider the long-term development of the city, leading to the strong economic, social and sustainable ecological environment impacts [5]. Currently in Hanoi’s urban areas, urban land use structure is seriously imbalanced has caused the permeable areas to be replaced by hard surfaces in addition to outdated underground drainage systems. Every year, Hanoi is always threatened by the risk of waterlogging. Therefore, Hanoi needs to change its policies on urban land-use, in order to balance the structure of urban land-use in the direction of enhancing green spaces and surface water, as well as improving impervious surfaces. At the same time, to solve the problems of urban waterlogging, Hanoi must change their measures of traditional urban water management in the direction of sustainable urban water management approaches in order to adjust the water cycle in urban planning and development.

### 4. Conclusion

Through a case study in Hanoi in 2018. Based on ArcGIS and ENVI platform with internet open data, the relationships between impervious surface percentage and frequency of urban waterlogging have considered to explore urban waterlogging risk. The study result was able to explain the relationship between impervious surface percentage and waterlogging occurrence frequency in study area with a confidence level of 63.2%. We found that the application of GIS technologies and internet open data is one of the inevitable trends in the research on urban waterlogging.

In fact, rapid urbanization and increased population pressure is accelerating the transformation of natural surface, usually by reducing in a decrease of vegetation land and increasing the urban hard
surfaces area. The urban hard surfaces such as rooftops, driveways, streets, swimming pools, and patios don't allow water to penetrate the soil. In addition, streets act as streams, collecting storm water and channeling it into waterways. This leads to the resulting increase in the volume of surface water and then aggravates urban waterlogging risks. These study results represent an important analysis step for Hanoi municipal government departments have the plans to control the impervious surface expansion in urban waterlogging risk management and urban planning.

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