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Research Article

USING INTERNET OPEN-SOURCE DATA FOR SPATIO-TEMPORAL CHARACTERISTIC ASSESSMENTS OF URBAN WATERLOGGING RISKS: A CASE STUDY IN HANOI, VIETNAM

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Abstract

In the context of climate change and rapid urbanization, waterlogging due to rainstorms is becoming more frequent and serious in developing countries, thereby posing increasing threats to the sustainable development strategies of the cities. One of the important means of solving this problem lies in elucidating the spatio-temporal distribution characteristics of waterlogging events. We applied the spatial analysis and statistical toolboxes implemented in ArcGIS with internet op`en-source data to assess the waterlogging risks in each area of Hanoi, Vietnam, for the period of 2012–2018. The results show that Hoan Kiem District had the highest waterlogging risk, followed by Dong Da, Ba Dinh, Thanh Xuan, Cau Giay, Hai Ba Trung, and Hoang Mai Districts. Similar to the urban surface expansion affected by urbanization, the risks are densely distributed in the city center and have the tendency to expand into suburban areas at locations surrounding the ring roads, the radial axis roads, and traffic intersections. At the same time, the frequency of waterlogging has a certain dependence on space, which means that the locations of urban waterlogging events were not randomly distributed. These results represent an important analytical step in urban waterlogging management to prevent and control urban waterlogging.

Keywords: Urban water logging risk, Internet open-source data, Spatial analysis, Arc GIS

INTRODUCTION

Urban rainstorm waterlogging is becoming a major concern for most of the metropolitan areas in the countries of Southeast Asia (Luo *et al.,* 2018). In the context of climate change, extreme rainstorm events are causing losses to the social economy, as well as affecting the living environment, daily life, and the sustainable development strategies of cities (Duan *et al.,* 2016; Duan *et al.,* 2014; Tang *et al.,* 2018). Because of swift urbanization, the permeable areas have been replaced by hard surfaces, urban streets act as streams by collecting rainwater, thereby increasing the volume of surface runoff, which is one of the most common causes of urban waterlogging (Foster *et al.,* 1993; Sajikumar and Remya, 2015; Tam and Nga, 2018). In 2017, Vietnam's urbanization exceeded 35% (Statista, 2019) and is estimated to reach nearly 56% by 2050 (Nguyen *et al.,* 2014). Urbanization in Vietnam poses many potential risks to urban areas with pressures being increasingly related to the environment and climate change (Nguyen and Tran, 2016).Hanoi is the capital of Vietnam and the typical city in the Red River Delta, as well as the most representative city suffering from serious urban waterlogging. Under the situation of rapid urbanization, compounding the negative influence of this development is the fact that the city's pump stations are operating beyond their capacities in addition to Hanoi's outdated underground drainage system's being rendered inoperative when rainfall is higher than 100 mm/hour (Mulyasari *et al.,* 2011). The severity and frequency of floods have been increasing. On 30 October 2008, Hanoi experienced the most extreme inner-city floods to date. The death toll reached a devastating number of 22 people. Many streets were flooded and some actually collapsed. Nearly 35,000 households were flooded. The estimated damage exceeded 3,000 billion VND (Tran *et al.,* 2015).

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Therefore, preventing and controlling the hidden dangers resulting from urban waterlogging have become an urgent mission for Hanoi's municipal governments. Adaptation measures have been developed to study the impact of urbanization on urban waterlogging problems include the causes of urban waterlogging (Ning *et al.,* 2017; Quan *et al.,* 2010; Wang *et al.,* 2017; Wu *et al.,* 2012; Yu *et al.,* 2018),urban stormwater control (Che *et al.,* 2013; Grey *et al.,* 2018), urban storm water management (Joksimovic and Alam, 2014; Martin-Mikle *et al.,* 2015; Sin *et al.,* 2014; Subrina and Chowdhury, 2018; Xie, 2013; Yazdi and Salehi Neyshabouri, 2014), urban waterlogging simulation (Xue *et al.,* 2016; Yin *et al.,* 2011; Zhang and Pan, 2014), and the spatial assessment of urban waterlogging risks and vulnerability in flood-prone areas (Liu *et al.,* 2016; Liu *et al.,* 2017; Pistrika and Tsakiris, 2007; Tang *et al.,* 2018; Tsakiris, 2014). In general, previous studies on urban waterlogging risk assessment have focused on GIS-based spatial analysis, including simulation models and scenario simulations that use terrain data, rainfall data, meteorology data, hydrological data, socioeconomic data, urban drainage systems, etc (Hu *et al.,* 2012; Quan, 2014; Sun *et al.,* 2010; Wang *et al.,* 2004; Zhao *et al.,* 2004). In addition, hydrologic and hydrodynamic-based mathematical simulation models are among the main methods for evaluating urban waterlogging risks (Liu *et al.,* 2016; Liu *et al.,* 2017; Tang *et al.,* 2018; Zhang and Pan, 2014). Internet open-source data are understood as the different types of data that can be provided freely to everyone for development, processing, storage, and organization according to the specific needs of users and without restrictions from copyrights, patents, or other mechanisms of control (Auer *et al.,* 2007). Currently, open urban data are very complete, easy to access. and highly quantitative. As a vital complement to traditional investigative data, open urban data can contribute to urban management and the solving of urban problems (Long, 2015). Many studies have achieved significant achievements in the application of open data to urban research and have great potential for urban waterlogging risk assessment(Lin *et al.,* 2018). Spatial analysis and statistical toolboxes implemented in ArcGIS provide tools for modeling and analyzing spatial distributions and relationships. In urban waterlogging risk assessment, these tools are used to elucidate the spatial distribution characteristics, assess the occurrences and relationships, and measure the spatial autocorrelations of waterlogging events. From our study, we were able to draw some obvious conclusions. First, urban waterlogging has been studied by a variety of methods that require large amounts of data, including those from field investigations, which are generally difficult to obtain. Second, in the current era of internet open-source data, the integration of GIS technologies is one of the most inevitable trends in the research on urban waterlogging. Taking Hanoi, Vietnam, as a case study, we aimed to elucidate the spatio-temporal characteristics of urban waterlogging risks in Hanoi for the period of 2012–2018.

DATA AND METHODS

Study area

Hanoi is located at the center of the Red River Delta (Fig. 1), which belongs to a tropical region that is greatly affected by the monsoon. The climate in Hanoi is very comfortable and four common seasons are discernible: January is the coldest month with a monthly mean temperature of 16.5°C and July is the hottest with 29.5°C. The annual average temperature is 23°C and precipitation is 1760 mm. The area receives about 1,562 h. of sunshine per year. The average altitude is 5–10 m above mean sea level with a terrain gradually sloping down in the North–South and West–East directions. Many areas in old Hanoi have an elevation of +5 m, which is significantly lower than the riverbed of the Red River (which has an average elevation of +7 to +8 m). As a result, Hanoi is very vulnerable to flooding during the rainy season. The study area is located in the inner city of Hanoi, which has an incredibly dense population and spans 454.9 km^2, including 12 urban and 2 rural districts, as well as a rich lake and river network.

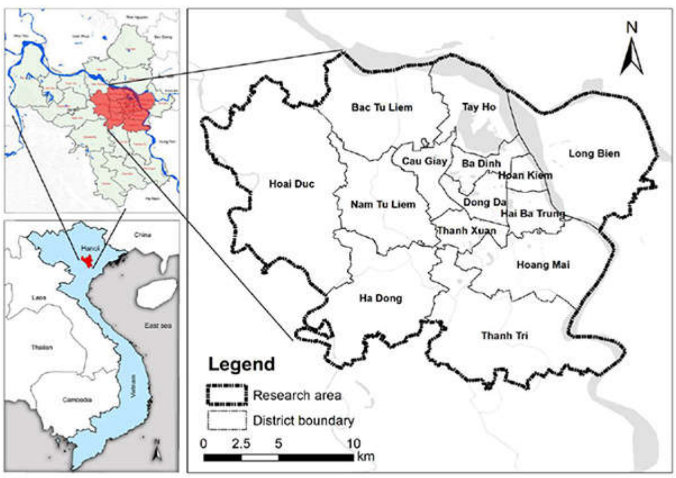

Fig. 1 Location of the study area

Data sources

Acquiring data on the waterlogging events is the key to the evaluation of waterlogging risks. We used Google's search engine (http://google.com.vn) to find news reports about urban waterlogging on the internet and selected the most useful reports. There were 21 rainstorms that had created a large waterlogged area in Hanoi during 2012–2018 and about 98 reports with 148 waterlogging events were adopted for analysis (Fig. 2). We used 30-m resolution Lands at 8 OLI/TIRS data by USGS from 7 June 2018 (path/row 127/45) as the remote sensing imagery for this study. The selected images had less than 10% cloud cover, which is representative of the season. High-resolution remote sensing images of Hanoi in 2018 were taken from Google Earth's aerial photographs. Administrative areas were taken from DIVA-GIS, road maps were taken from Open Street Map. All data sources are shown in Table 1.

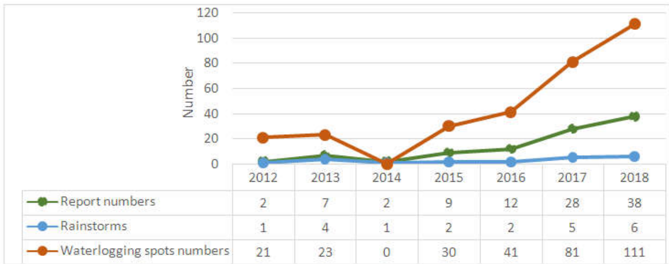

Fig. 2 Report number of 2012 – 2018

Data processing

Waterlogging risk areas: Waterlogging events were considered to be the most important resource in urban waterlogging risk analysis. Information, including location, time, and occurrence frequency, about urban waterlogging events was integrated with Microsoft Excel, then digitalized with ArcGIS to construct spatial distributions of the spots, which were regarded as risk sources. Areas that are 500 m distant from the boundaries of each source were regarded as risk areas because urban public service works in Vietnam within a residential unit (school, market, etc.) must have a service radius not exceeding 500 m. The distance for pedestrians to travel from their places of residence or work to public car parks must also not exceed 500 m(Vietnam-Ministry-of-Construction, 2008). Therefore, we adopted 500 m as the urban waterlogging risk radius and applied the Buffer tool in ArcGIS to analyzing the urban waterlogging risk areas (Fig. 6).

Waterlogging events density: We assumed that each district in the study area had experienced the same rainstorm, i.e., had been subjected to the same rainfall intensity and level of danger. Because the waterlogging events are recorded as points, it is very difficult to show a neighborhood's waterlogging situation. Therefore, we applied the Kernel Density Estimation (KDE) tool in ArcGIS to calculate the densities of geographical objects (Botev *et al.,* 2010). KDE can be calculated for point or line features. (Silverman, 1986)described KDE as a method that could handle comprehensive estimates of the distribution of events based on a finite data pattern. The purpose of using KDE in this study was to create a smooth density surfac of point or line events in space by calculating event intensity as density estimates(Xie and Yan, 2008).The general density estimation function is calculated as follows (Hashimoto *et al.,* 2016):

$$f(x) = \frac{1}{nh}\sum_{i=1}^{n}\frac{K(x-x_i)}{h}(i = 1,2,\dots,n) \qquad (1)$$

where x_i stands for the value of the variable x at location i, n signifies the total number of locations, h denotes the bandwidth or smoothing parameter, and K represents the kernel function, as explained in an earlier report (Silverman, 1986).

Table 1. List of data sources

Data	Format	Time	Source
Waterlogging information	Text	2012–2018	Google http://google.com.vn
Landsat satellite data	Raster	2018-6-07	USGS (https://glovis.usgs.gov)
High-resolution remote sensing image	Raster	2018	Google Earth aerial photo (Google Earth Pro)
Administrative areas	Shapefile	2018	DIVA-GIS (http://www.diva-gis.org/datadown)
Traffic map data	Shapefile	2018	Open Street Map (https://www.openstreetmap.org)

The relationships of waterlogging events

We applied the Getis-Ord Gi* statistic of the Hot Spot Analysis (HSA) tool in ArcGIS to evaluate the existence and the relationships of waterlogging events. The results show us which locations have many waterlogging events and help predict the causes for such spots. HSA is a spatial autocorrelation analysis (Odland, 1988)that helps us understand if an event would create spatial clusters and the impact of that event on surrounding events, i.e., the HSA tool works by looking at the relationships of each event within the context of a neighboring event. A high-value event may not be a statistically significant hot spot. In order for an event to become a statistically significant hot spot, the event must be of high value and must be surrounded by other events with high values as well (ArcGIS, 2018). This method is often used in research in social sciences, such as criminology(Eck *et al.,* 2005)and epidemiology (Ahmad *et al.,* 2015; Kao *et al.,* 2017).The indicator, Getis-Ord Gi*, is defined as follows (2) (ArcGIS, 2018).

$$G_i^* = \frac{\sum_{j=1}^{n} \omega_{i,j} x_j - \bar{X} \sum_{j=1}^{n} \omega_{i,j}}{S\sqrt{\frac{\left[n \sum_{j=1}^{n} \omega_{i,j}^2 - \left(\sum_{j=1}^{n} \omega_{i,j}\right)^2\right]}{n-1}}} (j = 1, 2, \ldots, n) \qquad (2)$$

where x_j is the attribute value for feature *j*; $\omega_{i,j}$ is the spatial weight between features *i* and *j; n* is equal to the total number of features.

Spatial autocorrelation of waterlogging events

We applied the Spatial Autocorrelation (Moran's I) tool in ArcGIS to measure the spatial autocorrelation of waterlogging events, which is the dependence of waterlogging events on space that is expressed as clustered, dispersed, or random. The Moran's I is calculated as follows:

$$I_i = \frac{y_i - \bar{y}}{s^2} \sum_{j=1}^{n} w_{ij} \left(y_i - \bar{y}\right); \qquad (j = 1, 2, \ldots, n) \qquad (3)$$

where I_i represents Moran's index of the research unit i,s^2 is the discrete variance of y_i, $\bar{y}$ is the mean value of y, and w_{ij} is the element of the weight matrix *w.* The adjacent relation is of the Queen type, i.e., the grids are adjacent to each other as long as there is a common boundary or vertex (Anselin, 1995; Yu *et al.,* 2018).

Attribute extraction: To extract the attribute values of the spatial factors, we applied the Zonal Statistics as Table (ZST) tool in ArcGIS to calculate statistics on the values of the spatial factor raster.

In ZST analysis, a statistic is calculated for each zone to extract the attribute defined by this zone dataset according to the values from another raster.

RESULTS AND DISCUSSION

General spatial distribution characteristics of waterlogging events

There were 21 rainstorms that created a large waterlogged area in Hanoi during 2012–2018 and the number of waterlogging events increased with time (Fig. 2). The total number was 148 in Hanoi with the most in Dong Da District, followed by Cau Giay and Hoan Kiem Districts. The numbers of events in Hoai Duc and Tay Ho Districts were much fewer (Table 2).

Frequency of waterlogging events

Table 2 and Fig. 3show the distribution characteristics of waterlogging events caused by rainstorms in Hanoi during 2012-2018. The range of the frequency was 1–11 times, most of which were 1–2 times (57.4%), followed by 3–4 times (20.3%), 5–7 times (10.8%), and 8 times or more (11.5%). The majority of high-frequency waterlogging events was located in Ba Dinh, Thanh Xuan, Hoang Mai, Cau Giay, Hoan Kiem, Dong Da, Hai Ba Trung, Bac Tu Liem, and Tay Ho District. Compared to Hanoi center, the frequencies in the suburban districts was lower.

Spatial–temporal distribution characteristics of waterlogging events

The spatial–temporal distribution of waterlogging events in the study area is shown in Fig. 3. There were 21 recorded waterlogging events in 2012 (Fig. 2), mainly at the center of Hanoi in Hoang Mai District. The events increased to a total of 41 in 2016. The distribution of these points expanded to the northwest, west, and southwest of Hanoi. In 2018, the occurrence of waterlogging events increased to 111 points and continued to expand to the west and northeast of Hanoi and other developed areas similar to the urban surface expansion affected by urbanization (Fig. 3b). The result shows that these waterlogging events reflect a significant expansion of urban waterlogging risks in time and space.

Urban waterlogging risk assessment

Urban waterlogging event density distribution: KDE was used to calculate the density of the 148 waterlogging events. At the same time, the ZST tool extracted attribute values from the results of the KDE. As we know, districts with high waterlogging densities will have high waterlogging risks,

Table 2. Frequency of waterlogging events in each district of Hanoi during 2012–2018

District	Waterlogging events		Occurrence frequency			
	Number	Proportion	>= 8 times	5 - 7 times	3 - 4 times	1 - 2 time
Ba Dinh	14	9.5%	3	-	4	7
Bac Tu Liem	4	2.7%	1	-	2	1
Cau Giay	20	13.5%	2	1	4	13
Dong Da	22	14.9%	1	4	3	14
Ha Dong	15	10.1%	-	1	4	10
Hai Ba Trung	5	3.4%	1	1	1	2
Hoai Duc	1	0.7%	-	-	1	-
Hoan Kiem	18	12.2%	2	2	4	10
Hoang Mai	13	8.8%	3	3	2	5
Long Bien	5	3.4%	-	2	1	2
Nam Tu Liem	10	6.8%	-	-	2	8
Tay Ho	2	1.4%	1	-	-	1
Thanh Tri	4	2.7%	-	1	1	2
Thanh Xuan	15	10.1%	3	1	1	10
Total	148	100%	11.5%	10.8%	20.3%	57.4%

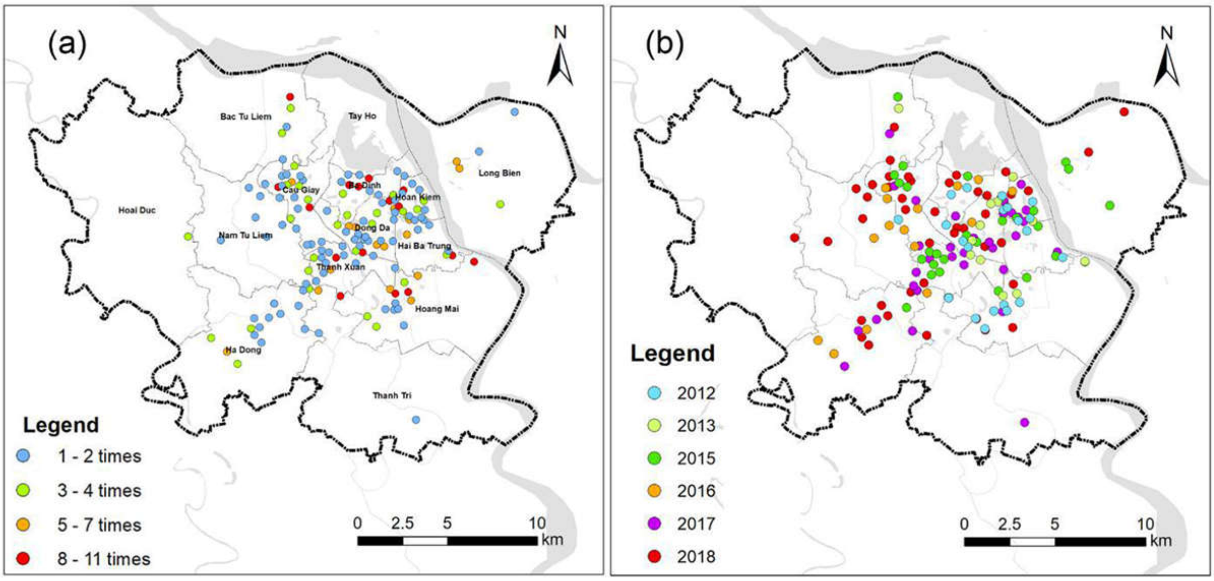

Fig. 3 Spatial–temporal distribution characteristics of waterlogging events in Hanoi during 2012–2018
(a) Waterlogging occurrence frequency; (b) Waterlogging event expansion

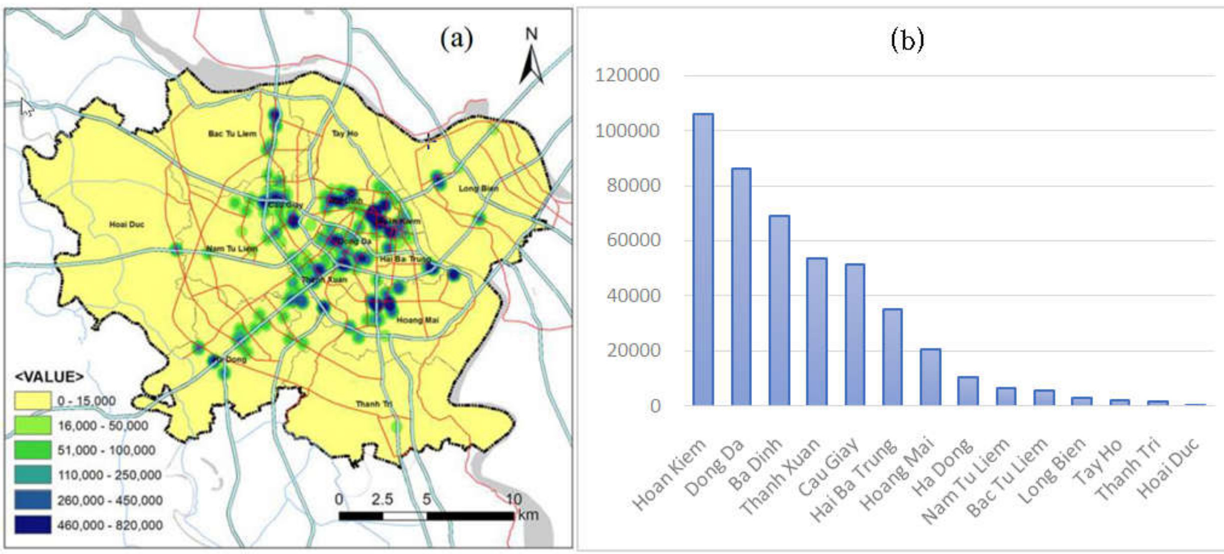

Fig. 4. Waterlogging risks in Hanoi during 2012-2018
(a) Waterlogging event density; (b) Waterlogging risk of each district

so the waterlogging risk in Hoan Kiem District was the highest, followed by Dong Da, Ba Dinh, Thanh Xuan, Cau Giay and Hai Ba Trung Districts (Fig. 4b). The spatial distribution characteristics of waterlogging event density are concentrated in the inner city of Hanoi and spread to the northwest, west, southeast, south, and northeast of the city with the tendency to continue expanding into the surrounding ring roads, radial axis roads, and traffic intersections(Fig. 4a).

Hotspot analysis of waterlogging events: HSA was conducted to evaluate the existence and relationships of the waterlogging events. Areas with high and very low waterlogging risks are shown in red (hot spot) and blue (cold spot), respectively. Dong Da District has many hot spots with a spatial distribution that is densely distributed in the city center and expanding to the surrounding area (Fig. 5).

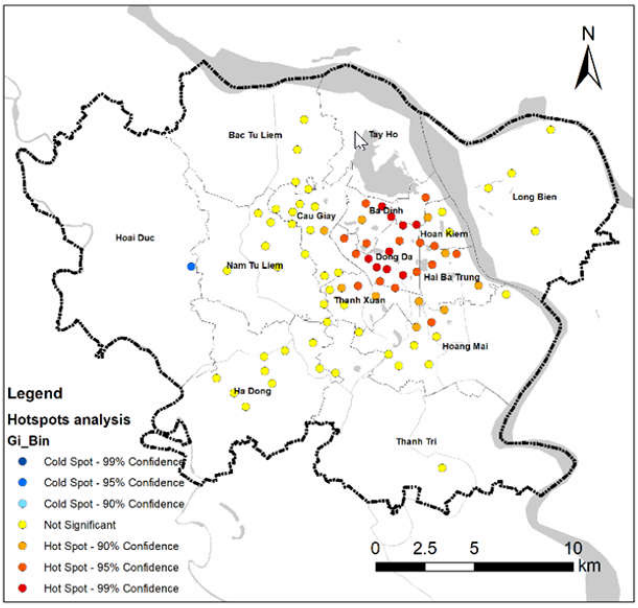

Fig. 5. Hotspot analysis map

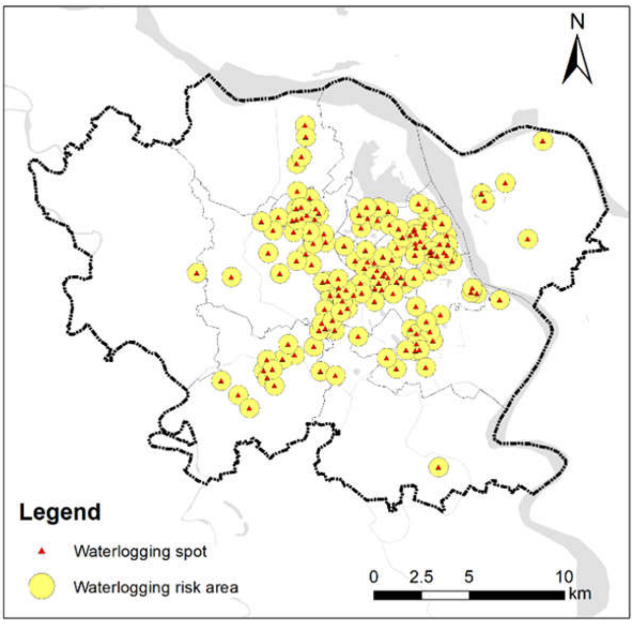

Fig. 6. Waterlogging risk areas

Spatial autocorrelation of waterlogging events: On the basis of the above analysis, we decided preliminarily that the waterlogging occurrence frequency had a certain dependence on space. To demonstrate this assumption, we applied the spatial autocorrelation tool to measure the spatial autocorrelation of the waterlogging events. The tool was run on the value of the waterlogging risk area (Fig. 6) after extracting the attributes from the results of the KDE, which produced a Moran's index of 0.18, z-score of 11.8, and p-value of 0.00(Fig. 7), indicating that the occurrences of the waterlogging events in the study area were not randomly distributed and were spread to adjacent areas in a spatial form of clustering. Hence, the waterlogging risk in Hanoi is different from the risks in cities such as China's Shanghai and Shenzhen, Bangladesh's Khulna, and India's Muzaffarpur. The risks in these cities are also very serious, but the occurrence frequencies of urban waterlogging were randomly distributed in space without a spatial form of clustering(Yu *et al.,* 2018).

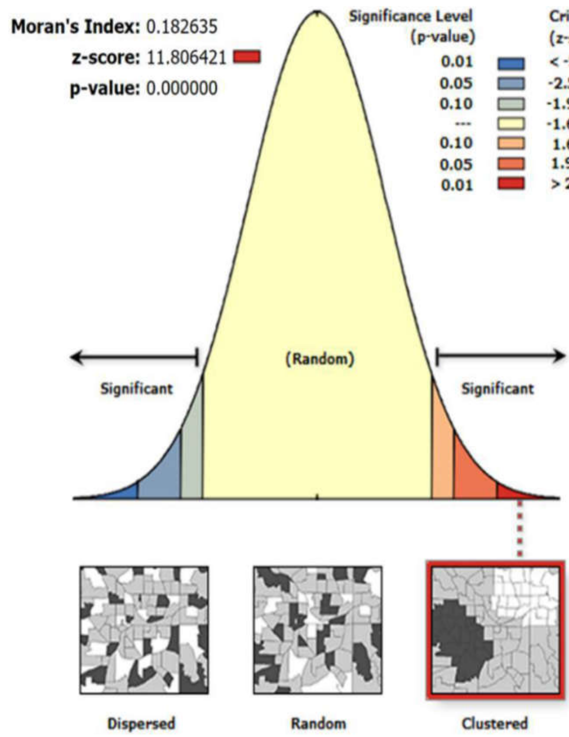

Fig. 7. Spatial Autocorrelation report

From the above results, we were able to draw several obvious conclusions. First, waterlogging events caused by rainstorms in Hanoi during 2012–2018 were densely distributed in the city center and had the tendency of continuing to expand into suburban areas at locations surrounding the ring and radial axis roads, as well as traffic intersections, similar to the urban surface expansion affected by urbanization. Second, the waterlogging occurrence frequency had a certain dependence on space, which means that the locations of the urban waterlogging events were not randomly distributed.

Municipal government management efficiency evaluation

Urbanization is an inevitable process that reflects the economic development of a country. However, if urban planning and management are not seriously considered for the long-term development of cities in the context of climate change, then urbanization will have strong economic, social and environmental impacts. In recent years, swift urbanization in Hanoi has caused the permeable areas to be replaced by hard surfaces. A swift rural–urban transformation has had adverse impacts on the environmental complex water management system of dikes, pumping stations, and sluices. The drainage system in Hanoi is located mainly in urban core areas and shared for both the drainage of wastewater and rainwater. Most of the drainage system is still operating in the form of self-flowing. Compounding the negative influence of this development is the fact that the city's pump stations are operating beyond their capacities in addition to Hanoi's outdated underground drainage system's being rendered inoperative when rainfall is higher than 100 mm/hour. In fact, Hanoi municipal government departments have deployed a plan to improve the short, medium, and long-term drainage networks with the aim of overcoming and reducing urban waterlogging hidden dangers. However, every year, the inner city of Hanoi is threatened by waterlogging risk.

Our research results indicate the suboptimal electiveness of the local government's waterlogging management. Therefore, we propose that the plan to overcome urban waterlogging in the future should emphasize the high-risk areas of Hoan Kiem, Dong Da, Ba Dinh, Thanh Xuan, Cau Giay, and Hai Ba Trung Districts, especially spots with high waterlogging frequency, promote forecasting, and control new waterlogging spots. Especially in the context of climate change, the situation of waterlogging in Hanoi, Vietnam, caused by rainstorms are becoming more frequent and serious. Therefore, Hanoi needs to change its policies on population and urban land-use. Such policies include encouraging residents from the city center to relocate to the suburbs to reduce population pressure with the concurrent relocation of agencies, factories, universities, hospitals, etc., 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 arising from urbanization, Hanoi's municipal government departments must change their measures of traditional rainwater management in the direction of non-traditional approaches in order to adjust the water cycle in urban planning and development. This approach can implement measures whereby rainwater can be held for storing, infiltration, percolation, evaporation, purification, and recycling via natural processes. Adaptation measures of technologies for rainwater control that are suitable to Hanoi include green roofs, permeable pavements, improved infiltration, rain gardens, wetlands, and green spaces, aimed at reducing the time of surface runoff formation while improving the urban environment, as well as maintaining and restoring urban natural hydrology.

Conclusion

Conducting a case study of Hanoi in 2012–2018 and using the ArcGIS platform, we applied spatial analysis and statistical toolboxes with open-source data from the internet to analyze the characteristics of the spatial–temporal distributions of waterlogging events and assess the urban waterlogging risks in each area of Hanoi. The result shows that these waterlogging events reflect a significant expansion of urban waterlogging risks in time and space, similar to the urban surface expansion affected by urbanization. These results represent an important step for future plans by Hanoi's municipal government to manage and overcome future urban waterlogging risks. We found that the application of GIS technologies with internet open-source data is one of the inevitable trends in the research on urban waterlogging. Internet open-source data can be applied to other cities for the assessing of urban waterlogging risks or solving of other city problems, including the spread of epidemics, environmental pollution, traffic jams, and traffic accidents. Furthermore, in the era of internet open-source data, other methods will be developed by the elucidation of the causes and roles of the spatial factors of urban surfaces to predict urban waterlogging risks. These issues should be researched and integrated into future overall urban development plans.

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