Chapter

Influence of Floods on Spatial Variability of Wetslums Using Geo-information Techniques: A Case Study of a Specific Human Habitat in Korail, Dhaka

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Abstract

A previous study by the authors found that most slum physical upgrading projects traditionally focus on basic services, elaborated with citywide data, without addressing locational and environmental aspects. However, such data tends to hide the highly heterogeneous nature of slums. Thus, this paper's objective is to further investigate the spatial variation resulting from the influence of water on the living conditions within slums, by proposing a framework that can quantify it. This framework is used to establish the correlation between the impact of flooding denoted by a Flood Proneness Index and living conditions denoted by a Slum Living Conditions Index in Korail, Dhaka. The paper concludes that in Korail, both flooding and living conditions exhibited spatial variability, with the former seeming to have a significant influence on the latter, particularly in areas located close to or on a water body. As a result, the paper proposes to define slums which exhibit considerable correlation between flooding and living conditions as wetslums. The analysis in Korail further revealed cluster formation and as such strengthens the hypothesis of locational variability in these specific human habitats. Subsequently, wetslum areas that require resilient physical upgrading are identified thus highlighting the importance for location-specific upgrading.

Keywords: flood proneness, living conditions, slum index, upgrading, slum heterogeneity

1. Introduction

A study made by Olthuis et al. in 2015 [1] investigated slum upgrading projects and revealed that most physical upgrading projects have focused primarily on improving household-based statistics such as water and sanitation while overlooking environmental and locational adaptation. This study also showed how location impacts diversity and influences evolution patterns in slums. As environmental and locational factors are crucial to the living conditions of a slum [2], ignoring these aspects is a threat to the effectiveness of any slum physical upgrading project. According to Olthuis et al. [1], the disregard for locational aspects may be attributed to the dominance of the UN criteria for defining slums. These criteria force authorities to develop numerical datasets that include characteristics such as number of households with access to water, sanitation, etc.

In addition, previous research has started to investigate the heterogeneity of slums by, for instance, exposing how aggregating data at city-level scale hides the spatial variation of slums [3]. Further studies [4, 5] have highlighted the considerable spatial variability in the extent to which a slum settlement exhibits characteristics of a slum—the so-called slumness [4]—and have discussed how slums are heterogeneous human habitats in all aspects ranging from socioeconomic to vulnerability [5]. These researches also have started to expose the dichotomous nature of existing slum classification systems that ignores their physical and social diversity. Thus, spatial variation or heterogeneity is an important but overlooked aspect of slums and has been studied only to a very limited extent in the past [6].

As a result, this paper intends to present a step toward filling this gap, through the study of the influence of location on the living conditions of slums near or on water. One of the influences of water on slums is the issue of flooding. Numerous examples of flooding in slums from Nigeria to Peru have been recorded and studied [5, 7–15]. The breadth of literature on the impact of flooding on slums confirms their vulnerability to such natural disasters, validating its choice as a major locational influence to be studied. Hence, this paper aims to further conceptualize the degree to which a slum settlement is spatially variable and subsequently addresses the influence of water and its flooding characteristics in the given variability.

Therefore, the end goal of this paper is to propose a framework that can quantify, in a studied slum, the influence of water—the proximity to a water body and flood risk vulnerability faced by its inhabitants—on its living conditions. To do so, the integral nature of two factors in defining the vulnerability of slums located near or on the water—flooding susceptibility and living conditions—needs to be emphasized. To this end, two indexes will be developed—a Flood Proneness Index and a Slum Living Conditions Index—taking Korail in Dhaka (Bangladesh) as a case study to test this methodology. At the same time, structurally and characteristically similar units will be defined and tested for correlation. Then, the correlation between flooding and living conditions should give us significant insights into the functionality of a slum—a key factor to consider for future physical upgrading projects.

2. Literature review

This section provides an overview of firstly living conditions within slums, secondly the impact of flooding on slums, and lastly the spatial heterogeneity of slums.

2.1 Living conditions in slums

Living conditions in slums have been defined in a range of ways. Gulyani and Bassett [2] have established the "living conditions diamond" as a framework to study the physical aspects of a slum's living conditions. The diamond has four physical components—tenure, infrastructure, unit quality, as well as neighborhood and location—seen as essential to determine the living conditions in slums.

Tenure, or a lack thereof, often is a key precondition determining investment in physical upgrading projects. Infrastructure, including physical services such as water supply or electricity, as well as public services, makes settlements and housing functional. Slums built on or extending into water bodies present a special case. They extensively use water as a major access network. Examples can be found in slums such as Makoko, Nigeria [16], or Isla Verde in Davao City, Philippines [17].

The third physical component—housing unit—investigates the quality of housing. This vertex incorporates building materials and the density of occupancy. The nature of materials used for roofing, foundations, and exterior walls can help determine the building quality. In some cases, slums might be erected on stilts like in Palembang, South Sumatra [14]; Korail, Dhaka [15]; or Ribeira Azul, Brazil [18]. Studies conducted by Flores-Fernandez [19] have showcased the creative approach undertaken by slum dwellers in risky areas to expand and/or develop their settlement. The key findings of this study have elaborated the organic and unique forms of the slum settlement, adapted to the morphological territorial characteristics (such as slope, height, profile, etc.).

Neighborhood and location comprise the final component. The settlements' location and connectivity can indicate how physically and environmentally vulnerable a slum is. Density, physical layout, and the presence or absence of amenities and services such as schools, open spaces, and community facilities are further factors that influence the living conditions of slums. Makoko in Lagos presents an example of a slum where the remote location in the lagoon alongside low status of the inhabitants is believed to lead to serious environmental and infrastructural deficiencies. For instance, this slum has an inadequate access to education and healthcare [16].

Taken together, all four components determine the physical living conditions in slums. In that way, the diamond is a strong framework to study a slum's living conditions. However, data availability for the individual components is often nonexistent or highly dynamic [2]. Any framework attempting to quantify the living conditions in slums therefore will have to be adaptable to changing conditions of slums. However, the lack of up-to-date data does not allow the precise overview of each one of these four components. Yet, modular components of the framework in themselves help understand the living conditions of the slum habitat.

2.2 Flooding in slums

Slums, by definition, are inclined to be located in hazardous areas [2, 9]. These include areas prone to flooding such as river floodplains, foreshore areas on mangrove swamps, or tidal flats [9]. Moreover, the high population density added to a lack of protection against climate change and sea level rise makes the urban poor increasingly vulnerable to flooding [20]. According to the United Nations International Strategy for Disaster Reduction (UNISDR) [21], rare big flooding events account for the biggest losses of lives and assets in urban poor settlements, where smaller more frequent events result in fewer deaths. However, the latter have predominant impact on urban poor due to the fact that there are events affecting their daily life, causing damage to housing, infrastructure, livelihoods, as well as their health. Indeed, the reports from the UNISDR [21] found evidences from cities in Africa, Asia, and Latin America suggesting that the increase in reports of weather-related disasters is a sign of the expansion of informal human habitats.

Douglas et al.'s [9] study of the urban poor in Africa presents the effects of flooding on slums. Among different causes of flooding, the study highlights how slums in urban areas are most often subject to localized flooding events and flooding from small streams. Moreover, the study also specifies that slums located near major rivers and on coastal areas face an additional level of vulnerability and threat.

The main threat caused by floods is not the flood itself but the stagnant water added to water pollution, in other words, prolonged floods [22]. They are caused by extensive urbanization, waterlogging, overly saturated grounds, and blockage of the sewage and drain systems by solid wastes [23]. Indeed, slums' growing population increases waste productions which are accumulating on-site due to the absence of proper waste management. For example, in Dhaka, only half of the total wastes are collected, and no waste collection is made in slums due to access difficulties.

The combination of solid wastes and human ones creates a major threat to slums—human waste could lead to sanitary disaster, and solid ones, when carried by water flow, are partially responsible for the destructions during floods as well as for the blockage of drains and sewages [24, 25]—worsening the risks faced by slum dwellers during prolonged floods. Another dramatic issue is the massive spread of diseases—long-lasting floods generated several health hazards, going from drinkable water contamination to mosquito infestation—and this risk increases in accordance with flood duration which could last several months [26].

The impact of prolonged floods on dwellers drastically limits access to basic needs such as food, drinkable water, medicines, and cloth as well as access to sanitation, shelters, and dry places to sleep [27]. Flooding also disrupts small-scale activities like petty and artisanal trading, thus threatening slum dwellers' livelihoods. Indeed, Kanke Arachchilage [28] shows how flooding disrupts the economic activities of rickshaw pullers. As streets are converted to streams, they are unable to work. Rather than get to a safer area, slum dwellers are often in a state of forced inertia during flooding conditions in order to not displace their assets and social and livelihood networks. Nevertheless, post-disaster, more than 50% of households have to be rebuilt or repaired [15].

2.3 Spatial heterogeneity of slums

Recent literature is increasingly studying the spatial variability apparent in slums and how to measure it [2, 4, 5]. For instance, in a study made in Union Territory, Chandigarh, Rao and Thakur [29] found that 15.5% of slum dwellers lived in high vulnerable areas, 44% in medium and 40.5% in low vulnerable areas.

The slum index introduced by Weeks et al. [4] presents an attempt to measure spatial variability of a slum in Accra. Each housing unit is scored, according to a binary system, as follows:

- If the housing unit does not have piped water, then $slum_1 = 1$ (else 0).
- If there is no toilet and no sewage connection, then $slum_2 = 1$ (else 0).
- If the number of persons per room is greater than 2, then $slum_3 = 1$ (else 0).
- If the building material is less durable, then $slum_4 = 1$ (else 0).
- If the resident is not the owner, then $slum_5 = 1$ (else 0)
- Slum index for each housing unit $(S_h) = \sum (slum_1 \ldots slum_5)$.

The results of the study indicated considerable variability in the "slumness" of the neighborhoods in Accra. Rather than defining households as "slum" or "not slum," the measure adds the number of slum conditions for each housing unit in a defined area to then calculate an average score for each neighborhood. As a result, each slum is placed along a continuum. A later study on the slums of Accra highlights how vulnerability even varies spatially in a single slum settlement [30]. Indeed, Jamestown in Accra, often considered as one slum, is demonstrated as a highly complex place with specific vulnerabilities varying within the neighborhood itself. By quantifying the spatial variability of vulnerability within slums, the slum index could thus help to develop a broader rating and monitoring systems for slums.

Therefore, once structurally similar units—the so-called clusters—are identified through an index, their interdependence can be investigated through spatial autocorrelation [31]. Spatial autocorrelation has moreover been widely utilized to assess the spatial dependency of space by measuring the variables of landscapes that influence spatial variability [32].

3. Framework and methodology

To investigate the relation between locational characteristics and living conditions in slums near water, three stages have been undertaken in the conceptual framework, namely, the creation of a Flood Proneness Index, Slum Living Conditions Index, and spatial pattern analysis (**Figure 1**). These stages are built around data from 2006 to 2016 of Korail, Dhaka, serving as case study in this work.

3.1 Case study: Korail, Dhaka

Surrounded by Banani Lake on the eastern and southern sides, Korail is the largest informal settlement in Dhaka and located in a low-lying, flood-prone area. It started to develop during the late 1980s on vacant high grounds but later expanded into more hazardous low-lying areas with houses built on the flood-prone water edges. Korail is mostly inhabited by people engaged in service jobs in the high-end area on the eastern bank of the lake. Population estimates vary enormously, from 100,000 people [15] living on approximately 90 acres to more recent newspaper reports suggesting numbers as high as 175,000 people living on 170 acres [33], which would point toward an increase of 75,000 people and 80 acres in only 4 years.

The slum's existing living conditions—stemming from its location and high population density—is further exacerbated by unmanaged waste disposal and changing climate and weather conditions. Almost every year, Korail is subjected to extreme and hazardous conditions, due to excessive rainfall, increased heat, and flooding [15, 34]. There have been at least 10 heavy floods that were recorded in Dhaka city between the years from 1954 and 2007 [35].

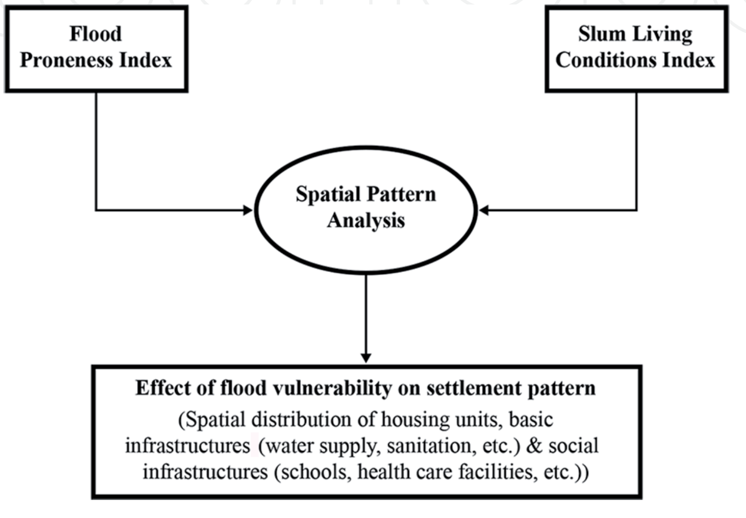

Figure 1.
Conceptual framework to assess flood proneness alongside living conditions [by authors].

Due to the lack of tenure in Korail, both the inhabitants and the government are reluctant to improve their living conditions [15]. Basic facilities, schools, and healthcare facilities are run by NGOs. Cameron [36] highlights the crucial role that NGO primary schools play in Korail, some of which host as much as 600 kids. Other types of education centers are kindergartens that accommodate around 300 kids.

To test the methodology of this study, a statistical analysis in the form of spatial autocorrelation is performed to identify building units that are exhibiting significant correlation. Secondly, these clusters make it possible to highlight spatial variability—through a multi-distance spatial cluster analysis (see Appendix A.1)—within the slum, assess the overall influence that water has on the slum, and thus help place Korail on a spectrum. The slum is situated amid poor environmental condition, siting mostly on low-lying areas which cause waterlogging and flooding in most building units inside the slum [37]. In these aspects, Korail is similar to many other slums around the work, thus making it a suitable case study.

Due to a lack of updated credible data, the conceptual framework (**Figure 1**) has been adjusted for Korail's spatial pattern analysis (**Figure 2**). Thus, data for only two of the four physical components of the living conditions diamond, infrastructure and neighborhood and location, were available and integrated in the framework.

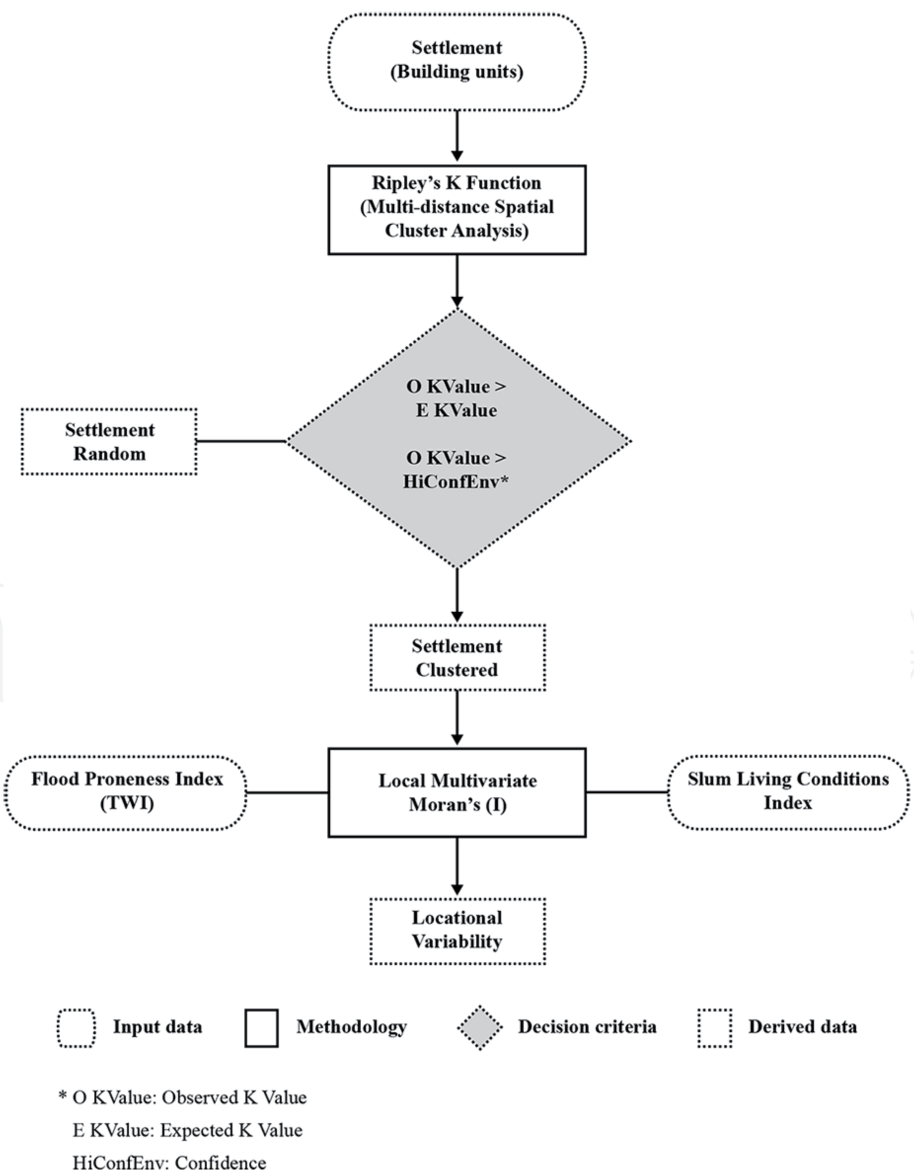

Figure 2.
Spatial pattern analysis in Korail, Dhaka [by authors].

These data are secondary data collected from research papers [15, 35, 37] and conference [7] as well as from institutions and NGO documents [28, 34, 36, 38, 39].

3.2 Stage 1: development of a Flood Proneness Index

A flood index can be determined by looking one or a combination of the following hydrological characteristics.

3.2.1 Physical conditions of the locations

Topographic Wetness Index (TWI): a hydrological analysis can be performed to retrieve a "Topographic Wetness Index" from Digitally Elevated Maps (DEM) to identify areas that are more susceptible to intense flooding due to the location's "slope" and "flow direction."

3.2.2 Dynamic variables

Rainfall data: crucial information required for identifying areas prone to flash floods. A study of rainfall and its intensity can aid the understanding of annual or monthly patterns [40].

Flood inundation: modeling inundation can predict the extent to which a floodplain is at the risk of flooding. Conventional inundation simulation involves overlaying water depths at different cross sections onto a DEM. Alternatively, inundation extents can be interpolated at cross sections [41].

3.2.3 Mapping flood-prone areas through the topographic wetness index in Korail, Dhaka

Due to the limited availability of flood inundation and rainfall data for Korail, open-source elevation data was chosen as the main input for the mapping of flood impacts. The elevation data helps to examine the TWI of Korail. A high indicator is considered to be illustrative for areas which are prone to drain due to excess flows of water during flooding conditions. A hydrological analysis was performed on the basis of TWI data from DEM. Based on this analysis, Korail was mapped into vulnerable and non-vulnerable zones.

The analysis of TWI required minimal data in the form of a DEM, which was obtained from the United States Geological Survey (USGS). An ASTER geo-dataset was retrieved in DEM format (ASTGTM2_N23E090) with the coordinates for Korail, Dhaka. The TWI was retrieved through the software TauDEM [42]. The topographic or compound wetness index is retrieved through the calculation of the ratio between slope and the specific catchment or contributing area [40]. In other words, the wetness index is a slope over area ratio. Although slope in this case is a much complex variable, it is achieved by studying the "flow direction" of steepest slopes in the elevation profile. Subsequently, the corresponding catchment area is identified at the scale of grid cells as "contributing area." Previous studies have considered TWI to be a cost-efficient method to summarize overland flash flood-prone areas [41]. TWI is dependent on two variables—D-infinity flow direction and D-infinity contributing area.

Calculating D-Infinity Flow Direction:

Flow directions are assigned based on the D-infinity flow method, which primarily captures the steepest slope on a planar block-centered grid. The grid presents the elevation value taken to represent the elevation of the center of the corresponding grid cell. The flow directions are recorded as angles in radians and are calculated counterclockwise. The direction of the steepest downward slope is gathered upon the triangular facet of a 3 × 3 grid cell; the resulting flow is the proportion between these two neighboring cells [43]. As seen in **Figure 3**, the grid is further divided into eight triangular facets between each cell and its neighbor.

The downslope vector within each of these triangular facets is taken into account, through which the slope and flow direction associated with the grid cells are produced. Slope is measured as drop/distance which is tan of the slope angle. Downslope vector ranges within or outside 45° angles.

Calculating D-Infinity Contributing Area

Contributing area in this case pertains to a specific catchment area, which is calculated as area per contour length using multiple flow directions or D-infinity method. Contribution (catchment) at each grid cell corresponds to its very own grid length. Equation (1) denotes the execution of TWI, wherein α is the contributing area and $tan\beta$ is the surface slope:

$$TWI = \ln\left(\frac{\alpha}{tan\beta}\right) \tag{1}$$

3.3 Stage 2: development of a Slum Living Conditions Index

Similarly to the hydrological analysis, data on service provision and access to healthcare and education in Korail was limited. Therefore, secondary data such as NGO presence in the slum was used to determine the access to education and health for the Slum Living Conditions Index. The slum was then broken down into building units with access to both education and health centers, neither education nor health centers or only education or health centers, and on or close to water.

The literature review showed that education centers serve roughly 900 settlements within Korail [36]. Due to a lack of concrete data on the service capacity of health centers within the slum, the national percentage for access to primary health center in Bangladesh was taken as an indicator for healthcare provision.

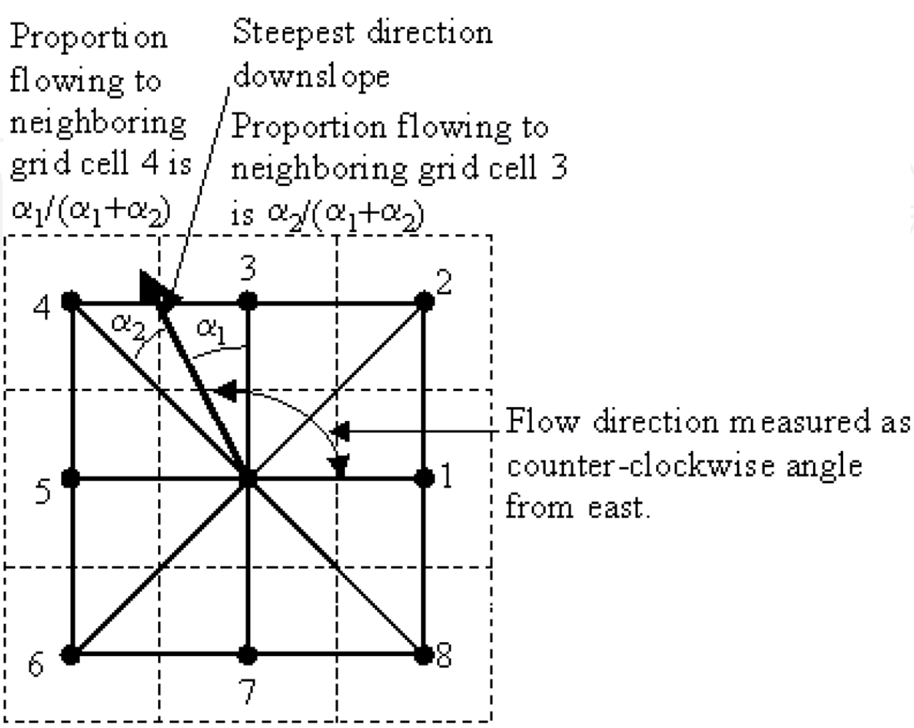

Figure 3.
D-infinity flow direction [43].

According to the Asian Development Bank [38], the index currently stands at 33.4%. As a result, 33% of the settlements within the slum were considered to have access to healthcare provision of static health centers. The location of the education centers and static health centers, which are functioning as general practitioners in the slum, was identified on the basis of BRAC's "frugal maps" [39]. Then, buffer zones were created to delineate building units that fell under immediate access to the said centers, based on the capacity of health or education centers (see Appendix A.2).

In addition, the building density of these units was also included in the Slum Living Conditions Index. Moreover, this factor was also used for a secondary study investigating the repartition of dense building units in the slum. To do so, a temporal study was conducted to assess the density of settlement with respect to distance from the water body (lake). The temporal aspect was in the form of assessment of built units prior to 2011 and after 2011 (till 2016) and based on satellite observation. Then, in GIS environment, built units were converted into point features. These point features were used as input for the point density function, which in turn allowed calculation of density for each point feature (built unit). Similarly, near function was used to calculate the proximity of each point feature from the lake.

As a result, the Slum Living Conditions Index combined service provision, density, and proximity to the water body. In the present case and as mentioned above, the available data were limited. Thus, in order to produce a precise vision of a living conditions, access to primary and updated data for all the four physical components of the 'living conditions diamond' will be necessary. Moreover, data about all the different types of services provided in the studied slum such as water pipe connection, sanitation access, or waste removal, for instance, will also have to be integrated, when existing, in this index.

3.4 Stage 3: analysis of spatial patterns

Then, the relationship between the Flood Proneness Index and the Slum Living Conditions Index is examined. The spatial autocorrelation technique allowed the study to conceive the statistical significance between the said indexes and identify the underlying cluster formations based on these factors. This spatial autocorrelation was performed through GeoDa [44]. Then, in a second time, this software was also used to investigate the influence of proximity to water body (distance) on density of the settlement through the performing of local Moran's I (bivariate) [45].

Through spatial analysis it is possible to identify clusters that represent the varying influences of both flooding and living conditions as well as the influence of proximity of water body to the density of the building units. Thus, two types of clusters (**Figure 4**) and two types of spatial outliers (**Figure 5**) can be identified.

- The two types of clusters include:
    - **High-High (HH)** clusters correspond to areas that are highly prone to flooding and have a high deficiency in living conditions, e.g., a low Slum Living Condition Index, while in the second analysis, these *High-High* (*HH*) clusters represent high distance from the water body and high density of the building unit.
    - **Low-Low (LL)** clusters correspond to areas that are not very prone to flooding and have a low deficiency in living conditions, e.g., a high Slum Living Conditions Index, while in the second analysis, these *Low-Low* (*LL)* clusters represent low distance from the water body and low density of the building unit.

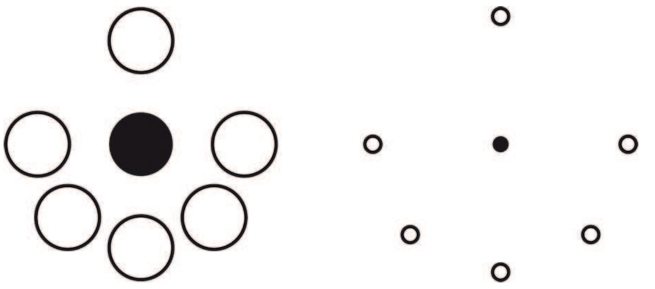

Figure 4.
Spatial clusters. High-High (HH) spatial clusters (left) and Low-Low (LL) spatial clusters (right) (adapted from [45]).

- The two types of spatial outliers include:
  - **High-Low (HL)** outliers correspond to areas that are highly prone to flooding but have low deficiency in living conditions, e.g., a high Slum Living Conditions Index, while in the second analysis, these *high-Low* (*HL*) outliers represent high distance from the water body and low density of the building unit.
  - **Low-High (LH)** outliers correspond to areas that are not prone to flooding but have a high deficiency in living conditions, e.g., a low Slum Living Conditions Index, while in the second analysis, these *Low-High* (*LH*) outliers represent low distance from the water body and high density of the building unit.

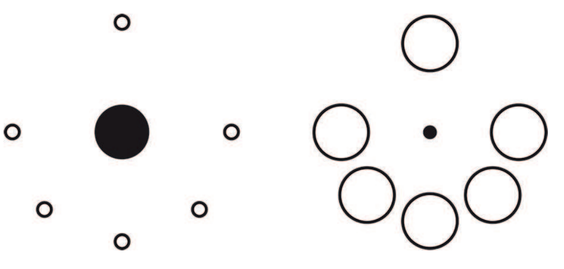

Figure 5.
Spatial outliers. High-Low (HL) spatial outliers (left) and Low-High (LH) spatial outliers (right) (adapted from [45]).

By looking at the combined influence of flooding and living conditions, the clusters aid an understanding between the two variables and help to classify a large slum into specific zones. At the same time, the temporal analysis allows the comprehension of the relation between the density of a settlement and its distance from a water body as well as observing where the newcomers settle. In other words, determine if the slum expands toward the water body.

4. Key findings

Now that the indexes are built, the spatial pattern analysis of Korail is used to produce several maps. These maps will now be utilized to investigate the influence of water on slums' living conditions.

4.1 Main findings

A number of observations can be made from the maps produced with the TWI, the Slum Living Conditions Index, and the spatial pattern analysis.

Firstly, there is a clear spatial delineation between planned and unplanned settlements. **Figure 6** shows that slum settlements have developed, on a majority, in the vulnerable zones—irrespectively of their proximity to the water. In contrast, the non-vulnerable zones are dominated by planned settlements.

Therefore, areas considered unsafe and thus devoid of any planned settlements seem to attract slum dwellers, which correspond to the results obtained by Douglas et al. [9] as well as Gulyani and Bassett [2]. In addition, **Figure 6** also exhibits the presence of building units located close to or on water, which is also demonstrated by **Figure 7**.

This confirms the observation made by Olthuis et al. [1]. Indeed, according to this study, these building units should be an indicator of Korail expansion toward Banani Lake caused by the increase in population occurring in this slum. This would demonstrate that new dwellers arriving in the slum tend to go to even riskier areas. However, this will have to be verified with the temporal study.

At the same time, it would mean that areas with a lower TWI—which are more elevated and thus "safer"—are most likely sought-after destinations in the slum, forcing those dwellers that do not find space here onto more hazardous locations.

This also explains the utilization of construction on stilt or artificial elevation observed in Korail by different research [15, 28], thus illustrating Flores-Fernandez's findings about the creative approach undertaken by slum dwellers to settle in risky areas [19]. As a result, a clear delineation in Korail's development pattern caused by topographic factors, such as elevation, seems to exist.

Secondly, according to **Figure 7**, the settlements which are the closest to Banani Lake exhibit the higher deficiency in living conditions. These observations are understandable due to the fact that these areas are the most exposed to flooding. In addition, the same figure shows that several of these zones correspond to a higher density in building arrangement. This however will have to be confirmed by the temporal study.

Moreover, when considering the maps used to build the Slum Living Conditions Index (see Appendix A.2), it appears that these areas are, for the great majority, not included in the health and educational centers' buffer zones. Nevertheless, when

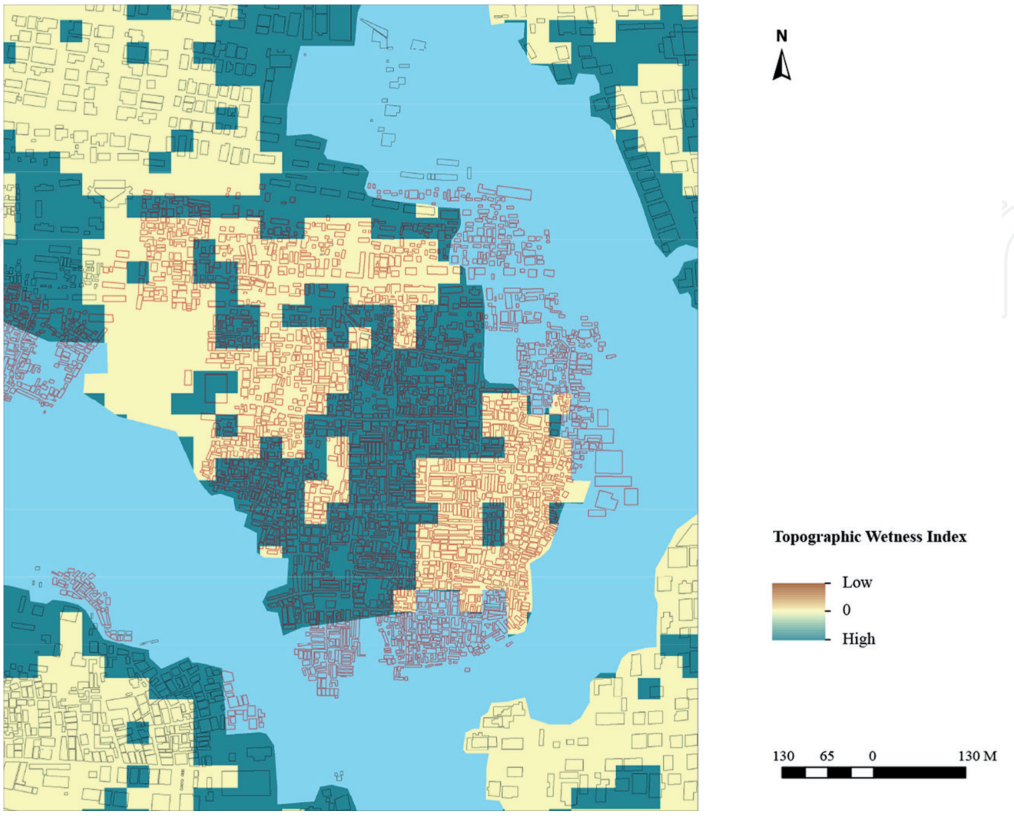

Figure 6.
Mapping flood-prone areas in Korail with TWI [by authors].

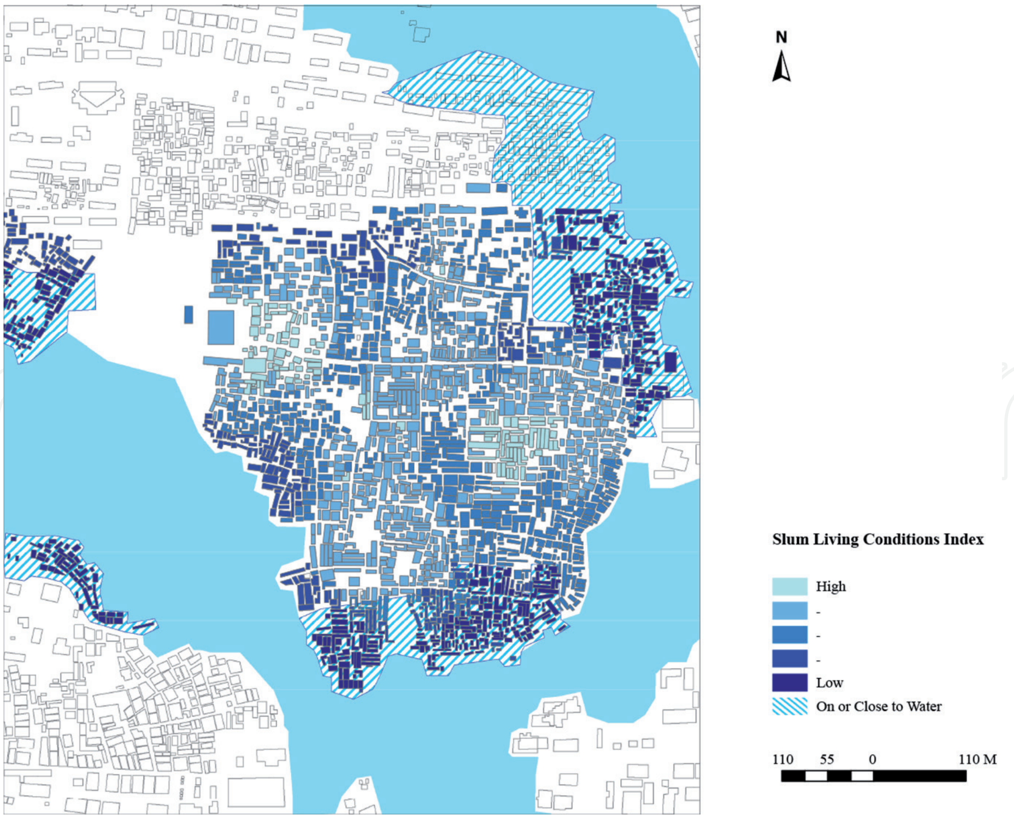

Figure 7.
Mapping the living conditions in Korail with the Slum Living Conditions Index [by authors].

comparing these figures to **Figure 7,** it comes into sight that some areas in close proximity of social centers are under-serviced. This can be attributed to the surge in unavailability of services within the slum [15, 38].

At this point, it seems that flood risks as well as proximity to water greatly affect slum dwellers' living conditions. This observation is similar to the one made by Kanke Arachchilage [28] which demonstrates the reduction of services and the increase of vulnerability for the dwellers living close and on Banani Lake. However, this observation has to be confirmed by the spatial variability study.

Thirdly, **Figure 8** demonstrates that hydrological conditions have a significant influence on the living conditions of Korail. Indeed, it confirms the observations that can be made when comparing **Figures 6** and 7, where the areas located in the most vulnerable parts, i.e., around the fringes of the lake or on it, have the highest deficiency in living conditions.

In addition, **Figure 8** shows this correlation between hydrological conditions and living conditions with a 99% confidence level. Thus, slums located close to a water body faced issues specific to this localization.

Lastly, **Figure 9** highlights that Korail is not a homogeneous slum but instead presents variable flood patterns and living conditions, thus revealing spatial variability of the vulnerability in the slum [4, 5] and presenting similar results as the ones observed by Jankowska [30]. As a matter of fact, this figure demonstrates the presence of "safe" zones with the identification of two **LL** clusters while also presenting the presence of small **LH** outliers that are located near the Banani Lake.

At the same time, a large north-south corridor located in the center of the slum presents one of the lowest deficiencies in living conditions and concentrates most of the services and social centers (see Appendix A.2) while being located in an area highly prone to flooding—in other words a **HL** outlier.

Furthermore, this map also confirms the observation made with **Figure 7** and by Kanke Arachchilage [28]. Indeed, the clusters located near or on the Banani Lake

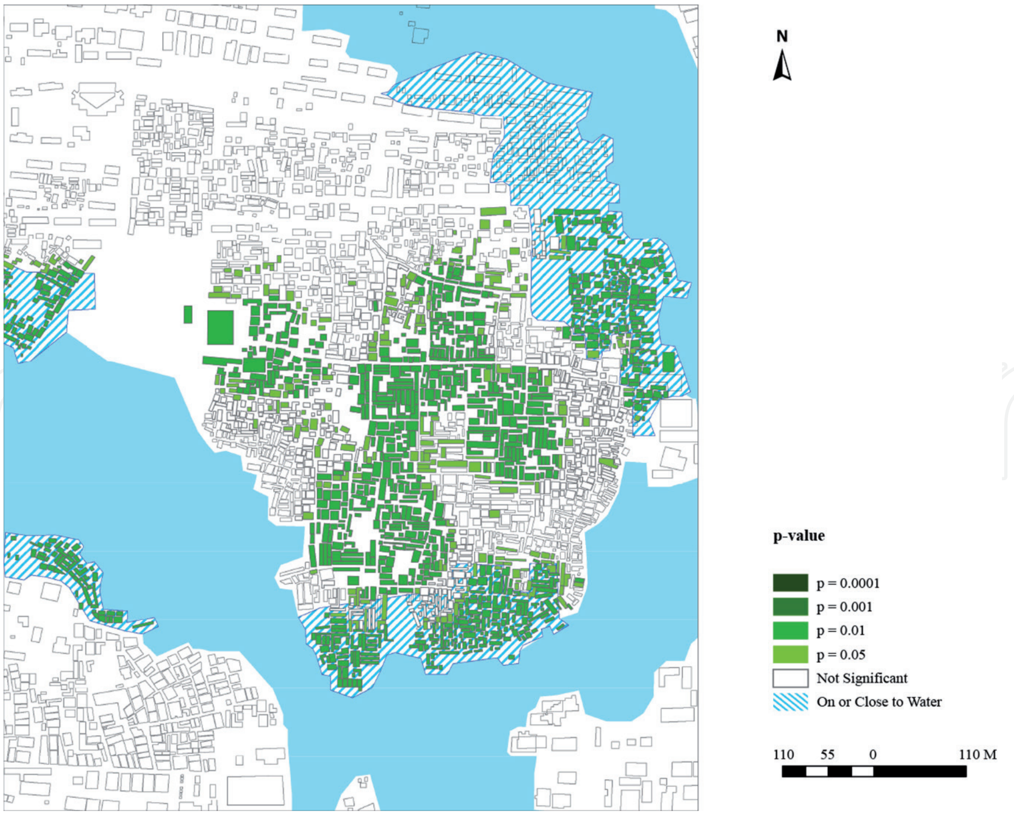

Figure 8.
Significance map (local Moran's I) of the correlation between flood proneness and living conditions in Korail [by authors].

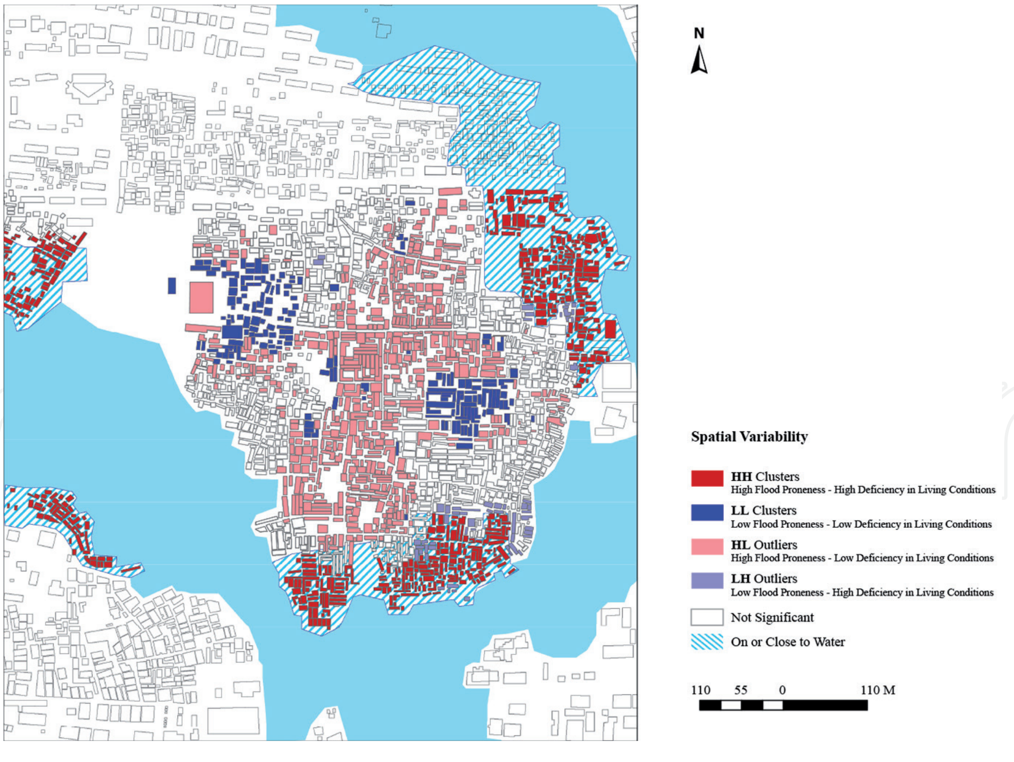

Figure 9.
Spatial variability and clusters in Korail in relation to flood proneness and slum living conditions [by authors].

are the ones presenting the highest risk of flood and the highest deficiency in living conditions—in other words, **HH** clusters.

As a result, flood risks and the proximity to a water body seem to have a considerable influence on the living conditions of the settlements. Concomitantly, the flood risks do not seem to permanently affect the living conditions of a settlement located further away from a water body, as demonstrated by the **HL** outlier. However, this may be due to its central location, in Korail's case.

In effect, this observation can be explained by the fact that social centers are more likely to be located in central and inland locations in the slum than toward the waterfronts to offer a more efficient catching area. For that reason, the presence of such outlier may not be a constant in all slums located close to a water body, and further investigation on this topic would be needed.

In any cases, outlier still experienced a strong reduction in living conditions during floods [15, 35] with the destructions [25] and disruption of the activities [28], including the social centers and the spread of diseases [26].

4.2 Other findings

Besides the examination of the relationship between the Flood Proneness and the Slum Living Conditions Indexes, a temporal spatial pattern analysis was made to investigate the relationship between the proximity from the water body and settlement's density. The purpose of this second analysis is double. Firstly it will serve to observe where the population is concentered in Korail, and secondly the temporal analysis will also help to determine if the slum expands toward Banani Lake as observed by Olthuis et al. [1].

Hence, the significance map in **Figure 10** shows that, in the slum, multiple settlements (in built units prior to 2011) in various locations exhibit significant correlation in terms of their density and distance from water body. Thus, several cluster formations can be observed in built units located close to the lake. Among them two are significant in the southern and northwestern part of the slum, and two smaller ones are located in the eastern and western part.

The spatial variability map in **Figure 10**, for its part, displays several spatial outliers *LH* (low distance-high density) that capture clusters of built unit presenting a high density and located close to the water body. Most of these clusters correspond to the built units identified in the previous figure.

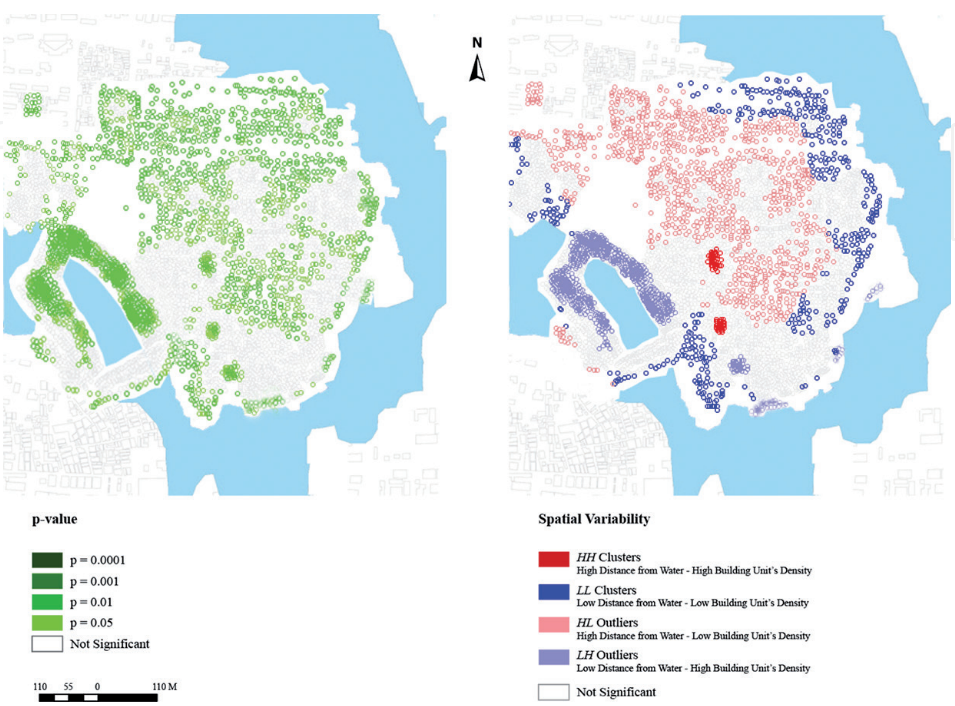

Figure 10.
Significance map (Local Moran's I) for built settlement prior to 2011 (left) – Spatial variability map (Local Moran's I) for built settlement prior to 2011 (right) [by authors].

In addition, this map also illustrates the fact that most of the dense settlements existing in Korail prior to 2011 are located close to the water bodies, surrounding the edges of the lake. Moreover, these areas are also the one presenting a high flood risk and a high deficiency in living conditions in **Figure 9**. As a result, the density of the built units increased as the distance to the water body decreased due to a negative correlation. This phenomenon can be an indicator of the slum's growth toward the water.

As for the dense settlements located further away from the lake, they are mainly localized in areas presenting a high flood risk and a low deficiency in living conditions (**Figure 9**) and are in the buffer zones of the social centers (see Appendix A.2).

The significance map in **Figure 10** showcases that the built unit development between 2011 and 2016 rapidly expanding toward the lake in the western part of the slum. Similar to the observation made prior 2011, this cluster shows significant influence of distance over density of the settlement.

This western expansion can be attributed to the previous observation, in which built units were rapidly expanding in the southern banks, which over a period of time left limited space for further encroachment. Therefore, Korail's expansion leads toward the Banani Lake.

The spatial variability map on **Figure 11** confirms the tendencies observed on the one in **Figure 10**: most of the dense settlements built between 2011 and 2016 in Korail are located close the lake. During this period, the expansion of the slum was mainly focused in the western banks and has steadily consumed the vast majority of area belonging to the lake. Other *LH* (low distance-high density) spatial outliers are also identified in the southern part of the slum around the *LH* outlier observed before 2011. This confirms the hypothesis of a transfer of the slum expansion from the southern part to the western one due to the disappearance of space for further encroachment.

Concerning the *HH* clusters (high distance-high density), the spatial variability map on **Figure 11** also displays similar results as the one in **Figure 10**. These clusters are all concentered in the southern part of the north-south corridor presenting

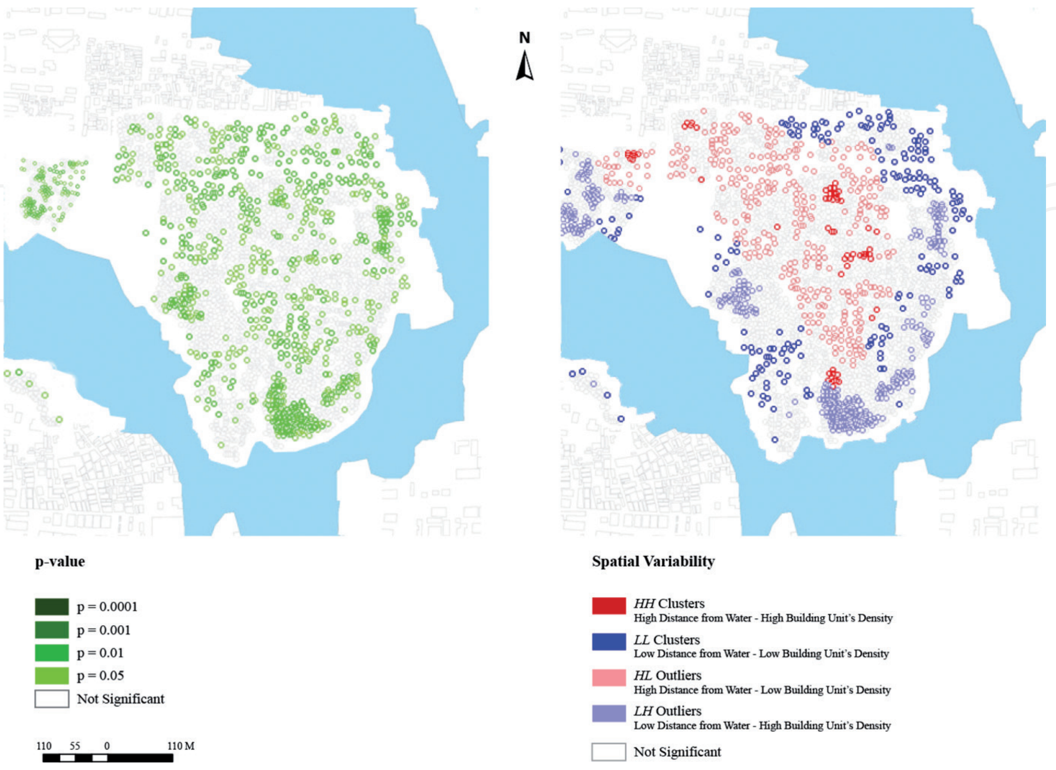

Figure 11.
Significance map (Local Moran's I) for built settlement 2011-2016 (left) – Spatial variability map (Local Moran's I) for built settlement 2011-2016 (right) [by authors].

high risk of flooding and low deficiency in living conditions (**Figure 9**) and are also located in the buffer zones of the social centers (see Appendix A.2).

Consequently, from the observations made from these maps, it appears that most of the dense building units built before 2011 and all the ones built between 2011 and 2016 are located in flood-prone areas and expand toward Banani Lake.

As a result, they are all affected by floods and the resulting hazards of such events. Furthermore, a vast majority of these built units are located close to or on the lake in areas with a high risk of floods and a high deficiency in living conditions. Hence, the living conditions of a large share of the population living in Korail are negatively affected either permanently or regularly by water.

Thereby, Korail can be defined as a **wetslum**—a slum or a large part of a slum where its proximity to a water body and the related flood risks considerably affect the living conditions of its inhabitants. In other words a **wetslum** is a slum where a considerable correlation between flooding and living conditions exists. Thus, **wetslums** are specific human habitats requiring specific environmental and locational management.

5. Conclusions

The framework conceptualized in this paper is inspired by the "living conditions diamond" developed by Gulyani and Bassett [2] as well as the "slum index" introduced by Weeks et al. [4]. They instilled the development of the Slum Living Conditions Index as well as the Flood Proneness Index used to quantify the spatial variability of vulnerability within Korail. Then, clusters were identified through these indexes, and the relationships between the two indexes were examined with a spatial autocorrelation through GeoDa.

It was then used to assess the overall influence of water on the living conditions of a slum. In addition, spatial autocorrelation was also conducted with a temporal analysis to assess the cluster's density with respect to their distance from the water body.

Nevertheless, the study performed in this paper to test the framework necessitated the adjustment of data for the construction of the indexes in reason of the lack of updated and credible data. As a result open-source data and secondary data from several sources were implemented.

The maps produced for the visualization of the two indexes (**Figures 6** and 7) show spatial disparities inside Korail for the exposition to flood risks as well as concerning the living conditions. These observations are confirmed by **Figure 9** where the clusters identified demonstrate that Korail is highly heterogeneous: results that are similar to the findings made in Accra [5, 30]. Indeed, **Figure 9** displays, for building units within **HH** clusters (high flood proneness-high deficiency in living conditions), a significant influence of flood proneness on living conditions in areas located close to the water body.

At the same time, building units within **HL** clusters (high flood proneness-low deficiency in living conditions) exist further away from the water body. These areas have a low deficiency in living conditions in reason of the proximity of several services—social centers in the present case. However, they are still impacted by flooding and thus experiencing periods of rupture in service provision, resulting in the increase of deficiency in living conditions.

As for the **LL** clusters (low flood proneness-low deficiency in living conditions), they are located in more elevated areas, where the rare **LH** clusters (low flood proneness-high deficiency in living conditions) are located in elevated areas close to the water body.

Therefore, these observations confirm the crucial role that water plays on the living conditions of such human habitat as well as the influence of a build unit's localization, such as its distance from a water body and physical factors, such as topography, within a slum. In addition, slums similar to Korail, in terms of flood risk and living conditions, are naturally dynamic—constantly evolving in terms of shape and size [1]. Indeed, **Figures 10** and **11** as well as researches [5, 25] show that Korail's population is growing and that this growth leads to the expansion of the slum toward Banani Lake's bank or directly on it, in the form of dense settlements. Furthermore, the comparison of **Figures 10** and **11** also exhibits the fact that this expansion takes place on any available space, thus explaining the shift observed in the new settlement location from the southern part (prior to 2011) to the western part (2011–2016) of the slum.

As a result, the specific human habitats that are **wetslums**—slums where a considerable correlation between flooding and living conditions exists—are likely to expand toward a water body, thus increasing the number settlements where water affects the living conditions - **HH** clusters.

Hence, this continuous evolution is making it increasingly difficult to provide appropriate interventions and upgrading measures. In that respect, contemporary geo-information and remote sensing technique has enabled researchers to interpret water condition and flood characteristic in an efficient manner. This creates an environment for intercomparison of multinational slums and extent to which their living conditions are affected by water bodies (wetslumness) based on satellite imagery and secondary data. However, such interpretation is due to the lacks of local data that prevent researchers to have a clear on to date vision of the studied settlement.

Thus, the framework conceptualized in this research allows the study of the dynamic characteristic of slums as well as determines locations which require critical upgrading. Indeed, understanding the spatial variability of slums is of crucial importance for slum physical upgrading projects, particularly for **wetslums** where the impact of flooding becomes a key factor which needs to be properly incorporated in order to ensure the success of any physical upgrading project.

5.1 Recommendations

Studying slums at a local scale provides a broader understanding on the organic growth of slums. This level of study captures the physical (topographic) characteristics that go on to influence the living conditions of that settlement. Slum physical upgrading projects need to acknowledge these characteristics in order to achieve sound success and target the right locations for intervention. Place-based upgrading measures will provide relief to slums that require immediate attention.

Slums exhibiting diverse neighborhoods (heterogeneous clusters) require dynamic physical upgrading interventions, which can adapt to the ever-changing environment of these human habitats. For instance, **wetslums** undergo seasonal constraints. They are exposed to heavy floods during certain season, while during the rest of the year, they undergo a dry spell. Dynamic physical upgrading must be able to adapt to these varying environment.

Another obstacle that decision-makers and slum welfare organizations alike are faced with is their ability to record and observe the effect of upgrading measures in real time. It is critical to evaluate slum physical upgrading projects and their positive effect (if any) on the inhabitants, which allows these projects to thrive and/or advance. Hence, there is a growing need to monitor and assess the influence of physical upgrading projects that can be done through modern geo-information platforms such as GPS surveys and web-based platforms for interview of stakeholders.

In short, living conditions in **wetslum** are significantly influenced by their flood proneness, localization, and topographic characteristics. As a result, these particular human habitats require specific physical upgrading projects in terms of dynamic intervention. Also, it is crucial to monitor such dynamic interventions post-implementation, in order to evaluate their real-time effects on the slum inhabitants.

Conflict of interest

None declared.

A. Appendices

A.1 Multi-distance spatial cluster analysis using Ripley's K function

See **Figure 12** and **Table 1**.

The observed K value is larger than the expected K value for the first four classes (distance bands): this proves the settlement pattern is more clustered than random at these distance (scale of analysis). Moreover, the observed K value is larger than the upper confidence envelope value (HiConfEnv), thereby proving the spatial clustering for these distance is statistically significant.

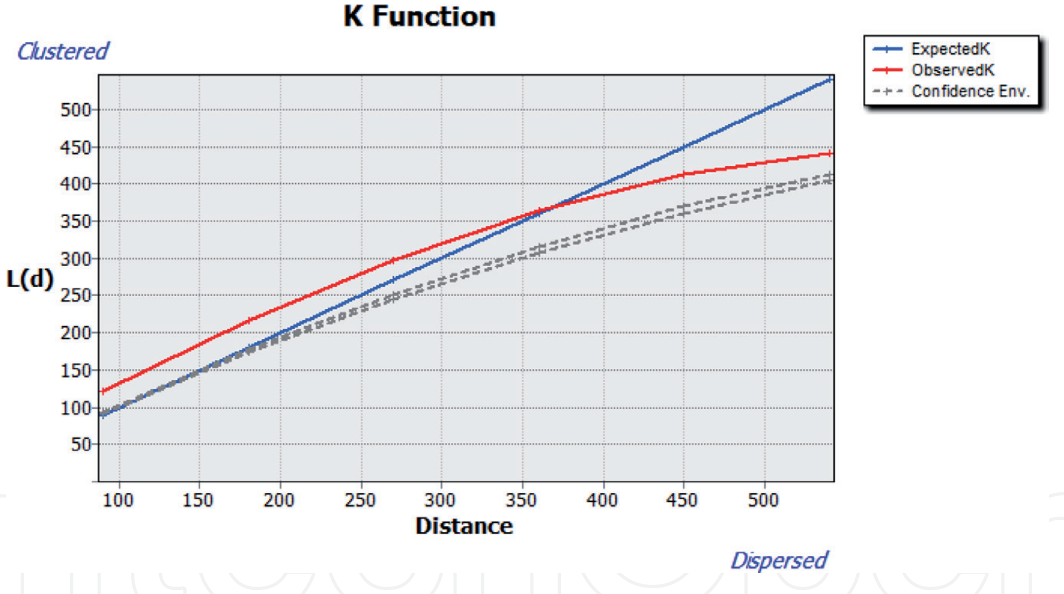

Figure 12.
Multi-distance spatial cluster analysis (Ripley's K function) [by authors].

Class	Expected K	Observed K	Diff K	LwConfEnv	HiConfEnv
0	90.00	121.25	31.25	91.30	92.84
1	180.00	217.21	37.21	172.93	177.08
2	270.00	297.82	27.82	245.12	251.23
3	360.00	364.51	4.51	307.67	315.45
4	450.00	411.80	−38.20	360.93	369.47
5	540.00	441.80	−98.20	404.88	412.90

Table 1.
Multi-distance spatial cluster analysis (Ripley's K function) [by authors].

A.2 Location and buffer zones of the education and health centers in Korail

See **Figure 13**.

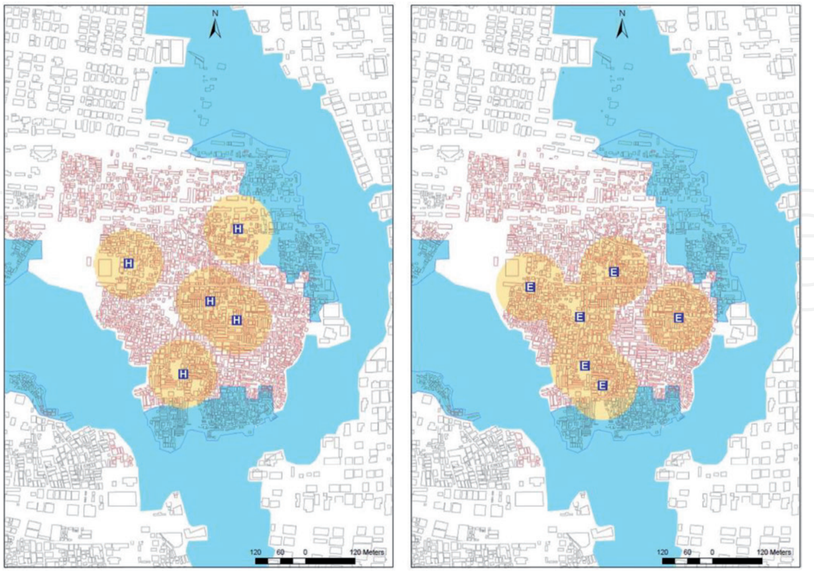

Figure 13.
Health centers and their buffer zone (on the left); education centers and their buffer zone (on the right) [by author].

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