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Article

Mapping Time-Space Brickfield Development Dynamics in Peri-Urban Area of Dhaka, Bangladesh

Mohammad Mehedy Hassan [1,*], Levente Juhász [2] and Jane Southworth [1]

[1] Department of Geography, University of Florida, Gainesville, FL 32611, USA; jsouthwo@ufl.edu
[2] GIS Center, Florida International University, Miami, FL 33199, USA; ljuhasz@fiu.edu
* Correspondence: mehedy@ufl.edu; Tel.: +135-2745-9364

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Abstract: Due to the high demand for cheap construction materials, clay-made brick manufacturing has become a thriving industry in Bangladesh, with manufacturing kilns heavily concentrated in the peripheries of larger cities and towns. These manufacturing sites, known as brickfields, operate using centuries-old technologies which expel dust, ash, black smoke and other pollutants into the atmosphere. This in turn impacts the air quality of cities and their surroundings and may also have broader impacts on health, the environment, and potentially contribute to global climate change. Using remotely sensed Landsat imagery, this study identifies brickfield locations and areal expansion between 1990 and 2015 in Dhaka, and employs spatial statistics methods including quadrat analysis and Ripley's K-function to analyze the spatial variation of brickfield locations. Finally, using nearest neighbor distance as density functions, the distance between brickfield locations and six major geographical features (i.e., urban, rural settlement, wetland, river, highway, and local road) were estimated to investigate the threat posed by the presence of such polluting brickfields nearby urban, infrastructures and other natural areas. Results show significant expansion of brickfields both in number and clusters between 1990 and 2015 with brickfields increasing in number from 247 to 917 (total growth rate 271%) across the Dhaka urban center. The results also reveal that brickfield locations are spatially clustered: 78% of brickfields are located on major riverbanks and 40% of the total are located in ecologically sensitive wetlands surrounding Dhaka. Additionally, the average distance from the brick manufacturing plant to the nearest urban area decreased from 1500 m to 500 m over the study period. This research highlights the increasing threats to the environment, human health, and the sustainability of the megacity Dhaka from brickfield expansion in the immediate peripheral areas of its urban center. Findings and methods presented in this study can facilitate data-driven decision making by government officials and city planners to formulate strategies for improved brick production technologies and decreased environmental impacts for this urban region in Bangladesh.

Keywords: Dhaka; brickfield; pollution; spatial analysis; GIS and RS; environmental degradation

1. Introduction

Due to rapid urbanization combined with industrialization and a steady economic development trajectory in Bangladesh, the demand for cheap construction materials such as handmade clay bricks has shown a significant increase in recent decades. As a result, brick making in Bangladesh has become the fastest-growing manufacturing sector, contributing 1% to the gross domestic product (GDP) and employing approximately 1 million people [1,2]. Different estimates suggest that approximately 7000 traditional brickfields have been established across the country [1–3]. Nearly 23 billion bricks are produced annually in these brickfields in Bangladesh by mining an estimated 3350 million cubic feet of soft clay, and burning 5.67 million tons of coal and 3 million tons of firewood [1]. The sector is the largest single energy consumer (i.e., firewood and coal) and is the main driver of deforestation [1].

In addition, brick manufacturing is the leading source of air pollution in the country, emitting an estimated 15.67 million tons of carbon [1] and other environmental pollutants such as ash, dust and sulfur dioxide gases into the atmosphere [4–8]. Such brickfield operations on a large scale are jeopardizing the country's air, water, soil, and ecology, as well as public health [2,9]. Potentially linked to this, premature deaths have also shown a steep increase nationally from 81,200 people in 1990 to 122,400 people in 2015 [10]. Apart from air pollution, traditional activities related to brickfields are associated with many physiological and industrial hazards. Heavy workload, postural issues, chronic musculoskeletal disorders, and repetitive movement disorders are prevalent among brickfield workers and have been increasingly reported in many studies. For example, one study found an increased level of respiratory symptoms and illness among brickfields workers in Larkana and Dadu districts, Sindh, Pakistan [11]. Other studies [12] observed that female brickfield workers are at a high of risk of suffering from occupation-related lower back pain (LBP) because of various types of hard and strenuous work associated with brick making [12,13]. Similarly, in [14], the authors examined occupational stress among molders and found severe grade III chronic energy deficiency with obstructive pulmonary disease among women brick molders in West Bengal.

Studying the spatial distribution of geographic events on the landscape is one of the oldest branches of regional science, environmental studies, economic analyses, and development studies [15–17]. Spatial analysis techniques help to identify the structures and also suggest reasons for spatial pattern characteristics [18]. Spatial analysis with geographic information systems (GIS) and the analysis of remotely sensed data are often used to monitor the space-time dynamics of geographical events. These have been proven to be effective tools in landscape planning and dealing with environmental problems such as air and water pollution, land degradation and site management [19,20]. Brickfield pollution is a critical issue; however, there have been only a few studies on addressing this topic in the greater Dhaka and larger region. For example, in [4], authors studied pollution from brick clusters in Dhaka, suggesting that the total emission of $PM_{2.5}$ is approximately 23,300 tons, followed by 15,500 tons of sulfur dioxide (SO_2), 302,000 tons of carbon monoxide (CO), 6000 tons of black carbon (BC), and 1.8 million tons of carbon dioxide ($CO_{2)}$ per year. A similar study examined particulate matter, black carbon, gaseous pollutants and volatile organic carbon on three different brick making technologies from eighteen selected brickfields and estimated that the total emission from brick kilns in Greater Dhaka region is approximately 4526 tons of $PM_{2.5}$, 304 tons of BC, 209,776 tons of CO_2, 8700 tons of CO, 19,441 tons of SO_2, and 835,450 tons of volatile organic compound (VOC) per year [5].

Admitting the severity of the impacts of the brick kilns located around densely populated areas and arable land, the Brick Manufacturing and Brick Kiln Establishment Control Act was enacted in the country in 1989. It was then revised in 1992, 2001 and 2013, banning all indigenous fixed-chimney brick kilns technology from being used for brick manufacturing. The Brick Manufacturing Act also prohibits using wood and substandard coal fuel to burn bricks. In addition, under this act, the construction of brickfield within the boundary of educational institutions, residential areas, businesses or protected areas, city corporations, municipalities, forests, wetlands, agricultural lands, and ecological crisis areas is prohibited. However, this legislation often seems to be ignored by the brick manufacturing industry.

Even though the consequences of the social-ecological issues outlined above can be severe, this research is not aimed at giving a systematic analysis of the topic. The motivation of this research lies in the fact that understanding the spatial and temporal patterns of brickfield distribution can facilitate various analytical tasks, such as the detection of areas with high brickfield density. With an increased understanding of the spatial and temporal development of brickfield locations city planners can potentially make more informed strategic decisions to improve a city's air quality from brickfield pollution and to protect critical ecological resources such as water and wetland, agriculture land, and forest from further degradation. Informed decisions about the brick manufacturing industry cannot be made without understanding the spatial distribution of existing brickfield locations. However, to the authors' knowledge, no such datasets exist. Therefore, the aim of this study is to extend the literature by describing the spatial and temporal patterns of brickfield manufacturing in the peri-urban area of the megacity Dhaka between 1990 and 2015. The study analyzes the spatial variation of brickfield locations as a point process employing the first-order geo-statistical techniques of quadrat counts and second-order statistics Ripley's K-function. Finally, this study examines whether existing brickfield locations in the peri-urban area of Dhaka follow current environmental legislation.

2. Materials and Methods

2.1. Study Area

The study area of Dhaka is the capital city of Bangladesh and is situated in the lower reaches of the Ganges delta, in the center of the country (Figure 1). It is arguably one of the fastest-growing and most densely populated megacities in the world and is globally ranked as the ninth largest urban area [21]. Although the area of the city core (Dhaka Metropolitan Area) is only 306 km^2, the mega-urban region extends to an area of 1528 km^2 (the Detailed Urban Planning area of greater Dhaka), and comprises six municipalities (Kadamrasul, Gazipur, Naryanganj, Sidirganj, Savar and Tongi) and several connecting smaller urban areas (Figure 1). Five major river systems cross the megacity, which are: the Buriganga-Dhaleshwari to the south, Bansi-Dhaleshwari to the west, Turag Rivers to the North, and the Shitallakhya-Balu to the east and southeast. Geomorphic classification reveals that a relatively young floodplain constitutes the largest area, followed by the higher terraces of the Pleistocene period. Low-lying swamps and marshes are found in and around the city. However, they are primarily located in the eastern and western part of the metropolitan area, which comprises approximately 300 km^2. These water bodies and wetlands around Dhaka are under threat from encroachment by brickfield expansion, infrastructure and residential development. This may increase the susceptibility to flooding during the monsoon seasons, with related heavy rainfall and possible cyclones.

2.2. Tracking Brickfield Locations

The brickfields in the study area are typically Bull's trench or fixed-chimney types, rectangular in shape and sometimes with rounded corners, attached with smokestacks 6 to 10 m in height on top. The bottom and side walls of the kiln are made with bricks, with the top left open [22]. The sketch of a typical Bull trench chimney is shown in Figure 2. The operation of a Bull's Trench is low tech, they are cheap to build, and they are often located in the lowlands of peri-urban regions of greater Dhaka, which floods during the monsoon season. As a result, they only operate during the dry months from November to May [1,23]. The same yard and kilns are used to repeatedly burn out soft muddy bricks into hardy ones. More than 90% of brick burning technologies in the study area (and in Bangladesh) are of the Bull's trench type.

These brickfields and brickyards are visually apparent in satellite imagery, both in high-resolution true color imagery or in false color composite multispectral imagery. In addition, their shape, structure, and the actual operating area is easily distinguishable and can therefore be traced from high-resolution satellite imagery (Figure 3). We digitized each potential brickfield site in four time steps—1990, 1995, 2005, and 2015—using Landsat imagery associated with Google Earth (GE) time-lapse and GE high-resolution imagery. Google time-lapse is a time-series visualization of global land changes. These are non-static images, spanning from 1984 onwards. Since we do not have any high-resolution imagery for the year of 1990 to verify brickfield locations on Landsat 30-m resolution images, we used as a proxy information to track brickfield cluster on Landsat images. Even though GE time-lapse imagery is more useful for change detection covering larger areas than micro-scale analysis, we found these time-series could still be useful when detailed high-resolution imagery is not available. Hence, we played back and forth with these time-lapse images to map and trace the approximate location of each brickfield on the Landsat images. Initially, we identified each brickfield site on the 2015 GE imagery and digitized their extent with polygon geometry. The centroids of these brickfields were also recorded as points.

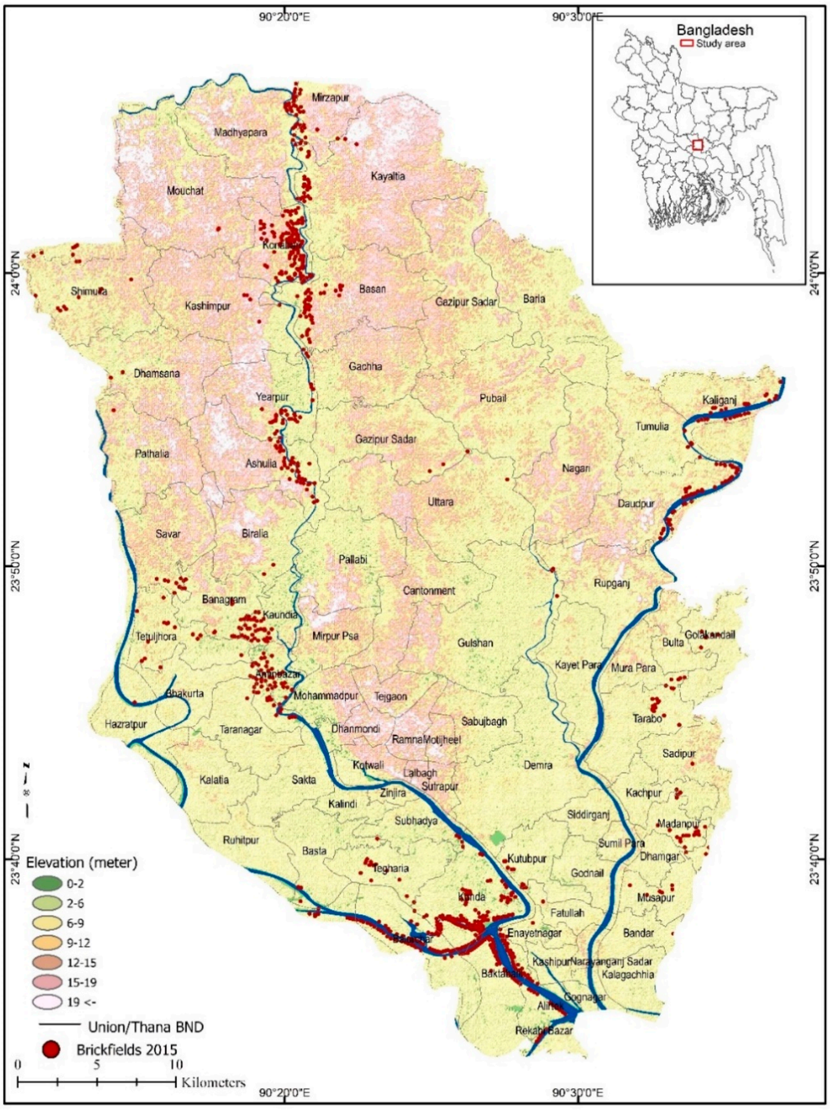

Figure 1. Elevation and brickfield locations in 2015 in greater Dhaka. Inset map in the top right corner shows the study area of greater Dhaka's geographical position (red square box) in Bangladesh.

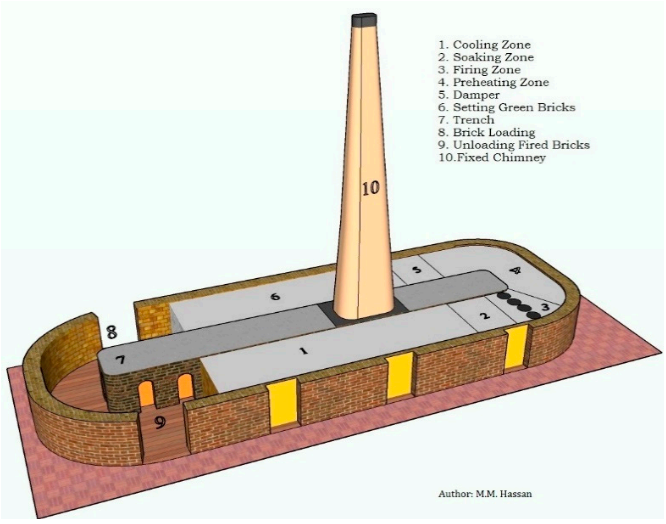

Figure 2. Schematic diagram of traditional fixed-chimney Bull trench clay-made brick burning kilns.

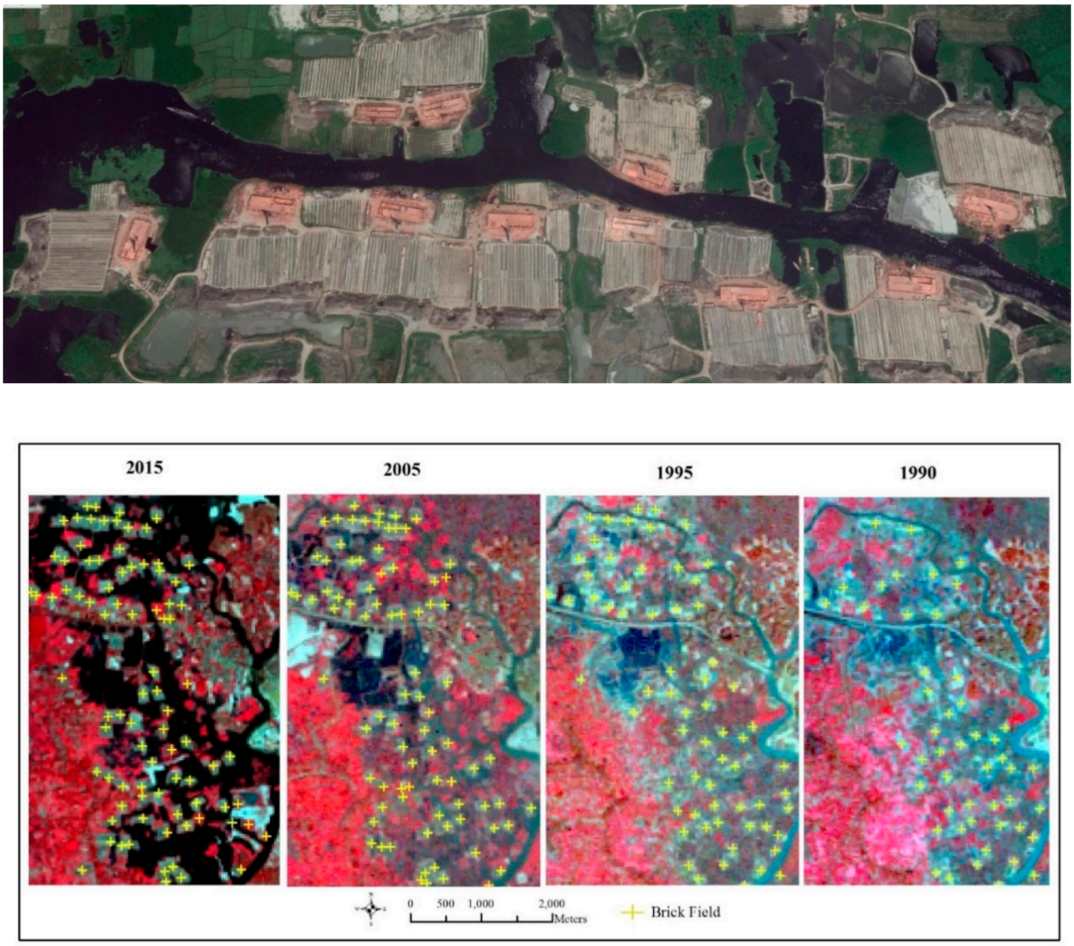

Figure 3. Shape and structure of traditional brickfields visible in high-resolution Google Earth imagery (**top**) and digitized brickfield locations overlaid on false color composite Landsat imagery across the study period (**bottom**).

Later, these digitized locations were overlaid on Landsat imagery obtained from 2015. The spectral signatures of brickfield and non-brickfield pixels were extracted and used to identify areas with similar reflectance profiles in Landsat images from 2005, 1995 and 1990. Additionally, each potential site was supervised carefully, and compared against the spectral signature derived from the Landsat imagery and image overlay techniques such as flickering, blending and swiping were employed [24] before we determined a location as brickfield.

As most of the brickfields in the study area only operate during the dry season (between November and May), we downloaded cloud-free satellite imagery for 1990, 1995, 2005, and 2015 during December and January. Urban growth and the land cover map of greater Dhaka were derived from a previous study [25]. Other datasets, such as the administrative boundaries in the study area, road networks and water bodies were retrieved from the Detailed Area Plan-2016 for the Greater Dhaka.

2.3. Analyzing the Spatial Process of Brickfields

This study used both first-order and second-order geostatistical techniques—namely, quadrat analysis and Ripley's K-function—to explore the spatial process of brickfield development. Point pattern analysis has been found to be a useful analytical tool in several disciplines; therefore, several methods have been developed to analyze point data [26]. Among these, quadrat analysis and Ripley's K function remain some of the most widely used methods. We calculated Chi-Square statistics and computed Ripley's K-function to describe the point patterns for each observation year, and compared the observed values with what would be expected under complete spatial randomness (CSR) generated by the uniform Poission point process, which is a well-documented process for generating reference point patterns representing CSR [27,28]. With CSR, we refer to point patterns generated by this point process in the remainder of the study.

Quadrat analysis is a relatively straightforward method for studying the spatial arrangement of point locations by counting the frequencies of points occurring in an area [28,29]. Quadrat-based aggregation of data points is a widely used method of spatial statistics utilized across many disciplines related to the spatial sciences, such as ecology [30], crop science [31], information science [32] or GIScience [33]. The technique has also been used to study health outbreaks [34], crime occurrence [35,36], and the spatial patterns of fire events [37]. In quadrat analysis, various geometric forms, such as circles or hexagons (as appropriate for the geographic phenomenon being studied) are used to aggregate the underlying point pattern. In this study, we utilized regular square grid cells. The modifiable areal unit problem (MAUP) is well known in the spatial sciences and describes the fact that analysis results are sensitive to the size of the spatial unit utilized in the analysis [38]. Different methods exist to deal with the effects of MAUP, such as zoning systems and sensitivity analysis; however, all methods have their drawbacks [39]. Here, instead of utilizing an arbitrary cell size deemed suitable for the study site, we chose to calculate an optimal cell size (l) [40] to account for MAUP. It is calculated as:

$$l = \sqrt{2a/n}$$

where l is the cell size (length of the quadrat), a is the area of the study area, and n is the total number of points in the study area. For example, in 2015 the total number of points is 917 and the area of the study area roughly covers 1700 km^2. Using the optimal quadrat size, a total of 514 quadrats were generated with a cell size of 1926 m. The resulting grid seemed visually appropriate to describe the spatial variation of brickfield locations, therefore other methods to address MAUP (such as a sensitivity analysis) were not explored further. These quadrat grid cells were then superimposed on point data and the number of points falling in each of the square cells was counted to construct the frequency distribution. The difference between the observed and expected number of brickfields were extracted for each quadrat which was used to calculate the chi-square (χ^2) statistic. To describe the point pattern, we then calculated

$$\chi^2 = \sum (O - E)^2/E$$

where O is the observed point count in a quadrat and E is the expected point count in a quadrat under CSR. A chi-square test of independence would require that all expected counts per quadrat be greater than five; therefore, we performed Monte Carlo randomization to determine empirical statistical significance levels. Namely, we calculated the χ^2 statistics for 1000 CSR patterns and determined

$$p = (NGE + 1)/1001$$

where NGE is the number at which the simulated statistics were greater than those observed.

Ripley's K-function can provide a more accurate analysis of point distributions [41–43] by describing point patterns over a range of distances. The K-function and its bivariate version are widely used in the literature, for example, to study the spatial structure of cysticercosis infection [44], to describe the attraction or repulsion between point sets in geo-gaming [45] or to analyze the distribution of points on transportation networks [46]. In addition, Ripley's K-function has been used in big data analysis [47]. Here we employed the K-function to determine how brickfield distributions vary over a range of distances. The K-function illustrates how the spatial clustering or dispersion of features changes when the neighborhood size changes. The K-Function can be given as

$$\mathbf{K}(r) = \lambda^{-1}\mathbf{E}[\textbf{number of brickfields within distance r of a randomly chosen brickfield}]$$

where r is the distance and λ is the density (number of brickfields per areal unit). Edge correction is necessary when the radius extends over the boundary of the study area, and it is done by multiplying the expression with a weight. This weight will be equal to 1 if a circle with r radius inserted on a random point is completely within the study area and will proportionally fall between 0 and 1 if a portion of that circle's circumference falls outside the study area [48]. The theoretical K function under CSR (for the homogeneous Poisson process) can be calculated as $K_{theo}(r) = \pi r^2$. When the observed K value is larger than the K_{theo} for a particular distance, the point distribution is more clustered than a random distribution at that distance. When the observed K value is smaller than K_{theo}, the pattern can be considered dispersed at that distance. Statistical significance can be tested with Monte Carlo simulation. The observed $K(r)$ for 1000 CSR patterns will establish a lower and upper confidence interval at the 99.9% significance level.

3. Results

3.1. Mapping Time-Space Brickfield Expansion in Greater Dhaka

Table 1 summarizes the spatial expansion of brickfield locations over the study period and reveals that the total number of brickfields in Dhaka grew by more than 271%, from 247 to 917. The spatial distribution of brickfield locations traced from satellite imagery is shown in Figure 4 for 1990, 1995, 2005 and 2015. Visually, there appear to be two major groups in 1990 in the west and southeast of Dhaka city. These brickfields were in Aminbazar (Savar Upazila) and Konda Union (Keranigang Upazila), mainly concentrated between the enclave of the Buriganga and the Dhaleshwari rivers. These two sites accounted for 93 percent of all brickfields in 1990. Konda and its adjoining area during 1990 had the highest number: 131 out of 247 brickfields, followed by 69 in Aminbanzar, 20 in Siddirganj, 14 in Konabari, and 13 Tarabo. Figure 5 displays the pattern of brickfield locations by sub-district (Thana) level across the greater Dhaka.

Table 1. Spatial expansion of brickfield locations between 1990 and 2015 in the Dhaka region.

Year	Number of Brickfields	Total Area [ha]	Total Area [km^2]
1990	247	349	3.49
1995	417	704	7.04
2005	836	2181	21.81
2015	917	2563	25.63

Due to the rapid urbanization in Dhaka between 1990 and 2005, the growth of brickfields increased quickly: from 247 in 1990, to 417 in 1995, 836 in 2005, and 917 in 2015. The urban/built-up areas increased at approximately the same rate during the same time period, from only 88 km^2 in 1990 to 378 km^2 in 2015 [25], which has ultimately resulted in more people being exposed to kiln pollution. The elevated land to the north and northwest of the old city center has supported urban expansion, whereas the low lying, swampy areas became the hotspot for brick manufacturing sites. The traditional sites, i.e., Aminbazar in Savar and Konda in Kerainganj, still hosted the highest number of brick manufacturing yards in 2015. However, they also thrived in other locations in the north, northwest (Ashulia) and northeast (Kaliganj-Daudpur) of the study area (see in Figure 1). Despite these extended brick manufacturing sites, the traditional brick manufacturing areas, like Aminbazar and Konda, also experienced a substantial expansion. For instance, between 1990 and 1995, the Aminbazar area witnessed a nearly 35% growth, whereas Konda and the surrounding areas experienced as high as a 78% growth during the same period. Among the five major areas in which brickfields are concentrated, as shown in Figure 5, the group near Konabari in Gazipur sadar had the highest growth from 1990 to 1995 and from 1995 to 2005, at 522% and 180% respectively. Later, between 2005 and 2015, the brickfield expansion and the numbers in this group remained unchanged. Apparently, the growth rate of brickfields between 2005 and 2015 declined compared to prior study periods. There are several possible explanations for this declining trend: first, the growth of brickfields is closely linked to the growth of urban areas in

Dhaka. For example, the total built-up growth rate in Dhaka between 1990 and 2005 was 72%, and between 2005 and 2015 it was 23% [25]. Meanwhile, the total brickfield growth rate during 1990–2005 was 238%, while it was 10% during 2005–2015, indicating built-up growth rate in Dhaka and brickfield expansion rates across Dhaka were declining compared to the previous decades. In addition, brickfield growth in the study area had probably reached an optimal level; as a result, existing plants were enough to supply the demands of brick for the megacity. Another reason could be the new environmental laws banning any type of fixed-chimney brickfield development across the country. Finally, green brick production and alternative building blocks are emerging as new technologies; as a result, current real-estate developers are interested in using more environmentally friendly building blocks.

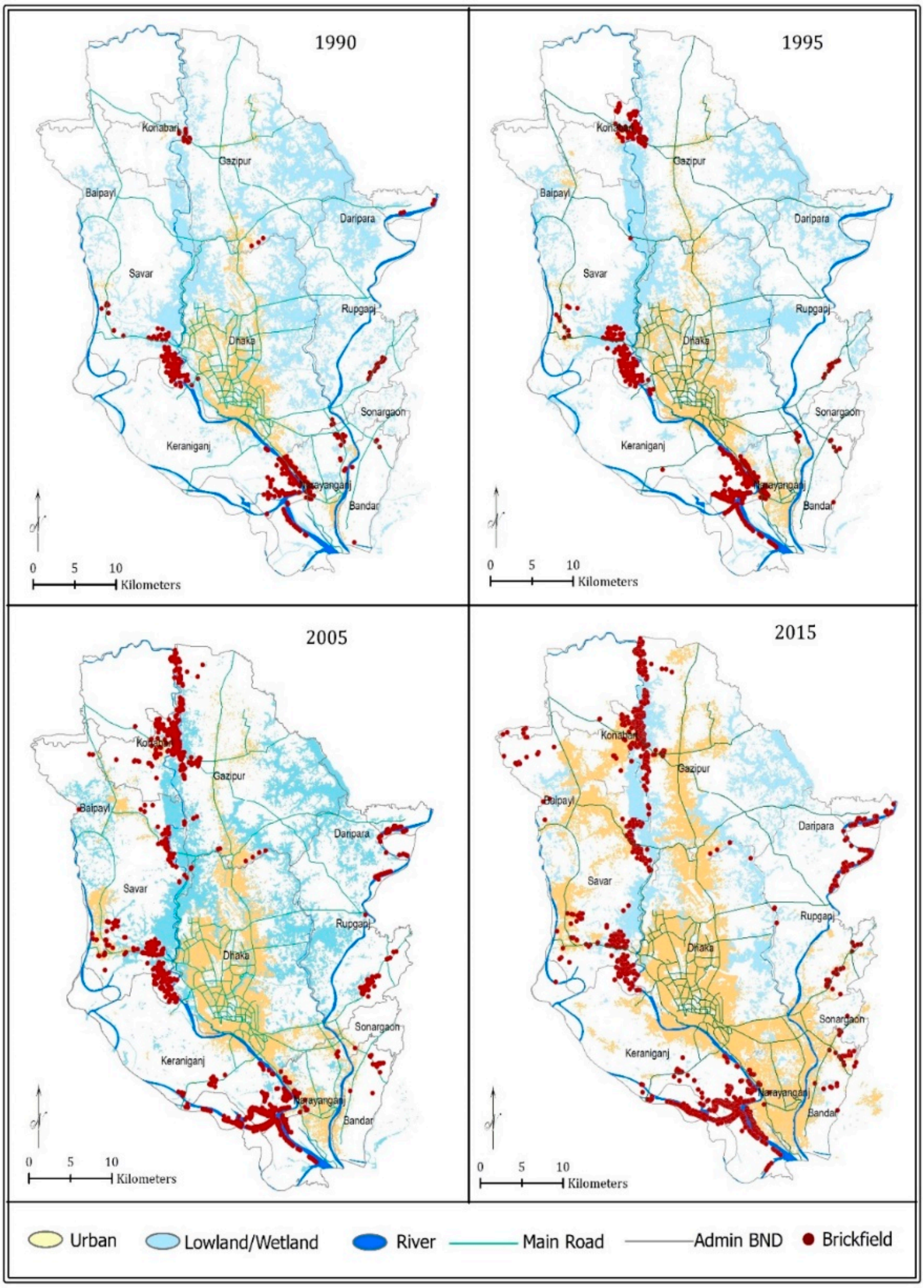

Figure 4. Brickfield spatial expansion in Greater Dhaka from 1990 to 2015.

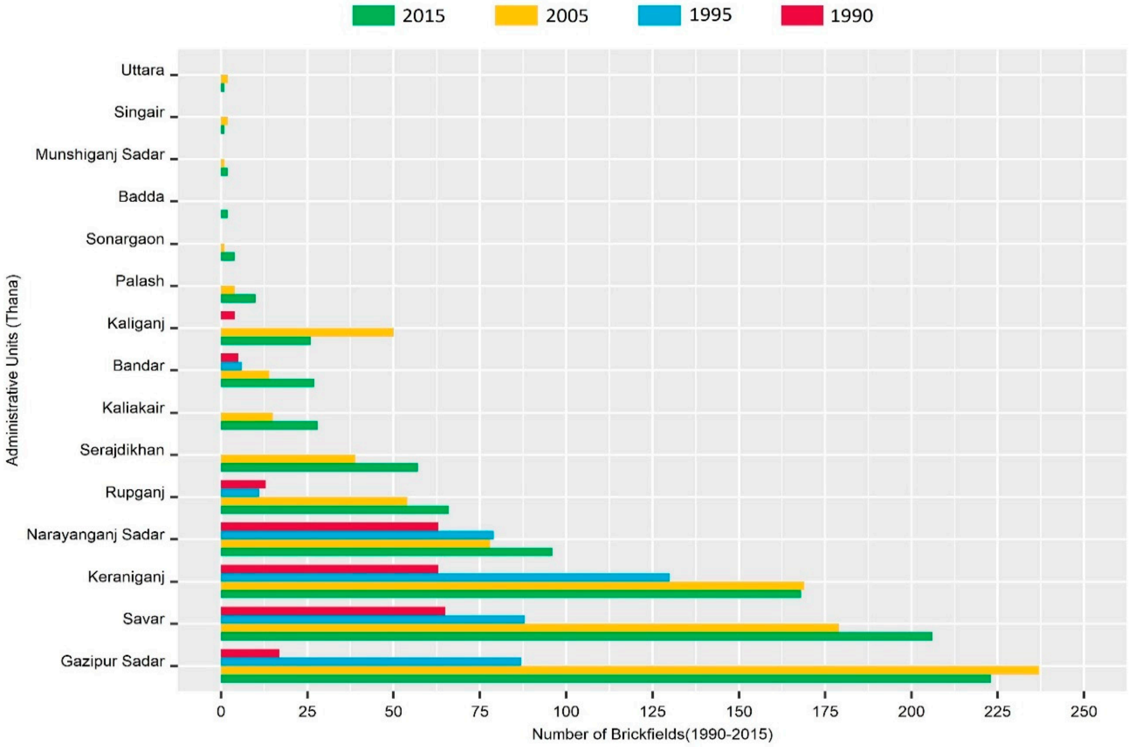

Figure 5. Pattern of brickfield distribution in Greater Dhaka from 1990 to 2015. Numbers of brickfields were aggregated at the Thana level (sub-district level).

Land occupied by these brickfields in the study area between 1990 and 2015 showed a marked increase. In 1990 the total land occupied by these brickfields was 349 ha, with an average yard size of 1.41 ha, which then increased to 2563 ha, with an average yard size of 2.79 ha in 2015. Such huge amounts of occupied land, mainly on riverbanks and lowlands in the city outskirts, are subject to erosion and flooding during the rainy season. Due to comparatively cheap land for brick manufacturing yards and the necessary resources of earth and natural fuel found across the river channel surrounding Dhaka, a large quantity of brickfields can be found in these swampy areas in the Dhaka peri-urban locations.

3.2. Cluster Analysis of Brickfield Locations

The goal of the cluster analysis was to confirm that the spatial distribution of brickfield locations is the result of a non-random spatial process; in other words, the brickfields are spatially concentrated. To evaluate this, two methods were employed. First, quadrat analysis was conducted separately for each observation year. The number of brickfield locations was counted for each year and for each quadrat, and the chi-square (χ^2) statistic was calculated for each point pattern. The statistic was compared with empirical χ^2 observations from 1000 random samples to assess statistical significance. Table 2 lists the results of this analysis in a tabular format and reveals that these locations did not develop in a random pattern, but rather show signs of strong clustering, statistically significant at the 99.9% level. χ^2 is a measure of the clustering, and a steady increase in χ^2 values between 1990 and 2015 indicates that the level of clustering increased over the years. In other words, the location choice of newly established brickfields was affected by previous brickfield locations and new brickfields were attracted by existing locations.

Table 2. Results of the quadrat analysis reveals that brickfield locations are clustered.

Year	Number of Brickfields	Number of Quadrats	Observed χ^2	Point Pattern	p-Value
1990	247	130	2795	Clustered	0.001
1995	417	198	4994	Clustered	0.001
2005	836	450	9942	Clustered	0.001
2015	917	494	10,321	Clustered	0.001

A somewhat more refined measure, Ripley's K-function, was also computed for brickfield patterns in 1990, 1995, 2005 and 2015. An advantage of the K-function is that it assesses clustering in relation to neighborhood size. We calculated the K-function at measuring sizes of up to 8 km for all years. Figure 6 shows the observed values (solid black lines) compared to the theoretical K-function, which denotes CSR. K-values for all distances in all years were found to be larger than the theoretical values, indicating that brickfield locations are clustered across the entire study area and for all years of the study. We established high and low confidence envelopes (grey areas in Figure 6) from Monte Carlo simulation by calculating K for 1000 CSR point patterns. The observed values are larger than the highest confidence envelope at the 99.9% confidence level.

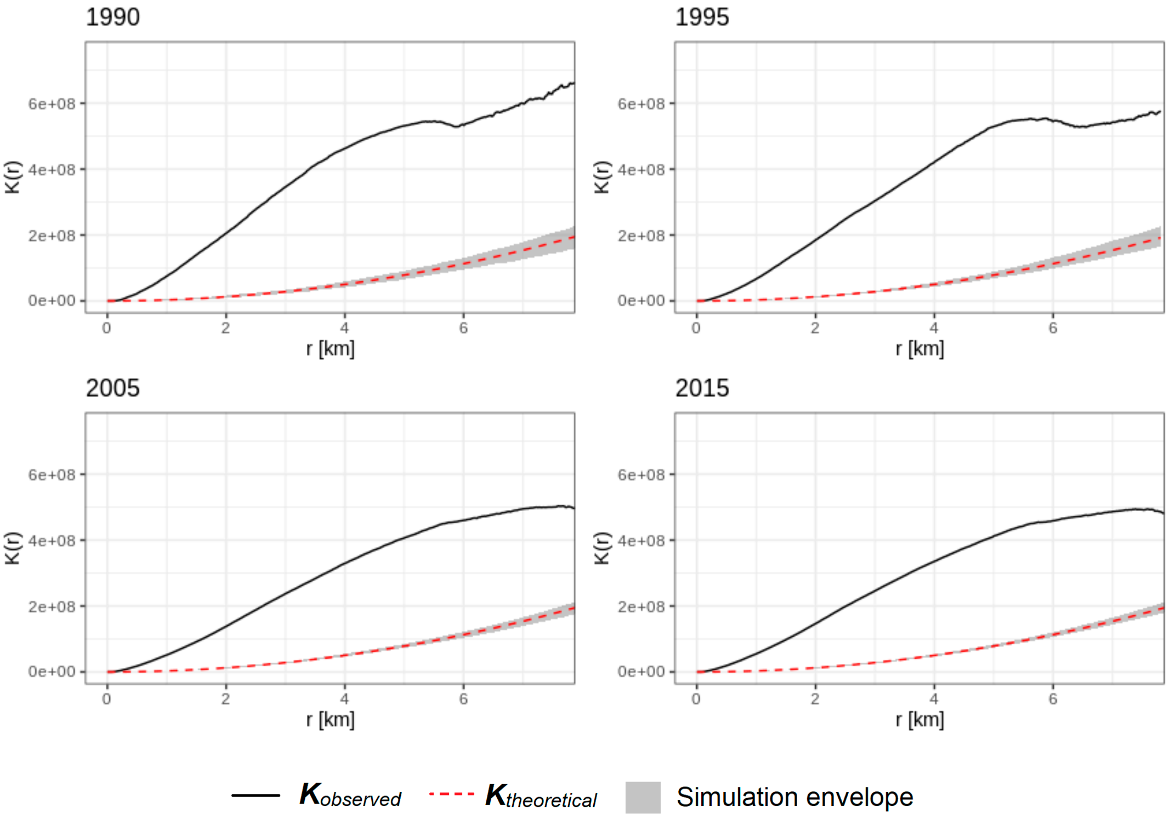

Figure 6. Observed Ripley's K-function (solid black line) compared to the theoretical K-function (red dashed line). Grey areas denote simulation envelopes from Monte Carlo simulations with 1000 iterations.

3.3. Brickfield Location Analysis in Relation to Other Geographic Features

Since the brick manufacturing industry was found to be highly concentrated in certain areas, we also evaluated their locations in relation to other geographic features. Namely, we calculated six sets of nearest neighbor distances measured from brickfield locations to the closest urban area, rural settlement, wetland, river and local and national roads for 1990, 1995, 2005 and 2015. Similarly, all newly developed brickfields were identified over three periods: 1990–1995, 1995–2005, and 2005–2015, and similar measures were calculated to investigate whether location characteristics of brickfields had changed in relation to the above six geographical features across these time periods.

Figure 7 plots nearest neighbor distances as density functions. Density plots were chosen to avoid arbitrary binning of the data over different ranges of distances, which would have been required in order to show distributions as histograms. The area below each density curve is equal to 1, which is a convenient way to highlight the differences between the yearly distribution of nearest neighbor distances. For each year, the shape of the density curves for rural areas (Figure 7b), wetland (Figure 7c), rivers (Figure 7d), and local roads (Figure 7f) are similar, indicating that most brickfields remained at approximately the same distance from these objects. One possible explanation for this is that the brick manufacturing industry did not favor rural areas, and local roads play a minor role in brickfield expansion. However, the similar patterns for wetlands and rivers are due to the fact that brickfields in the Greater Dhaka area are traditionally located mainly on riverbanks and wetlands surrounding its periphery. Similar patterns were also observed for the newly developed brickfields as seen in Figure 8b–f. All newly developed brick manufacturing sites tend to be setup in wetland areas, and close to riverbanks. The possible explanation for this trend is related to the location of cheap land and access to transportation along with the availability of raw materials such as earth surrounding the river channel across Dhaka.

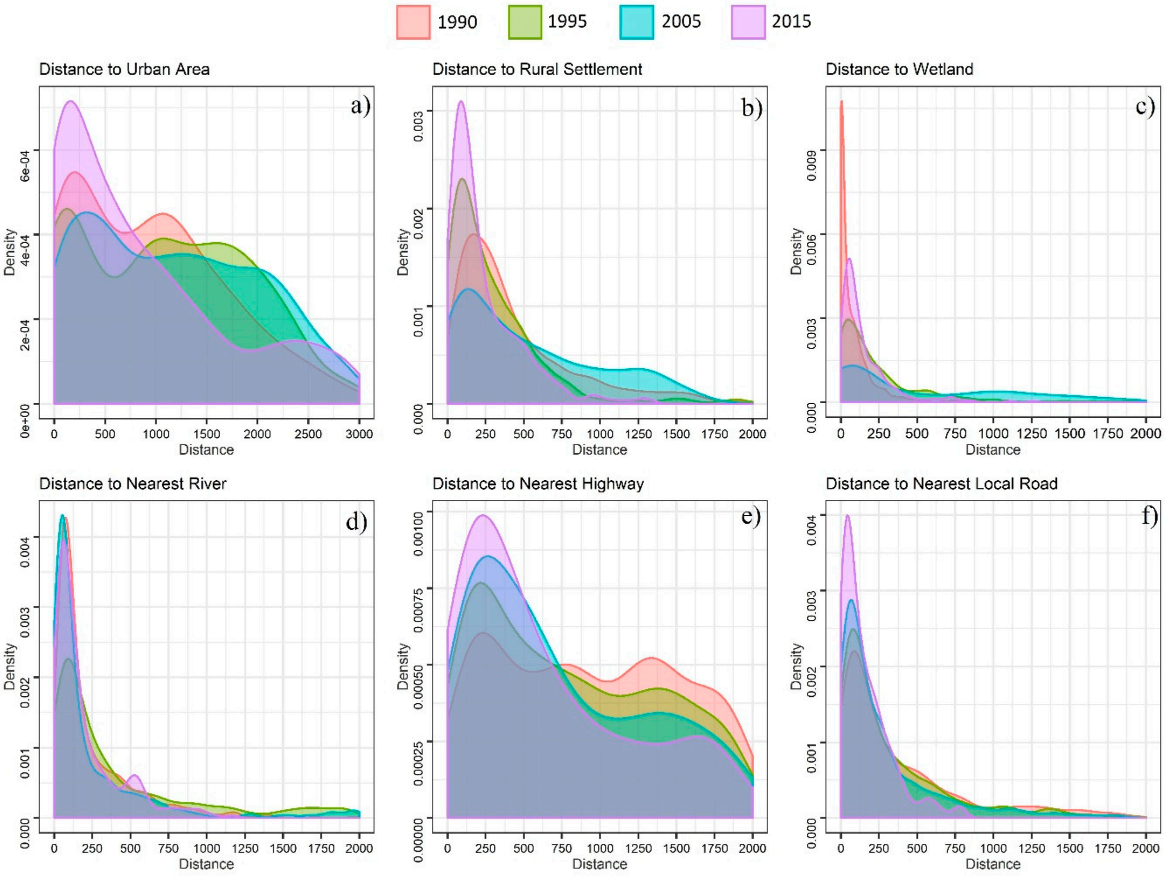

Figure 7. Nearest neighbor distances between brickfields and urban areas (**a**), rural settlements (**b**), wetlands (**c**), rivers (**d**), highways (**e**), and local roads (**f**) plotted as density functions. Distance on the horizontal axes are indicated in meters, and vertical axes represent bandwidth along with the peak of a density where values are concentrated over the interval.

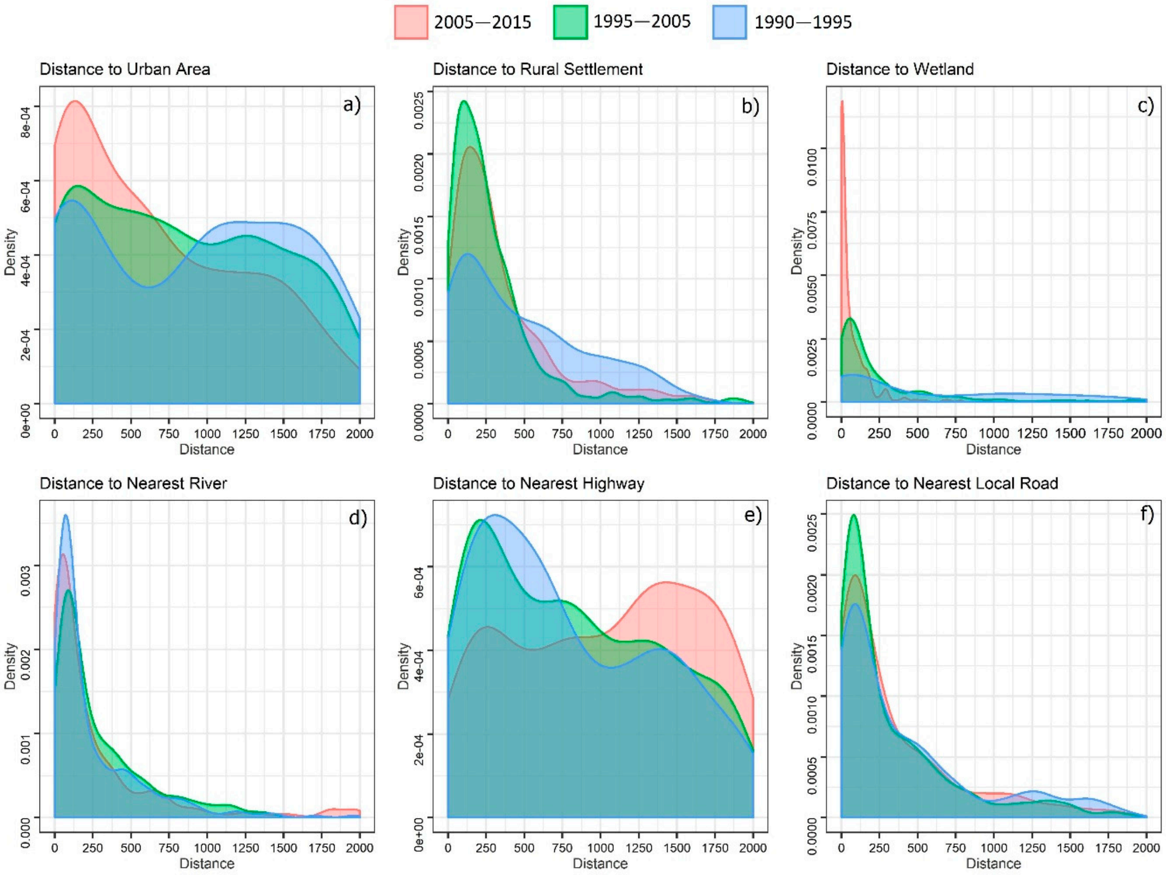

Figure 8. Nearest neighbor distances between newly set up brickfields and urban areas (**a**), rural settlements (**b**), wetlands (**c**), rivers (**d**), highways (**e**) and local roads (**f**), plotted as density functions. Distance on the horizontal axes is indicated in meters, and vertical axes represent bandwidth along with the peak of a density where values are concentrated over the interval.

Due to the high demand of land for urban development, the peri-urban wetlands of Dhaka have become a target for urban development. As a result, residential areas were found to be situated closer to areas where brickfields are concentrated in more recent periods, which can be visually confirmed in Figures 7a and 8a. In fact, 60 brickfields were situated in what was classified as urban area in 2015, which is an unprecedented increase from the 20 urban brickfields in 2005. Similarly, the number of brickfields found in ecologically sensitive wetlands increased from 17 in 1990 to 363 in 2015, which corresponds to 40% of the total brickfields. Overall, the location analysis not only confirms what is suggested by satellite imagery (i.e., brickfields prefer to develop on riverbanks, Figures 7d and 8d) but also provides additional insight that otherwise would be hard to determine from satellite imagery. Specifically, this analysis highlights the shifts in recent data to overlapping residential and brickfield locations, which is of specific concern for human health.

4. Discussion

Brick manufacturing in Bangladesh has become the fastest-growing industrial activity, and the country is globally ranked as the fourth-largest bricks producer [12]. If the current population growth (2.18%) and expansion in construction sectors (growth ranged from 8.1% to 8.9%) continues, then Bangladesh will require four million new houses annually to meet the demand of the growing population [1]. This will allow further growth of brick manufacturing activities, with an estimated growth rate between 2 and 3% over the next decade [1]. However, brick making in Bangladesh is a highly polluting, energy intensive, and carbon-emitting activity, producing 15.67 million tons of CO_2

annually [1], which makes this industry sector one of the largest sources of greenhouse gas emission in the country.

There are approximately 7000 brickfields in Bangladesh [3]. The megacity Dhaka contributes around 13% of the total brickfields in the country. Although there is an urgent need for national policy action to find cleaner and more sustainable brick production, the transformation of existing brick kilns to more environmentally friendly technologies have been stalled due to inadequate information on the brickfields and insufficient policy instruments, and the absence of technical alternatives. Hence, this study aimed to assess the spatial and temporal dynamics of brickfields expansion from 1990 to 2015. The temporal growth of brickfields in this study was documented by using remotely sensed data, whereas spatial characteristics as point processes were analyzed using quadrat analysis, Ripley's K-function and nearest neighbor analysis. Some limitations of the methodology need to be pointed out. To address the modifiable areal unit problem (MAUP), we calculate an optimal cell size to delineate spatial units across the study area instead of using arbitrary cell sizes. However, other methods also exist for dealing with MAUP. Moreover, these simple methods presented in this study do not allow the assessment of underlying causes of this clustering, such as the location of natural resources and infrastructure required by the brick manufacturing industry. As mentioned above, the method presented in this manuscript does not allow the assessment of causal effects of clustering. Therefore, more work needs to be done to understand the driving factors behind brickfield location clustering. To overcome this limitation future work should focus on understanding how socio-economic factors and characteristics of the built and natural environment are associated with brickfield locations.

Our study confirmed that brickfield locations showed signs of significant clustering, and that they had become spatially more concentrated over the years as new brickfield locations were established in the proximity of existing ones. Our analysis highlights that brickfield locations are spatially concentrated in a few areas in Dhaka, and therefore that the strong spatial concentration of polluting kilns causes increased stress to their surrounding areas, including urban areas with significant population. The expansion of brickfields has been attributed to ever-increasing urbanization, and industrialization in the capital city and surrounding areas has highlighted a soaring demand for cheap, affordable construction materials, such as clay-made brick. While the rise of the brick industry has brought more work opportunities in the peri-urban area of Dhaka, it has also become one of the largest contributors to air pollution in the city, with increasing numbers of chronic obstructive pulmonary diseases such as asthma, bronchitis, and other pulmonary complications [2,9]. There is an immediate threat from the pollution from brick kilns is the population near areas with high brickfield density, as the wind spreads dust from the brick-making sites to nearby towns and villages. Due to Dhaka's rapid urbanization and population growth, people living in peri-urban areas (close to brickfields) increased over the last few decades. For example, results from the spatial distribution of brickfields and population growth dynamics in the study area shows approximately a half million people were living within 1 km of brickfields in 1990. Using the fine-scale population data, this figure is estimated at 1.5 million in 2010, and 1.65 million by 2015. This indicates that residential areas are moving towards peri-urban areas, close to brick manufacturing locations due to a shortage of space for urban development in core city areas. The average distance to urban areas from brickfields was approximately 1500 meters in 1990 and 1995. This distance decreased to less than 500 meters in 2015, as the city observed rapid urban growth with expansion into the outskirts. Also, such indigenous brick-making processes are also linked to increasing soil degradation and declining agricultural yields [49].

Dhaka city and its suburban areas have encroached upon the existing rivers, canals, and wetlands, which have been filled in over the past years—mostly for housing expansion amid rapid urbanization. While wetland in the eastern periphery is being severely encroached by landfilling, wetlands in the west of the metropolitan area, along the river Turag, are being encroached by brickfields, with towering chimneys to satisfy the rapid urbanization in the capital. In 2015, 363 brickfields from this study were identified located in wetlands, of which 207 brickfields were in the lowlands along the Turag River (see in Figure 9a), and 97 brickfields were found in the lowlands in Aminbazar. In addition, approximately 550 brickfields were located on riverbanks in the study area while 78% of brickfields are located within a 1km zone of the main river channel. Among these, the highest share of brick industries was located in the Turag basin, followed by Dhaleshwari, Buriganga, and Shitalakshya. Such large-scale encroachment of environmentally sensitive wetlands and river channels in and around the city both by urban and brickfield expansion has made the city almost unlivable. As Dhaka city has a very poor surface drainage system and the low-lying water bodies used to work as flood water retention areas during the monsoon, encroachment by brickfields and housing expansion has had a significant impact on this system (see Figure 9b,c); as a result, the city has been facing flooding during the heavy downfalls in the wet season.

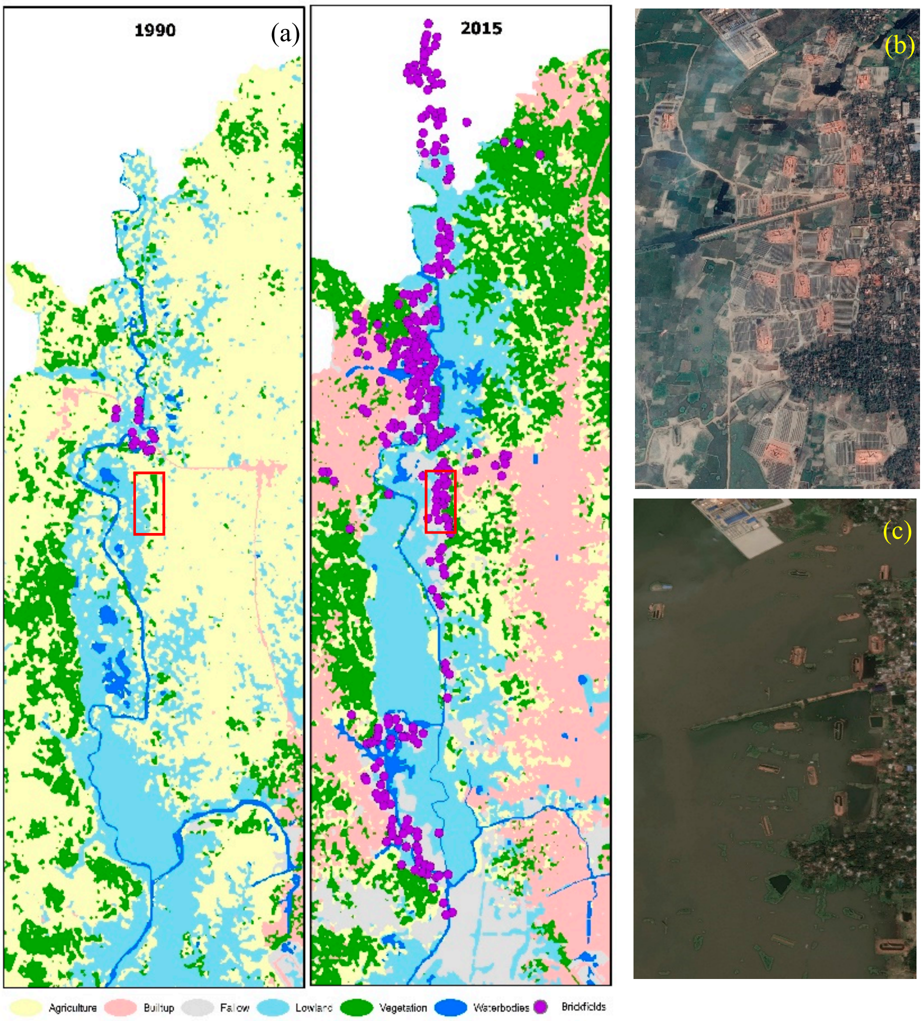

Figure 9. Subset of land cover map in the north-west of greater Dhaka between 1990 and 2015. (**a**) A substantial expansion of brickfield in wetland and across river channel during the study period. (**b**) Cluster of brickfields (location is highlighted in red color on landcover map) in the wetland of Basan in Gazipur, north of Dhaka metropolitan area, shown on a Google Earth image during the dry season (January 20, 2018). (**c**) The same area during the wet season (June to October) inundated by monsoon.

This study highlights the potential increasing threats to ecology, population and the megacity Dhaka from brickfields during the twenty-five-year study period. Even though the Brick Kiln Establishment Control Act, first enacted in 1989, governs the expansion of brickfields, the unprecedented growth of brickfield locations found in this study suggests that the legislation is not being enforced. The unplanned development of Brickfields in Dhaka and across the country seems completely unsustainable. Therefore, immediate measures should be taken to limit traditional brickfield operations in the country in order to reduce their impact on the country's critical ecological resources, agricultural lands, and the population's health and wellbeing.

5. Summary and Conclusions

This study examined spatial patterns of brickfield development surrounding the megacity of Dhaka between 1990 and 2015 using remotely sensed data and GIS. Brickfield locations were identified based on Google Earth and Landsat imagery, and the degree of spatial clustering was assessed using quadrat analysis and Ripley's K-function.

Despite the variation in capturing spatial processes among the employed methods, all brickfields were clustered across the study area, and were strongly concentrated in southeast and northwestern peripheries of Dhaka. Both the brickfield numbers and locations increase significantly over the study period. In 1990, there were only two major brick manufacturing areas located in Konda and Aminbazar in the Southeast and West of the Dhaka metropolitan area. However, in 2015, five major groups with significant brickfield manufacturing activities were identified, located in the east, west, northwest and southeast peripheries of the city. Such large numbers of brickfields in the immediate periphery of the capital city Dhaka were developed by defying the existing environmental legislation. The brickfield location analysis reveals that by 2015, brickfields are located less than 500 m from the nearest urban centers, near rural settlements, in wetlands, along river channels, all of which present severe threats to population health, ecology and urban sustainability of the greater Dhaka.

In addition to describing the methodology for identifying brickfield locations on satellite imagery, the study contributes to the issues associated with brick manufacturing in multiple ways. The brickfield location analysis presented in this study not only confirms what is suggested by satellite imagery (i.e., brickfields typically concentrated on riverbanks), but provides additional insight that otherwise would be hard to interpret based on visual analysis of satellite imagery alone. The study also showed that the Brick Manufacturing and Brick Kiln Establishment Control Act is not being enforced. If this is not changed, the health-related and environmental consequences of uncontrolled brick manufacturing could potentially multiply.

As urbanization increases in the Dhaka region and surroundings, cheap and affordable construction materials are required. However, traditional polluting brick kilns should be transformed into clean, energy-efficient, and environmentally friendly brick-making technology. Instead of developing brick kilns haphazardly in the city periphery, they could be relocated to special zones, ensuring protection for all ecological resources, including air, water, forest, and all land resources. As the government of Bangladesh is committed to decreasing air pollution to zero, environmentally friendly building materials should replace the traditional brick manufacturing processes. Also, public awareness of the harmful effects of soil-burning blocks should be developed. Finally, all measures should be taken to curb the ongoing air, water and land pollution across Bangladesh and in particular, in Dhaka.

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