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Development at the cost of unsustainable degradation of wetlands: Unraveling the dynamics (historic and future) of wetlands in the megacity Dhaka

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ABSTRACT

Despite the recognized role of wetlands in providing ecological benefits for human wellbeing, ~70% of global wetland ecosystems have been destroyed since the 1990s. Further intensive studies revealed that 3.4 million km^2 of natural wetland has declined since 1700. In particular, wetland habitats in the world's megacities have been replaced unsustainably by faster economic, urban, and population growth, and have received less attention in research and policy. However, wetlands degradation in the megacities of developing countries is not quantified and the trends of Land Surface Temperature (LST) are not well understood. Therefore, we are making our first attempt to unravel the historical and future spatiotemporal dynamics of wetlands and the trends of LST in the megacity of Dhaka. The results show that Dhaka lost ~69% of wetlands and LST has increased between 3.44°C and 9.35°C from 1990 to 2020. An environmental Kuznets curve analysis implies that the point has not yet been reached for wetlands when economic development feeds back to the sustainability of the environment. This assumption coincides with our model-based prediction, as respectively ~74% and ~90% of wetlands area of Dhaka city will be decreased by 2050 in Business as Usual (BAU) and development scenarios, whereas, ~66% of wetlands area will be decreased under conservation scenario over the time period of next 30 (2020 to 2050) years. Our findings suggest that it will be incredibly challenging to restore wetlands to their 1990s condition. Efforts to preserve them should be made, as they potentially provide a nature-based alternative for coping with wetland sustainability and climate change.

1. Introduction

Wetlands cover 6.5% of the earth's surface, yet they provide ecosystem services worth equal to Int$47.4 trillion per year [1], and ~12% of global carbon is stored in wetland areas (International Panel on Climate Change [IPCC] [2]. Wetlands are labeled as a "kidney" due to their function in hydrological circulation [3] and a "biological supermarket" for providing food, fodder, and water to humans [4,5,6]. In general, the Ramsar Convention on Wetlands (1971) defines wetlands as "areas of marsh, fen, peatland or water, whether natural or artificial, permanent or temporary, with water that is static or flowing, fresh, brackish or salt, including areas of marine water the depth of which at low tide does not exceed six meters" [7]. This complex and active wetlands habitat includes rivers, streams, marshes, ponds, rice fields, and coastal areas.

Approximately 3.4 million km^2 of global natural wetland has declined since 1700 [5] .~70% of wetlands have disappeared since 1900 AD, and the rate of wetlands disappearing become three-time higher in the 20th century [1] due to factors such as population growth, increased economic development, land conversion, pollution, overharvesting and overexploitation [8,9], urbanization [10], and agricultural [11], and industrial development [12,13]. The destruction of wetlands is more prominent in densely populated countries (e.g., China) [14], rapidly developing countries (e.g., Bangladesh and India) [14;15], and countries with shortages of water (e.g., Australia) [16], and countries with strong agro-industrial systems (e.g., the USA) [17]. Among the drivers of wetlands destruction, urbanization is one of the most prominent [18], as it transforms wetlands areas into human settlements [19]. Wetlands

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degradation (a negative trend in wetland conditions) is comparatively higher in urban areas due to the rapid increase in population since the industrial revolution took place across the world. Though the rate of urbanization was initially higher in developed countries, it is now also increasing in developing countries [20,21] such as Bangladesh [22]. Dhaka is Bangladesh's capital and one of the world's fastest-growing megacities [14]. People from all over the country migrate to this city to earn a livelihood [23], mitigate poverty [24], and seek a better life, and all these factors are rapidly increasing the urbanization of the city. As a result of this rapid urbanization, Dhaka's population increased from 3 million to 18 million between 1980 and 2018. In order to create space for such a dense population (41,000 per square kilometer), which constitutes 10% of the total population of the country [14], wetland ecosystems have been converted into human settlements in Dhaka [25]. The degradation of the wetland ecosystems has not only destroyed several ecosystem services that provided food and water but also released a substantial amount of carbon that was stored in the wetlands. The National Adaptation Programs of Action (NAPA) have emphasized a climate adaptation and mitigation plan for Dhaka. However, unless the wetlands are restored, it is unlikely that this plan will be successful. Furthermore, wetlands could address social, economic, and environmental challenges as a nature-based solution, which is a new umbrella concept for addressing sustainability challenges such as climate change and pollution [26]. Despite recognizing the wetland ecosystem's benefits and contribution to climate change adaptation and mitigation [27], previous studies did not address the time-series nature of the changing wetlands, trends of LST in Dhaka, and implications for wetlands conservation are still unclear.

Despite the significance of wetlands in megacities [28,29,30], previous studies have mostly focused on built-up areas [e.g.,31,32], plant cover or green space change [e.g.,33,34,35], and urban heat islands [e.g., 36,37,38,39]. Though several research focused on the megacity of Dhaka, their primary emphasis was on urban expansion mapping [40, 41,42,43,44,45,46]; a few studies also focused on wetland [47,48,49] area mapping without investigating historical and exploring future dynamics of wetlands linking surface temperature in Dhaka city. To the best of our knowledge, this research is the first to unravel the dynamics (historical and future) of wetlands and analyze the temporal and spatial dynamics of Land Surface Temperature (LST) in the megacity of Dhaka.

Therefore, we have used remote sensing to unravel the spatiotemporal dynamics of the wetlands and LST in Dhaka. The overall objective of this study has been achieved by (1) analyzing the temporal dynamics of changes in wetlands between 1990 and 2015; (2) assessing the spatial heterogeneity of wetland dynamics across the city between 1990 and 2015; (3) analyzing the temporal and spatial dynamics of LST between 1990 and 2019; (4) exploring future temporal and spatial dynamics of wetlands between 2020 and 2050; and (5) providing the policy implications of wetland dynamics in relation to conservation and wetland management strategies.

Section 2 details the study's methodology in terms of data collection, pre-processing, image classification, detecting changes, and estimating Land Surface Temperature (LST) (Section 2.6). Section 3 discusses the trends in LULC since 1990 (Section 3.1), the distribution and seasonality of wetlands (Section 3.2), LST (Section 3.3), and future dynamics of wetlands (Section 3.4), then discusses and concludes the research findings of this study.

2. Materials and methods

2.1. Study area

Our study area (SI Fig. 2) is the city of Dhaka, which is the 11th fastest-growing megacity in the world. Dhaka is situated at 23°42′ N, 90°23′ E, close to the center of Bangladesh. The city, which is the capital of the country, is expanding faster than any other city in Asia (4.24% per year) due to higher economic growth [50].

The population of Dhaka increased from 3 million in 1980 to 18 million in 2018. Due to the very high growth rate of the population, it is one of the most densely populated cities in the world [51]. Its high economic growth and position as the center of Bangladeshi political and economic activity have attracted millions of people to seek work and make their homes in this congested city. Dhaka's wetlands play a significant role; they act as a rain and stormwater reservoir and serve as a natural drainage system for the city. They carry water to rivers or canals, capture heat emitted by different land objects, provide a rich habitat for biodiversity, store greenhouse gases, and protect residents from excessive heat production. However, due to drastic urban development, the total wetlands area in Dhaka is decreasing [52,53,54]

Unplanned urbanization in Dhaka has destroyed natural areas, including most of the wetlands in the city [55]. The development of the ready-made garment industry within and around Dhaka is another prime factor that has accelerated wetlands degradation. In general, the city's rapid growth and development have caused encroachment, degradation, and dysfunction in the wetlands area. In this paper, according to the IPCC report [56], the definition of wetlands degradation was limited to a negative trend in wetland condition (area/size of the land) due to methodological limitations using remote sensing techniques and the aim of the study. It is evident that cropland in Dhaka decreased by 7,614 ha, green space by 2,336 ha, and water bodies by about 864 ha between 1960 and 2005 [45,46]. The city's population is likely to double to more than 35 million by 2035 [57,58]. In addition to this population growth, air and water pollution, urbanization, and climate change have made Dhaka's social-ecological systems highly vulnerable. In order to cope with climate change and other environmental drivers, restoring the wetlands is an essential strategy for fighting climate change and enabling cities to thrive [59,60,61].

2.2. Methods

Landsat and Sentinel -2 images were downloaded in order to identify the LULC change-related expansion of Dhaka over time, (SI Table 1). Atmospherically corrected surface reflectance bands of Landsat images were obtained from the United States Geological Survey (USGS) website. Temporal data for the years 1990, 1995, 2000, 2004, 2010, and 2015 – each dataset is taken from the month of January except for 2004 – were collected. We used the December 2004 image; a suitable image was not available for January 2005. Winter months with similar phenological stages were chosen for the study in order to avoid cloud disturbance in optical imagery. Furthermore, Sentinel-2 imagery with a higher spatial resolution (10 m) was chosen in order to delineate the smaller wetlands more accurately. As Sentinel-2 does not have legacy data (it was only launched in 2015), we only used two scenes. Sentinel-2 images for the months of November 2017 and March 2018 were downloaded to understand the seasonal variation of the wetlands. November is the month just after monsoon offset (temporary/seasonal wetland), and March is considered to be the month before monsoon onset (permanent wetland). As such, these images depict (SI Fig. 1) the difference between the maximum and minimum dimensions of the wetlands in Dhaka. After the Sentinel -2 images were downloaded, they were atmospherically corrected using *sen2cor* in the Python environment [62]. We consider the minimum mapping unit as 30m^2. The nature and topography of the floodplain wetland of Dhaka covers small to relatively large wetlands. They could be connected or independent.

Multiband/layer stacking was performed in QGIS. The Dhaka district boundary (Shapefile) was chosen as an area of interest (AOI) to clip the multi-band imagery, and a "no data" value was set at "-9999". All the images were then set as several False Color Composites, appropriate for identifying different features in ArcGIS. The training data were generated as a polygon for five predefined "Classes" – wetland, agricultural land/grassland, landfill (waste dumping and earth filling), built-up, and tree vegetation – in order to measure the changes in different classes over time. For each class, 65 polygon training data were generated.

Table 1
Summary of Land Use Land Cover Classification Statistics between 1990 and 2020

Land type	1990		1995		2000		2004		2010		2015		2020	
	Area (ha)	%	Area (ha)	%	Area (ha)	%	Area (ha)	%	Area (ha)	%	Area (ha)	%	Area (ha)	%
Wetland	3448	11.28	3145	10.28	2947	9.64	2348	7.68	1972	6.45	1838	6.01	1068	3.50
Grassland	23193	75.88	20891	68.35	19935	65.22	19683	64.39	18541	60.66	14987	49.03	8699	28.46
Built-up	2448	8	4666	15.26	5408	17.69	6647	21.74	7091	23.2	11695	38.26	14327	46.87
Tree	1028	3.36	1253	4.09	1591	5.2	1313	4.29	1060	3.46	1126	3.68	5636	18.44
Landfill	447	1.46	609	1.99	683	2.23	573	1.87	1900	6.21	918	3.00	834	2.73

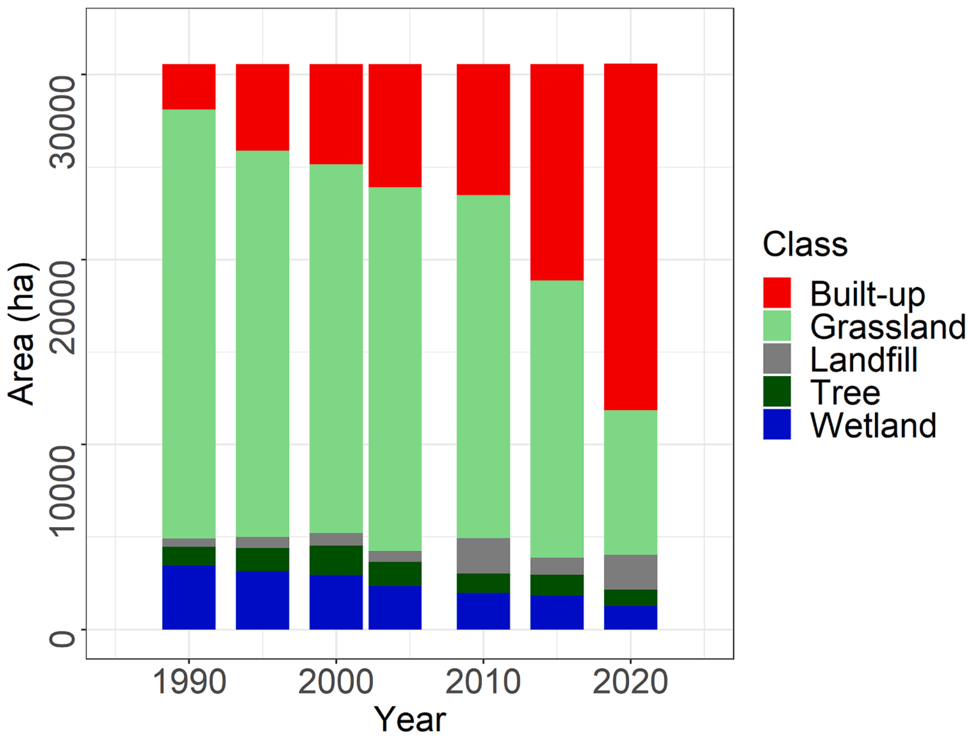

Fig. 1. Distribution of different LULC classes from 1990 to 2015, showing the proportion of LULC in Dhaka.

We used the “random forest” algorithm in R to conduct the supervised image classifications. Using training data and satellite images, a random forest model was generated. The model was implemented throughout the whole scene. Finally, supervised classified output was obtained. “Random forest” is a bagging algorithm with a preformation ensemble learning technique. It can reduce the overfitting problem of decision trees and reduce variance, thus improving classification accuracy [63]. It is a widely used image classification algorithm.

Accuracy assessment of any classification is very important for ascertaining how well a classification worked and how to interpret the classification’s usefulness. In this study, overall classification accuracy was measured using equation (i),

$$\text{Overall Accuracy} = \frac{\text{Total number of correctly classified pixels}}{\text{Total number of reference pixels}} \quad \text{(i)}$$

SI Table 2 presents the accuracy assessment of the image classification, including overall accuracy, overall error, and overall kappa for both Landsat and Sentinel. Overall accuracy is often used, as it is the simplest and one of the most popular accuracy measures in remote sensing studies [64]. Overall, our study’s accuracy assessment shows 97-99% accuracy for both Landsat and Sentinel images.

Change detection analysis was carried out using the cross-classification and tabulation tools available in QGIS, which is an open-source Geographic Information System. To compare the changes over the years, Landsat imagery for the period 1990-2015 was analyzed. In addition, Sentinel-2 imagery was acquired and analyzed in order to compare the seasonal variation of the wetlands. The application of these techniques helps to investigate major changes in the study area. In this case, we used cross-tabulation analysis on a pixel-by-pixel basis to assess the quantity of conversions from a particular land cover class to other land cover categories and their corresponding area over the period evaluated.

Land surface temperature (LST) is the relative temperature emitted by the earth’s surface; it is measured from the upper atmosphere using a remote sensor. The Thermal Infrared Sensor (TIRS) measures LST in two thermal bands (10.6-12.51 micrometer wavelength) with a technology that applies quantum physics to detect heat. The technique has been widely used for water and wetland monitoring [65]. LST is the combination of all temperatures emitted by bare soil, water, vegetation, and other physical infrastructure [18,66]. It can be an essential tool for measuring differences in an urban area’s observed ambient air or the temperature differences released by different components of the earth’s surface. In addition, LST data can be utilized to detect individual objects/features’ temperature.

To estimate the LST, a customized R script was used following the equation (ii, iii, and iv) below.

$$\text{Radiance}(L) = M_L * Q_{cal} + A_L \quad \text{(ii)}$$

Where, M_L = Band-specific multiplicative rescaling factor from the metadata; Q_{cal} = Corresponds to band 10; A_L = Band-specific additive rescaling factor from the metadata

$$\text{Then calculating TOA} = 0.0003342 * \text{''Band10''} + 0.1 \quad \text{(iii)}$$

TOA to Brightness Temperature (BT) conversion

$$BT = (K_2/(\ln(K_1/L) + 1)) - 273.15 \quad \text{(iv)}$$

Where, K_1 = Band-specific thermal conversion constant from the metadata; K_2 = Band-specific thermal conversion constant from the metadata

Further raster-based linear regression was carried out to ascertain the trend (1990-2020) of LST. We calculated the adjusted R^2, trends, and levels of significance at the pixel level. In addition, we used correlation analysis to investigate the relationships between LST and Land use change (NDVI). Finally, maps were prepared. Findings from the LST analysis were compared against findings published in previous research [67,68]. Though LST (our analysis) for landfills and built-up areas and average air temperature data from the weather station in Dhaka were compared and found similar trends for 2010 and 2020 but not previous trends from 1990 to 2010 possibly due to the lower degradation of wetlands and other vegetation which help to balance urban environment as a nature-based solution [41,69]. In addition, the meteorological station data is useful in providing information on overall (aggregated and non-spatial) air temperature, instead of LTS according to land use classes such as wetlands, trees, and grassland. However, it has been acknowledged the linkages between air temperature and LTS, which is influenced mainly by air temperature together with other factors such as elevation, slope, and other socio-environmental factors [70].

Both spatial and temporal LULC changes were modeled using a CA-Markov model. This model predicted characteristics and trends of LULC change over time by combining cellular automata with the Markov chain. For the land change modeler, assessing gains and losses, net shifts, and simulating LULC changes between the various LULC classes is essential [71]. It encompassed both static and dynamic performance measures for predicting land cover changes [72,73]. The dependent and independent covariates were used to predict the LULC change. This study considered dependent variables such as elevation (DEM), slope, aspect, and distance from the road network. In this study, from the ASTER-DEM, we calculated elevation, slope, and aspect using ArcMap. The slope and aspect data reveal that the study area comprises a more or less flat surface. Distances to main roads were designed with vector layers from the open street map (OSM). The distance from the aquaculture area map specified excessive aquaculture growth in the main area and a smaller amount of growth in the farthest area. Distance from major roads, slope, and elevations contribute mainly to the LULC change and impede agriculture development in the study site. All these independent and dependent variables were used as input factors to develop the transition potential matrix.

To validate the results simulated by CA-Markov model, the actual (observed) map of 2020 was compared (e.g., visual, various kappa statistics) with the simulated map of 2020 (Fig. 5). The evaluation of simulated and observed maps showed that the value of kappa accuracy was 0.89%. Therefore, according to the results, the CA-Markov model was able to predict urban land cover change for the study region with high accuracy. The land use changes were validated by validating a stratified random sample of 100 points. Respectively 70 and 30 points were randomly chosen from each classified image with ArcGIS 10.5 software. Later, the random points and reference images were taken in QGIS software, and accuracy was estimated with the class accuracy plugin. For reference images, we have used the Landsat images that were used for classification purposes and maintained the exact time frame to better estimate our accuracy. After that, an accuracy sheet was created with overall kappa statistics and overall accuracy.

Based on LULC maps of 2015 and 2020, the land change modeller was used to generate the predicted LULC map. To simulate the 2025 and 2050 predictions, the transition areas and probability matrices were developed using IDRISI software [74].

3. Results

3.1. Trends in LULC since 1990

The spatiotemporal distribution of different LULC is presented in Fig. 1. From 1990 to 2020, including our five investigated land-use types, changed Dhaka. To monitor the study area's biophysical changes, Dhaka has been classified into five different classes: waterbody/wetlands, built-up, agricultural land or grassland, landfill, and tree vegetation.

As seen in Fig. 1, the land use types that increased the most were built-up land and landfill, which increased by ~9,250 ha (30.26% of the total area) and ~1,500 ha (4.90% of the total area), respectively, during the period under study. Urbanization was confined to the southern part of the city in the early 1990s. The post-1990s distribution of different land uses and land covers show that, in contrast, urbanization expanded rapidly between 1995 and 2015, and became dominant over other land-use types. Built-up land expanded in every direction over the 25-year period (Fig. 1 and Table 1). Fig. 1 indicates that grassland was previously the dominant land use type and was mostly converted into built-up areas. In the 1990s and 2000s, built-up areas expanded from 2,448 ha to 4,666 ha in the city's northern part. By 2004, built-up areas rose to 6,647 ha, expanding into the western part of the city. The most recent estimate of the total of built-up areas was 11,695 ha in 2015.

In addition to built-up areas, landfill areas also increased significantly after 2004. SI Fig. 3 and 4 shows the cumulative landfill area from 1990 to 2015. This highlights those landfill areas expanded at a higher rate between 2005 and 2010 than between 1990 and 2004.

In contrast to the expansion of built-up and landfill areas, grassland and wetlands decreased in order to make space for urban areas. In the 1990s, wetlands were one of the most dominant land cover types in Dhaka, especially in the north-eastern and north-western parts of the city. The total loss of wetlands between 1990 and 2015 was 1,610 ha; it was initially converted to landfill then to built-up land (Fig. 1 and Table 1). The total area covered by wetlands was, on average, 3,448 ha in the 1990s. It decreased to 2,947 ha, 2,348 ha, 1,972 ha, and 1,838 ha, respectively, by 2000, 2004, 2010, and 2015.

3.2. Distribution and changes in wetlands in comparison to other LULC in Dhaka

The distribution and changes in wetlands are presented in SI Fig. 3 and 4 and Table 1. The wetlands in Dhaka clearly degraded from 11.28% in 1990 to 6.01% in 2015 due to the conversion of wetlands to built-up areas. Wetlands distribution was mainly in the range of 10-11% before the 2000s but decreased to 6.01% between 2000 and 2015. The percentage of decrease in wetland areas was 8.78%, 6.29%, 20.32%, 16.01%, and 6.79% respectively in the periods of 1990-1995, 1995-2000, 2000-2004, 2004-2010, and 2010-2015. The fastest wetlands decrease occurred during the 2000-2004 and 2004-2010 periods.

There was a significant increase in built-up areas during the periods of 1990-1995 and 2010-2015. Built-up areas increased from 8% in 1990 to 38% in 2015. ~12% of this increase occurred between 1990 and 2000 and ~20% between 2004 and 2015. From 1990 to 2015, the total built-up area increased by 30.26%.

During the 2000-2010 period, most wetlands areas were transformed into landfill areas. Later, these landfill areas were converted into grassland and then into built-up areas. Though some of these areas reverted to wetlands in 2015, this resulted from digging up the land to fill other wetlands using earth materials (e.g., mud) from the newly dug wetlands. In 1990, the wetland areas totaled 3,448 ha and the built-up areas totaled 2,448 ha; by 2015, the wetland areas totaled 1,838 ha and the built-up areas totaled 11,695 ha. In November 2017, the area under wetlands in Dhaka was about 4,124 ha. This study has shown that the total area of wetlands in March 2018 was 1,506 ha, which is only one-third of the maximum seasonal wetlands area. This means that the difference between seasonal and permanent wetlands is 2,618 ha, which is a 174% variation. SI Table 3 and SI Fig. 1 show that from November 2017 to March 2018, the wetlands reduced by 2,618 ha, a reduction of 63.48%.

3.3. Estimation of Land Surface Temperature (LST) over the years (1990-2020)

The spatial pattern of LST in Dhaka and the LST trends for different LULC are presented in Fig. 2, 6, and SI Fig. 6. In 1990, mean LST range figures were generally in the range of 16.93-19.43°C, 17.03-19.65°C, 17.11-20.01°C, 18.01-23.21°C, 18.83-25.79°C, 19.59-26.32°C, and 20.37-28.78°C, respectively, in 1991, 1995, 2000, 2004, 2010, 2015 and 2020. The overall LST in Dhaka increased between the 1990s and 2020. In 1990, the lowest average LST estimated in Dhaka was 16°C, and the highest was 19°C. In 2000, the lowest and highest LSTs were 17°C and 20°C. More than 28 years after the estimated 1990 temperatures, in January 2020, the lowest LST had increased to 20°C and the highest to 29°C.

SI Fig. 6 shows the overall LST trends for different LULC types between 1990 and 2020. LST in wetlands areas has increased less than LST in other LULC types. However, many wetlands were transformed into landfills, which were later converted into built-up areas. Our analysis shows that the LST in landfills and built-up areas increased from 19.43 °C to 28.78 °C and 18.85 °C to 26.66 °C, respectively. In addition, the spatial analysis of LST in Dhaka (Fig. 3 and 6) also shows that the highest LST increase was in the areas where wetlands area converted to landfills. The differences in LSTs between 1990 and 2020 for wetland, tree, grassland, built-up, and landfill areas were 3.44 °C, 4.58 °C, 7.13 °C, 7.81 °C and 9.35 °C, respectively. Regression analysis (Fig. 3) reveals that the rate of LST changes (~ 0.5 °C/yr) was higher in the areas where wetlands were converted to built-up areas between 1990 and 2020. LST in built-up areas, where deforestation has converted grassland and trees into built-up areas, increased at a rate of (~0.2°C/yr) during the period 1990-2020.

A strong connection (Fig.4) was found when comparing the relative wetland area to GDP. It appears that declining wetland area loss has been tightly connected with economic expansion, yet there are no obvious investments being made to restore the depleted wetland.

3.4. Exploring future dynamics of wetlands

After validating the observed and simulated maps, CA-Markov model was run considering three scenarios to explore the future dynamics of wetlands in Dhaka city in 2050 (Fig. 7). In the Business as Usual (BAU) scenario, we explored the future dynamics of wetlands in Dhaka city by considering the current transition matrix of 2015-2020. This BAU scenario predicted that if Dhaka city's land-use trends (last 5 years) remain persistent then after 30 years, the built-up areas of Dhaka city will increase by 1,722 ha (9.20%), which will significantly affect other land cover types (Fig. 7). This is mainly because, at present, there is very little space for the expansion of urban area in Dhaka city. As a result, a key component of the ecosystem, ~74% of wetlands will be decreased over the time period of the next 30 years.

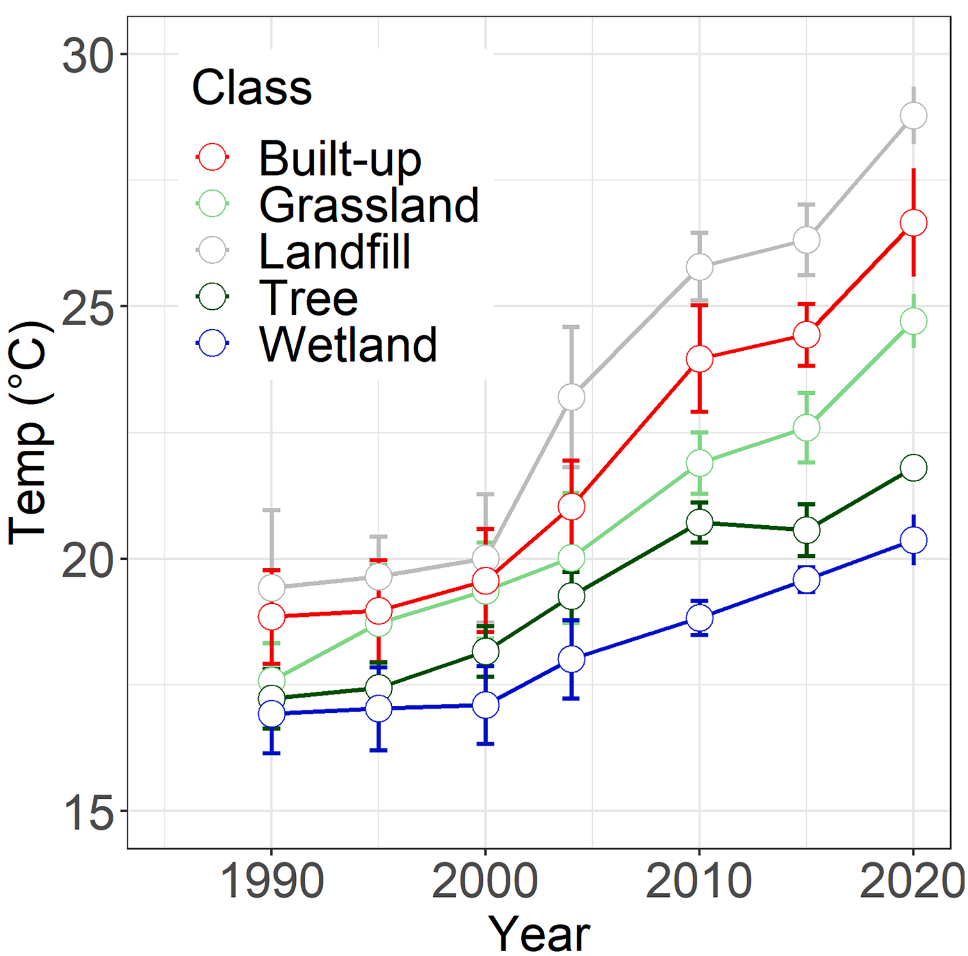

Fig. 2. The temperature of different land use and land cover in Dhaka shows the increasing land surface temperature over the period.

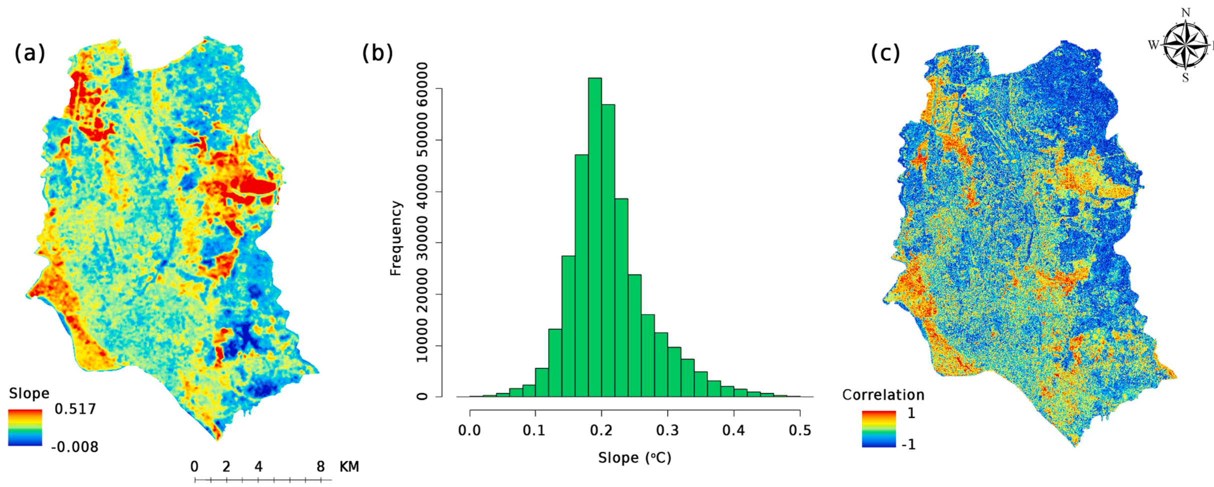

Fig. 3. a) Linear regression analysis shows the trends in the land surface temperature (LST) of Dhaka from 1990 to 2020. b) Frequency of slope value. c) The result of the correlation analysis between LST over the period from 1990 to 2020.

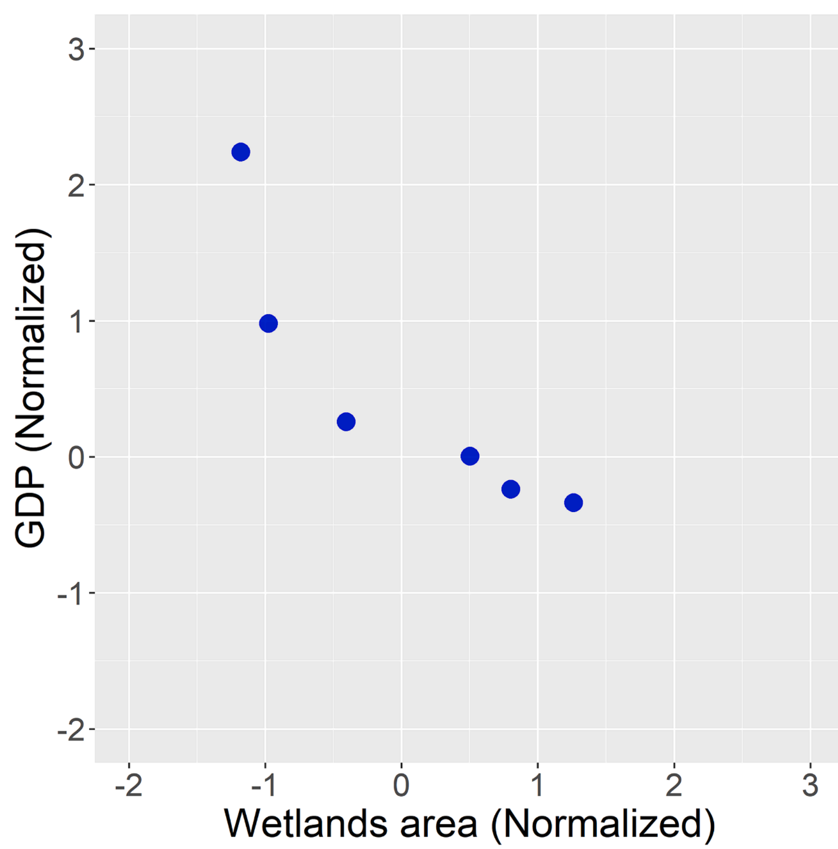

Fig. 4. Relative wetlands area versus GDP, where wetlands area z-scores are interpreted as GDP increase (similar to an environmental Kuznets curve). The strong association indicates that deteriorating wetlands area loss has been strongly coupled with economic growth, but no investment is visible for restoring the depleted wetland.

In the second scenario, we considered the conservation approaches by limiting the rate of expansion of built-up areas to protect the natural ecosystems such as wetlands, tree cover, and grasslands from further deterioration. This scenario hypothesized that if the government can slow down urban growth by imposing strict laws and policies to protect wetlands (no further loss of wetlands area after 2020), then, according to our model, built-up areas could grow by only 4.09% wetlands will be decreasing by 66% over the period of 30 years, which is a very small percentage of loss to compared to development scenario.

We run our model based on the development scenarios, in which, hypothesized development as a priority over environmental concern (e.g., conserving wetlands) by building more infrastructures to boost the economy, which will ultimately be favorable to aggressive urban growth. In such a case, the projected urban growth will be 20% from 2020 to 2050, and therefore, there will be very little space for other types of land use types such as wetlands. This development scenario predicted that, almost 79% area of Dhaka city will be converted into built-up areas whereas ~90% of wetlands area will be lost by 2050.

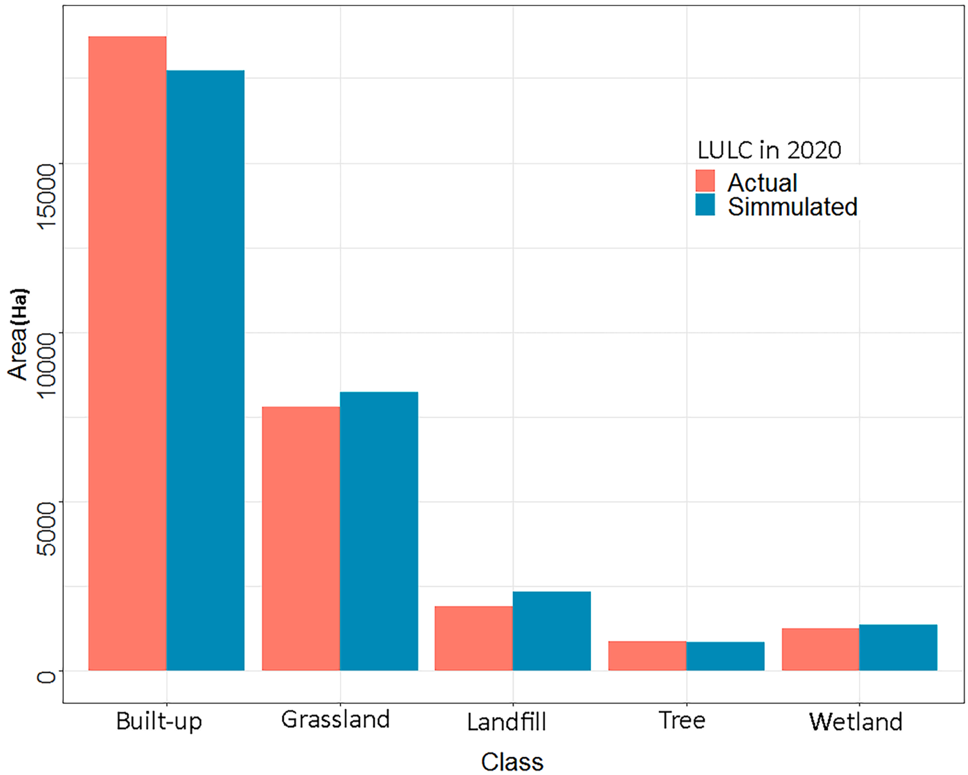

Fig. 5. Bar graph showing the strong agreement between actual and simulated area of land use and land cover in Dhaka city.

4. Discussion

There were three significant land-use changes, progressing as follows: built-up land expansion, grassland decrease, and wetlands decrease. First came the expansion of built-up land (9,247 ha, also called urbanization and industrialization in Dhaka). The most obvious conversion occurred in the south of the city. The second phase was deforestation, with a total of 8,206 ha of grassland transformed into other land-use types. The rate of built-up land expansion was highest between 2010 and 2015, and the loss of grassland was also highest during that period.

4.1. Legacy of wetland loss

The wetlands area totaled 3,448 ha (11.28%) in 1990, but over time it decreased to 1,838 ha (6.01%) and had become one of the minor LULC classes by 2015. While wetlands areas were decreasing, built-up areas were increasing; in 1990, the total built-up area was 2,448 ha (8%), but by 2015 it had reached 11,695 ha (38.26%). These changes may have influenced the increasing LST in Dhaka. In 1990, the LST ranged from 10-24°C; it had reached 20-30.9°C by 2020.

Initially, the urbanization process started with the conversion of fallow land and land near developed areas. However, in later stages, due to the increasing pressure caused by the expanding population, urbanization was conducted in scattered and unplanned ways that involved the destruction of other land types in Dhaka. In order to create space for growing urbanization, wetlands areas were converted to other land use types, mainly built-up areas.

4.2. Changes of Land Surface Temperature in Dhaka City

The LST of landfill areas in Dhaka increased by 20.37°C to 28.78°C between 1990 and 2020. The analysis in this study shows that the warmest surface in the city is the sand-filled wetland area. While the LST in wetlands increased by 3.44°C between 1990 and 2020, the LST in the landfill and built-up areas that had been transformed from wetlands increased by 8.51°C. The positive association between LST and wetlands, as well as the higher rate of LST change in the built-up areas, converted from wetlands, also highlight (SI Fig. 6) the fact that the conversion of wetlands into built-up areas may have resulted in higher LST. LST is one of the most critical parameters in the energy and water balance, and its increase may have consequences for human life at local and global scales [75]. Even a small increase in LST may create massive disruption to urban life [76,36,37,40]. Therefore, this increase in LST is alarming and may have drastic consequences for humans. Conservation of the remaining wetlands, greenery, and open space is necessary to prevent further increases in the surface temperature.

4.3. Urbanaization at the cost of unsustainable degradation of wetlands

The unplanned destruction of the wetlands has had an extremely negative impact on the health of the city; it has also increased the risk to human life. As such, proper plans should be made for the use of the wetlands so that they can help sustain urban life [77]. In particular, the 9°C-plus increase in LST in the sand-filled wetlands shows that the destruction of the wetlands, combined with climate change and pollution, has already accelerated the temperature increase in Dhaka. Considering the future projection of climate change [78] and wetlands degradation in Dhaka, it is not erroneous to assume that this may create an urban heat island that could negatively hamper the social and economic development of Dhaka.

This study shows (Fig. 1, 6 and 8) that the Dhaka wetlands were transformed into landfill areas, which were then converted to settlement areas. These filled wetlands have been used in the construction of large-scale residential areas (e.g., Basundhara, Purbachal) and industrial areas (used for garment factories). Despite the government's emphasis on the protection of wetland areas, recent mega-projects such as Metrorail in Dhaka have used types of the landfill that were previously wetlands. It is not the intention to limit the implementation of development plans. However, the degradation of wetlands could be avoided when

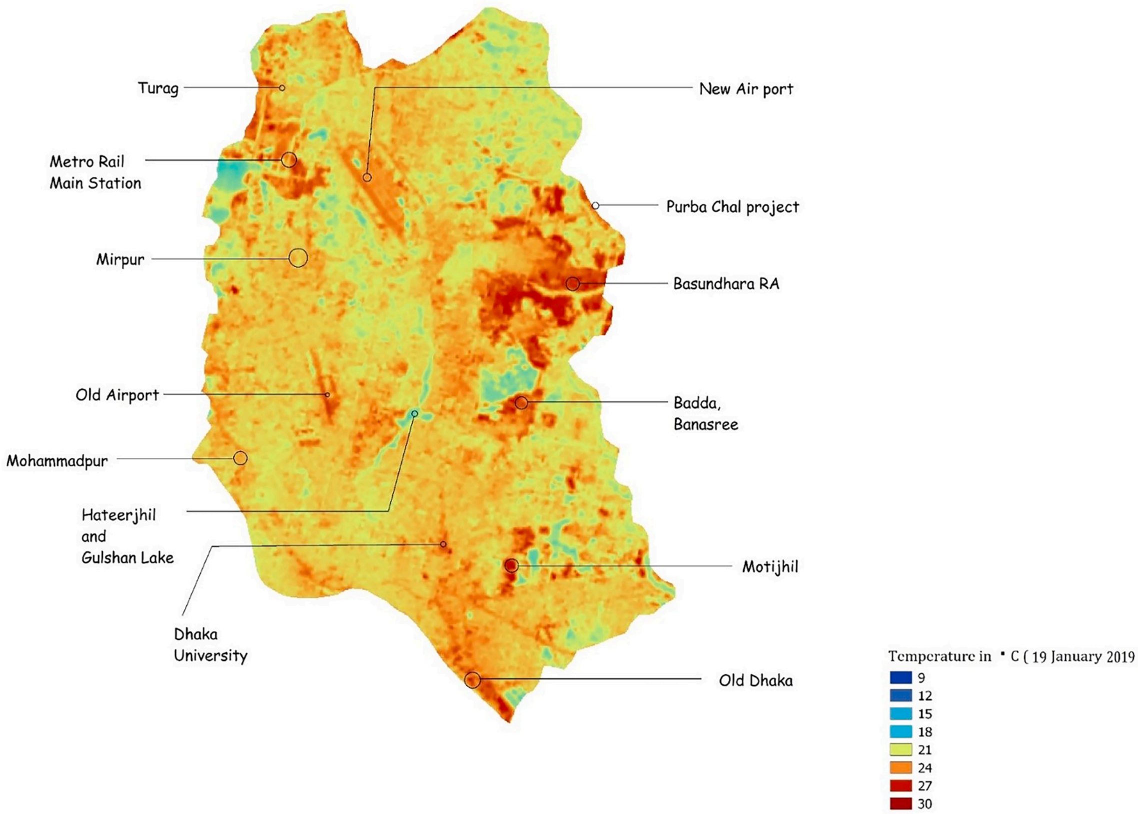

Fig. 6. Land Surface Temperature map (January 19th, 2019) of Dhaka, showing hotspot areas, many of which are former wetlands depleted by landfills, including major infrastructure projects (Metrorail) and residential areas (Basundhara, Badda, Purbachal).

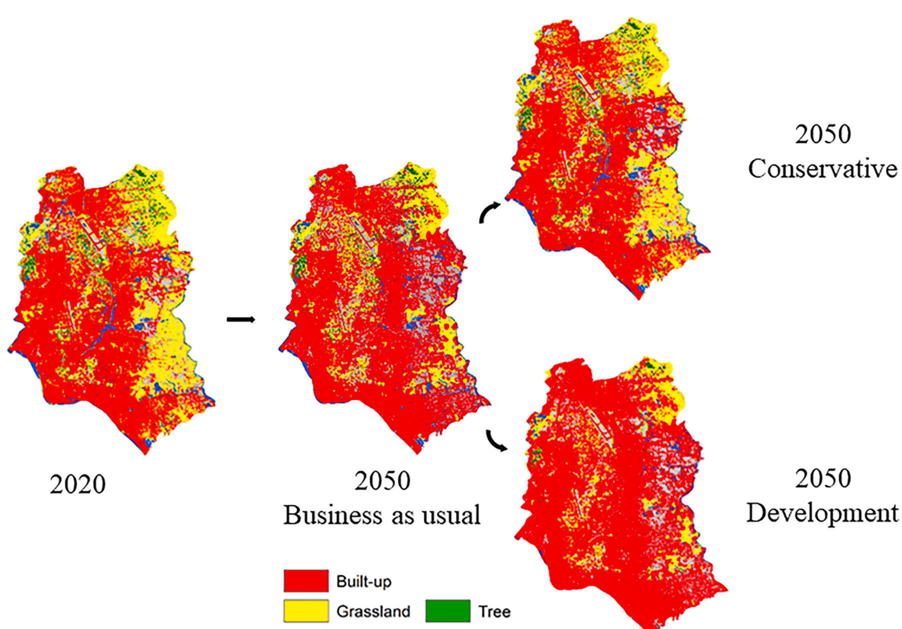

Fig. 7. Showing the base map (2020) and simulated (2050) land use and land cover map of Dhaka city considering conservative and development scenarios.

developing major infrastructural projects.

But is it possible to restore the wetlands? An environmental Kuznets curve (Fig. 4) shows the association between Gross Domestic Product (GDP) and wetlands. This simple bivariate plot sets out the relationships between economy and environment over the years [79,27]. The curve implies that the wetlands have degraded as the economy of Dhaka has grown. It is evident from many countries (both middle and high-income) that environmental degradation reduces when higher GDP is used to invest in environmental restoration, such as the processes involved in wetland restoration and conservation. However, in Dhaka, it could be

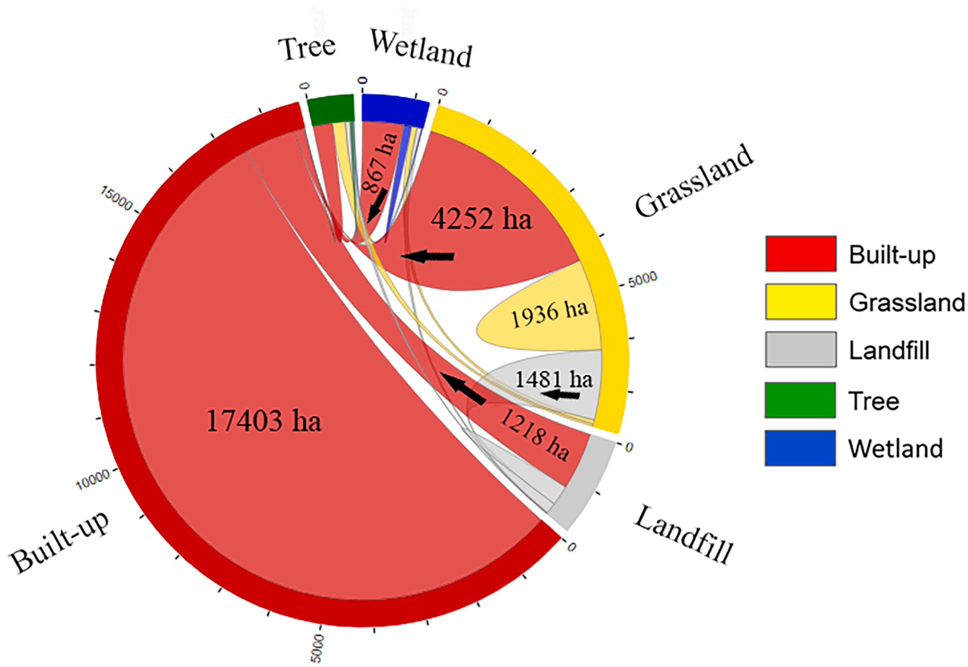

Fig. 8. The simulated land use land cover change between 2020 and 2050 development scenario. Showing the potential wetland area loss due to urbanization.

highly challenging to return to the turning point for wetlands restoration. Similar findings were predicted from model-based simulation for land-use change by 2050. Wetland restoration will be highly challenging, as the deterioration of wetlands areas was predicted to continue both in BAU and development scenarios. In development scenarios, around 90% of the total area will be converted to built-up areas by 2050. In general, ~74% and ~66% of wetlands area will be lost by 2050 due to the fastest-growing urban area in Dhaka city. The chord diagram (Fig. 8) shows the overall land conversion simulation from 2020 to 2050 based on the development scenario run in the CA-Markov model. The model demonstrated that 867 ha of wetlands area will be converted into built-up areas by 2050.

Long ago, a "no net loss" target to prevent the conversion of wetlands was adopted by many countries, including China [80] and the USA [81]. However, in Bangladesh, no such initiatives have been taken, though the country is a Ramsar signatory and obligated to mitigate wetland loss. Realistic strategies are required to develop in order to restore and conserve the wetlands. For example, Bangladesh has set a target (National Target 11) to bring 3% of wetlands under the umbrella of protected and ecologically critical areas and to develop and implement a restoration plan for degraded wetlands by 2021 [82]. However, as 69% of Dhaka wetlands have been degraded within the last 30 years, and considering the city's future growth, it appears unrealistic to include only 3% of wetlands within a protected and ecologically critical area.

Furthermore, considering the degradation (69%) of the wetlands, model-based land use simulation by 2050, recent significant projects (e.g., Metrorail), and the industrial boom that has relied on sand-filled wetlands in Dhaka, it is unlikely that Bangladesh will achieve its national Sustainable Development Goals (SDGs) (National Target 15.1) [83], of ensuring the conservation, restoration, and sustainable use of wetlands and other ecosystems by 2020. The increase in LST in wetlands areas and the positive relationship between LST increase and wetlands degradation also suggest that, no matter what adaptation and mitigation strategies are undertaken in response to climate change in urban areas, it will be highly challenging to achieve SDGs (13: Climate action) by 2030 in Bangladesh. Therefore, an effective restoration plan and implementation are urgently required if Bangladesh is to achieve its SDGs and other national plans. In addition, the restoration of wetlands could be usefully integrated into future climate adaptation plans [84] as a nature-based solution.

5. Conclusion

In this research, using a long time-series (~30 years) of remote sensing images, we have unraveled the dynamics of LULC and highlighted the transformation of wetlands into urbanized areas and the increase in LST in Dhaka, the world's fastest-growing megacity, for the period of 1990-2020. This research shows that wetlands and grassland areas have decreased in order to create space for rapidly growing built-up areas, which have increased due to urbanization and industrialization. In summary, around 1,000 ha (69%) of Dhaka's wetlands area was lost between 1990 and 2020. This decrease in wetlands coincided with an increase (9°C) in LST over a similar period (1990 to 2020). As a result of the degradation of the wetlands, other ecosystem functions such as provisioning services (e.g., fish), regulating services (e.g., carbon storage), and habitat services (e.g., biodiversity) were lost during the time period under study. Despite implementing several initiatives and policies, the wetlands loss continues at a high rate, which may not slow down in the future given the future projection of population increase and economic development such as industrialization in Dhaka. We suggest that related policy frameworks such as NAPA, wetland conservation, and Delta planning are necessary to integrate and implement a wetlands management and restoration plan.

Declaration of competing interest

The authors declare no competing interests.

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None.

Author contributions

HA and MM equally contributed as the first author. HA, MM and MSH conceptualized the idea for this manuscript and the data analysis plan. MM and HA analysed the data. HA, MM and MSH wrote the manuscript. MGM, MTT, and AK have contributed to the final version of the manuscript. All authors read and approved the final manuscript.

Supplementary materials

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