# **Impact of decreased wetlands on microclimate of Kolkata, India**

by

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# ABSTRACT

The Landsat images were used to assess landuse/landcover (LULC) changes in Kolkata Metropolitan Development Area (KMDA) from 1990 to 2011 and in East Kolkata Wetlands (EKWs) from 1972 to 2011using a geographic object-based analysis (GeOBIA) technique and post-classification comparison. Then, the Weather Research and Forecasting (WRF) model was applied to investigate impacts of LULC dynamics on micro-climate using three scenario analyses (real condition scenario; urbanization scenario; and irrigate cropland expansion scenario). Results suggested that built-up area increased almost twice in 2011 when comparing it to 1990. The increased area was mainly coursed by conversions of wetlands and croplands. More specifically, EKWs decreased by 17.9% between 1972 and 2011. Urbanization can greatly increase regional temperature and stimulate sensible heat fluxes but reduce latent heat fluxes and albedo. On the contrary, the expansion of irrigated croplands decreased the temperature and sensible heat fluxes but increased latent heat fluxes and albedo.

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# 1. Introduction

Wetland ecosystems are transitional regions between terrestrial and aquatic ecosystems with unique soil conditions, plants, and animals, and are hot spots for both the carbon and nutrient cycles (Mitsch & Gosselink 2007). In recent years, due to population growth and urbanization, wetland areas are gradually undermined and converted into built-up areas and agricultural lands (Scoones 1991; Hartig et al. 1997; Carlson & Arthur 2000; Parihar et al. 2013). Land use and land cover (LULC) change significantly alters wetland ecosystems through impacting plant communities and microclimate thereby changing fluxes in water, nutrients, and energy across the land-atmosphere interface. For example, expansion of built-up area significantly changes evapotranspiration and runoff generation by increasing impervious surface areas. This process is more evident in developing countries due to their higher urbanization rates than in developed countries (Henderson 2002; Cohen 2006).

The Kolkata Metropolitan Development area (KMDA) is the capital of the state of West Bengal, India. As one of the largest Asia's urban centers, this region experiences a rapid urban population growth in recent decades. As reported by UN Habitat (2013), the population of the KMDA was 15.55 million in 2010 and increased by about 97.08% relative to 1975 (Taubenböck et al. 2009). The continuous population growth stimulated rapid urban development and urban expansion in this area and threatened the land cover of other types, especially the East Kolkata Wetlands (EKWs) that are located in the eastern part of KMDA  (Bhatta, 2009; Parihar et al. 2013; Sharma et al., 2015). Wetlands are important land cover types in India because they have reduced soil erosion and act as water receivers and nutrient purifiers for local ecosystems (Bhatta, 2009; Parihar et al., 2013). In 2002, EKWs were designated as the "Wetland of International Importance" under the Ramsar Convention (Parihar et al. 2013). However, total wetland areas continuously decreased in recent decades due to human population increase and intensifying anthropogenic activities. Conversion from wetland to built-up area in Kolkata not only affects ecological function of a region, but also alters microclimate and influence the premonsoonal rainfall pattern (Mitra et al. 2012). Therefore, it is necessary to investigate the impacts of wetland changes on climate in tropical regions since decreases in wetland areas may have the most adverse influence on human society and natural resources.

### 1.1 Objectives

In this thesis, a comprehensive analysis of LULC change effects on climate in Kolkata city was conducted. By classifying land covers in different years, spatially and temporally patterns of land cover change during different periods were analyzed. Then, the Weather Research and Forecasting (WRF) model was used to simulate potential impacts of land cover changes on temperature, rainfall, and heat flux. This study concentrated on three research questions: 1) How has KMDA land cover changed over time? 2) How much wetland area has lost in EKWs over study period? 3) Does the wetland conversion have any potential influence on the regional microclimates in KMDA? Based on these three questions, the objectives of this study are

1) to investigate land cover changes in KMDA from 1990 to 2011 using classification and post-classification, especially the wetland conversion in this area;

2) to study wetland conversion pattern at EKWs from 1972 to 2011 in detail;

3) to quantify the influence of wetland conversion in KMDA on microclimate based on the Weather Research and Forecasting (WRF) model simulation.

## 1.2 Thesis Structure

Chapter 1 briefly introduces the background, scientific questions, objectives, and structure of this thesis.

Chapter 2 analyzes land cover change in Kolkata city, especially the patterns of urban expansion and wetland shrinkage in 1990, 2000, and 2011. Geographic object-based classification was used to directly classify Landsat images of the above three years and post-classification was applied to present land cover changes by comparing each class over time.

Chapter 3 concentrates on the wetland area in the EKW area only. This chapter presents spatial and temporal changes of wetland and built-up area in East Kolkata wetlands in 1972, 1990, 2000 and 2011. In this chapter, Geographic object-based classification and post-classification were also applied for data analysis.

Chapter 4 investigates potential influence of land cover change on micro-climate change by Weather Research and Forecasting (WRF) model. Three scenario analyses were conducted to identify contributions of wetland shrinkage on temperature, precipitation, and energy changes.

Chapter 5 summarizes the significance and understanding of the impact of LULC change especially wetland conversion on the microclimate of the Kolkata city.

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# 2. Land cover change in Kolkata Metropolitan Development area from 1990 to 2000

## 2.1 Introduction

With continuous increases in population and development of industry, rapid land use land cover changes are incessant in developing countries (Sharma et al., 2015). India is one such example experiencing rapid urbanization due to urban population growth (UN, 2012). Land covers in cities, and especially megacities in India have been altered by the urban population increase. Kolkata is the second largest metropolis in South Asia. The population density of Kolkata was over 24,000 persons $km^{-2}$ in 2001 (Karar and Gupta, 2006). Increasing population growth has stimulated rapid urban development and agricultural expansion over the past 70 years after India achieved independence (UN Habitat, 2013). According to Taubenböck et al. (2009), Kolkata showed the highest built-up densities over all the other metropolitan areas in India. The rapid development of urban area has substantially undermined other land cover types, especially wetland areas which could probably have a profound influence on the surrounding environment and microclimate (Mitra et al., 2012; Sharma et al., 2015). Therefore, a better understanding on land cover changes is necessary for further climate study in the Kolkata city.

With the explosion of satellite data collection in recent decades, multiple methods have been developed in land use/land cover (LULC) change studies. These methods can be generally categorized into two consecutive steps including classification and post-classification comparison (Zhou et al., 2008). The classification method refers to techniques that use various classification algorithms to directly obtain land cover information from remotely-sensed data (Yuan et al., 2005). Techniques adopted in the classification method include pixel based and object based classifications (Dronova et al., 2011; Whiteside et al., 2011).

Recently, the Geographic Object Based Image Analysis (GeOBIA) has been widely used in image interpretation. GeOBIA not only considers spectral and textural information that is used in pixel-based classifiers, but also includes shape characteristics and context in adjacent pixels (Myint et al., 2011). Geographical/geometric features (e.g. shape, adjacency, and topological entities) are usually included in objects rather than in individual pixels. Object based analysis is able to provide useful information that cannot be obtained from individual pixels and can be easily performed by setting a series of classification rules (Whiteside et al., 2011). Therefore, the performance of GeOBIA is usually more efficient than the pixel-based classifier in processing data with relatively high spatial resolutions (Gao and Mas, 2008; Kindu et al., 2013). Besides the high efficiency, GeOBIA can also eliminate the salt and pepper effect that is caused by closely located pixels classified into different land cover types, which usually occurs in pixel-based classification. In addition, the GeOBIA has fewer errors in identifying distinct edges of different land cover types and performs better in temporal analysis of LULC change than the pixel-based methods (Dingle Robertson and King, 2011). Therefore, in this chapter, the GeOBIA was employed to investigate the land covers in Kolkata city expecting a better classification of the LULC than traditional pixel based classification (Gao and Mas, 2008; Kindu et al., 2013).

Post-classification comparison provides land cover information by contrasting each land cover class over time (Dewan and Yamaguchi, 2009) and thus has been widely used for LULC change detection in various studies (Yuan et al., 2005; Zhou et al., 2008). An advantage of this method is that it reduces change influences of using data provided by multiple sensors under different atmospheric conditions or vegetation phenology stage (Yuan et al., 2005; Zhou et al., 2008). A disadvantage is that this method is subject to error propagation because the accuracy of post-classification comparison largely depends on the accuracies of the individual classification for different time periods (Yuan et al., 2005; Dewan and Yamaguchi, 2009). Therefore, high accuracy in image classification is a prerequisite to produce reliable land cover change information.

In this chapter the GeOBIA method and post-classification comparison were applied to detect land cover changes in Kolkata Metropolitan Development Area (KMDA) from 1990 to 2011. Objectives of this chapter were: 1) to investigate land cover changes in the KMDA region using GeOBIA classification; 2) to analyze wetland conversion in recent years through post-classification.

## 2.2 Study area

KMDA is the economic and cultural nucleus of eastern and north-eastern India. This region is located in the eastern part of India with latitude ranging from 22°19' N to 23°01' N and longitude from 88°04' E to 88°33' E. The total area of this region is approximate 1851 km$^2$. It is one of the largest urban centers in Asia, and include the Kolkata Municipal Corporation (KMC), 38 other municipalities, 77 non-municipal urban towns, 16 suburban districts, and 445 rural districts (Dasgupta et al. 2012). The KMDA has a tropical climate with a hot and humid summer and a dry and cool winter. The annual mean temperature of this region is 24.8 ℃ and precipitation is about 1600 mm yr$^{-1}$ with a short and intense rainfall period during monsoon season from June to September ( Dasgupta et al. 2012; Mitra et al. 2012). The total population in KMDA was about 15.55 million in 2010 and will continue to increase in the near future (UN Habitat 2013)..

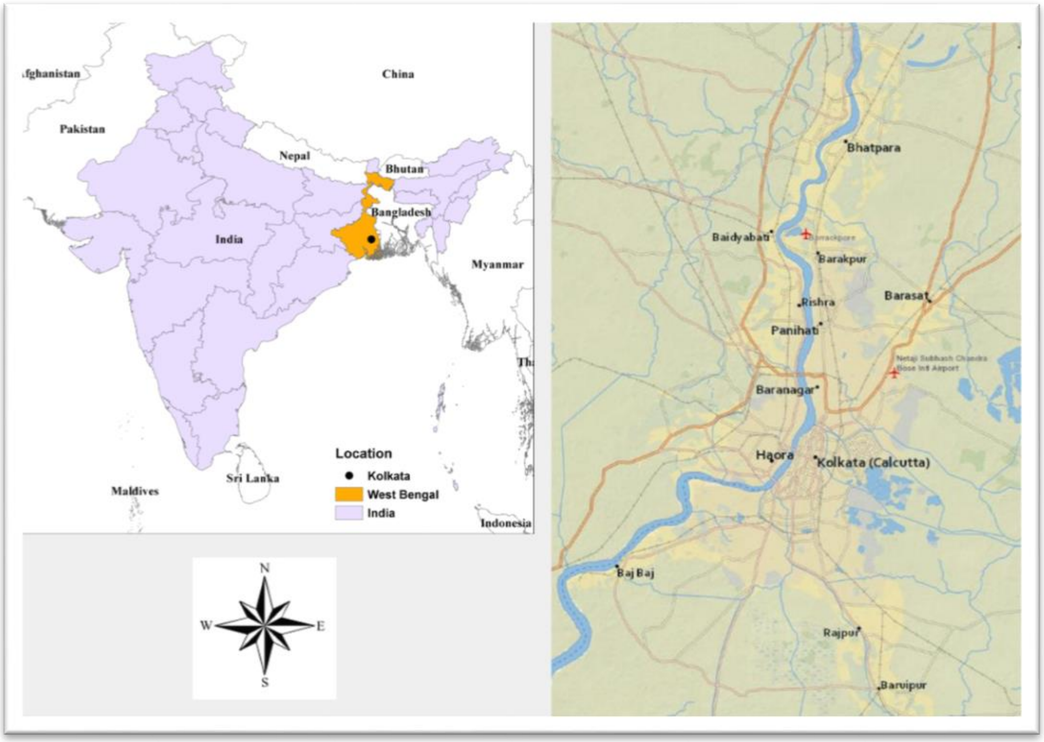


**Figure 2.1 Location of the Kolkata Metropolitan Development area (KMDA)**

## 2.3 Methods

### 2.3.1 Data Collection

This chapter was conducted using Remote Sensingtechniques. They are a vital part of delineating temporal changes of land use and land cover. The first step was to download remotely sensed images from the USGS Glovis, website (http://glovis.usgs.gov/). Landsat 5 and 7 TM and ETM data were processed to level 1T (terrain-corrected) which corrected geometric and radiometric errors based on satellite positioning, sensor orientation, ground control, and a digital elevation model (DEM). For Landsat 5 MSS, only geometric correction was performed based on satellite positioning (Howat and Eddy, 2011). Images produced in cloud-free dry seasons (November or December) were chosen, and in total three images in 1990, 2000, and 2011were selected (Table 2.1). Dry season images were chosen because wetland vegetation stands out from surrounding plants with a relatively higher vegetation cover density during this period. In this case, the confusion of wetland vegetation with cropland can be minimized due to a lower plant cover density in cropland from November to December which is during or right after sowing of crops (Banik and Sharma, 2008). Meanwhile, misclassification of wetland and deciduous forest can also be reduced because of the deciduous forest was largely senescent in this period (Munyati, 2000). The 1990, and 2000 images were all re-registered to the 2011 image to make the study area perfectly match in three images.

**Table 2.1 Landsat images selected for this study**

| Datasets | Data source | Year | Specification | Purpose |
|---|---|---|---|---|
| Landsat 5 TM (138, 44) | Glovis | Nov. 14, 1990; Nov. 08, 2011 | Six visible and IR bands, with a spectral resolution 30×30 m | Image classification |
| Landsat 7 ETM (138, 44) | Glovis | Nov. 17, 2000 | Six visible and IR bands, with a spectral resolution 30×30 m | Image classification |
| Google Earth | Open source | Oct. 26, 2011 Feb. 10, 2005 | Natural/True color image, < 3m | Classification Validation |
| City growth map | National Atlas and Thematic Mapping | From pre-1756 to 1990 | 1:100,000 | Classification Validation |

All satellite images were geometrically validated using a historical map and Google Earth images (high resolution images for 10 February 2005 and 26 October 2011). The historical map was collected from the National Atlas and Thematic Mapping Organization, India with a scale of 1:100,000. For Google Earth images, historical images for Oct. 26

2011 and Feb. 10, 2005 were used as references for data interpretation and classification accuracy assessment of the Landsat images. Moreover, the classification results were also compared with original Landsat images since there were few reference data for the study area (Parihar et al., 2013).

### 2.3.2 LULC Classification

#### *2.3.2.1 GeOBIA Classification*

In this chapter, GeOBIA technique was to process the selected Landsat images. Four land cover types were identified from the Landsat image data including wetlands with water body only, wetlands with vegetation, built-up areas, and all other land cover types (including forest, agriculture, and bare land). The GeOBIA method consists of two steps including segmentation and rule-based classification (Zhou et al., 2008; Zohmann et al., 2013). In segmentation, image data is divided into recognizable objects. Here a multi-resolution segmentation with eCognition developer 8.64.0 software was used. The segmentation algorithm is a bottom-up merging technique, beginning with a single pixel and uses similarity rules to merge image data into larger units that is set by users (Zhou et al., 2008; Kindu et al., 2013; Zohmann et al., 2013). Parameters used in this process include: scale, shape, and compactness. The scale parameter is influenced by image heterogeneity (considering object feature, color, and shape) and directly controls object sizes (Benz et al., 2004). The greater the scale parameter is, the larger the average size of the objects that are defined. Whiteside et al. (2011) emphasized the importance of scale parameter selection in the GeOBIA classification. Large scale values may under-segment the image, leading to a large number of mixed land covers; while small scale values could lead to over-segmenting the image, causing high numbers of adjacent objects to be classified with the same land cover. The shape parameter adjusts shape of objects using spectral values of image layers. A maximum shape parameter of 1.0 suggests that created objects would not be related to the spectral information, while with values less than 0.1 means the object is spectrally homogeneous (Myint et al., 2011). According to Moffett and Gorelick (2013), wetland features could be better distingushed using a low shape parameter. The compactness parameter balances the compactness and smoothness of object boundaries. In this study, the three parameters were estimated by visual interpretation to make sure most objects after segmentation are internally homogenous (Zhou et al., 2008). Based on the trial and error process, the scale parameters in this project were set to 3 for Landsat MSS image and 5 for Landsat TM and ETM images with a shape parameter of 0.2 and a compactness parameter of 0.7 for the two types of images, respectively

The rule-based classification used to define land cover class for each object implemented the characteristics of brightness, size homogeneity, as well as Normalized Difference Water Index (NDWI) and Normalized Difference Vegetation Index (NDVI) (Gao, 1996; Zhou et al., 2008). NDWI was applied to separate water bodies from other land cover types (Bal ҫik, 2014). NDWI is a typical index in the multiple-band method used to identify water surface from Landsat image data, as vegetation and open water show distinctively different features of reflectance over the near infrared and green bands (Gao, 1996; Chen et al., 2006; Bal ҫik, 2014). Similar to NDWI, NDVI is another widely used multiple-band method to extract vegetation (including wetland vegetation, agricultural plants and forests) from urban areas in this study. In the vegetation group, wetland vegetation is distinguished from other land cover type because wetland vegetation has higher NDVI values due to the low plant cover density in cropland from November to

December which is during or right after sowing of crops (Munyati, 2000; Banik & Sharma, 2008). Vegetation adjacent to a water body are most likely to be wetland vegetation according to the wetland definition (Cedfeldt et al., 2000; Wright and Gallant, 2007). Therefore, besides NDVI, distance to water was also used as a rule for wetland vegetation classification in processing satellite data. Brightness and size homogeneity were also applied to further separate built-up areas and other land cover types (Salehi et al., 2012). Four images were classified with similar rulesets but different threshold values for all classes.

#### *2.3.2.2 Accuracy Assessment*

The eCognition software provides four accuracy assessment methods including classification stability, best classification result, error matrix based on Test and Training Area (TTA) mask, and error matrix based on sample. According to eCognition 8.64.0 user guide (http://www.ecognition.cc/download/eCognition_8.64.0_Release_Notes.pdf), the classification stability computes the difference between the largest and the second largest membership values for each pixel and sums for the whole class. The best classification result shows a visual representation of the pixel with the largest membership value. The error matrix based on TTA mask uses test areas as reference data to check results of classification. The error matrix based on sample is similar to error matrix based on TTA mask, but it considers samples not pixels of a TTA mask. In this study, the error matrix based on TTA mask was chosen as the assessment method, which is commonly used for accuracy evaluation in remote sensing data classification (Zohmann et al., 2013). A TTA mask with 200 test objects was created for each image and verified using the historical map, the Google Earth images and the classified images by previous studies. Then the masks were loaded in eCognition software to compare if the classes in the classified images are in agreement with the test areas in the mask. After comparison, the overall accuracy, producer's accuracy, and user's accuracy were provided by the error matrix and the percentage of objects that was correctly identified for each class can be obtained. The producer's accuracy shows the omission errors related to a class. It is derived from the number of correctly classified pixels of a class divided by the total number of pixels of that class used for assessment. The user's accuracy measures the commission errors related to a class. It is calculated by the number of pixels correctly classified divided by the total number of pixels predicted to be that class in the assessment (Foody, 2005).

### 2.3.3 Post-classification Comparison Change Detection

Post-classification is a commonly used method to validate and compare the rate of change of LULC. Here it was applied to investigate change of LULC from 1990 to 2011 in the study area. Based on the classified images, two periods were compared to demonstrate LULC changes with time, including 1990-2000 and 2000-2011. For each period, a matrix process was used to compare two classified vector images using ERDAS software. Using the classified images as input files and selecting a default 1 meter as the output cell size, the two vector images were converted to a raster image with changing areas in the attribute table to present land cover changes. Land conversion was quantified by comparing the area value of one class with the corresponding value of that class in the other image. This value is expressed as a percentage of LULC changes ($P$, %) (Eq.1) (Kindu *et al*., 2013) and quantified as a conversion rate ($r$) (Eq.2):

$$P_i = \left(\frac{A_{i,final} - A_{i,initial}}{A_{i,initial}}\right) \times 100 \quad \text{(Eq.1)}$$

$$r_i = \left(\frac{A_{i,final} - A_{i,initial}}{\Delta_{year}}\right) \times 100 \quad \text{(Eq.2)}$$

where *i* refers to the *i*th class of land cover for change detection, $A_{initial}$ and $A_{final}$ are the areas of class in the initial year and in the final year, respectively, $\Delta_{year}$ represents the total years between the initial year and the final year. For *P* and *r*, positive values suggest an increasing area of that land cover class during study period, while negative values suggest a decreasing land cover area with time.

## 2.4 Result and discussion

### 2.4.1 Accuracy Assessment

Accuracy assessment of the classification results was conducted by checking the user's accuracy and producer's accuracy for each land cover types, as well as overall accuracy and kappa statistics for the each classified land cover maps. In general, the GeOBIA classification provides reasonable land cover information for the study area since the overall accuracy of the satellite image interpretation ranged from 81.1% to 88.0%. Of all the four land cover types, wetlands with water bodies had the highest accuracy. Both the user's and the producer's accuracies for this land cover type were over 90%. For the built-up area, the accuracy analysis showed comparable producer's and user's accuracy in 1990. The user's accuracy was lower than that of producer's in 2000 but higher in 2011. For the wetlands with vegetation, the producer's accuracy was higher (95.1%) in 1990 than the other years. For the other years, both producer's and user's accuracies ranged from 74.5% to 85%. Highest user's accuracy occurred in 1990, whereas the highest producer's accuracy occurred in 2011.

**Table 2.2 Summaries of classification accuracies (%) for Landsat images of 1990, 2000, and 2011**

| | **Water (wetlands)** | **Vegetation (Wetlands)** | **Built-up areas** | **Others** |
|---|---|---|---|---|

| | | | | | |
|---|---|---|---|---|---|
| **1990** | **User's Accuracy** | 100 | 83.5 | 83.7 | 97.4 |
| | **Producer's Accuracy** | 94.3 | 95.1 | 83.7 | 77.8 |
| | **Overall Accuracy** | 88.0 | | | |
| | **Kappa Statistics** | 83.2 | | | |
| **2000** | **User's Accuracy** | 94.2 | 85.0 | 73.6 | 83.4 |
| | **Producer's Accuracy** | 99.6 | 74.5 | 84.7 | 71.4 |
| | **Overall Accuracy** | 81.1 | | | |
| | **Kappa Statistics** | 72.8 | | | |
| **2011** | **User's Accuracy** | 100 | 77.9 | 83.5 | 87.6 |
| | **Producer's Accuracy** | 91.7 | 84.1 | 75.8 | 97.4 |
| | **Overall Accuracy** | 84.9 | | | |
| | **Kappa Statistics** | 79.1 | | | |

Uncertainties of in the data analysis lie in the data sources, classification methods used in data processing, as well as the insufficient use of field data in this study. One major uncertainty source for our classification is the satellite data. In this study, only three years were chosen depending on availability of good images. Land cover change information in other years between the three period were not included and may result in inaccurate estimations of the land cover change patterns in the study area (Hansen and Loveland, 2012).

The data processing method is another uncertainty source. Land cover change analysis for the subtropical landscape is especially challenging due to overlap of spectral signature among different land cover types. It is common that misperception occurred on spectral signature between woody wetland and forest, rice field, as well as between built-up and barren land (Parihar et al., 2013). Environmental variability also influences the spectral response of land surface features. For example, changing soil moisture affects the spectral reflectance of vegetation and other land cover types, and makes it difficult to separate wetland with vegetation and other land cover types. In vegetated areas, high soil water contents often reduce the spectral reflectance, especially for the near and shortwave infrared wavelength bands (Lobell and Asner, 2002; Pan et al., 2013). As a result, land cover classification based on pure spectral signatures in the wetland environment may result in poor classification performance. In addition, more ground truth activities should be performed to improve the land cover classification and for the evaluation of classification results.

### 2.4.2 Land cover changes in KMDA

Spatial distributions of major land covers in the study area can be found in the classification results of the satellite images (Figure 2.2). Wetlands and the other category land cover are the two major land cover types. Percentages of total wetlands were 43.90%, 35.12% and 33.42% in 1990, 2000 and 2011 respectively. Wetlands with surface waters were mainly distributed along the Hooghly River, and the southeastern areas in this region. In 2000, surface waters also appeared in southwest parts of this region. Areas along the river channel are also regions where vegetated wetland area are located. Large areas of vegetated wetland were mainly located in the southern parts of the study area in 1990. In eastern parts of this region, vegetated wetlands were mainly scattered among other land cover types. In 2000, vegetated wetland areas in the south parts were reduced significantly, and the reduction trend continued in 2011. Built-up regions were mainly distributed along the river, especially around the Kolkata city. Locations of area with large built-up regions remained unchanged in the study area but size of the built-up regions increased, especially in south and southeast Kolkata.  In addition, built-up areas spread out and scattered over much larger regions in 2011 than the other two years.

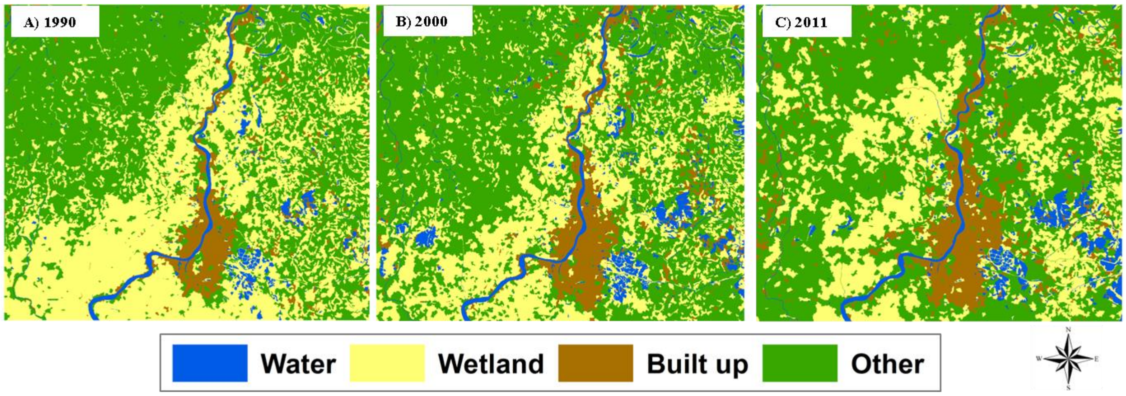


**Figure 2.2 Land cover of Kolkata Metropolitan Development area (KMDA) in 1990, 2000 and 2011**

**Table 2.3 Summaries of land cover areas in KMDA based on Landsat image classification for 1990, 2000, and 2011**

| | | Water (Wetlands) | Vegetation (Wetlands) | Total (Wetlands) | Built-up areas | Others |
|---|---|---|---|---|---|---|
| **1990** | **Area (km$^2$)** | 163.99 | 2052.54 | 2216.53 | 280.25 | 2552.58 |
| | **% of area** | 3.25 | 40.65 | 43.90 | 5.55 | 50.55 |
| **2000** | **Area (km$^2$)** | 265.50 | 1507.77 | 1773.27 | 403.47 | 2872.63 |
| | **% of area** | 5.26 | 29.86 | 35.12 | 7.99 | 56.89 |
| **2011** | **Area (km$^2$)** | 237.71 | 1449.72 | 1687.43 | 536.38 | 2825.51 |
| | **% of area** | 4.71 | 28.71 | 33.42 | 10.62 | 55.96 |
| | | | | | | |
| **Relative change 1990-2011 %** | | 44.95 | -29.37 | -23.87 | 91.39 | 10.69 |

Land cover changes during the study years are depicted in table 2.2 and figure 2.2. According to my analysis, urban built up area increased by 91.39% during the study period. In 1990, built up area only cover 5.55% of this region, with an area of 280.25 km$^2$. From 1990 to 2000, build area increased by 2.44% and reached a total of 403.47 km$^2$. In the 2000s, urban sprawl increased at a similar rate compared with that of the 1990s. During this period, built-up area increased by 32.9% compared with that of 2000 and reached a total of 536.38 km$^2$ at the end of the study period. The fast growing build-up area resulted in significant conversions of wetland to urban and other land cover types. From 1990 to 2000, total wetlands decreased 443.26 km$^2$, and the reduction was mainly contributed by wetlands with vegetation, which decreased by 544.77 $km^2$, whereas wetlands with water bodies increased by 101.51 $km^2$ during the same period. The increased water body may be caused by a high precipitation rate at this region in 2000, which increased areas of wetlands and water bodies of temperate wetlands (Rao et al., 2004). For the second period, total wetland areas further decreased, but at a much slower rate. The period from 2000 to 2011 witnessed a decrease of 85.84 $km^2$ in total wetland areas, and this reduction was attributable to both wetlands with vegetation and surface waters. Besides built-up areas and wetlands, other land cover types identified in this study also showed significant changes, especially for the 1990s. During 1990 and 2000, this land cover category increased by 320.05 $km^2$. However, in the second period (2000-2011), total area of this category did not show significant changes.2.4.3 Land conversions among major land cover types in KMDA

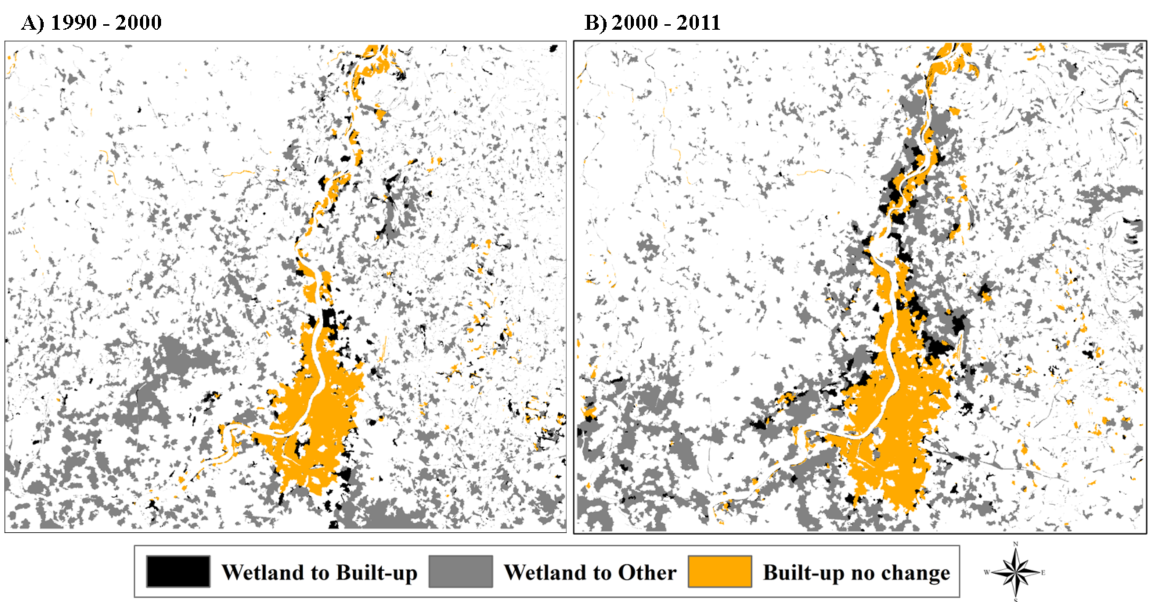


**Figure 2.3 Land cover change maps of the KMDA from 1990 to 2000 and from 2000 to 2011**

Figure 2.3 demonstrates land cover conventions in the two time periods. From 1990 to 2000, urban area in the central regions of the study area has increased dramatically. Urban sprawl also occurred in the southern edges of the Kolkata city. During this period, land conversion from wetlands to other land cover types mainly scattered in the southern parts of the study area, especially in the southwest parts. Land conversions between 2000 and 2011 from wetland to urban area were significant. In this period, the results showed large areas of wetland conversion along the Hooghly River channels in the northern regions of the Kolkata city. Meanwhile, there were also large areas of wetlands converted to other land cover types and the conversion mainly occurred along the Hooghly River, in southwestern and northeastern areas of this region.

Natural properties and human activities are two major groups of drivers accounting for land cover change (Veldkamp and Fresco 1996). Specifically, natural properties refer to physical and chemical conditions of soil, climate factors, as well as pest and disease impacts, whereas human factors reference to population increase and economic activities. For the KMDA area, natural and anthropogenic factors both resulted in land cover changes. For example, wetland ecosystems are sensitive to amount of water supply (Erwin, 2009). During low precipitation periods, some temperate wetlands may dry up or even be used as croplands (Parihar et al., 2013). This shows a natural factor influencing land cover types. Population growth is another major reason for the urban sprawl. UN habitat (2013) showed that population increased by 50% from 1990 to 2011 in this area. As presented in previous sections, increasing urban areas were mainly distributed in areas adjacent to the Kolkata area. Expanding population requires extra supply of food, facilities for housing as well as infrastructures for transportation and commercial activities. As a result, wetlands or other land cover types in the adjacent regions of the Kolkata city were removed and cleared for construction.  Increasing populations also required more agricultural products which led to expansion of other land cover types from 1990 to 2000.

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# 3. Spatial and Temporal Patterns of Wetland Cover changes in East Kolkata, India from 1972 to 2011[1]

[1] This chapter has been accepted by *Journal of Applied Geospatial Research*. (Li, X., Mitra, C., Marzen, L., & Yang, Q. (2015). Spatial and Temporal Patterns of Wetland Cover changes in East Kolkata Wetlands, India from 1972 to 2011. International Journal of Applied Geospatial Research (Accepted).)

## 3.1 Introduction

Wetland ecosystems are transitional regions between terrestrial and aquatic ecosystems with unique soil conditions, plants, and animals, and are essential components of terrestrial carbon and nutrient cycles (Mitsch and Gosselink, 2007; Cui et al., 2009; Li et al., 2012). Initially, conversion of wetland areas to agricultural lands was a main reason for wetland loss globally. Large areas wetlands were converted to cropland to sustain food production for the ever-increasing population (Rijsberman and De Silva, 2003). In recent time population growth and urbanization have further undermined wetland areas and gradually converted them to built-up areas and agricultural lands (Bolca et al., 2007; Cui et al., 2010; Parihar et al., 2013). Drainage ditches for cropland have significantly lowered the water table depth of wetlands and reduced water-storage capacity and changed local hydrological cycling such as precipitation and runoff (Bartzen et al., 2010). Wetland conversion to built-up area results in an increase in impervious surfaces which may cause increases in evapotranspiration and runoff (Carlson and Arthur, 2000). These changes may also increase temperature due to rising greenhouse gas emissions from human-related sources and reduced vegetation covers (Chen et al., 2006; Bal ҫık, 2014). Therefore, a thorough investigation of LULC dynamics on wetland ecosystems is the key to understandings of LULC change-induced hydrological, ecological and climatic processes.

The geographic object-based analysis is being widely used for wetland classification in recent years (Dingle Robertson and King, 2011; Dronova et al., 2011; Moffett and Gorelick, 2013). As introduced in Chapter 2, it can reduce the salt and pepper effect and has fewer edge errors compared with the pixel-based methods. Since high spectral and spatial heterogeneities exist in wetland classification due to differences in water depths and vegetation, the process is highly context-dependent (Wright and Gallant, 2007; Cui et al., 2010). The features of object-based analysis make GeOBIA a very useful method in investigating changes in wetlands over long periods. Identifying related indices is the key for wetland detection during the classification process. Water body is a commonly used index to identify wetlands in satellite images (Mitsch and Gosselink, 2007). Surface water shows relatively higher reflectance in the visible wavelengths and lower reflectance in near-infrared wavelengths than other land cover types, so it can be extracted through a multi-band technique which considers the reflectance of water over multiple bands (Jensen, 2006; Campbell and Wynne, 2011). The Normalized Difference Water Index (NDWI) is a typical index in the multiple-band method used to identify water surface from Landsat image data, as vegetation and open water show distinctively different features of reflectance over the near infrared and green bands (Gao, 1996; Chen et al., 2006; Balçik, 2014). Moreover, Munyati (2000) used dry season Landsat images to distinguish wetland vegetation from deciduous forest since wetland vegetation shown a higher Normalized Difference Vegetation Index (NDVI) than deciduous forest that was largely senescent in autumn.

In this chapter, the GeoBIA and post-classification comparison were applied to detect wetland shrinkage in East Kolkata Wetlands (EKWs), India, from 1972 to 2011. EKWs are important to Kolkata, eastern India because they have reduced soil erosion and act as water receivers and nutrient purifiers (Bhatta, 2009; Parihar et al., 2013). In 2002, the EKWs were designated as “Wetland of International Importance” under the Ramsar Convention. However, due to the rapid population growth, large areas of wetlands have been converted to agricultural and built-up areas, especially for vegetated areas of wetlands which are more susceptible to human disturbances and can be easily transformed to croplands and built-up areas (Hartig et al., 1997; Bartzen et al., 2010; Parihar et al., 2013). The substantial decrease in wetlands has raised increasing concerns and also helped etch out the research question for our study - How EKWs land cover has changed over time? Though Parihar et al. (2013) have studied open water area shrinkage in EKWs using a traditional pixel-based classification, they paid little attention about the vegetation areas of wetlands. In this study, the GeOBIA was applied in an attempt to accomplish a more detailed wetland classification of EKWs considering both water bodies and wetland vegetation. The objectives of this study were: 1) to classify LULC in EKW region using GeOBIA classification; 2) to analyze and quantify LULC dynamics during the study period; 3) to discuss spatial patterns of wetland conversion. Results of the study provide useful information on the historical LULC changes which can be used to assess impacts of land conversions on regional hydrology, biodiversity and climate in Kolkata city which experience intensive urbanization and agricultural expansion.

### 3.2 Study Area

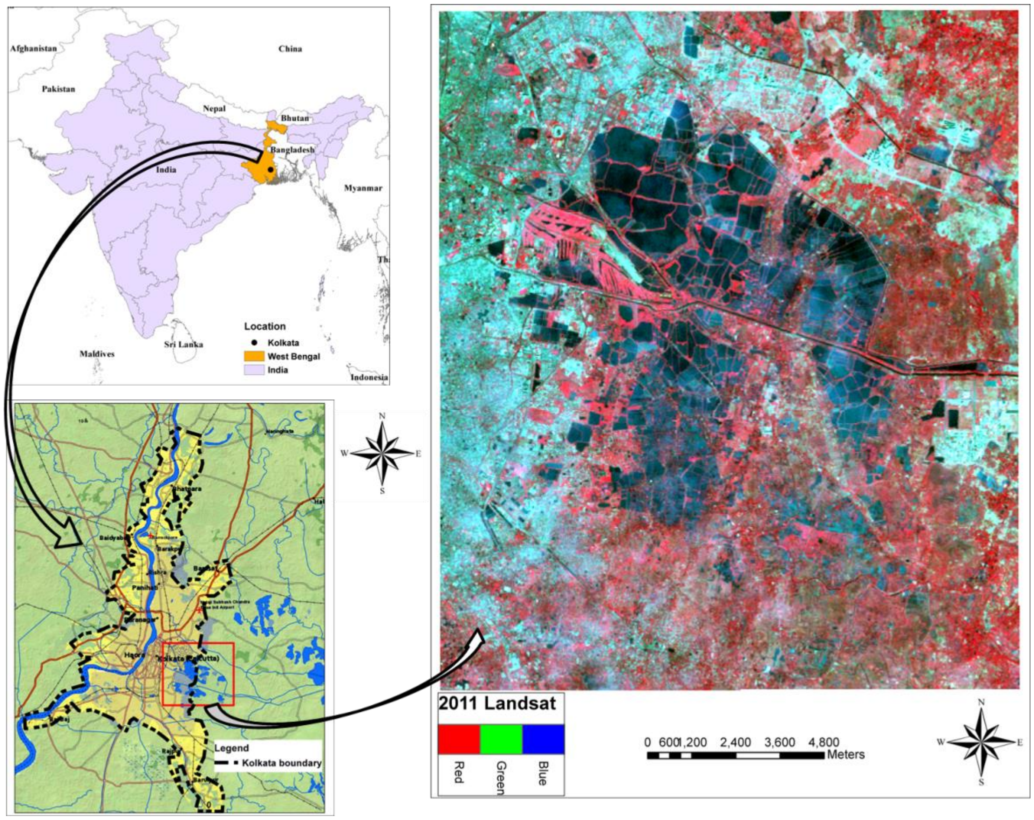


**Figure 3.1 Location of the East Kolkata Wetlands (EKWs)**

The EKWs that are located along the eastern edge of the Kolkata, between 22°25’ and 22°35’ latitude and 88°22’ and 88°32’ longitude (Figure 3.1). The study area has a tropical climate with a hot, humid summer and a cool, dry winter. Annual mean precipitation is 1600 mm and mainly occurs from June to September (Mitra et al., 2012; Parihar et al., 2013). Maximum temperature during summer (April to May) is around 40 ℃ and the minimum temperature in winter (December to January) is about 10 ℃. Wetland is the primary land cover in this area.

### 3.3 Data Collection

This study is heavily dependent on Geographic Information Science (GIS) techniques. They are a vital part of delineating temporal changes of land use and land cover. The first step was to download remotely sensed images from the USGS Glovis, website (http://glovis.usgs.gov/). Landsat 5 and 7 TM and ETM data were processed to level 1T (terrain-corrected) which corrected geometric and radiometric errors based on satellite positioning, sensor orientation, ground control, and a digital elevation model (DEM). For Landsat 1-5 MSS, only geometric correction was applied based on satellite positioning (Howat and Eddy, 2011). Images generated in cloud-free dry seasons (November or December) were chosen, and in total four images in each year for 1972, 1990, 200, and 2011 (Table 3.1) were selected. The 1972, 1990, and 2000 images were all geo-registered to the 2011 image.

**Table 3.1 Datasets of this study**

| Datasets | Data source | Year | Specification | Purpose |
|---|---|---|---|---|
| Landsat 1 MSS (148, 44) | Glovis | Dec. 11, 1972 | Four bands, with a spectral resolution 80×80 m | Image classification |
| Landsat 5 TM (138, 44) | Glovis | Nov. 14, 1990; Nov. 08, 2011 | Six visible and IR bands, with a spectral resolution 30×30 m | Image classification |
| Landsat 7 ETM (138, 44) | Glovis | Nov. 17, 2000 | Six visible and IR bands, with a spectral resolution 30×30 m | Image classification |
| Google Earth | Open source | Oct. 26, 2011 Feb. 10, 2005 | Natural/True color image, < 3m | Classification Validation |
| City growth map | National Atlas and Thematic Mapping | From pre-1756 to 1990 | 1:100,000 | Classification Validation |

All satellite images were geometrically validated using a historical map and Google Earth images (high resolution images for 10 February 2005 and 26 October 2011). The historical map was collected from the National Atlas and Thematic Mapping Organization, India with a scale of 1:100,000. For Google Earth images, historical images for Oct. 26 2011 and Feb. 10, 2005 were used as references for validation and data interpretation of the Landsat images. Moreover, the classified data were also compared with original Landsat images since there were few reference data for the study area (Parihar et al., 2013).

After LULC change analysis, population data in Kolkata city were also collected to further investigate if the population growth of Kolkata city could be a cause for possible wetland conversions. The population data were collected from studies of United Nations (2005) and UN Habitat (2013) and were linearly interpolated to generate population data in 1972, 1990, 2000, and 2011.

## 3.4 Results and Discussion

### 3.4.1 Wetland Shrinkage and Built-up Area Expansion

Wetlands (including open water and wetlands with vegetation) were the major land cover type in study area, accounting for 53.9 percent of the total region in 1972 (Table 3.2). From 1972 to 2011, total wetland areas decreased by 28.1 $km^2$, leading to a 17.9 percent reduction. Open water area showed relatively low variability among the four study years (ranging from 39.6 $km^2$ to 43.8 $km^2$) and was about 5 percent smaller in 1972 than other years; while vegetation zones of wetlands decreased about 30.0 $km^2$ during the 39 years, accounting for 25.4 percent of the total region in 1972. This result is reasonable because open water area can also be influenced by precipitation. Low monsoonal rainfall was found in EKWs during 1972 (Mitra et al., 2012), which might reduce areas with surface water in some seasonal wetlands and wetlands with low water depth. For the vegetation zones, since most land is arable with a lower water depth than in open water, they were vulnerable to human activities and were readily used for urban construction and agricultural development (Yuan et al., 2005; Biswas, 2010). The results further suggest that wetlands cannot be effectively classified if water bodies are used as the only indicator. This may be one reason for the low accuracies in wetland classification in the study by Parihar et al. (2013).

The percent of built-up areas is the lowest among all land cover types in 1972, but it increased rapidly over the past 39 years (Table 3.2). In 1972, built-up areas only covered about 10 percent of our study area. Due to rapid urbanization, built-up areas increased to over 197 percent and covered about 30 percent by 2011. Wetland areas were not only converted to built-up areas, they were also replaced by other land cover types (converted ~29.7 percent of the total areas of other cover types in 1972). The increased rate of built-up areas is similar to the conversion rate obtained by Parihar et al. (2013) who found an increase of 166 percent in built-up areas from 1973 to 2010 in this area. Land cover change rates increased faster in the recent two decades compared to the years between 1972 and 1990 (wetlands: -7.4 percent; built-up areas: 8.5 percent; other: 8.1 percent). From 1972 to 1990, 7.4 percent of wetlands were converted to other land cover types and resulted in an 8.5 percent increase of urban area; whereas from 1990 to 2011, wetland areas were reduced by 11.3 percent, whereas urban areas increased by 161.3 percent.

**Table 3.2 Summaries of land cover areas based on Landsat image classification for 1972, 1990, 2000, and 2011**

| | | Water (Wetlands) | Vegetation (Wetlands) | Total (Wetlands) | Built-up areas | Others |
|---|---|---|---|---|---|---|
| **1972** | **Area (km$^2$)** | 39.6 | 117.6 | 157.2 | 30.5 | 104.4 |
| | **% of change** | 13.6 | 40.3 | 53.8 | 10.4 | 35.7 |
| **1990** | **Area (km$^2$)** | 43.3 | 102.3 | 145.6 | 33.1 | 112.9 |
| | **% of change** | 14.8 | 35.1 | 49.9 | 11.3 | 38.7 |
| **2000** | **Area (km$^2$)** | 43.8 | 89.0 | 132.8 | 56.6 | 102.2 |
| | **% of change** | 15.0 | 30.5 | 45.5 | 19.4 | 35.0 |
| **2011** | **Area (km$^2$)** | 41.4 | 87.7 | 129.1 | 86.5 | 76.0 |
| | **% of change** | 14.2 | 30.1 | 44.3 | 29.7 | 26.1 |
| | | | | | | |
| **Relative change 1972-2011 %** | | 4.5 | -25.4 | -17.9 | 183.6 | -27.2 |

### 3.4.2 Accuracy Assessment Results

The overall accuracies for the classifications based on images from 1972, 1990, 2000, and 2011 were 81.3 percent, 89.5 percent, 86.9 percent, and 89.9 percent, respectively, with Kappa statistics ranging from 74.8 percent to 86.5 percent (Table 3.3). The user's and producer's accuracies were consistently high, ranging from 64.9 percent to 100 percent for the four classes. The classification accuracy for 1972 was the lowest among the four years. This was due to the low spatial resolution of the Landsat MSS image, which caused uncertainties in object identification (Baker et al., 2013). The overall accuracies in our classification are being about 20 percent higher for all four image classification compared to Parihar et al. (2013) study.

**Table 3.3 Summaries of classification accuracies (%) for Landsat images of 1972, 1990, 2000, and 2011**

| | | **Water (wetlands)** | **Vegetation (Wetlands)** | **Built-up areas** | **Others** |
|---|---|---|---|---|---|
| **1972** | **User's Accuracy** | 98.6 | 64.9 | 93.8 | 68.5 |
| | **Producer's Accuracy** | 97.3 | 81.8 | 81.3 | 60.5 |
| | **Overall Accuracy** | 81.3 | | | |
| | **Kappa Statistics** | 74.8 | | | |
| **1990** | **User's Accuracy** | 100 | 89.4 | 87.0 | 82.1 |
| | **Producer's Accuracy** | 98.4 | 90.2 | 84.5 | 83.6 |
| | **Overall Accuracy** | 89.5 | | | |
| | **Kappa Statistics** | 85.6 | | | |
| **2000** | **User's Accuracy** | 98.3 | 82.5 | 69.6 | 89.4 |
| | **Producer's Accuracy** | 84.0 | 87.3 | 90.2 | 88.6 |
| | **Overall Accuracy** | 86.9 | | | |
| | **Kappa Statistics** | 82.2 | | | |
| **2011** | **User's Accuracy** | 100 | 81.5 | 91.5 | 84.8 |
| | **Producer's Accuracy** | 96.7 | 86.0 | 96.1 | 80.7 |
| | **Overall Accuracy** | 89.9 | | | |
| | **Kappa Statistics** | 86.5 | | | |

### 3.4.3 Conversion of Wetlands

Post-classification was used to detect conversions of wetlands to other land cover types in different time periods. In total, about 38.6 $km^2$ of wetlands were converted to built-up areas over 39 years. Built-up areas were expanding in the western parts of EKWs (Black color in Figure 3.2) as the Kolkata Metropolitan Development Area (KMDA) that is located in the north-west of EKWs has limited space for urbanization (Bhatta, 2009). Therefore, arable lands in wetlands attract people from KMDA for settling down, causing conversions of wetlands to built-up and other LULC types (Biswas, 2010). From1972 to 1990, only about 8.2 $km^2$ of wetlands were converted to built-up areas; from 1990 to 2000, 11.6 $km^2$ of wetlands were converted to built-up areas. The conversion rate of wetlands to built-up areas in 1990 to 2000 is about 2.5 times higher than that from 1972 to 1990 (Table 3.4). The rate has continued to increase and urban expansion was found in southern and northern parts of wetlands in the period from 2000 to 2011 as a result of population growth in KMA (Biswas, 2010; Black in Figure 3.2C).

**Table 3.4 Conversion of wetland to other land cover types during 1972 – 1990, 1990 – 2000, and 2000 – 2011**

| | **Wetlands (No change)** | **Built-up (No change)** | **Others (No change)** | **Wetlands to Built-up** | | **Wetlands to Others** | |
|---|---|---|---|---|---|---|---|
| | **Area ($km^2$)** | **Area ($km^2$)** | **Area ($km^2$)** | **Area ($km^2$)** | ***r*** **($km^2$ $yr^{-1}$)** | **Area ($km^2$)** | ***r*** **($km^2$ $yr^{-1}$)** |
| **1972-1990** | 99.3 | 15.3 | 56.3 | 8.2 | 0.46 | 49.1 | 2.73 |
| **1990-2000** | 99.7 | 25.4 | 64.0 | 11.6 | 1.16 | 33.8 | 3.38 |
| **2000-2011** | 87.5 | 43.1 | 44.5 | 18.8 | 1.71 | 25.7 | 2.34 |

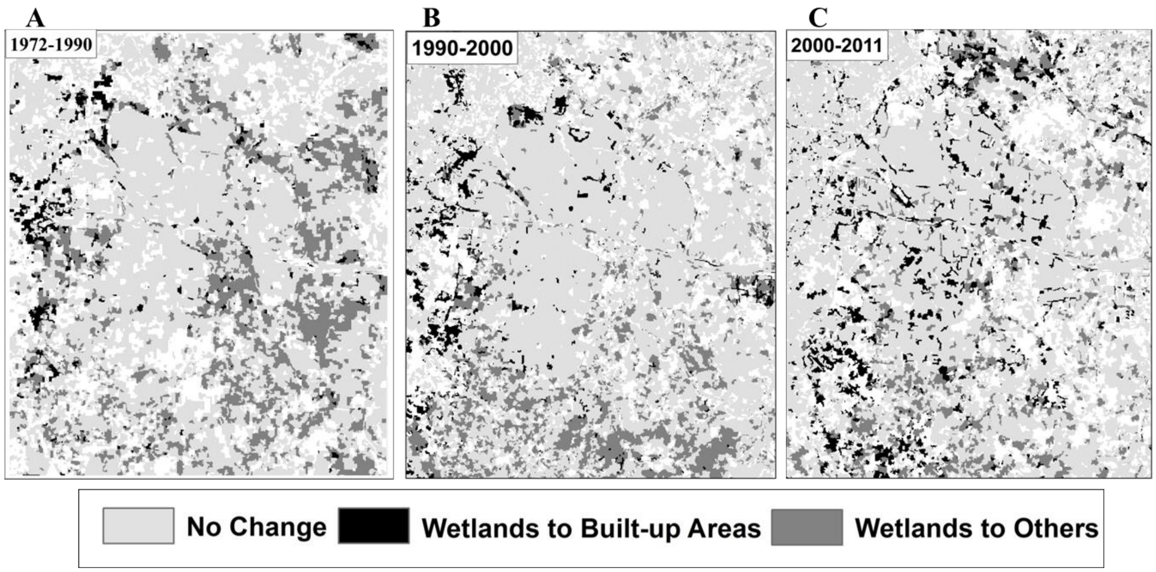

**Figure 3.2 Land cover change maps of the study area from 1972 to 1990, 1990 to 2000, and 2000 to 2011**

Conversion of wetlands to croplands and forests occurred in the eastern EKWs and their conversion rates were higher than changes of wetlands to built-up areas during the study period (Table 3.4 and Dark Gray in Figure 3.2). Lowered water depth areas in wetlands allowed farmers to convert wetlands for crop cultivation (Gupta, 2013). About 49.1 $km^2$ of wetlands were replaced by other land covers from 1972 to 1990. According to Parihar *et al*. (2013), the conversion was mainly from wetland areas to croplands, which was caused by decreasing water depth in the wetland due to siltation and lack of water (Biswas, 2010). The relatively high conversation rate of wetlands to other land cover types may also be caused by the low spatial resolution in 1972 image that decreases class differences between vegetated wetlands and other vegetation regions during image classification (Parihar *et al*., 2013). The low user's accuracies for these two land covers further indicates that part of agricultural areas may be mis-classified as wetland vegetation. Between 1990 and 2000, agriculture expansion shifted from western to southern parts of wetlands (Figure 3.2B, Dark Gray) and about 33.8 $km^2$ of wetlands were converted to other land cover types. The conversion rate decreased slightly in the period from 2000 to 2011 when about 25.7 $km^2$ other land types increased at the expense of wetlands.

### 3.4.4 Population Growth and LULC Changes

Decrease of wetland areas was significantly negatively related to population growth (Figure 3.3A, $R^2$=0.9567, $P < 0.05$), suggesting that population growth may be an important factor responsible for wetland area change. In this case, the increase of population explained 95.67 percent of the variation of wetland shrinkage. An upward trend can be found between built-up areas and population growth with a regression coefficient of 0.8486 (Figure 3.3B). However the trend is insignificant due to limited dataset. For the regression between population and other areas, an upward trend was found during the early period of population explosion (Figure 3.3C) following with a downward trend.  This result is consistent with the previous studies which found an increase of other land cover types (forest, agriculture, and bare land) in the 1980s, but a decrease of the same type in the 1990s in Kolkata area (World Bank, 2011; Parihar *et al*., 2013).

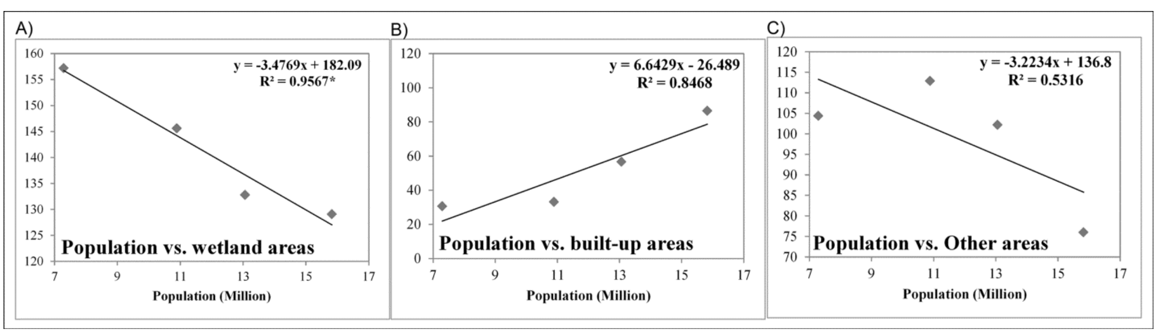


**Figure 3.3 Relationships between area changes (km2) of land cover types and population growth**

## 3.5 Conclusions

Kolkata city in eastern India has seen unprecedented growth in recent years and in the process a lot of the wetlands bordering the city have been transformed into built-up and other land cover types. In this study four remotely sensed images (1972 – 2011) were used to delineate the temporal and spatial patterns of wetland conversion to built-up areas or to other types of land cover. The satellite data were processed using GeOBIA method and post-classification comparison. GeOBIA as a classification technique using shape, adjacency, and topological entities is increasingly becoming a better method than the traditional pixel based classification. Accuracy assessment of classification indicated that GeOBIA can provide accurate land cover conversion information with overall accuracies ranging from 81.3 percent to 89.9 percent for the four classified images. The study suggests a rapid decrease of wetland areas in EKWs due to an expansion of urban areas and other land cover types (i.e. croplands, forests, and bare land). According to post-classification, about 24.5 percent of wetlands have been converted to built-up areas over the past 39 years change and the conversion rates increased with each time period analyzed. Western EKWs showed a higher rate of area change than other parts of the study area. Conversion of wetlands to other land cover types is also a reason for wetland shrinkage in EKWs, which occurred mainly in eastern and southern parts of EKWs. The categorical estimation of EKWs LULC conversion is a much needed assessment aligned with rapidly growing urban development in the global south. It will help in understanding the land-atmospheric dynamics, social and economic transitions in vulnerable areas like EKWs. To further utilize this study EKWs LULC classification will be fed into the Weather Research and Forecasting (WRF) model (Skamarock et al., 2008) to investigate the role of wetland conversion in influencing the microclimatic variability in and around Kolkata City. Studies like the above are a step further into quantifying the impacts of population pressure on resources and land cover types which will help plan better for a sustainable future in fast growing developing world urban areas.

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# 4. Impact of wetland area decrease on microclimate as detected by Weather Research and Forecasting (WRF) Model

## 4.1 Introduction

Microclimate is the climatic conditions on a specific local scale. It synthesizes "the ambient physical conditions due to either atmospheric variables or exchanges with other bodies over a period of time representative of all the conditions determined by the natural and manmade forcing factors" (Camuffo 1998, p8). The atmospheric variables including temperature, humidity, and precipitation are important for human existence and can be influenced by human activities (Hartig et al. 1997; McMichael et al. 2006). Meanwhile, microclimate also affects the ecological processes of ecosystems. Elevated temperature tends to increase crop yields (Stone et al. 1999; van Ittersum et al. 2003) and to precede phenological events of plants such as leafing, flowering, and shooting (Estrella et al. 2007). Precipitation and soil moisture play important roles in controlling the plant productivity and regional nutrient cycling (Schuur 2003; Heisler-White et al. 2008).

Land use/land cover (LULC) dynamics is one of the main factors causing changes in microclimate in recent decades (Rahman, 2014). Wetlands are essential components of microclimate because they have their own characteristic moisture cycles due to the specific aquatic plants present (Carrington et al. 2001). Conversion of wetland areas to agricultural lands was a main reason for wetland loss in the world due to the increased population pressures, and the conversion rate has been further accelerated dramatically in the 20th century due to reductions in runoff and increase in evapotranspiration under climate change (Hartig et al. 1997; Rijsberman and De Silva, 2006). The drainage ditches built for agriculture have significantly lowered the water table of wetlands and reduced water-storage capacity, changing local hydrological cycling such as evapotranspiration and runoff (Bartzen et al. 2010). Moreover, Marshall et al. (2004) suggested that shifts of wetlands to croplands have resulted in or increased the severity of freezes in South Florida because decreases in water depth influenced the effective heat capacity and lowered the minimum temperature. Besides water storage, changes in vegetation types can also influence precipitation and local water cycling due to differences in evapotranspiration (Kutzbach et al. 1996; Carrington et al. 2001).

Decreases in wetland regions not only alter compositions of plants but also influence the permeability of surface land. Conversion of wetland to built-up areas increases the impervious surfaces that increase surface runoff, and therefore impacting the water cycle of the region. Along with increased built-up areas elevated temperature can also be observed due to urban heat island effect, which is mainly caused by elevated heat emissions from human-related sources and reduced vegetation covers (Weng et al. 2004; Chen et al. 2006; Tan et al. 2009). Carlson and Arthur (2000) investigated the effects of LULC dynamics on microclimate at three different locations by satellite imagery in Philadelphia, PA, U.S. Experimental results suggested that areas with large water bodies were sensitive to built-up area expansion. The temperature increased 38% while the moisture decreased 14% when a region changed from an open water body to 30% urbanized area (Carlson and Arthur 2000).

Influences on microclimate due to LULC change can be explored by the Weather Research and Forecasting (WRF) model (Hong et al. 2009; Mahmood et al. 2011). The WRF model is a fully compressible, non-hydrostatic numerical weather prediction system used for weather forecasting and atmospheric research (Skamarock et al., 2008). It has been developed by a community of government agencies and researchers. The model is able to conduct both real data simulations (observations, analyses) and idealized atmospheric condition predictions and to serve a wide range of application areas from meters to thousands of kilometers (http://www.wrf-model.org/). The efficiency of the model has been proved in several research fields including air quality prediction (Misenis and Zhang 2010; Zhang et al. 2010a), fire-weather simulation (Mölders 2008), extreme weather simulation (Wang et al. 2006; Evans and McCabe 2010), as well as climate change issues (Jiménez et al. 2011; Zaitchik et al. 2013).

Various studies have used the WRF model to successfully assess the impact of LULC dynamics on microclimate. As discussed above, changes in land cover can significantly alter the microclimate of a region. The WRF model is highly sensitive to vegetation fluctuations and land use changes (Hong et al. 2009; Mahmood et al. 2011). Zhang et al. (2010b) utilized WRF model to investigate the microclimate change in China. They found that conversion of cropland to urban space increased both temperature and precipitation but decreased surface humidity with a stronger influence in summer than in winter. Mahmood et al. (2011) used the WRF model by combining it with the National Center for Atmospheric Research's (NCAR) fifth generation mesoscale model (MM5) model to investigate the responses of climatic indices on LULC dynamics in Western Kentucky, USA. Results suggested that changes in land use influence latent heat flux, temperature, relative humidity, as well as wind. However, the impacts were diminished during nighttime. More specifically, by incorporating Noah Urban Canopy together with WRF model, Grossman-Clarke et al. (2010) explored how much urban expansion contributes to an increase in near-surface air temperature and they observed the maximum temperature increase when irrigated agricultural lands were replaced by suburban areas.

Under the pressure of rapid population growth, it is easy to expand agricultural and built-up areas at the expense of wetlands because drained wetlands provide perfect sources for arable lands in dry season (Scoones 1991). It is necessary to evaluate how greatly the microclimate can be altered due to wetland shrinkage as that could influence economic growth and have impacts on human health. In this chapter, WRF model was applied to investigate influences of LULC change and wetland conversion on temperature, precipitation, latent heat flux, sensible heat flux, and albedo at Kolkata city. The study will be of first order significance in assessing the role of urban area increase on Kolkata's local hydrology and climate.

## 4.2 Material and Methodology

### 4.2.1 Methods

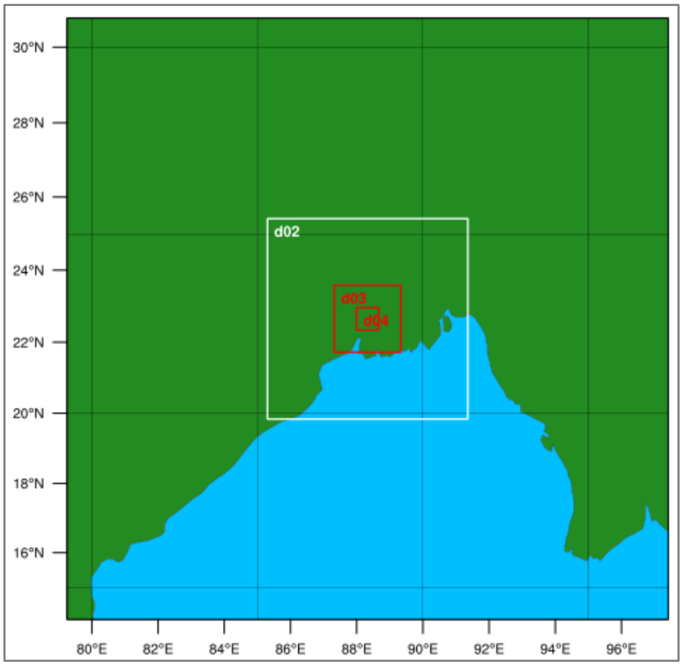


**Figure 4.1 Four nested domains selected for model simulation**

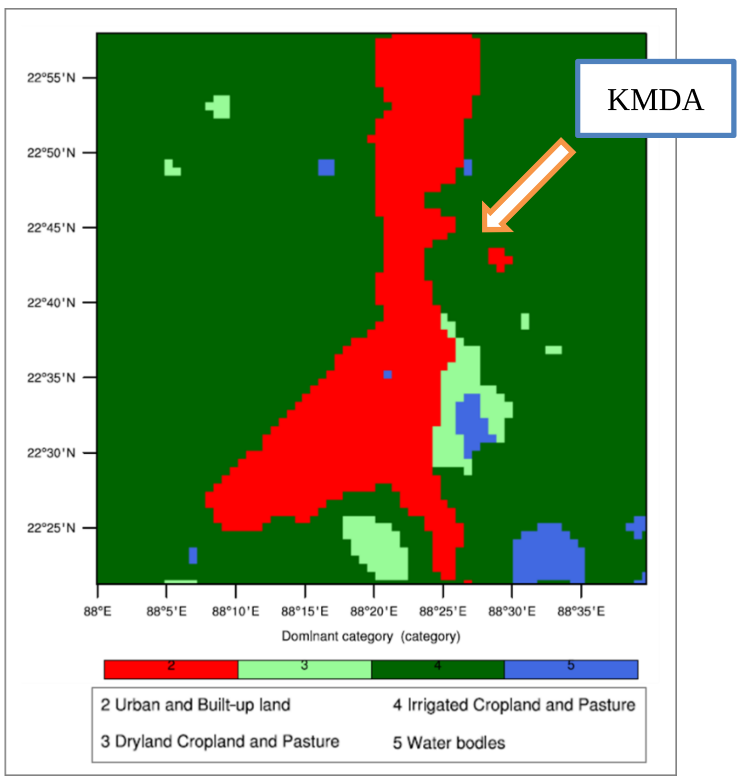


**Figure 4.2 Domain d04 showing Kolkata city**

The effects of wetland shrinkage on the microclimate of Kolkata city were explored by the WRF model simulation using scenario analyses. This model allows for both idealized simulation based on existing data in WRF and simplified analytic orography as well as real weather simulation based on observational data. WRF 3.5.1 in a one-way nesting technique was applied in this chapter. Four domains (d01 to d04) were included, which have resolutions from 27 km to 1km (Figure 4.1) and KMDA is located in the center of domain d04 (Figure 4.2).

A series of physics components were developed for the model simulation, including microphysics, radiation, surface layer and boundary layer parameterization, as well as cumulus parameterization. Both sophisticated physics and simple physics schemes are included in the model directed to different targets since the model is developed for both research and operational groups (Skamarock et al., 2008). As a result, to improve the model efficiency, selections of schemes are important because schemes may perform differently at different scales and different regions (Chen and Dudhia 2000). For example, Kumar et al. (2010) compared performances of three cumulus schemes in Indian rainfall forecast and found that Betts-Miller-Janjic scheme performed better than Kain-Fritsch and Grell-Devenyi schemes in the monsoon region and was able to capture monsoon precipitation at multi-scales (Kumar et al., 2010). Noah Land Surface Model (Noah LSM) is the widely used land-surface layer scheme. It connects atmospheric characteristics with land-surface properties (i.e., land uses) to evaluate heat transport and moisture exchanges (Hong et al. 2009). This scheme has been successfully applied for temperature and precipitation prediction under land use change conditions in various cities (Borge et al. 2008; Jiang et al. 2008; Hong et al. 2009; Grossman-Clarke et al. 2010). In this chapter, WRF Single-

Moment 5-class microphysical scheme was applied to predict water vapor and condensate as cloud, rain, cloud ice and precipitation ice (Skamarock et al. 2008). The Noah LSM scheme was selected as land-surface layer scheme. The rapid radiative transfer model for GCM (RRTMG) was used to determine transfer processes of longwave radiation (Iacono et al. 2008) and Dudhia scheme was chosen for shortwave radiation. Yonsei University scheme was applied to solve turbulent vertical fluxes throughout the planetary boundary layer (PBL) (Hu et al. 2010). For the cumulus scheme, Betts-Miller-Janjic scheme was used in this chapter. Some details of the model configuration were listed in Table 4.1.

**Table 4.1 Model configuration and physics schemes during simulation**

| | |
|---|---|
| Number of domains | 4 |
| Resolution | 27 km (domain d01), 9 km (domain d02), 3 km (domain d03), 1 km (domain d04) |
| Number of grid points | 70 × 70 (all domains) |
| Map projection | Mercator |
| Central point of the domain | Central latitude: 22.66 °N<br>Central longitude: 88.33 °E |
| Microphysics scheme | Single-Moment 5-class microphysical scheme |
| Land-surface layer scheme | Noah land surface model |
| Radiation scheme (long wave) | Rapid radiative transfer model for GCM (RRTMG) |
| Radiation scheme (short wave) | Dudhia scheme |
| Boundary layer physics | Yonsei University scheme |

| | |
|---|---|
| Cumulus convection scheme | Betts-Miller-Janjic scheme |

***4.2.1.1 Scenario Analyses***

Scenario analyses were conducted to quantify contributions of wetland conversion to microclimate changes. This study used three scenarios running from November 2011 to January 2012. The reason for choosing this period is because this period is the dry season in Kolkata city, which can reduce anomalous precipitation due to the influence of monsoon rainfall.

Scenario 1: Real weather simulation

A real weather running was first applied to simulate microclimate in KMDA during the chosen period. This process used the 33-category U.S. Geological Survey (USGS) Land Use/Land Cover system as LULC data for Kolkata city.

Scenario 2: wetland and cropland to built-up conversion

The assumption in this scenario was that conversions of wetlands and croplands to built-up areas are the assumed LULC change during study period. Other LULC patterns are kept unchanged similar to LULC patterns in 2011. To achieve this object, parameters of "dryland cropland and pasture", "irrigated cropland and pasture", "herbaceous wetland", and "wooded wetland" were changed to parameters of "urban and build-up land" in LANDUSE.TBL and VEGPARM.TBL and re-run the weather simulation.

Scenario 3: wetland and dryland cropland to irrigate cropland conversion

The assumption in this scenario was that conversions of wetlands and dryland cropland to irrigate cropland are the assumed LULC change during study period. Other

LULC patterns are kept unchanged similar to LULC patterns in 2011. For this case, parameters of "dryland cropland and pasture", "herbaceous wetland", and "wooded wetland" were changed to parameters of "irrigated cropland and pasture" in LANDUSE.TBL and VEGPARM.TBL.

Daily temperature, precipitation, latent heat flux, sensible heat flux, and albedo in scenario 2 and 3 were compared with the variables in real weather simulation (scenario 1) to extract the contributions of different land cover conversions on micro-climate change.

#### *4.2.1.2 Model evaluation*

Model performance evaluation is an important step for model assessment and development. In this chapter, it was conducted by comparing temperature and precipitation that obtained from real simulation with observational data. Three criteria were applied to evaluate temperature simulation in this chapter. The first one used the coefficient of determination ($R^2$) that obtained from linear regression between the simulation and observation. The higher $R^2$ is, the better model performance it indicates.

The second criterion applied the Theil's inequality coefficient (*U*, Theil, 1966):

$$U = \sqrt{\frac{\sum_{i=1}^{n} \Delta_i^2}{\sum_{i=1}^{n} Observed_i^2}} \qquad (4\text{-}1)$$

where $\Delta$ is the difference between the observed and simulated data and *n* is the total number of the compared data. *U* when close to 0 suggests a perfect model performance.

Model efficiency (ME) was also used as the third criterion:

$$ME = 1 - \frac{\sum_{i=1}^{n} \Delta_i^2}{\sum_{i=1}^{n} (Observed_i - \overline{\Pr edicted})^2} \quad (4\text{-}2)$$

in which a perfect fit between the observed and predicted data is considered when *ME* is equal to 1. The model performance is no better than an average value if *ME* is 0 and is poor if *ME* is negative.

For precipitation, the coefficient of determination ($R^2$) was also determined for model evaluation. Unlike temperature evaluation that used all simulated data, the determinate of $R^2$ only included days with measurable precipitation amount. Besides $R^2$, bias precipitation factor was applied because the dataset do not follow normal distribution. The bias factor is the ratio of total number of correct forecast of precipitation occurrence to the total number of observed precipitation occurrence (Duethmann et al., 2013).

Changes of climate variables (temperature, precipitation, latent heat flux, sensible heat flux, and albedo) with time were evaluated through mean values and standard deviation. Moreover, to investigate the significance of changes of climate variables in different study years, paired *t*-tests were also applied.

### 4.2.2 Data

Climate variables, such as precipitation and temperature between 1972 and 2012 were collected from the Dumdum station (22˚39' N, 88˚26'W) for WRF model performance evaluation. The station is located in Kolkata city. In addition, NCEP/NCAR reanalysis data at 2.5 °×2.5 °resolution were used as references for observed and simulated data comparison.

## 4.3 Results and discussion

### 4.3.1 Scenario 1 – real weather simulation

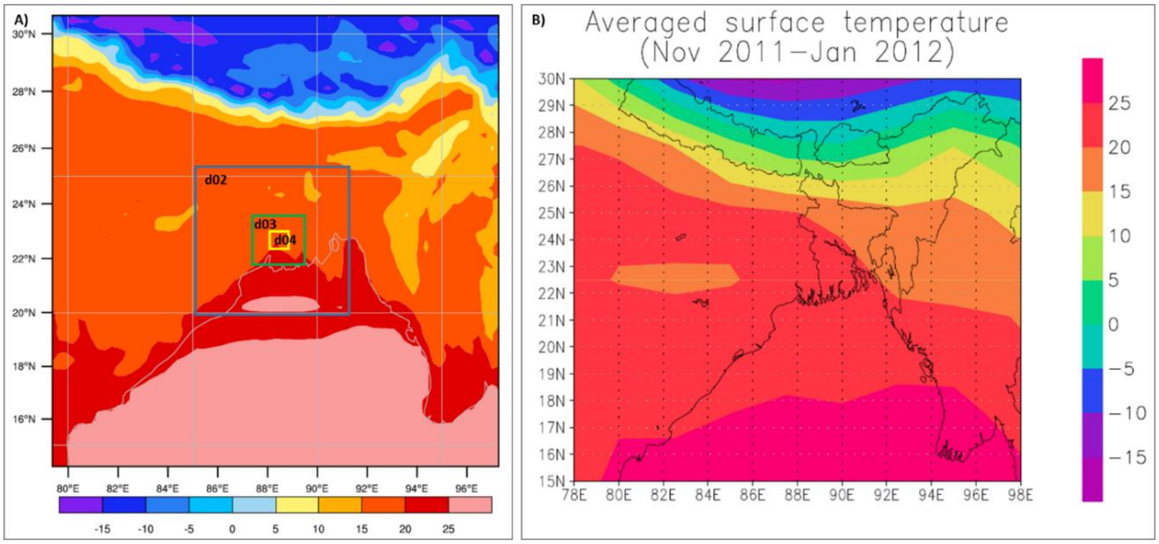


**Figure 4.3 Comparison of mean daily temperature in domain 1 between A) simulated data and B) NCEP/NCAR reanalysis.**

The simulated temperature data in domain 1 was compared with reanalysis data at 2.5 °×2.5 ° resolution (Figure 4.3). The general spatial variations are similar between two figures. During study period the highest temperature was found in ocean area with a mean daily temperature above 25 ℃; while the lowest temperature was observed in Tibet area with a mean daily temperature below -15 ℃. The temperatures of inland India are in a range of 15 ℃ to 25 ℃. However, our model simulation shows a higher temperature variation in Myanmar than the reanalysis data.

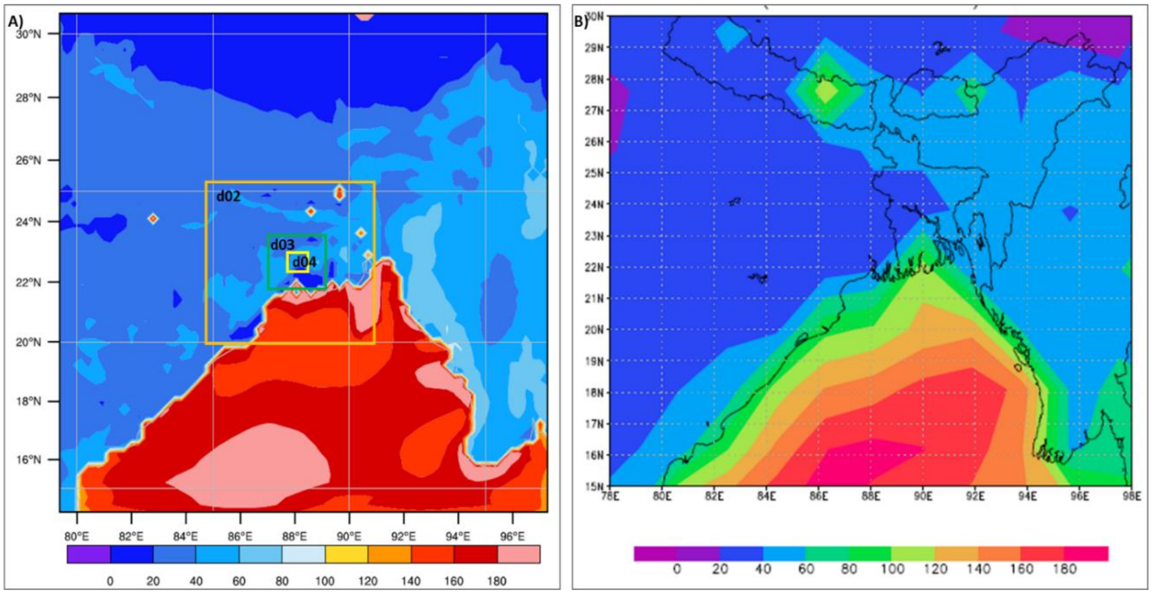


**Figure 4.4 Comparison of mean daily latent heat flux in domain 1 between A) simulated data and B) NCEP/NCAR reanalysis.**

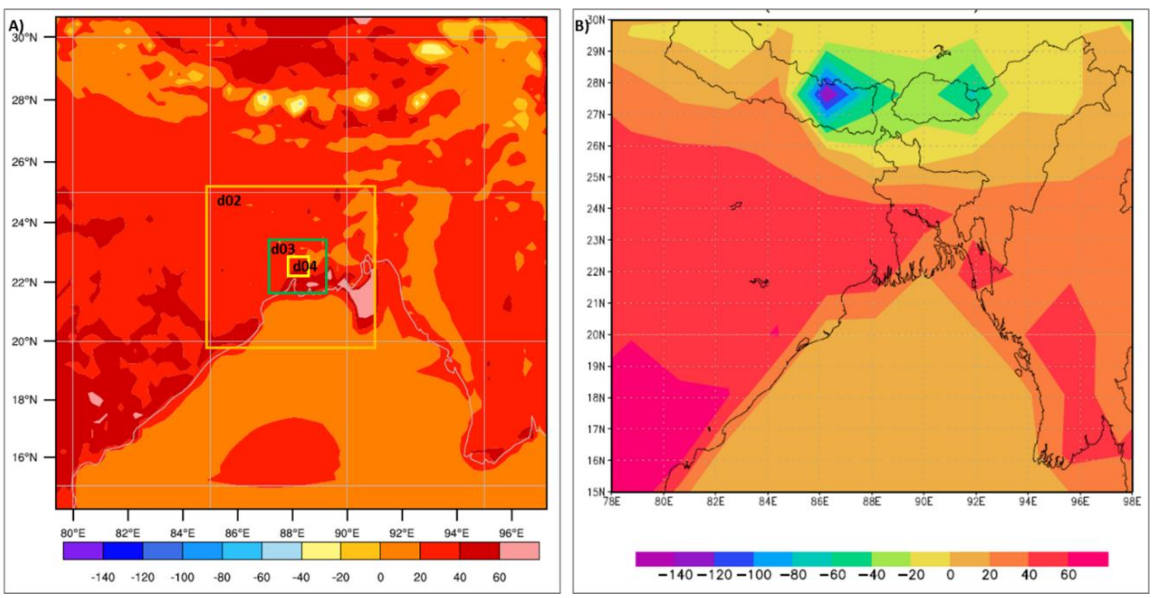


**Figure 4.5 Comparison of mean daily sensible heat flux in domain 01 between A) simulated data and B) NCEP/NCAR reanalysis.**

Simulated heat fluxes by WRF were also evaluated against the reanalysis data. In this study, latent heat flux refers to the energy flux exchange between land surface and the atmosphere that is used for phase changes of water through evapotranspiration and subsequent condensation, whereas sensible heat flux refers to the energy fluxes during temperature changes of the land surface. For both simulated data and reanalysis data, high latent heat fluxes were observed in ocean areas while relatively low fluxes in inland area (Figure 4.4). Similar as temperature, the simulated data shows a higher variation in Myanmar than the reanalysis data. For sensible heat flux, the ocean has relatively low values compared with inland area (Figure 4.5). It varies from 40 W $m^{-2}$ to 60 W $m^{-2}$ in India in our simulated data, which is similar to reanalysis data. However, our simulated data have higher values in the northern part of our study region (Himalaya Mountain) than the reanalysis data. This suggests that a further selection on schemes related to sensible heat flux may be needed for studies for high elevation areas.

**Table 4.2 Assessment of temperature simulation**

| | $R^2$ | *U* | *ME* |
|---|---|---|---|
| Temperature | 0.790*** | 0.067 | 0.708 |

**Table 4.3 Assessment of precipitation simulation**

| | Bias (%) | $R^2$ |
|---|---|---|
| Precipitation | 31 | 0.659*** |

Moreover, model performance was evaluated by comparing simulation with field data at the Dumdum station. Here two major meteorological factors including daily temperature and daily precipitation were used. In general, the model has decent representations of the two selected climate factors (Table 4.2 and Table 4.3). Determination of coefficient ($R^2$) for temperature simulations is 0.79 and this value is statistically significant. The Theil's inequality coefficient for temperature is 0.067, which suggest that temperature was well simulated by the model. In addition, ME value (0.708) is close to 1 and further indicates that the real-simulation reasonable matched observed data. Determination of coefficient for precipitation simulation is 0.659 and also suggested that the modeled precipitation events matched observation well. Bias between model simulation and field data indicate that there are some discrepancies between modeled and simulated precipitation.

The WRF model has been widely used in simulating regional meteorological conditions (Evans et al., 2012; Shrivastava et al., 2015; Yang et al., 2015). A variety of evaluation methodologies have been developed to evaluate the performance of the model (Jankov et al., 2005). Results of the evolution in this study is consistent with previous studies that shows less bias in temperature simulation than that in precipitation (Evans et al., 2012). In addition to the uncertainties in input land cover data and temporal/spatial resolution multiple driving forces, physical options in model parameterization could be an important cause for the discrepancies between model simulation and observation (Shrivastava et al., 2015). In the future, model performance could be potentially improved by optimizing multiple parameterization schemes (Lee et al., 2011).

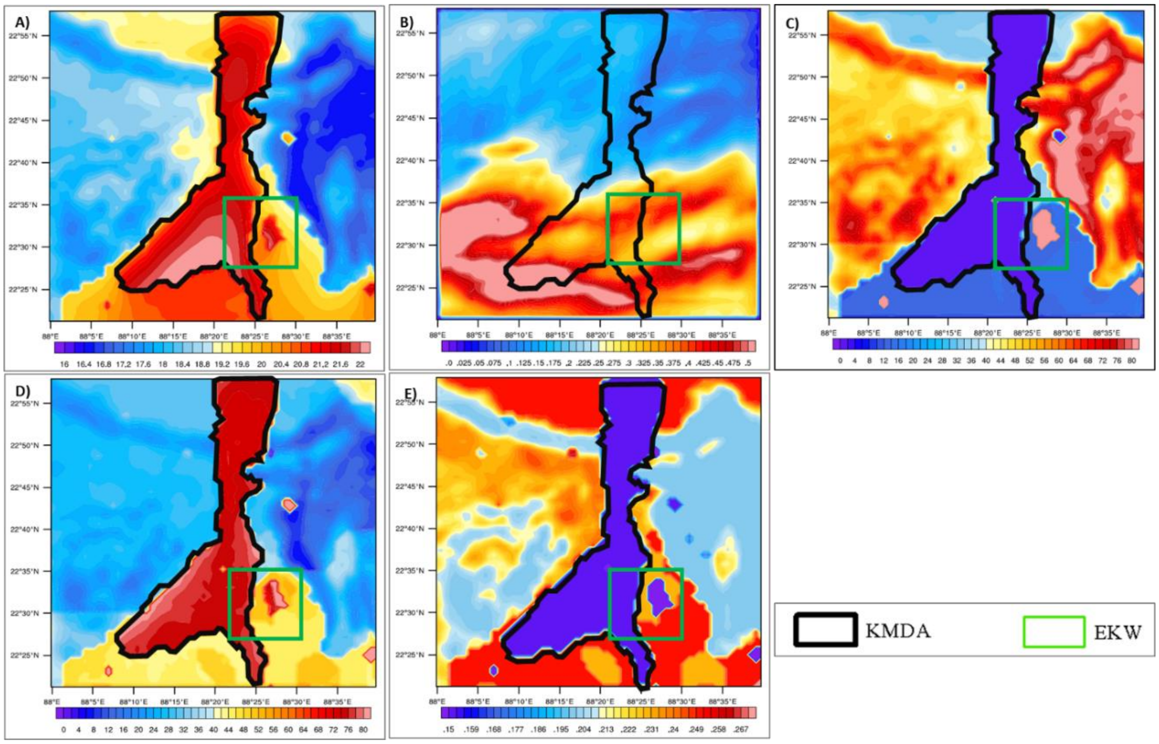


**Figure 4.6 Spatial variation of climate variables in real simulation (Scenario 1). A) temperature (℃), B) precipitation (mm), C) latent heat flux (W m$^{-2}$), D) sensible heat flux(W m$^{-2}$), and E) albedo.**

Figure 4.6 presents the spatial distribution of simulated meteorological variables from scenario 1. Due to the heat island effect, the KMDA area has much higher average temperature than the rest parts of this region (Yap and Oke, 1974; Stewart and Oke, 2009). Temperature in southern coastal regions was also higher than that in the land parts. Lowest temperature in the study period occurred in the eastern parts of this region. Results of the temperature simulation indicate that urban heat island and the different specific heat of land and oceans are the two factors determining the thermal environment in this region. Precipitation in the southern parts of this region is higher than the northern areas. Precipitation in the urban area was not different from that in rural areas, and thus suggests that regional circulation plays a more important role in determining spatial patterns of precipitation. Patterns of the latent heat fluxes are contrasting with that of temperature. In the KMDA region and the southern parts of the study area where heat fluxes from land to the atmosphere are low, average temperatures are mainly over 19 ℃. Conversely, in the rest cropland regions which show much higher latent heat flux (generally over 40 W $m^{-2}$), temperatures were generally below 19 ℃. Low water contents in soils of built-up regions were mainly responsible for the low latent heat fluxes in urban regions. Contrasting patterns between latent heat flux and temperature is in line with the previous investigations that reported the cooling effects of plantation relative to built-up regions. However, it should be noted that even latent heat flux at the EKW region was high, it did not result in low temperature in this region. Instead, temperatures in this area are comparable with that in the urban regions. Possible explanation can be derived from the EKW distribution of the sensible latent flux figure. As depicted in figure 4.6D, water body of EKW region had high sensible heat fluxes during winter time, and thus resulted in the relatively higher temperature (Sánchez-Carrillo et al., 2004). Due to the low specific heat in urban area, urban areas tend to be net source of sensible heat, whereas the rest parts of the study area tended to obtain energy from the atmosphere to support evapotranspiration.

**4.3.2 Scenario comparison**

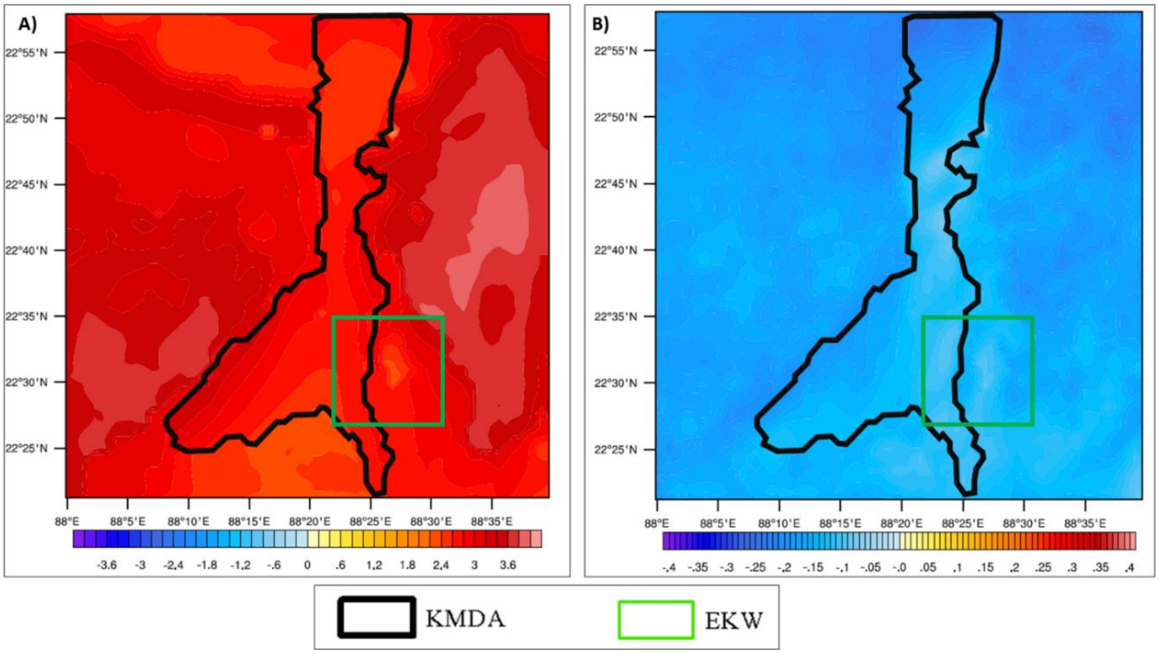


**Figure 4.7 Mean daily temperature (℃) changes following LULC change. A) Scenario 2 – Scenario 1, B) Scenario 3 – Scenario 1.**

Model simulation indicated that changing land cover scenarios greatly altered multiple meteorological factors and associated water and energy fluxes. Figure 4.7 demonstrates the spatial differences in temperature of the two land cover change scenarios relative to the real simulation. Land conversion from wetlands and dryland croplands would result in over 3.0 ℃ increases of temperature in most parts of the study area. Land conversion has been considered as one of the most significant and far-reaching modifications to the natural ecosystems (van Asselen and Verburg, 2013). Built-up areas dramatically altered surface areas, thermal characteristics, moisture pathways and tend to add extra energy supply relative to ecosystems (Grimmond, 2007). Our simulation indicated that if the study area was totally urbanized, average temperature would increase by 1.2-4 ℃ in most parts of the study area. This elevation is consistent with the previous investigations for major Asian cities (Taniguchi et al., 2007).

Comparison between scenario1 and 3 indicated that expanding irrigated cropland mainly resulted in reductions in temperature. In most parts of the study area, decreased temperature was less than 0.3 ℃. Reduction in temperature in scenario 3 could be attributed to the enhanced ET and heat capacity in irrigated cropland compared with dry wetland (Kalnay and Cai, 2003).

One phenomenon should be noted here is that heat-island effects and the cooling effects not only affect areas with changing land cover types, but also happen in the KMDA region. High temperature in the urban area (Figure 4.6A) would be further enhanced by urban sprawl in the adjacent rural regions. Similarly, expansion of irrigated area would also contribute to reducing urban temperature. This study highlights the far-reaching impacts of land conversion on regional climate systems and suggests that a systematic analysis that considers both direct and indirect impacts from land conversions will be necessary for assessing potential consequence of land cover change in the future (Feddema et al., 2005).

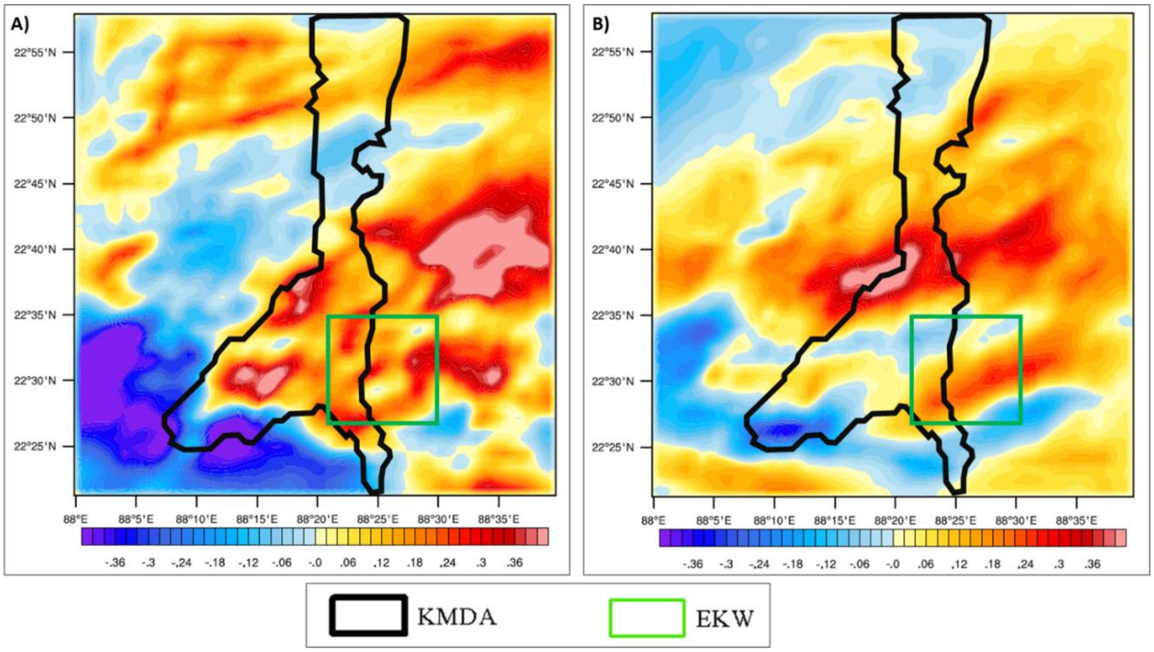

**Figure 4.8 Mean daily precipitation changes (mm) following LULC change. A) Scenario 2 – Scenario 1, B) Scenario 3 – Scenario 1.**

Impacts of land cover changes on precipitation are complicated (Mahmood et al., 2010). Figure 4.8 shows that land cover conversion induced both increased and decreased precipitation in the study area. For urbanization scenario, precipitation center tends to move northeastern ward and leads to increased rainfall in the northeastern parts of this region. This may be caused by downwind effect. In real weather simulation, the precipitation is extremely higher in Jan. 7$^{th}$ and Jan 8$^{th}$ than in other days with southwest winds. The low-level prevailing wind tends to advect the moisture and low level convergence downstream urbanized area and thus leads to enhanced precipitation some distance downwind of urban areas (Shepherd et al., 2002). For the EKW domain, precipitation is mainly enhanced, except for in the central areas where wetlands are located. For the KMDA domain, rainfall was generally stimulated in the south, but reduced in the central-north areas. Northern regions of the study area also received higher rainfall relative to the control simulation. Decreased precipitation can be found in the southwestern parts of this region.

Impacts of urbanization on rainfall patterns have been widely documented, especially for major metropolitan areas. In consistent with some of the previous investigations, this study also shows that response of precipitation to urbanization is not as evident as that of temperature (Tayanc and Toros, 1997). Underlying mechanisms regulating rainfall response to urbanization have not been adequately explored yet. Urbanization induces a series of complicated changes in land surface roughness, soil moisture and the exchange of water and energy between land and the atmosphere (Lamptey et al., 2005). These changes can either offset or enhance each other and thus further complicate the spatial patterns of precipitation (Trusilova et al., 2008).

Expansion of irrigated cropland tends to move the precipitation center to the central regions of the study area. Figure 4.8B suggests that most parts of the central and eastern areas would experience enhanced rainfall. Reduced rainfall was mainly located in the southwestern and northwestern parts of the study area. For the EKW domain, irrigated cropland tends to enhance precipitation in most parts of this area. In the KMDA domain, precipitation showed significant increases in the center of the city but decreases in northern and southern parts of the city. In the southeast corner of the city, precipitation was significantly reduced.

Previous studies have reported that expansion of irrigation has positive impacts on precipitation (Wei et al., 2012). Increases in precipitation are possibly caused by enhanced evapotranspiration following expanded irrigated land (Deangelis et al., 2010). Similar to the impacts contributed by urbanization, precipitation changes in scenario 3 may also due to the differences in land surface for different areas (Wei et al., 2012) , or the complicated changes in atmospheric circulations (Kueppers and Snyder, 2012).

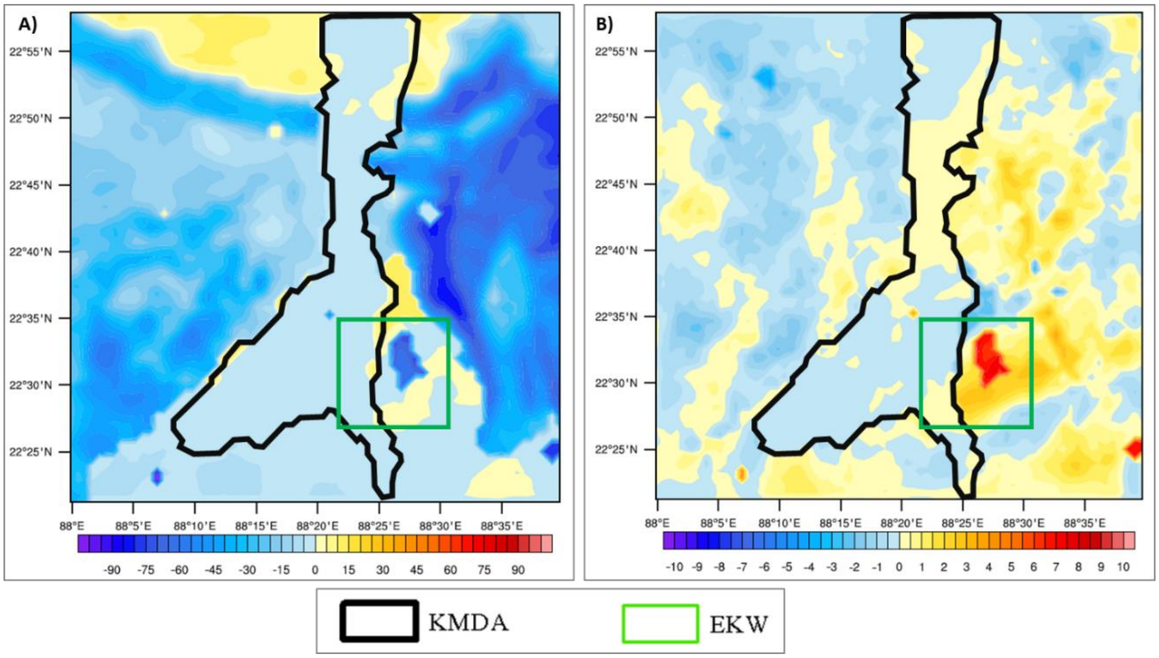


**Figure 4.9 Changes of mean daily latent heat fluxes (W m$^{-2}$) following LULC change. A) Scenario 2 – Scenario 1, B) Scenario 3 – Scenario 1.**

The majority of the study area received reductions in latent heat fluxes under the urbanization scenario (scenario 2). For the KMDA and the southern parts of the study area where built-up land covers are the primary land cover types, latent heat flux did not show much different. In the EKW domain, land cover conversion reduced evapotranspiration and resulted in reductions of energy fluxes by more than 60 W m$^{-2}$. In the eastern and western regions where cropland was the major land cover type before urbanization, latent heat flux was generally reduced. Changes in latent heat fluxes were mainly caused by the changes in soil water contents (Zhang et al., 2010). Conversions from natural ecosystems, especially wetlands, to paved surfaces tend to alter the natural water cycling processes such as water infiltration and associate water movement in soil. High percent of impervious surface area favors surface runoff generation but reduces evapotranspiration (Trusilova et al., 2008).

Response of latent heat fluxes to land conversions from wetland and dry cropland to irrigated cropland show significant heterogeneity in the study area. Eastern parts of the study area generally experienced increased heat flux, whereas in most western parts lateral heat fluxes were reduced. In the EKW domain, expansion of irrigated cropland significantly enhanced latent heat fluxes. Changes in latent heat fluxes following expanding irrigated cropland could be partially explained by the fact that irrigation generally enhanced evapotranspiration (Wei et al., 2012). However, some other indirect impacts associated with changes in the atmospheric circulation, may also responsible for the changes in land surface heat fluxes. For example, reduced latent heat fluxes in the northwestern parts of the study area could possibly be attributed to the reduced precipitation and cooling effects of irrigation (Nagler et al., 2007).

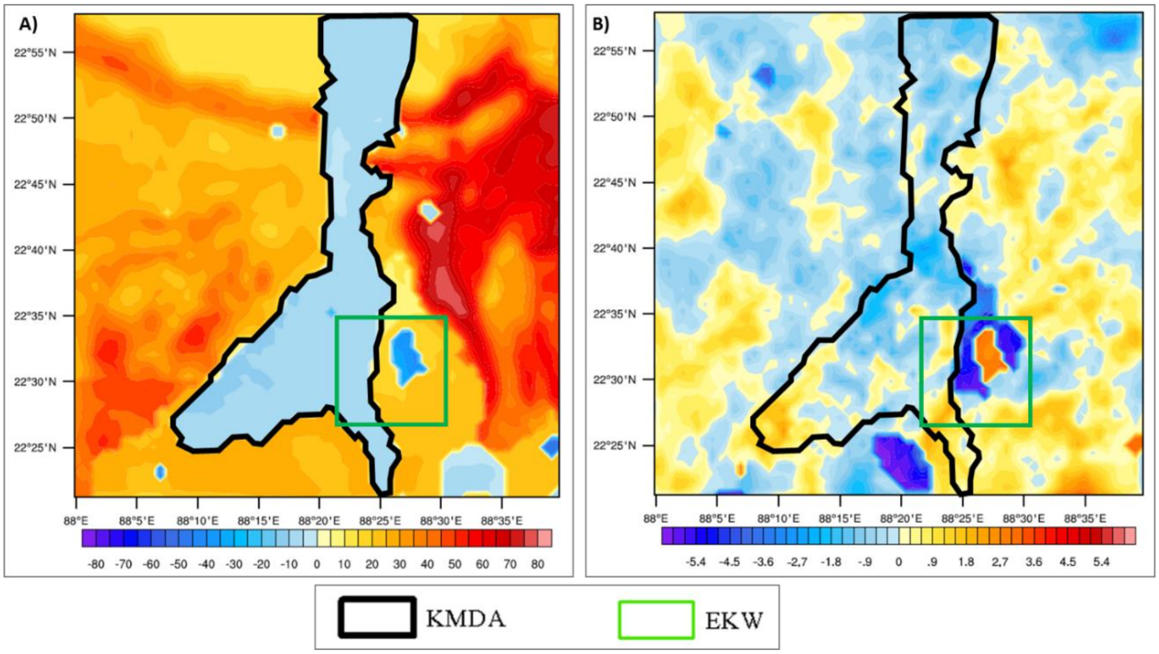


**Figure 4.10 Changes of mean daily sensible heat fluxes (W m$^{-2}$) following LULC change. A) Scenario 2 – Scenario 1, B) Scenario 3 – Scenario 1.**

Sensible heat flux is mainly determined by the temperature difference between land surface and the atmosphere (Yap and Oke, 1974). Heat island effects following urbanization increase local land surface temperature and stimulate heat emission from land to the atmosphere (Rizwan et al., 2008). Spatial distribution of the difference in sensible heat flux shows that urbanization greatly enhances heat flow between land and the atmosphere. For the KMDA area where most built-up areas are located, sensible heat fluxes were not changed much by the expanding urban area in the adjacent areas. Results of this study is consistent with previous studies that reported increased sensible heat flux and decreased latent heat flux following urbanization due to the conversion of natural vegetation to built-up surfaces which have lower albedo than natural ecosystems (Kueppers et al., 2008).

Although increasing irrigated croplands mainly reduced air temperature in this region (Figure 4.7), changes in sensible heat fluxes are either positive or negative relative to the unchanged land cover scenario. Figure 4.10 indicates that in the western and eastern regions of this study area, sensible heat fluxes are mainly enhanced, whereas in the central regions, the heat flux is mainly reduced. In the KMDA domain, where land cover is consistent between the two simulations, sensible heat flux was also reduced and thus suggested that irrigation activities in the local areas may affect energy fluxes in surrounding areas (Stohlgren et al., 1998).

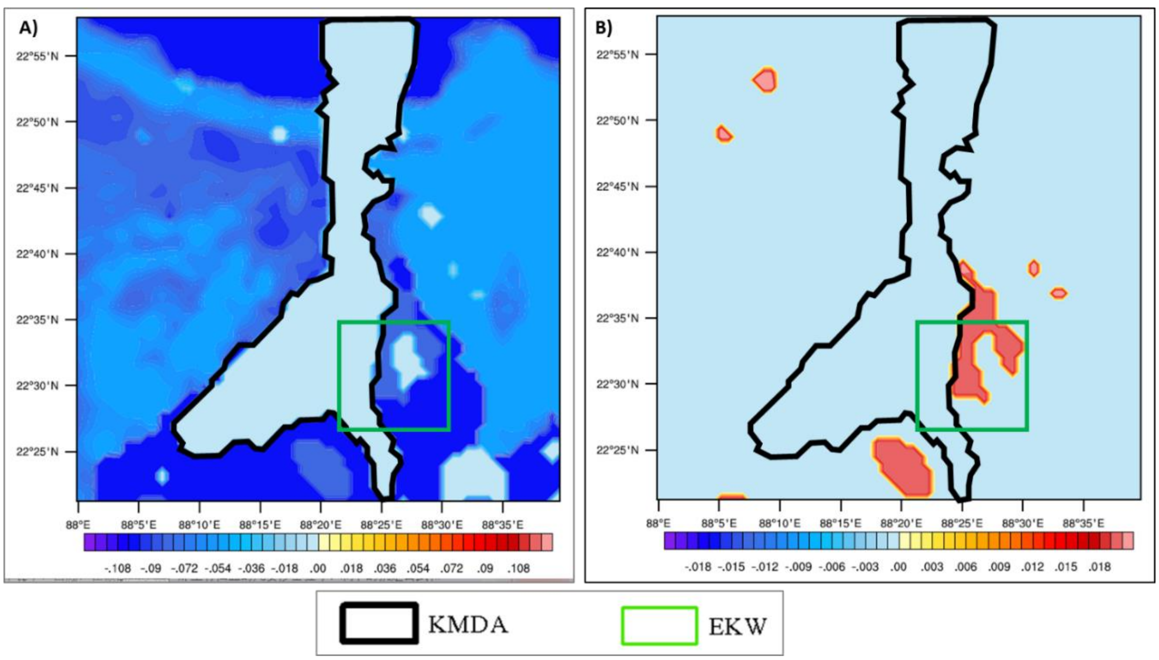


**Figure 4.11 Changes of albedo following LULC change. A) Scenario 2 – Scenario 1, B) Scenario 3 – Scenario 1**

Albedo is the fraction of solar energy reflected from the Earth back to space. It can be changed by land cover change. Royer et al. (1988) found a decrease in surface albedo when vegetation converted to urban areas. The relatively low albedo in urban areas than cropland may be caused by the multireflection effect between buildings (Wang et al., 2007). Besides that, more aerosol emissions in urban area absorb solar shortwave radiation and lower albedo of urban (Wang et al., 2007). Similar trend can be found in our study. A decreased albedo was observed around the KMDA when croplands and wetlands were converted to built-up areas, which can be a major reason for temperature change in study region (Figure 4.11A; Betts, 2001; Myhre and Myhre, 2003).

Although the replacement of dryland croplands and wetlands to irrigated croplands led to an increase of precipitation and soil moisture, which is usually followed with a reduction of shortwave reflection (Graser and Van Bavel, 1982; Wang et al., 2005), our study suggests an increased albedo in Figure 4.11B. The result suggests that rather than soil moisture, other factors, such as plant types, may play an important role in determining the albedo in the KMDA.

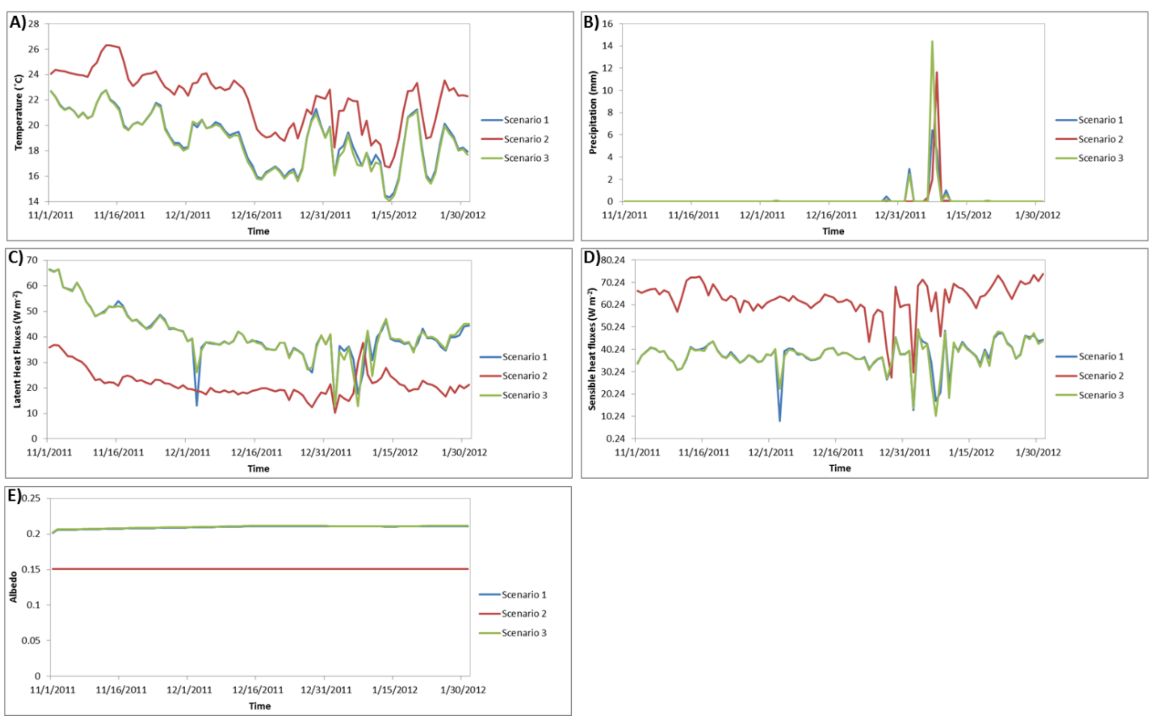


**Figure 4.12 Comparison of climate variable changes among three scenario analyses. A) temperature (℃), B) precipitation (mm), C) latent heat flux (W m$^{-2}$), D) sensible heat flux(W m$^{-2}$), and E) albedo.**

This study also checked the temporal patterns of major meteorological variables from the three scenario simulations (Figure 4.12). Results indicated that scenario 1 and 3 generated similar temperature time series from the beginning of November, 2011 to the end of January, 2012. In the two scenarios, temperatures generally had decreasing trends with significant variability occurring in January of 2012. The study indicated that urban sprawl could dramatically increase average temperature. Due to the changing albedo and hydrological cycles, urban area tended to have higher temperature (Ren et al., 2008). However, the temporal variation of temperature from scenario 2 is similar to that of the other scenarios, and thus suggested that atmospheric circulation play the primary role in determining temporal changes in temperature.

Winter is a dry season in India since most of the rainfall events occur in the monsoon season (Krishnamurthy and Shukla, 2007). The three simulations agreed well in that no precipitation occurs in November and December of 2011, which is similar to the observational data. The simulations were also consistent in the occurrence of rainfall events in January 2012. However, the magnitudes of rainfall were divergent from the three simulations. For the two rainfall events occurred around December 20$^{th}$ and in the beginning of January, scenario 1 and 3 had similar estimates. However, precipitations from scenario 2 during these two events were significantly lower in the scenario 2 simulation. Largest discrepancies among the three simulations occurred to the rainfall events occurs around January 7$^{th}$. For this event, scenarios (2 and 3) with changing land cover types tended to induce heavy rainfalls compared with the real simulation.

Changing land covers could largely change the energy exchange between land and the atmosphere (Douglas et al., 2006). For the latent heat flux, both scenario1 and 3 showed similar temporal patterns which decreased with time during the study period. The temporal trend was similar to that of temperature, and indicated that low temperature may reduce evapotranspiration and associate energy fluxes in January of 2012 (Lamptey et al., 2005). The two scenarios had very close estimates, especially in the last two months in 2011. In January of 2012, latent energy flux was a bit higher than that of scenario 1, but their temporal variability was almost identical. This study suggests that urbanization would totally alter the exchange between land and the atmosphere (Kueppers and Snyder, 2012). Increasing urban areas significantly reduced lateral heat fluxes relative to the other two scenarios. In addition to the magnitude, temporal variability in scenario 2 was also much lower than the other simulations.

In contrast to the patterns of latent heat flux, sensible heat fluxes demonstrated increasing trends during the study period. Again, scenario 1 and 3 had similar temporal patterns, but scenario 2 resulted in much higher sensible heat fluxes relative to the other two simulations. Moreover, sensible heat fluxes following the urbanization scenario increased greatly and suggested that urbanized land surfaces are important heat generating source (Kitada et al., 1998).

Since albedo is determined by the land use covers, it only showed slightly increasing trend temporal changes as land cover types were fixed for each simulation. Albedo in scenario 1 and 3 were all around 0.21, and indicating that land conversion from wetland and dry cropland to irrigated cropland did not significantly change the average albedo of the entire region. However, urbanization at the expense of natural and agricultural ecosystems tended to increase albedo.

**Table 4.4 Mean daily and standard deviation (SD) of climate variables of d04 in scenario analyses**

| | Scenario 1 | | Scenario 2 | | Scenario 3 | |
|---|---|---|---|---|---|---|
| | **Mean** | **SD** | **Mean** | **SD** | **Mean** | **SD** |
| **Temperature (℃)** | 18.97 | 2.08 | 22.12 | 2.24 | 18.83 | 2.13 |
| **Precipitation (mm $day^{-1}$)** | 0.171 | 0.87 | 0.155 | 1.23 | 0.230 | 1.557 |
| **Latent heat flux (W $m^{-2}$)** | 41.20 | 9.76 | 21.60 | 5.25 | 41.24 | 9.66 |
| **Sensible heat flux (W $m^{-2}$)** | 37.65 | 6.60 | 62.95 | 7.80 | 37.52 | 6.40 |
| **Albedo** | 0.209 | 0.002 | 0.151 | 0.000 | 0.210 | 0.002 |

Compared with the albedo in unchanged land cover setting (scenario1) which had higher percentage of surface waters, expansion of urban area (scenario 2) tended to decrease land surface albedo (Table 4.4). In scenario 2, albedo decreased by approximately 25%. Changes in the reflectance of solar radiation are important reasons for the related changes in water and energy fluxes (Twine et al., 2004). Compared with scenario 1, sensible heat flux in scenario 2 increases by 25.30 W $m^{-2}$ (about 67% increase). Increased energy input could significantly alter the thermal conditions and lead to heat island in urban areas (Atwater, 1975). Our simulation indicated that land conversion from wetland and cropland to urban areas in the study area would increase average temperature by 17%. Admittedly, lower specific heat capacity of built-up area relative to water bodies should also be responsible for the increased temperature following urbanization (Lamptey et al., 2005). In addition, expanding impervious surface areas in scenario 2 also dramatically affected water cycling (Jacobson, 2011). A decreased precipitation of domain 4 can be observed in scenario 2 relative to scenario 1 due to a northeast movement of precipitation.

Comparison of regional average water and energy fluxes between scenario 3 and scenario 1 indicated that conversion from wetland and dry cropland to irrigated cropland had much smaller impacts on regional climate system than that of urbanization (scenario 2). Model simulation suggested that average albedo and energy fluxes in scenario 3 are similar as that of scenario 1. One significant change in scenario 3 was the increased precipitation relative to the real simulation. Table 4.4 indicates that precipitation increases by approximately 35% after land conversion. This change is in line with previous studies which reported that irrigation could potentially increase precipitation (Deangelis et al., 2010).

**4.4 Limitation of the research and future directions.**

In this chapter, USGS land Use/Land Cover system was used as land cover input for WRF model simulation. However, as shown in Figure 4.2, the USGS classification does not distinguish EKWs from surrounding croplands, which may increase errors in weather and climate simulation and inaccurately estimate land cover change effects on climate. To get more precise simulation on microclimate, using self-classified images is the best way to improve the accuracy of land cover input to the model. The EKWs were successfully classified in chapter 3 with overall accuracies ranging from 81.3 percent to 89.9 percent. Therefore, one further step of this study is to revise land cover input based on self-classified images to better simulate the influence of wetland conversion on microclimate in KMDA.

## 4.4 Reference


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# 5. Summary

Wetlands are important transitional ecosystems between terrestrial and aquatic ecosystems due to their unique roles in water, carbon, and nutrient cycles. In recent years, due to population growth and urbanization, wetland areas are gradually undermined and converted into built-up areas and agricultural lands. This is especially true in the densely populated and fast growing Kolkata Metropolitan Development area (KMDA) area. Investigating the impacts of land cover conversion on local and regional climate systems will provide useful information for land cover management and land cover policy making. In this study, LULC change was analyzed using Landsat images in the East Kolkata Wetland (EKW) areas and the entire KMDA region from 1972 to 2011. After that, potential impacts of the urbanization and expanding irrigation croplands were estimated by feeding the Weather Research and Forecasting (WRF) model with different land cover change scenarios.

Built up area in KMDA increased by 91.39% from 1990 to 2011. The fast growing build-up area resulted in significant conversions of wetland to urban and other land cover types. From 1990 to 2000, total wetlands decreased 443.26 $km^2$, and the reduction was mainly contributed by wetlands with vegetation, which decreased by 544.77 $km^2$, whereas wetlands with water bodies increased by 101.51 $km^2$ of the same period. From 1972 to 2011, total wetlands in the EKW region decreased by 28.1 $km^2$, leading to a 17.9 percent reduction. Open water area showed relatively low variability among the four study years (ranging from 39.6 $km^2$ to 43.8 $km^2$) and was about 5 percent smaller in 1972 than other years; while vegetation zones of wetlands decreased about 30.0 $km^2$ during the 39 years, accounting for 25.4 percent of the total region in 1972.

To explore the potential impacts of land conversions, two future land cover change scenarios were framed. For the urbanization scenario, the assumption is that all the wetlands and croplands would be converted to built-up area; for the irrigation expansion scenario, the assumption is that all wetlands and dry croplands would be replace by irrigated wetlands. These scenario analyses indicated that land cover change could dramatically affected multiple weather and climate variables. Model simulations indicated that urbanization would greatly increase regional temperature in this area, but expanded irrigation would have a cooling effect in this region. Impacts of land use changes on precipitation are complicated. In the urbanization scenario, precipitation center tends to move eastern ward and leads to increased rainfall in the eastern parts of this region. Increased irrigation would stimulate rainfall in central and eastern areas but reduce rainfall in southwestern and northwestern parts of the study area. This study suggests that urbanization would totally alter the flux exchanges between land and the atmosphere. Increasing urban areas significantly reduced lateral heat fluxes and albedo. Sensible heat fluxes following the urbanization scenario are mainly above zero and suggested that urbanized land surfaces mainly act as heat sources.

This study investigated historical land cover changes in the KMDA area and projected future climate change driven by potential land cover changes. Climate change projection not only predicted the future spatiotemporal patterns of multiple climate factors, but also provide some insights into policy making related to land cover management, water resource management, and agriculture management to adapt and mitigate future climate changes in this populous region.