Urbanization and Its Impact on Groundwater Resources: A Case Study

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This thesis is dedicated to those people who believe that knowledge is the ultimate resource for life.....

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Proforma -II

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Abstract

Urban land is increasing all over the world with the increase in population. Process of urbanisation transforming the rural land into an urban area. This process creates demand for natural resources and consumes a significant amount of it within a small area. Groundwater is one of the resources that is interacting with urban areas excessively. The urban hydrological cycle is getting modified with huge demand for water and groundwater being abstracted disproportionately from its source. In this study, the impact of urbanisation on groundwater resources has been analysed to identify the spatio-temporal effect of an urban area on groundwater resources. Briefly, the contemporary situation regarding urbanisation and groundwater resources has been observed in this study along with an extensive literature review on urban groundwater studies. Further, a case study has been formed to identify location-based observation on this topic. Kolkata has been selected as the study area. It is a city in eastern India administrated by Kolkata Municipal Corporation where the urbanisation process is dominating the land and groundwater-related issues are the most common ones. In this study main objective was to recognise the effectiveness of urbanisation on the groundwater of Kolkata. This study mainly depended on spatio-temporal analysis based on geoinformatics. Primarily, urbanisation has been identified using satellite data and the situation of groundwater resources has been identified based on secondary data that have been collected from authenticated sources. The study majorly focused on the last three decades (1990-2020) to capture the urban-groundwater interaction in Kolkata for a longer period of time. Kolkata has a long history of urbanisation but the urbanisation process is not properly planned. The land is situated in the Bengal basin, where the dominance of clay is prominent in soil and the aquifer is confined in nature. From the result, it has been analysed that, Northern part of Kolkata was densely urbanised with high density built-up than the southern part. Further within the observational period, urbanisation mainly captured the land from the southern part where built-up area increased rapidly encroaching the green spaces and water bodies. Consequentially, the impervious surface increased over the total land of Kolkata modifying the permeable surface. Parallelly, groundwater levels continuously declined over the years even changes in groundwater quality degraded with time. Finally, it has been revealed that groundwater levels declined at a high pace where the lands are covered with densely built-up areas. Comparatively groundwater level declined at a slow pace where green spaces are dominant. Overall built-up area and groundwater level share an opposite co-relation and the effectiveness of the built-up area is high on the groundwater level in the eastern part of Kolkata. As impervious surface increased that reduced the groundwater recharge proportion over the years. Groundwater quality in Kolkata is very fluctuating in nature but hydro-chemical parameters like Chloride, bicarbonate, and sulphate, are consistently present in alarming amounts. TDS is significantly high and it is increasing in concentration over the years. A significant amount of iron is present in groundwater making the groundwater reddish. Also, a sufficient amount of hardness in groundwater creates

scaly deposits. Harmful polluting properties are increasing in the groundwater of Kolkata over the years and urbanisation creating a definite impact on it. The most degraded condition of groundwater quality in landfill areas shows the effect of urbanisation most prominently. In near future, land subsidence, seawater intrusion and health issues will be serious concerns for Kolkata. Mass awareness, artificial recharge and rainwater harvesting are the ultimate options that need to be applied in Kolkata immediately.

List of Abbreviations

Abbreviation	Definition
BC	Before Christ
BIS	Bureau of Indian Standards
BOD	Biological Oxygen Demand
CGWB	Central Groundwater Board
COD	Chemical Oxygen Demand
DESA	Department of Economic and Social Affairs
DLR	Deutsches Zentrum für Luft- und Raumfahrt e.V.
DPSIR	Drivers-Pressures-State-Impacts-Responses
EEA	European Environmental Agency
EHZ	Eocene Hinge Zone
FAO	Food and Agricultural Association
GEE	Google Earth Engine
GIS	Geographical Information System
GLDAS	Global Land Data Assimilation System
GRACE	Gravity Recovery and Climate Experiment
GSI	Geological Survey of India
HDB	High Density Built-up
IWD	Irrigation and Waterways Department
KMC	Kolkata Municipal Corporation
LDB	Low Density Built-up
LST	Land Surface Temeparature
LULC	Land Use and Land Cover
LULCC	Land Use and Land Cover Change
MODIS	Moderate Resolution Imaging Spectroradiometer
MODIS	Moderate Resolution Imaging Spectroradiometer
MT	Metric Tonne
NASA	National Aeronautics and Space Administration
NIR	Near Infrared
NRSC	National Remote Sensing Centre
SQL	Structured Query Language
SRTM	Shuttle Radar Topography Mission
SWID	State Water Investigation Directorate
SWIR	Shortwave Infrared
UAE	United Arab Emirates

Abbreviation	Definition
UK	Unite Kingdom
UN	United Nations
UNDP	United Nations Development Programme
UNESCO	United Nations Educational, Scientific and Cultural Organization
USA	United States of America
USDA	U.S. Department of Agriculture
USGS	Unite States Geological Survey
WBDMD	West Bengal Disaster Management & Civil Defence Department
WHO	World Health Organisation
WHYMAP	World-wide Hydrogeological Mapping and Assessment Programme
WQI	Water Quality Index
WRIS	Water Resources Information System.

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Part I

Urbanisation and Its Impact on Groundwater Resources

Chapter 1

Background of the Study

1.1 Introduction

Urbanisation is the inevitable phenomenon for social and economic development (Liang & Wang, 2019). Urbanisation process refers to the demographic process where people migrate to live within an urban environment other complex sets of economic, social, cultural, technological and environmental processes are involved in urbanisation (Kitchen & Thrift, 2009). It is assumed that the economic development of a country significantly depends on its magnitude of urbanisation. Presently more than 50% of the world's population are residing in urban areas, whereas in 1950, it was just 30% and it is estimated that, in 2050 around 9.8 billion people will reside in urban area which will be 68% of the total population (United Nations, 2018). Certainly, urbanisation process cooperates in a multi-dimensional development approach for a country or a region but it has definite negative impacts on the environment also. Water resource is one of the most important natural resources that is needed to sustain life but the situation is alarming in the case of the urban area. Urban area has definite characteristics regarding the consumption of water where a high amount of water is consumed from a comparatively small area. Supply of this freshwater comes from either surface water sources or groundwater sources. In most urban areas around the World, groundwater resource is the ultimate reliable source to cater for the demand. Groundwater holds approximately 99% of freshwater resources and it is comparatively less contaminated than other sources. It is easily accessible and held in large amounts as a reserve below the surface. Groundwater abstraction in the urban environment is a common practice for years specifically where groundwater is the only resource. Generally, groundwater is treated as a non-renewable resource as it takes thousands of years to replenish itself. Groundwater is often referred to as an invisible resource and estimation of this resource is comparatively a complex process, it is identified as an undervalued resource and awareness about the importance of groundwater resources are limited to people. Continuous groundwater abstraction from a location for over years create an impact on the subsurface environment.In such case water level declination, contamination of pollutants, and land subsidence are the common effects. Important global cities like Mexico City, Tokyo, London, Paris, Delhi, Beijing, Dhaka, and Jakarta along

with many other important cities have already observed the negative impact of groundwater abstraction (Howard & Gelo, 2001; Llamas et al., 2003). Overall an intensifying situation has been drawn by analysing the dependence of groundwater in innumerable cities (Shrestha et al., 2016). It is estimated that presently, nearly two billion of the urban population are directly dependent on groundwater as a water supply. Recently questions have been raised about the sustainability of the environment in a populated urban area. Finding the actual cause and effect of urbanisation on groundwater resources have become one of the most important subject within the overall context of global climate change and the development of response strategies.

1.2 Significance of a case study

In light of this above situation, the impact of urbanisation on groundwater resources has been studied in this thesis. It has been observed from previous researchers that urban groundwater scenario is distinct and mostly different from the other city. So, It has been decided that apart from understanding the process of urbanisation and its impact on groundwater resources, an area has to be chosen where both of these processes create significance and interconnect with each other. For this, Kolkata has been taken as a study area along with findings on the effect of urbanisation on groundwater resources. It is the most important city in the eastern part India and the gateway for other several adjoining countries. It has been observed that Kolkata has a distinct history of urbanisation at least for the last two hundred years. Having a comparatively better situation in surface water sources, Kolkata still depends on groundwater as an water source. Groundwater withdrawal is a common exercise for public water supply and private consumption over years. From the published research and reports it has been observed that recently after the beginning of globalisation in India, significant changes in land use have been observed in Kolkata that directly reflects the urbanisation process with other changes like declining groundwater level, mixing of pollutants as contaminants in groundwater, the possible presence of arsenic in groundwater, seawater intrusion and land subsidence. Limited number of researchers have tried to identify the actual impact of urbanisation on groundwater resources for Kolkata. Already a research gap has been identified in this context. Assuming that Kolkata faces a definite impact of urbanisation on groundwater resources, this study has been processed further with the context of this concept.

1.3 Objectives

The study has been proceeded following these objectives are mentioned below:

- To gather knowledge about the process of urbanisation and groundwater resources individually and its contemporary situation globally.
- To identify different aspects about the general interaction process between an urban area and groundwater resources on a global scale.

- To review the impact of urbanisation on groundwater resources maintaining a time frame in between 1990 to 2020 through scientific literatures.
- To analyse the evolution of the study area with the prospect of urbanisation.
- To understand about the physical characteristics of the study area.
- To understand about the socio-economic status of the study area.
- To analyse the process of urbanisation approaching different aspects of it through spatio temporal analysis for the study area.
- To identify the condition of groundwater resources through spatio-temporal analysis for the study area.
- To understand the impact of urbanisation on groundwater resources following different aspects retrieved from the previous objectives.
- To discuss overall observation about the impact of urbanisation on groundwater resources specifically for Kolkata along with identification of solutions and recommendations for betterment.

1.4 Study framework

1.4.1 Sources of data

Detailed spatio-temporal datasets are needed to accomplish the process. Worldwide urbanisation related data have been collected from organisations like United Nations and World Bank. For groundwater related study, worldwide data has been collected from various organisation like WHYMAP, UN-IGRAC, IAH and UN-WATER. For the case study, detailed locational data is needed. Primarily thirty years (1990-2020) of timespan has been selected to analyse spatio temporal changes in urbanisation and groundwater resources of Kolkata. Urbanisation has been analysed based on high resolution satellite data that have been collected from USGS to generate accurate and detailed result. For groundwater resource analysis this study mostly relied on chronological secondary data that have been collected from various governmental organisations like CGWB, SWID and WBPCB etc. For overall understanding about the scenario of Kolkata, relevant data have been collected from KMC and previously collected relevant data and literatures of various researchers also incorporated to gather idea about the study area.

1.4.2 Applied methodologies

Understanding about the impact of urban area on groundwater resources is a really complex task. These two independent major themes must correlate with each other to make it decidable. So this thesis is majorly based on geospatial analysis to achieve the desired result. For this advanced remote sensing technology has been incorporated in this study to capture changes in the urban land for the long period of time and observe chronological evolution in this study

area. Groundwater related data has been curated spatially and temporally. Descriptive statistical analysis has been approached throughout the study to calculate the spatio temporal changes over the time frame. Repeated usage of regression analysis and time series analysis have been the major proponents of this study.

1.4.3 Applied tools

Microsoft Excel and Word used in this study for tabulation of data and writing respectively. For statistical analysis, advanced statistical programming language R (v. 4.0) has been used. For spatial analysis, GIS software like, QGIS (v. 3.16) and ArcMap (v. 10.3) have been used extensively. Figures have been edited in Inkscape software and this thesis has been written and edited in typesetting software system Latex and references relevant to this study was managed in reference managing software Mendeley desktop (v. 1.19.8)

1.5 Chapter outline

This thesis contains altogether 11 chapters. Each chapter consists of an introduction, specific objectives, relevant data, suitable methods and conclusion. A brief outline of each chapter is as follows:

Chapter 01

The first chapter begins with a notable context behind the study of urban groundwater issues. Significant problems have been identified regarding groundwater issues in urban area. Major objectives have been incorporated into the study. The study framework discussed here mentions needful methodologies. Justification behind the selection of a case study is briefly uttered here. Limitations related to this kind of research have been mentioned and further scope has been raised here. Brief idea about each chapter has been enumerated for a better perception about the thesis.

Chapter 02

Two different concepts, urbanisation and groundwater resources have been attributed here with proper definitions for a better understanding. Worldwide spatio-temporal changes in urbanisation process have been speculated in this chapter. Later, the importance of groundwater resources have been acknowledged. Details about the available amount of groundwater source, groundwater recharge and abstraction scenario have been mentioned here.

Chapter 03

The interaction between an urban area and groundwater resources have been specified in this chapter. Briefly historical examples were added to recapitulate the usage of groundwater

resources ages ago. The basic concepts have been clarified here mentioning certain advantages and disadvantages of urban groundwater usage to get an idea about the diversified utilisation of this resource and exploitation related to it. This chapter captured every possible aspect of urban groundwater resources and acknowledged the worldwide impact of urbanisation on groundwater resources in various cities.

Chapter 04

In this chapter, an extensive literature survey has been done to understand the perspective of the researchers and the methodologies followed in urban groundwater studies. This chapter incorporated significant studies on urban groundwater within the time from 1990 to 2020.

Chapter 05

Evolution from old Calcutta to recent Kolkata has been revisited in this chapter in light of urbanisation process. Importance of Kolkata as an urban area has been analysed from past to present. From the inception of this city to its present structure and all the journey in between mentioned in this chapter. Different identical characteristics of Kolkata as a district, as a municipal corporation and as a megacity all have been clarified here. The geographical location of Kolkata has been described here, which has been used for the case study.

Chapter 06

Physical setup of Kolkata has been mentioned in this chapter. Elevation, slope, geology, geomorphology, and soil type have been mentioned in details. The subsurface environment of the study area was also discussed through detailed observation of lithostratigraphy, subsoil characteristics, aquifer characteristics and borewell data. Thirty years of climatic condition have been analysed to understand the local rainfall and temperature characteristics. The land surface temperature has been analysed to understand the local land characteristics on soil moisture retaining capacity. This chapter briefly defined the physical properties of Kolkata that harmonise the process of urbanisation.

Chapter 07

Distinct urban features like land use patterns, urban amenities, transport networks, and water supply all are described here. Briefly, socio-economic perspectives have been incorporated in this chapter that directly reflects the process and depth of urbanisation in Kolkata.

Chapter 08

In this chapter, the process of urbanisation has been identified using geoinformatics and analysed spatiotemporally. Different kinds of remote sensing techniques have been applied to analyse the process of urbanisation between 1990 to 2020. The urban area of Kolkata has been assessed

with three different correlating factors of urbanisation. First of all, landuse and landcover change has been analysed using a supervised machine learning process to identify changes in different land classes over time. Next, the built-up area has been identified through web computing to analyse the changing pattern of built-up that directly reflects the process of urbanisation. Further changes in the impervious surface have been identified for the city within time frame of 1990 to 2020 with a maximum likelihood classification algorithm. Furthermore, different urbanisation indices have been applied to understand the urbanisation scenario quantitatively for Kolkata.

Chapter 09

Details about the groundwater resources of Kolkata have been highlighted in this chapter. Groundwater scenario of Kolkata has been compared with other adjoining districts. Groundwater resources have been assessed from decadal to seasonal timespan. Physiochemical parameters have been analysed spatially and temporally. Changes in water quality and composition have been analysed also. Briefly, characteristics of groundwater resources have been captured from every perspective that represents the actual scenario of Kolkata.

Chapter 10

All the efforts that have been put into the previous chapters have been assimilated into this chapter. The impact of urbanisation on groundwater resources have been analysed in detail. Two different entities of an urban area i.e., urbanisation and groundwater resources have been correlated here with different regression models and time series analysis. Spatio-temporal changes in both variables have been connected here to generate the main theme of this study.

Chapter 11

It is the concluding chapter of this study, where major findings have been delivered. Understanding the effect of urbanisation on groundwater resources following a case study on Kolkata has been discussed. Further remedial measures have been identified and the future scope related to this study has been discussed.

1.6 Limitations and scope of the study

The execution of this study is based on detailed spatial and temporal data. Detailed locational data from past to present needs to be available in every phase of this study. Data collection was the most crucial part of this study where authenticated secondary data were more valuable than primary surveys as this study is based on the chronological evolution of urbanisation and its impact on groundwater resources. It has been realised that groundwater-related data is really limited and from that available data either locational details are missing or chronology has not been maintained properly. Individually, all of the authorised departments were visited physically, but in most cases, historical data were found to be either unavailable or missing. Irregularity in

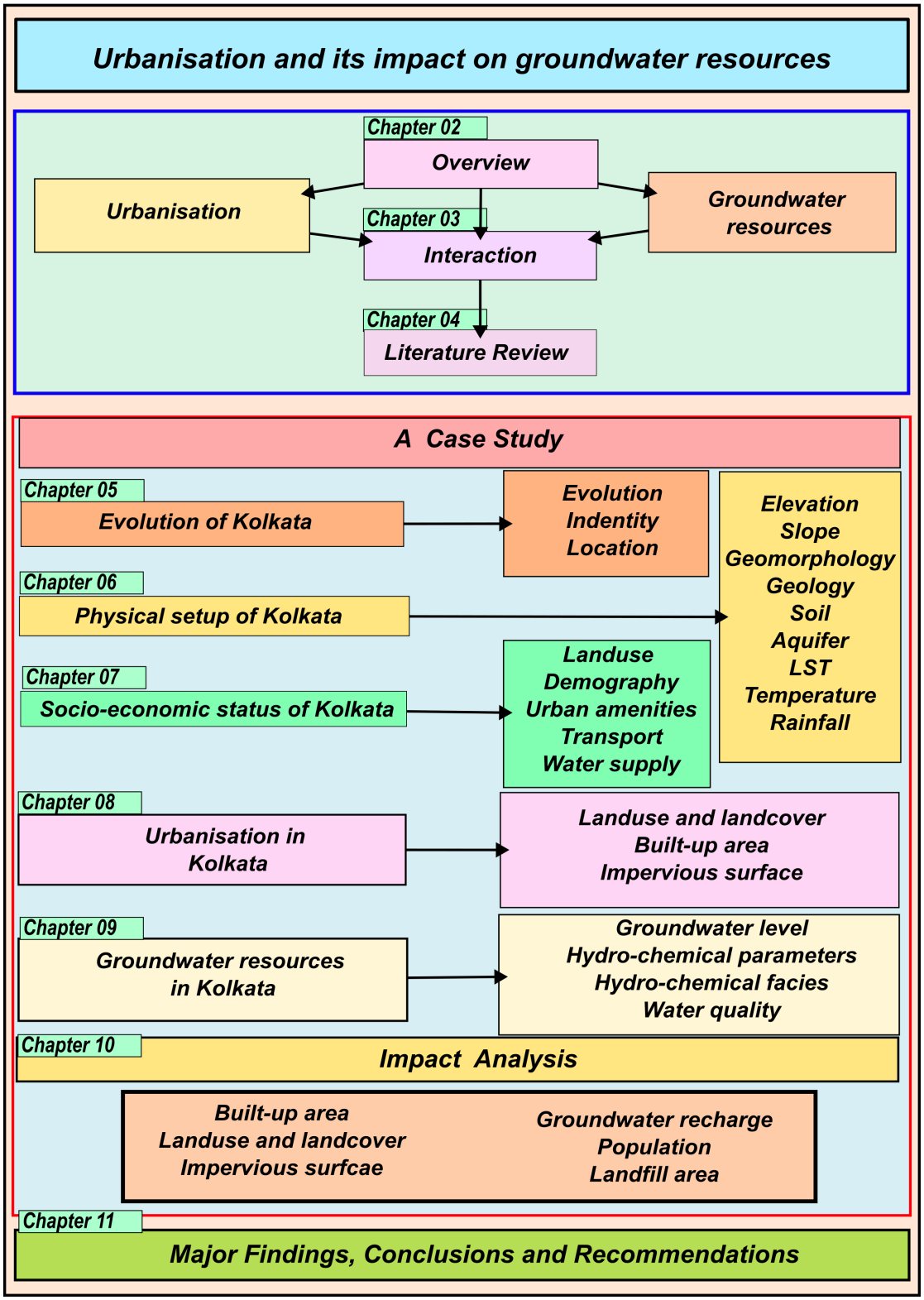


Figure 1.1. Schematic framework of the study

chronological datasets and erroneous data has been found as a major limitation of this study. Strangely it has been observed that, for the same place and same period, groundwater data

differed with different governmental organisations. Validation and authentication of datasets was the toughest job throughout the study.
Presently, Kolkata is divided into 144 wards. This study remained limited to 141 wards of KMC. Three wards were excluded from the study because previously that part of the land was not an urban area at all and data related to it not goes with the theme of this study. The observation period for this study is mostly limited to thirty years (1990-2020). Retrospection was only limited within the literature review because further detailed analysis could not be possible without sufficient historical data. It is another limitation of this study. Groundwater consumption data from households are unavailable and if available that lacks in minuteness. This study remained limited within a small sphere due to diverse obstacles but the further scope of this alarming topic does not end here with this study. Further detailed data collection using modern appliances will create immense scope to make this study more accurate and precise.

References

Howard, K. W. F., & Gelo, K. K. (2001). Intensive groundwater use in urban areas: the case of megacities. In *Intensive use of groundwater challenges and opportunities* (pp. 35–58). Retrieved from https://www.fundacionbotin.org/89dguuytdfr276ed{_}uploads/ObservatorioTendencias/PUBLICACIONES/LIBROSSEMINTERN/intensiveusegroundwater/cap02-intensiveuse.pdf

Kitchen, R., & Thrift, N. (2009). *International encyclopedia of human geography.* doi: 10.5860/choice.48-0052

Liang, S., & Wang, J. (2019). *Advanced remote sensing: Terrestrial information extraction and applications*. Elsevier. Retrieved from https://linkinghub.elsevier.com/retrieve/pii/C20170034894 doi: 10.1016/C2017-0-03489-4

Llamas, R., Custodio, E., Lopez-Geta, J., & de la Orden, J. (2003). *Intensive use of groundwater: challenges and opportunities*.

Shrestha, S., Pandey, V. P., Shivakoti, B. R., & Thatikonda, S. (2016). *Groundwater Environment in Asian Cities*. Elsevier. Retrieved from https://linkinghub.elsevier.com/retrieve/pii/C20140022174 doi: 10.1016/C2014-0-02217-4

United Nations. (2018). *World Urbanization Prospects 2018* (Tech. Rep.). Retrieved from https://population.un.org/wup/

Chapter 2

Overview of Urbanisation and Groundwater Resources

2.1 Introduction

In the beginning, it is important to gather preliminary knowledge about the principal concepts of the study. Urbanisation and groundwater resources are the two important theme of this study and these two themes are quite different from each other. Urbanisation distinguish the characteristics of a city or an urban area whereas groundwater resources are naturally available in the earth. Former one can be counted as anthropogenic activity and later one is natural resource. So basic knowledge about two concept must be clarified from the beginning.

2.2 Objectives

Major objectives have been short-listed to make a clear concept about urbanisation and groundwater resources. Those are mentioned below:

- To overview different concepts related with urbanisation and groundwater resources.
- To analyse contemporary scenario of urbanisation and groundwater resources around the world.

2.3 Concept of urban

2.3.1 Definition of urban

The word urban is an adjective. The word came from the Latin word *Urbanus*, where *urbs* mean city. According to Oxford dictionary it relates to town or city[1]. The term *Urban* can used

[1] Oxford Advanced Learner's Dictionary

differently in various approach. Basically, urban has a physical entity and urban as a term can be used to define quality also (Pacione, 2013).

Urban as a physical entity

To identify urban place, some physical entities are important to understand the location and extent of the city.

Population Size Urban area are related to place and it has a strong weightage on population. Usually there is no fixed rule about the number of populations of an urban area. It differs from place to place.

Economic Base In selected area it can be called as urban when it holds a strong economic base. As an example, in India one specified area will called as urban if there 75% of the populations runs by other than primary activities.

Administrative Criteria Most of the urban area is defined and specified by its legal administrative boundary. Most of the urban area is ruled by a specific administrative body which is only dedicated to it. Municipal corporations usually governs the urban area.

Functional definition Problems of under bounding and over bounding has been addressed by this functional definition according to urban researchers. Functional activities differ from its adjoining places in case of an urban region.

Urban as a quality

It differs from the definition of urban as a physical entity. It calculates the urban milieu on people's lifestyle. Every person has a different perspective on same urban space. For a homeless person it is an unbearable place whereas, for successful business person it is a favourable location to prosper.

Cognitive Mapping Mental mapping of an urban area defines the subjective characteristics of the urban place. Urban quality of life or urban environment can be area of interest for geographers, environmentalists.

Urbanism as a way of life Urban area possess a different nature of lifestyle and it differs from other adjoined area. It may differ from other urban area but dominantly an urban area holds a definite way of life with time.

2.3.2 Urban civilisation from historical perspective

Gordon Childe was an archaeologist, he wrote an essay about the urban revolution which was published in 1950, on that he described that a *'city is hard to define'*. He used the word *revolution*

for city to culminate progressive changes in economic structure and social organisation. On an other essay, he described the basic ten characteristics of urban civilisation from an historical and geographical point of view (Figure 2.1).
According to Childe (1950), depth of urbanisation depends on size and situation of an area where main focus is based on economy where surplus is stored, even class based social structures are observed and governed by exclusive governing bodies. Apart from primary characteristics, urban civilisation must be a hub where a global influences from another contemporary urbanisation can observed and practised.

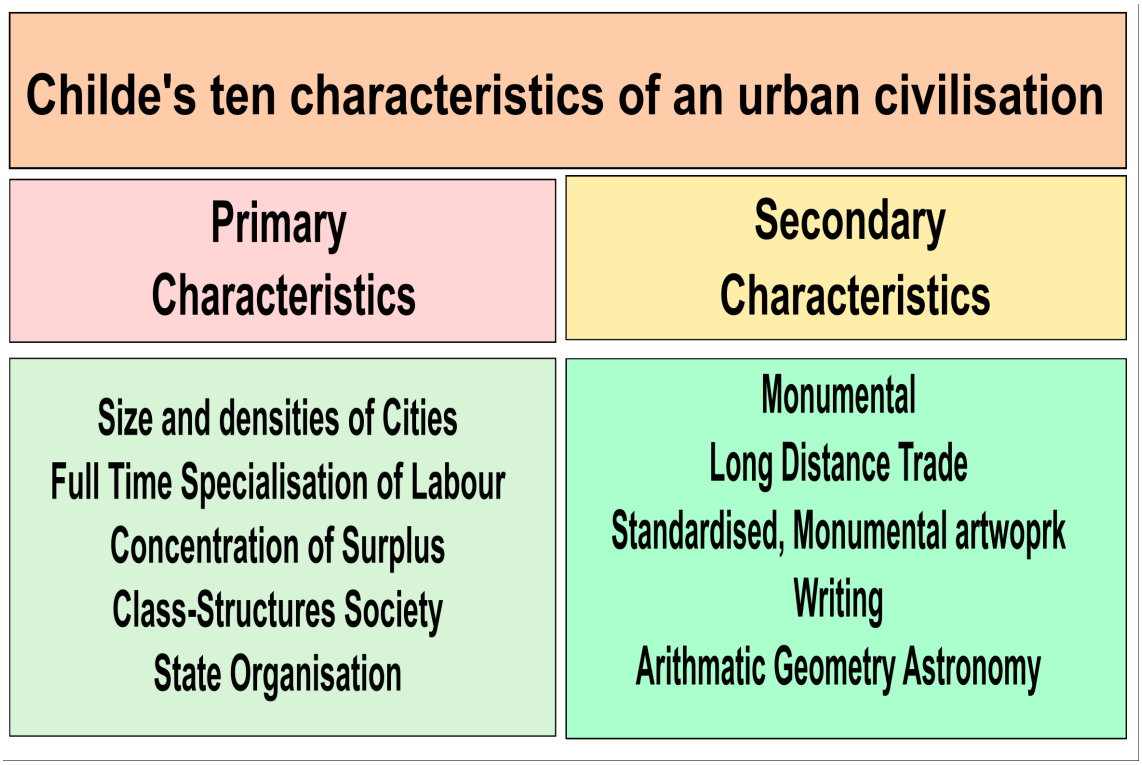


Figure 2.1. Needful primary and secondary characteristics of an urban civilisation; Source: Gordon Childe, 1961

2.3.3 Theories of urban origin

From the beginning, origin of an urban area was not according to geographical dimension, it was more based on some fundamental tenets. According to Carter (1981), *First* fundamental doctrine behind urban origin was geographical determinism, it came from the anthropo-geography supported by Friedrich Ratzel. Basically, believed notion was on *man-land relationship*. Humankind was the product of the earth and blindly dependent upon the environment. So most of the developed human settlement took the opportunity from the nature and build up its residing place (Meyer, 2020).
Second tenet was about *diffusionism*, that contemplated with environmentalism (King, 2022). Traits what were established on a place that was speeded not only for their similar environmental

condition but cultural similarities under contrasted environment supported the diffusion process. City was having an independent characteristic. Further, influence of cities speed up to vast its geographical location.
Third conviction was generated on nineteenth century based on geographical values. People started to believe in *evolution*. Simple lifestyle changed into complex longings. Cities were developed with different kind of needs like mining, farming, and other needful activities. Proper villages with sustaining mentality formed town and ultimately that changed into city.
Emergence of urban area can be explained by major four proposals given by archaeologist, social scientist, and historians. These has been mentioned below:

Hydraulic Theories The idea of *surplus* that basically came from the agricultural revolution that stimulated to form urban area. Development in agriculture gave birth to the concept of bureaucracies. Applying the water resource in irrigation, more production in agriculture seemed to differentiate in areas that are the environmental bases of urbanism (Carter, 2016).Woolley (1957) depicted this concept in his discussion *'The urbanization of society'*, that in history of mankind the idea of *hydraulic society* is closely related with the ecological prioritisation of an urban area.

Economic Theories Several urban theorists have put their view on economical approach. Mainly it suggests the valuation of economy in society and its priority. According to them, trading networks built within the region concentrated based on a place which was main stimuli for the formation an urban area. Agricultural economy differentiated the land into rural and urban. One place for production and another for trading was maintained from the history of civilisation. This economic prioritisation ultimately developed an urban area.

Military Theories With natural progression of society, agricultural and trading related formation was started with time and developed cities. According to some theorist, *protection* was another important propaganda by the rulers at the time. Physically and economically secured places were highly prioritised and that stimuli helped people to gather in one place and then tighten the security.

Religious Theories Strong *religious belief* based on a specified location and its importance among believers often concentrated an urban area relating to a religious practise.

2.4 Concept of urbanisation

Urbanisation[2], the term is related with the process *Urban*. It is noun form of urban. Urbanisation has different perspective in different countries. Definition of urbanisation should not be generalised. Any area already claimed to be urban or qualifies to be an urban area certainly

[2]It is noteworthy to mention that,*Ubanisation* and *Urbanization* are both English terms, represent *same* meaning but *"z"* is used in American English and *"s"* is used in British English

has different criteria. Urban geographers, urban planners usually helps to define the range of urbanisation.
Because of the process urbanisation, there can be seen a natural increase in population at a place where it is called as city. All the cities, towns etc. are related with the term urbanisation. Generally, where people decide or bound to live, maintaining urban culture, facility and abiding urban administration that can be termed as city or town.
The focus of urbanisation specialises in between the boundaries of the city. Understanding of Cities will be equally important to think of urbanisation geographically.

2.4.1 Sociological perspective of urbanisation

In sociological perspective urbanisation can be described by two concepts prominently. Those are *functionalism* and *conflict theory*. Functional perspectives on urbanisation generally focus on the ecology of the city, while conflict perspective tends to focus on political economy. Eminent scholars from different field described about there perspective on urbanisation, those are mentioned below:

Jmaes E. Vance According to Jmaes E. Vance, from the early time man tried to move to the city to gain freedom and to make change in life. Culture has proved to be an important factor in developing a city. Not only a city holds a rigid culture but invites other cultures to cope up with it, as a result it amalgamates. Understanding the dynamism in human activity, city would be a great example. urban society changes so rapidly that hardly it can be contemplated by other human groups. Insight of a city specifically needed to know more about urbanisation for that morphology of a city must be understood well (Vance, 1978).

Gideon Sjoberg Gideon tried to change the perception about cities. Changing from cultural perspective he was keener on industrial development. According to him, proper concept of city started after the development of industrial development. before the industrial development the viewpoint of an urban area was different and changed hugely after the industrial development. His study was centred on modern Europe (Manella & Sjoberg, 1961).

Marx/Engels According to them urbanisation creates because of capitalism. They viewed the possibility of concentration of mass will be inevitable and that will create misery that ultimately turn to be a revolution and to some extent it is necessary to break the nexus of the traditional community (Katznelson, 1993)

E.W Burgess Burgess supported the concept of Darwin. According to him, *social darwinism* is the reason behind the growth of a city. Competition is the ultimate catalyst for urbanisation. Scarcity of urban resource makes the degree of urbanisation prominently. Land leads the competition groups and ultimately it affects the urban space. Required areas demand high price. Ultimately competition for land and resources makes spatial differentiation of the urban space (Burgess, 2008) .

Effect of economic development in a country must be reflected through its urbanisation process. At least initial urbanisation process certainly runs by locational economic advantage. (Di Clemente et al., 2021)
According to UN, world population division, complex socio-economic process of transformation of rural settlement into urban settlement can be termed as urbanisation. demographic and social. (United Nations/DESA, 2019)

2.4.2 Different level of urbanisation

Urban area develops within a locational barrier. Spatially it varies by locational boundary. Further details on urban study look upon the internal and external variability in an urban area. This is the generalised form an urban area which followed across the globe. It simplifies the framework of the urban structure from the complex definition of real world (Pacione, 2013). A brief description on the level of analysis in urban study has been done here for better understanding (Figure 2.2).

The Neighbourhood Collective households or homes in a specific area limited by a location is called neighbourhood. Usually, people with certain level of homogeneity resides in a neighbourhood. Residents of the that place usually somehow dependent on each other and they usually have kind of equal socio-economic background. Different Residential segregation can be defined by variety of neighbourhood in a place.

The City Cities are defined by their economy generation and consumption, centre for cultural reciprocity and social grid. Formally it is governed by an administration dedicated only for the governance of the city. Economic evaluation and social interactions vary on spatial scale. City is an important unit for researchers. Each city differs from other in various aspect. City carries a distinct characteristic by its own.

The Region The influence of an urban area extends to its limits to cover up the surrounded rural areas. Productivity, economic development, higher standard of living attracts the people from the adjoining area also which are not yet a part of the city. On a whole the combination of city and locational sphere of influence cumulatively treated as the region.

The National system of Cities In case of some cities, socio economic influence and dominance effects the nation. Planning, governance, administration in the city reflects its imprint on the adjoining area, these kind o influential cites hold a grip over the country. These cities attract investments and intellectual properties from the whole world.

The World system of the cities This concept depicts for those cities those are interdependent with them globally. Important cities in the world are connected mainly by economical perspective and political approach. Global development in sphere of research and development, education,

banking, hospitality is consciously growing up here. Dependence of other cities and countries on these cities, defines the importance of the city.

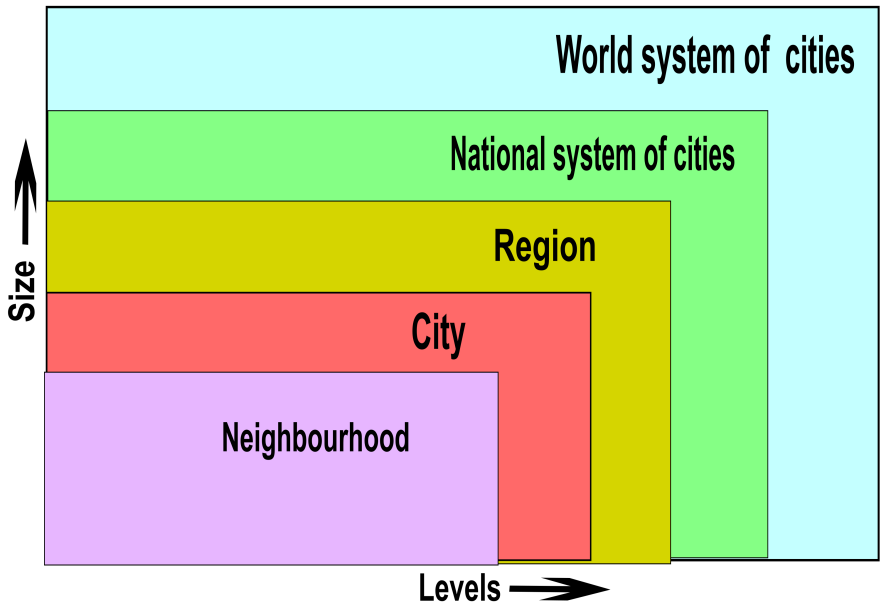


Figure 2.2. Schematic diagram showing level of urbanisation ; Source: (Pacione, 2013)

2.4.3 Historical evidence of urbanisation

The concept of city was developed much before the starting of Gregorian age. Archaeological advancement with time documented five major civilisations. These historical testaments gives us proof of urban society in them. Some of the prominent historical evidences identified reflecting the urban culture from distant past, it has been mentioned below:

Mesopotamia The concept of city is believed be to found first in Mesopotamia that was existed near 3500 B.C. It was placed beside the Tigris and Euphrates River. It was fertile land, there was abundance of water. They had food and structure to reside.It was the basic structure of urbanisation, in the Mediterranean area, along with Sumerian empire in the vicinity.

Egypt One of the early civilisations along with development in urban mentality was built up in bank of Nile River in Egypt. Middle east experienced an urban hearth about 3500 B.C. there was a city which was treated as capital and it was fortified and garrisoned also. Concept of abundance of amenities in concentrated form have been initiated from these urban hearths.

The Indus Valley This civilisation appeared around 2500 B.C. It was established on the western side of the Asia on the bank of the river Sindh. A proper planning for layout of the city has been identified by archaeologist about the city. This valley civilisation was mainly departed in Harappa and Mohenjo-Daro. There was significant evidence of urban structure in the core

concept of the city which till now being used. The inception of modern cities has been initiated from such city.

The Yellow River It was situated beside the yellow river in China. It is also called as Hoang Ho Civilisation in the Neolithic age there was trace of Civilisation.at that the pre mature concept of urbanisation has also been found. Example of city planning has also been found in the context of Chinese history. Ancient Chinese wall remaining there.

Mesoamerica Earliest cities has been found on Mexico. The existence of Mayan civilisation has been found on Guatemala Honduras Mexico. Strong evidence regarding urbanisation proves that it was one of the ancient civilisations of the world.
Above mentioned civilisations have given a brief idea on the concept of urban hearth that incepted long before.Generally, urbanisation was initiated with the process of civilisation.

2.4.4 Contemporary scenario of urban world

The contemporary urban world can be defined from last hundred years of the modern world, where urbanisation process has created a promising and effective impact on the human settlement system. Growth of the modern world in terms of every aspect of economic and social development mostly depends on the urban perspective. Even the significance of a country depends on its urbanisation factor. Urban development upgrades the status of a region in every aspect. Urbanisation parallelly uplifts the position of the city among all other neighbouring regions and sometimes an urban area holds the potential to rule the world. On the opposite side, negative impacts of urbanisation on the physical and cultural environment should be worth mentioning. Growth of urbanisation process began effectively after the beginning of nineteenth century (Davis, 1955). Now the contemporary situation of the world has been discussed here for a brief idea of past and present situation of Urbanisation. Ample proportion of riverine landforms, plain land, and arable lands create scope for productivity, soothing climate and other physical and socio-economic factors proved to be a crucial factor in holding vast amount of population. The urgency of urbanisation was initiated first in the western world. American and European continents transformed their agrarian civilisation into urbanisation through the industrial revolution. This transformation was limited to a specific region but the economic development and cultural evolution in the urban area attracted other regions in the eastern part of the globe. Ruling nature and dominance of Europeans through governance ultimately spread the effect of urbanisation around the world. After the end of imperialism and monarchy in most parts of the world with development in science and medical practice the population started to increase in mainly colonial countries, after independence. African, Latin American and Asian countries where rapid change in population growth was a critical issue, adopted urbanisation abruptly. The pressure of population among countries created new urban areas in search of economic independence. Most of the urban areas in emerging countries were built up to boost economic activities. Cultural diffusion, acculturation and independence from a conservative mindset involved people in urbanisation.

Continuously, the population is increasing in the world. According to UN Report (2005), in the middle of the twentieth century, there were nearly three billion people around the world, in the next twenty years population was near about four billion and after a decade that crossed five billion. At the beginning of twenty-first century population increased to six billion but a rapid change can be observed in the next twenty years, in these decades, population already has crossed seven billion. It is significant that in Asian continent, the total population has increased more rapidly than any other continent and the growth rate is also the highest. It can be depicted that, population of Asia and Africa directly reflects the global population. Whereas, in Europe total population tends to decrease with time nowadays (Figure 2.3a.; Appendix, Table 1). Urbanisation process is directly related to rapid change in population. As published data by United Nations, Department of Economic and Social Affairs (2005), global urban population data nearly correlates with changes in total population and it is also relatable with urban population change in Asian continent. Significantly, most positive change in urban population was observed after the beginning of the twenty-first century in Asia. Comparatively, the urban population increased most, than in other continents. The growth rate is minimum or it is mostly stagnant in European continent. Data from the present make a clear picture of the prospects of the urbanscape. It is can be understood that scope has been limited in Europe and North America about further urbanisation but, in Asia and Africa, there is lot of scope for urbanisation (Figure 2.3b.; Appendix, Table2).

Past, present scenario and future scope of urbanisation in these continents better understood

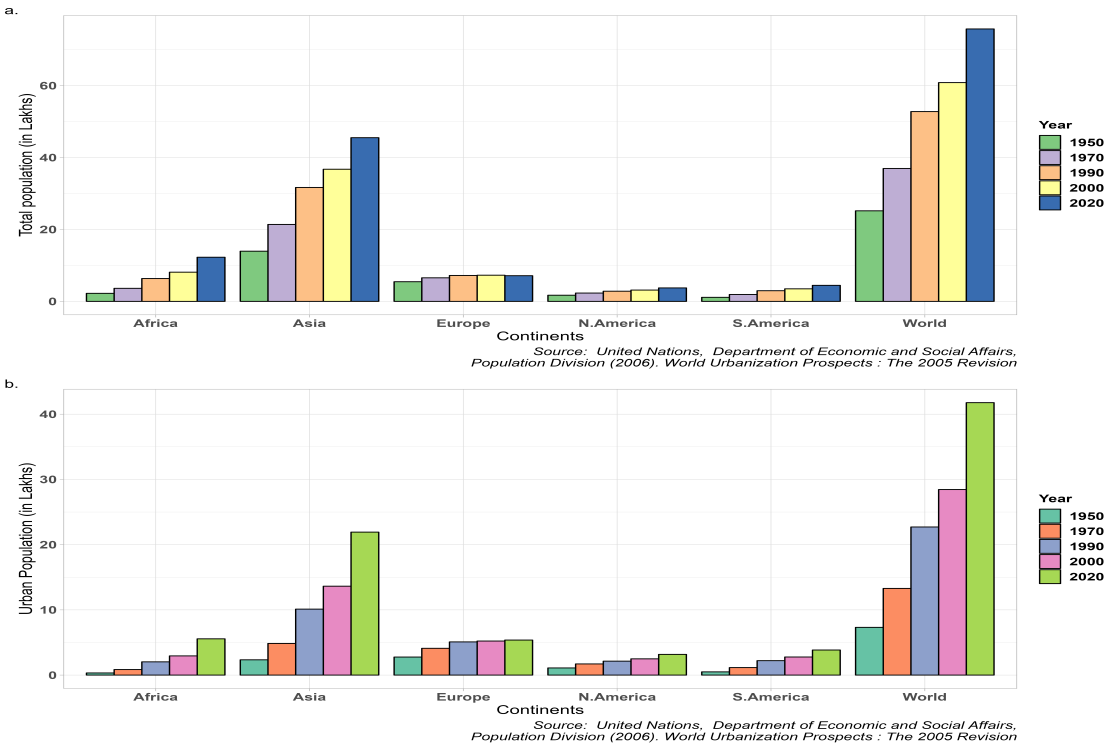


Figure 2.3. Continent wise a) total population, b) urban population over time; Source: (UNDP, 2006)

by the percentage of urbanisation in continents. In 1950, 29% of the world was under the part of urbanisation process, at that time only 14% and 16% of the land was part of urban area in African and Asian continent respectively whereas in Europe about 50% of the land was covered with urban area and for North America it is about 64%. After fifty years with the beginning of this century, 46.7% of the area were urbanised around the world. In Europe around 70% and in North America around 80% of the land were urbanised. Within fifty years of timespan, percentage of urbanisation increased more than double in Africa and Asia; it was 36.7% and 37.1% respectively. In next twenty years, Urbanisation process was checked in Europe, North America and South America. Expansion of further urbanisation became limited to 4-5%. Simultaneously for Asia and Africa, 10% average increase in urban proportion has been observed. In 2020, 48.1% of the world space has been occupied with process of urbanisation. Among other continent expansion of urbanisation was more in Asia than other continents (Figure 2.4a.; Appendix, Table 3).
Expansion of urbanisation can best be analysed by identifying growth rate of urbanisation. According to the UN report, growth rate urbanisation has been assessed within a range of five years for prominent understanding about the change. Worldwide urbanisation growth rate was 1.33% in between 1950 to 1955. Urban Growth rate was close to 1% for Europe and North America whereas continents with colonial impacts, upgraded their land into urban area near about 2% on average. For Africa, it was 2.65% and for Asia it was 1.93%, South America was also having a growth rate of 1.99% within five years at the time of 1950. After two decades, urban growth rate chocked worldwide; it was limited to 0.6%. Surprisingly for North America it was null at the time span of 1970 to 1975 whereas urban growth rate was 1.82% for Africa and 1.06% for Asia, Urbanisation was minimised in Europe also. With the beginning of this century, urban growth rate was 1% in first five years. Urban growth rate was highest in Asia. Continents like Europe and North America checked the urbanisation process to 0.2%. Within the time span of 2020 to 2025, World population growth is expected to be within 0.8%. In Europe and North America will be in the same growth rate for urbanisation however continuous positive growth can be clearly projected further for Asia and Africa (Figure 2.4b.; Appendix, Table 4)

2.4.5 Major Urban agglomerations in the world

UN, department of Economic and social affairs produced a report on largest 30 urban agglomeration. Report defined urban agglomeration as amount of population contained within contiguous territory inhabited at urban density levels regard to administrative boundaries (United Nations/DESA, 2019). At the middle of the twentieth century (1950), New York-Newark ranked top above all thirty major UA with 12 million population, Tokyo was the next. Osaka was after it with 7 million population. Paris ranked fourth as a major UA and first in Europe. Calcutta (Kolkata) was on seventh the rank with population near about 5 million; it was first UA among other UAs in India. Mexico City was within top ten UAs. At the end of this century, population of Tokyo exceeded than any other agglomeration with 34 million population and Osaka was just after Tokyo with 19 million population. In 1995, Mexico City was on the third place of the

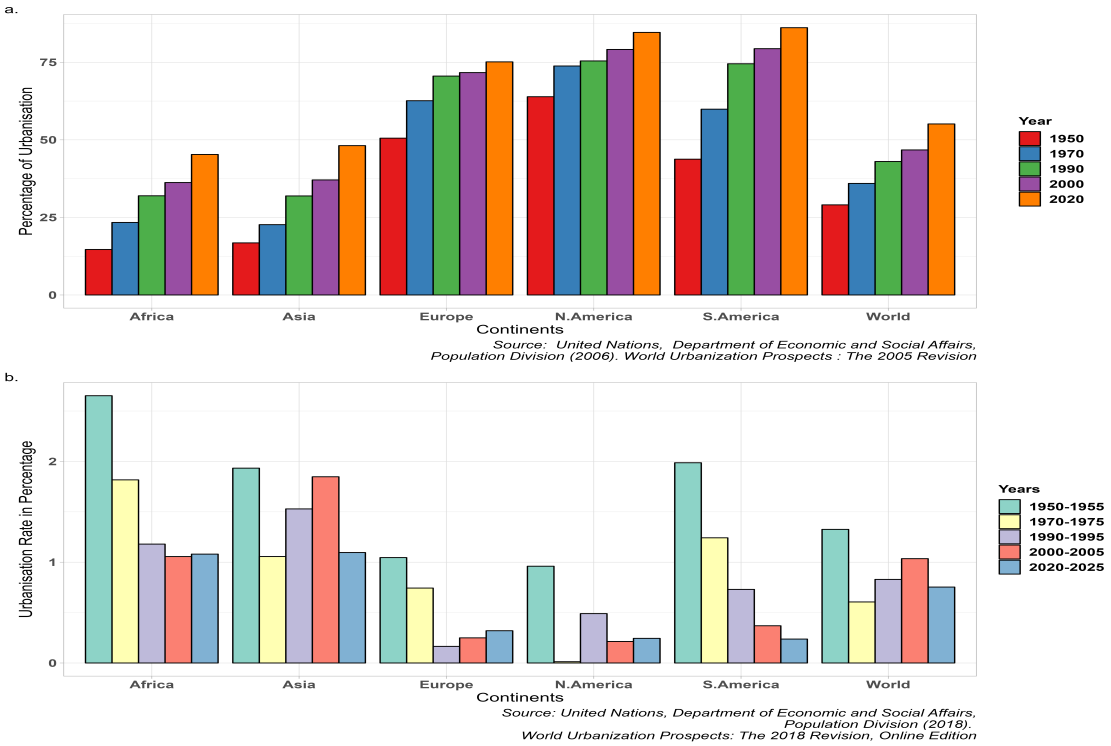


Figure 2.4. Continent wise a) percentage of urbanisation, b) urbanisation rate; Source: (UNDP, 2006)

ranking with 17 million population. Ranking dropped for Kolkata from India and population of Delhi and Mumbai crossed the population of Kolkata. Cairo from Africa was part of top ten UAs. Within fifteen years a shuffle in ranking can be observed. In 2010, Tokyo was top in ranking with 37 million population, Now Delhi became the second largest population among UAs in India with 22 million population. Shanghai from China included in top three with 20 million population. European cities were not within top ten rank. African city, Egypt secured 9th rank as an UA. Another UA Beijing was included in top ten ranking. It is expected in the report that, in 2035 Delhi will be the largest city all over the world with 43 million population. Tokyo and Shanghai will be next accordingly. Dhaka, another UA from Asian continent will be fourth in ranking with 31 million population. Egypt from Cairo will be in fifth position and Mumbai from India will be in 6th position. Kinshasa from DRC will be new addition to top ten list with 27 million population. Lagos from Nigeria, Karachi from Pakistan, Istanbul from Turkey, Bagota from Columbia will turn to be major UAs in the future world. European UA Paris will be on the last in top 30s in 2035 as projected.

It is clear from the above observation that, in previous century with higher population than any other UAs, European and American UAs had the dominance over the World But with time, decrease in total population and other environmental issues population of UAs will be reduced. opposite scenario, can be observed from Asian and African countries. In near future there will be dominance of UAs mostly from South Asian part. North African UAs will also rise up. Developed countries further will check population for UAs but in developing countries more

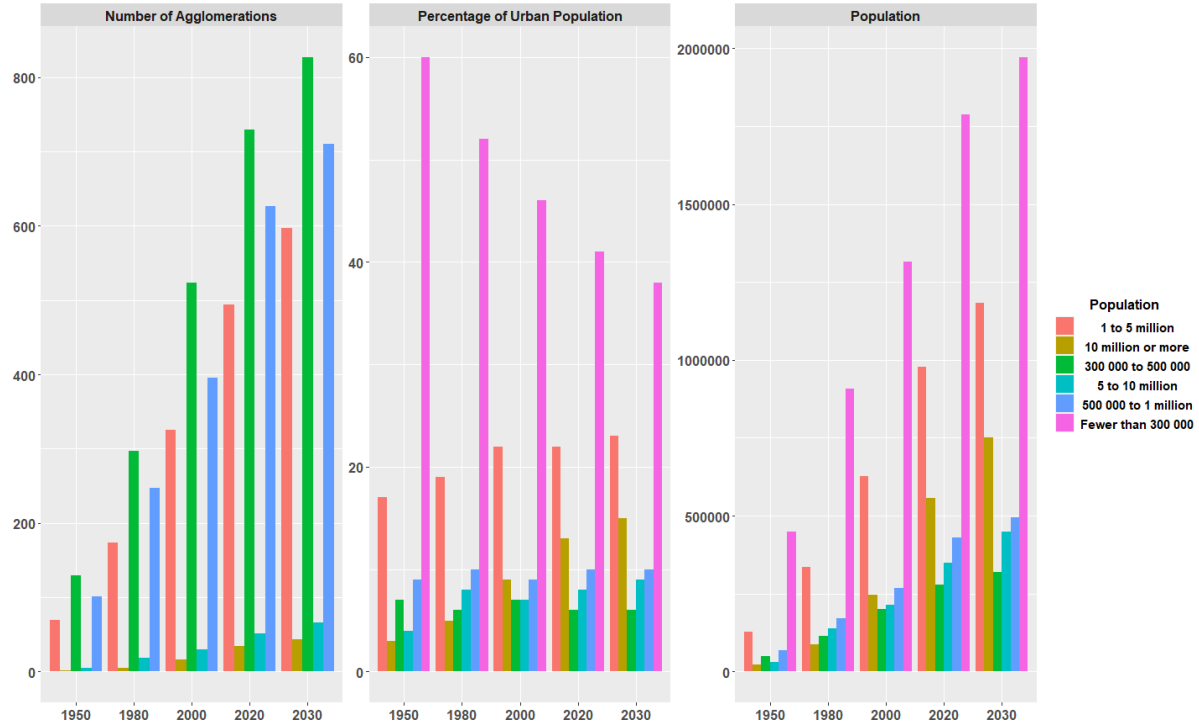


Figure 2.5. Status of world urbanisation scenario from 1980 to 2030; Source: (UNDP, 2018)

cities will be created to cope up the pressure of urbanisation.

2.4.6 Past, present and future status of the urban world

The situation of urbanisation has been described here from the year 1980 to 2030 (Figure 2.5; Appendix, Table 5). It can be observed that, broadly world population can be divided into different clusters. Minimum urban population can be observed from 0.3 million people within an administrative boundary. next clusters limits within 0.5 million people in an urban area, as it goes to its next limit it extends up to 1 million people and the rest of the clusters goes maximum up to 10 million or more people within an administrative boundary. Urban population has increased in all respect.

More than 45 crore people lived in cities with less than 3 lakh population, in 2000 it increased to 131 crore people and in 2035, more than 197 crore people will reside in urban area with population less than 3 lakh. In 1950, more than 12 crore people used to live in under urban area which area limited by 1 to 5 million people, more than 62 crore people lived in such cities in the beginning of twenty-first century however in 2030 it will be more 118 crore people. Such cities which have more than 10 million of population on those cities, more than 2 crore people used to live in 1950 and there was 24 crore people in 2000, and in 2030 it will be up to 80 crore people.

Worldwide percentage of urban population in less than 3 lakh populated cities was 60% in 1950 but with time it decreased up to 46% in 2000, and it will be decreased up to 38% in 2030. There was 3% urban region with a population of more than 10 million in 1950, but it increased three times in next fifty years.at will be increased more than 5 times in 2030, then it will be 15% other

populated urban clusters that showed insignificant change with time.
According to number of urban agglomeration, there was 129 urban agglomeration in 1950, with a population of 3 to 5 lakh, significantly it changed to 524 in 2000 and it will be 846 in 2030. Number of this kind of agglomeration increased 400% from 1950 and it has a scope to grow much more. Same goes for urban agglomeration with a population with 5 lakh to 10 lakh people, it was 101 in 1950 and the number increased to 396 in 2000 and it will possibly increase to 757 in 2030. Exponential growth applies to cities populated with more than 10 million people also. In 1950, there were two urban agglomerations with more than 10 million population in 2000 it increased to 16. It is projected that there will be more than 43 UA with more than 10 million population in the world in 2030.
This descriptive quantification shows a clear picture of interest towards urbanisation. The pace of urbanisation has accelerated mainly after developing economic relations between countries. Need for urbanisation for better economic prosperity has been an inevitable step for humankind and in every country it can observe. Urban region with a limited population of 5 to 10 lakh of people has exceeded mostly and megacities with more than 10 lakh people also took shape with time in every densely populated area. The tendency of urbanisation has been seen more in developing countries than in developed countries at present time.

2.5 Concept of groundwater

2.5.1 Brief description about groundwater

Water is the need for life. Three quarter of the world is covered by water. Upon the Earth's surface and beneath the earth's surface presence of water is observed. According to its presence, it can be divided into surface water and subsurface water. Vast part of the total available water is consumed by subsurface or groundwater. It can be termed as *invisible* resource as it is absent from people's view. Groundwater is treated as a *sustainable* resource. It is the source of fresh water for human. Groundwater represents about 30% of the total fresh water resources. From the other 70%, about 69% of the water is captured through ice caps, snow, and glaciers, and only about 1% of fresh water is available in rivers and lakes (Shiklomanov & Rodda, 2004) (Figure 2.6). The geographical distribution of groundwater is closely related to the geological structure of the earth's crust. Climatic factors like precipitation, evaporation etc. also play an important role. The exact estimation of groundwater resources is very difficult. Groundwater is static and dynamic in both ways by its movement.
Water of the river flows in the catchment area on earth surface whereas, groundwater resides in aquifers; it is the water bearing formation. Aquifers are three-dimensional continuous subsurface domains and are less visible than catchment areas. Groundwater flow in aquifers depends on the capability of the aquifer (size, permeability etc.). Recharge plays an important role in movement also. Groundwater recharge is mostly done by precipitation. Groundwater discharge is done from different types of wells or it outflows into another water resource. Groundwater recharge and discharge ultimately balance the water cycle. Groundwater flow is generally slower than rivers, but it is difficult to estimate; so it follows indirect methods like simply measuring the

amount that is entering or what is leaving the aquifers. It is termed as *groundwater flux*.

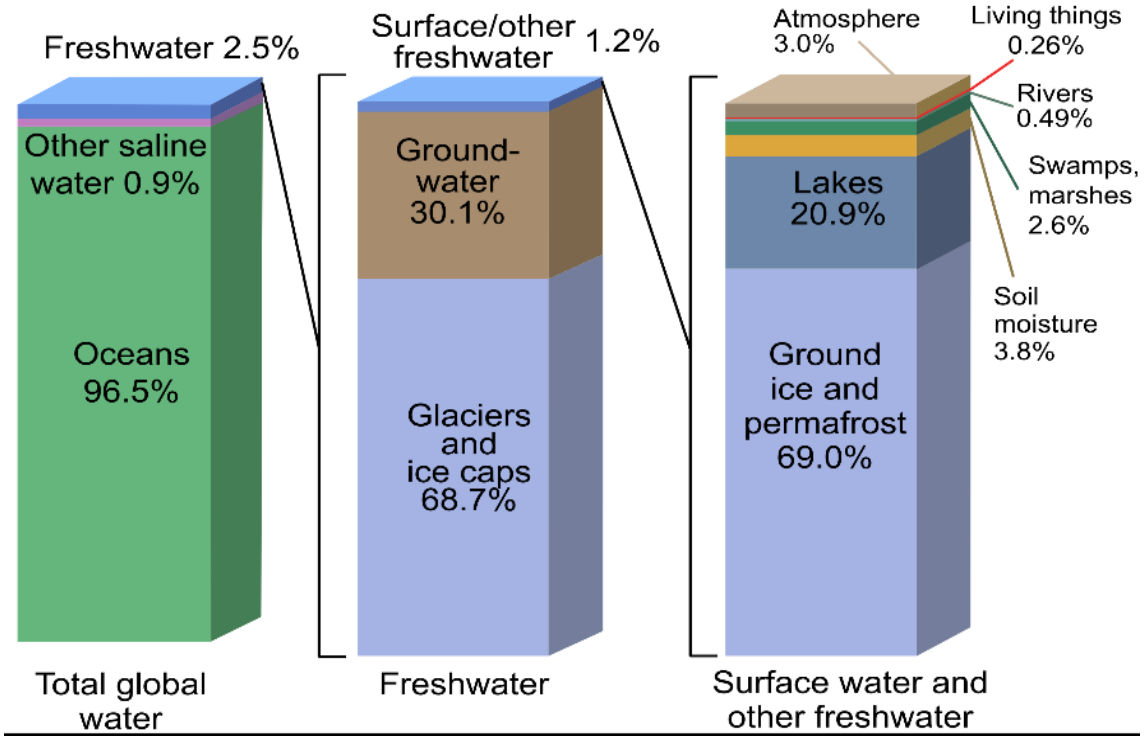


Figure 2.6. World Distribution of Water (Source: Wikipedia)

2.5.2 Availability of groundwater

Groundwater plays an important part in environment. It balances the global hydrological cycle. Maintains the water level by providing waters to rivers, lakes. Different plants and species living beneath the surface depend on groundwater. It is treated as one of the major drinking water resources for mankind for ages. It also plays an important role in economy, as it is the main source of irrigation in agriculture and industrial water demands. Subsurface environment is covered with groundwater throughout the world but it is not ubiquitous in all parts of the world. Availability of groundwater depends on climatic factors like precipitation, evaporation and definitely on infiltration. Accessibility of groundwater is directly related with process of runoff too.

Researchers have identified three broad vertical zones according to presence of groundwater (Shiklomanov & Rodda, 2004). *First* zone is highly dynamic residing just below the surface and it reflects the overlying condition of geological and climatological characteristics. *Second* zone reaches up to the sea level and dependent on aquifers and aquiclude layer beneath the earth surface. *Third* zone deep down up to 2000 m from the sea level. This zone is dependent on large scale earth formatting layers. Effective porosity varies within zones as 15%, 12% and 5% respectively (Table 2.1).

Table 2.1. Natural Groundwater Resources in the upper layer of the Earth's crust; Source:(Shiklomanov & Rodda, 2004)

Continent	Total Resource of groundwater $km^3 \times 10^6$	Zone 1	Zone 2	Zone 3
Asia	7.8	1.3	2.1	4.4
Africa	5.5	1.0	1.5	3.0
Australia & Oceania	1.2	0.1	0.2	0.9
Europe	1.6	0.2	0.3	1.1
North America	4.3	0.7	1.2	2.4
South America	3.0	0.3	0.9	1.8

2.5.3 Geographical distribution of groundwater

Availability of groundwater depends on water holding capability of aquifers and those indirectly depends on geological structure, geomorphology of the land and climate. Occurrence and movements of groundwater can be depicted on two aspects of the subsoil.
a) composition of the subsoil in terms of their rock properties (porosity, permeability, fissuring, solubility) these properties locally conduct and store the groundwater, b) the regional structure (thickness, lateral extent, depth) these two factors are needful to the describe the status of specific hydrogeological area. Aquifer system are the appropriate spatial units for assessing and managing the groundwater resources.
WHYMAP (2015) assessed the groundwater resources worldwide (Figure 2.7). They divided available groundwater resources into three major divisions: 1) uniform groundwater basins , 2) complex geological structures, 3) local and shallow aquifers. These major divisions also represent different amount of groundwater recharge capacity per year. Major groundwater basin found in large sedimentary riverine basins whereas, complex geological structures describes the heterogeneous folded or faulted structures. Localised and shallow aquifers represents those areas where groundwater overlying in shallow layers upon the weathered bedrock.

2.5.4 Groundwater recharge

Richts et al. (2011) analysed the groundwater resources all over the world. Major Groundwater basins are residing in different parts of the world. Asia, Europe, South America, and Australia are the continents among them (Figure 2.7). These groundwater basins mostly residing under riverine landforms. Geological impact has made complex hydrogeological structures throughout the world. In Africa and South America portion of complex structure is minimum. Mostly the world is covered by local aquifers which is shallow in nature. These aquifers are independent and maintains its cycle locally. Groundwater recharge in major groundwater basins varies from place to place. The scope of recharge ranges from 2 mm/year to more than 300 mm/year. Northern part of Europe and Russia have low to high potentially of recharge throughout the year. Very low potentiality of recharge is limited to mainly tropical area and parts of the continents those are covered by desserts. Very high potentiality of groundwater resource through recharge can be found on equatorial part of the earth, the middle portion of Africa and northern portion of South

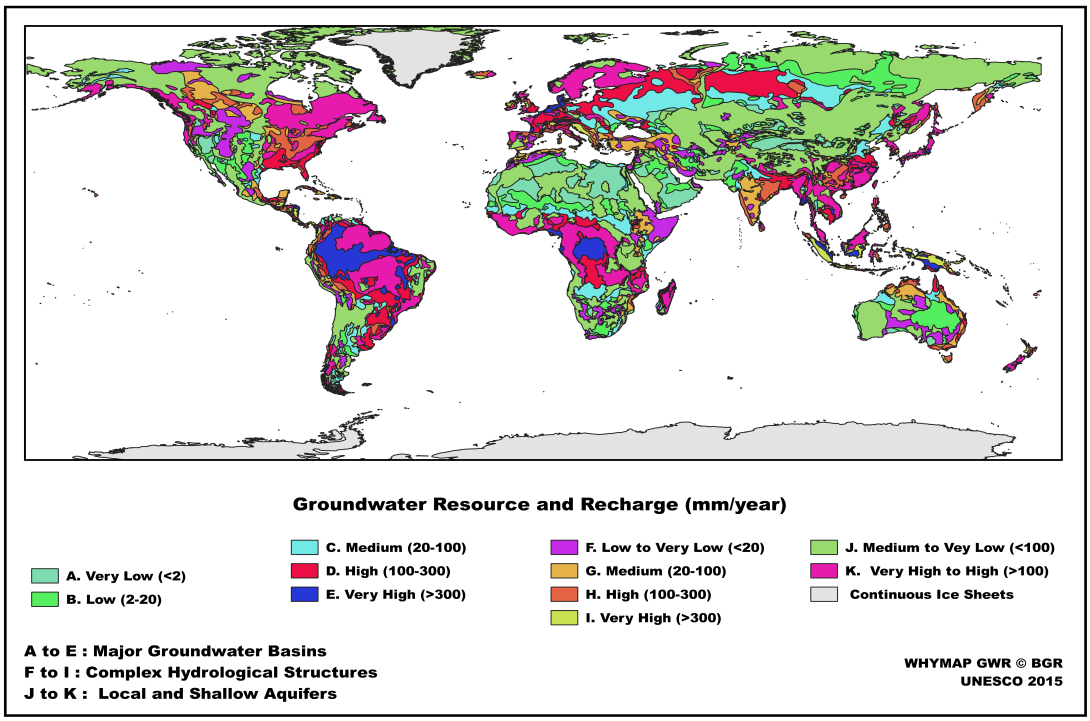


Figure 2.7. Major groundwater resources and recharge areas in the world, (Source: Richts, 2011)

America. Western side of the North America has low to medium groundwater recharge potential (300 mm/year). In south Asia, India mostly holds medium to high groundwater recharge potentiality (20-300 mm/year). In Central Africa and Northern part of the South America rest of the local aquifers have high recharge potentiality.

2.5.5 Groundwater abstraction

World groundwater monitoring organisations have collected all the data from countries all over the world. It is showing that, Asia abstracts most the groundwater among all other continents. About 70% of the groundwater over the world is utilised by Asian countries from its source. North America is next in consumption. This continent consumes about 15% of groundwater through the process of abstraction. Worldwide, groundwater mostly utilised in agriculture and 70% water is abstracted for irrigation purpose. Around 21% water is used for domestic purpose that includes drinking also. Industrial sector uses 9% of groundwater all over the world. Asian countries use 75% of groundwater for irrigation and 16% in domestic purpose. Asia and North America consumes 1/3 of its water by abstraction from groundwater (Table 2.2).

It can be observed that, most of the populated countries consumes groundwater higher than countries with lower population density. The reason is clear. Demand of water usage intends people to use groundwater for their different need. India, Pakistan, Bangladesh are the countries that abstract most of the groundwater. Their abstraction intensity is near about 100 mm/year, that defines abstraction is about 100 km^2/year per km^3. Another populated countries like, USA, China, UAE, South Africa, Argentina, Peru, Egypt comes after asian countries. Tropical and

Table 2.2. Estimation of total groundwater abstraction by continent based on extrapolation (reference year 2010); Source: (Margat, 2013)

Continent	Irrigation (km^3/year)	Domestic (km^3/year)	Industrial (km^3/year)	Total (km^3/year)	%
North America	102	33	8	143	14.6
Central America	4	8	2	14	1.4
South America	13	8	5	26	2.6
Europe	26	33	13	72	7.3
Africa	26	13	2	41	4.1
Asia	514	111	55	680	69.3
World	688	209	85	982	100

temperate region countries use the most of the groundwater. Effect on groundwater resource abstraction certainly depends on the fluidity of groundwater.

In present day, availability of groundwater and usage of groundwater highly varies spatially. Significantly it is observed that groundwater table is declining in several parts of the world where available supply is lower than amount of abstraction(Figure 2.8). Groundwater level is declining at high rate where, population density is higher and demand of freshwater is high. American countries like Mexico, USA, middle eastern countries like Dubai, Qatar and Asian countries like India where groundwater table significantly declining at high pace. Where as in Northern Africa, Southern Australia, where groundwater decline rate is slow and low. Inconsistent pattern has been observed for rest of the world. Scenario of groundwater abstraction can be easily estimated from the table below where India is top among groundwater abstraction, China and USA comes after it (Table 2.3).

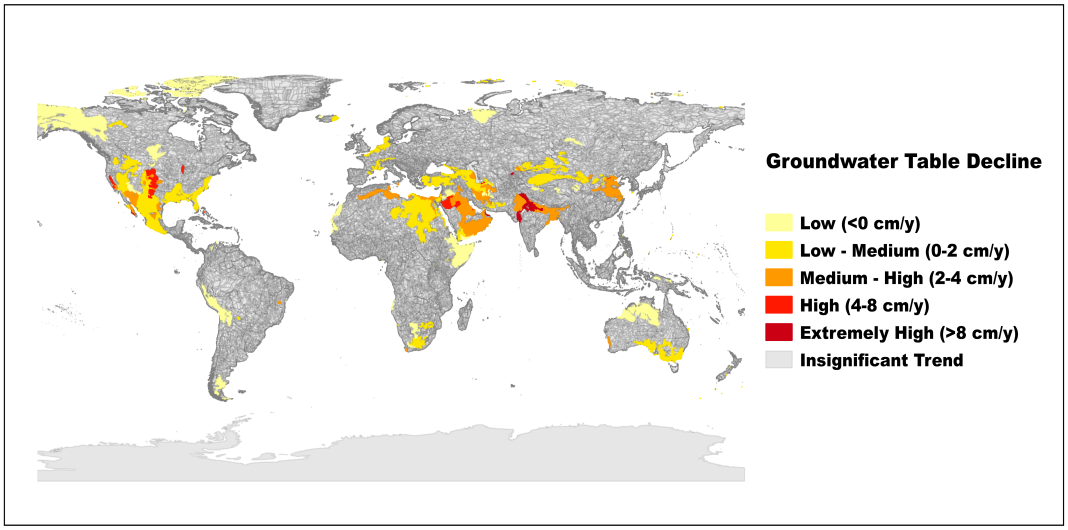


Figure 2.8. Regions with declining groundwater table; Source: (Hofste et al., 2019)

Table 2.3. Top ten groundwater abstracting countries as per 2010; Source: (Margat,2013)

Rank	Country	Abstraction (km^3/year)
1	India	251
2	China	112
3	USA	112
4	Pakistan	66
5	Iran	64
6	Bangladesh	30
7	Mexico	29
8	Saudi Arabia	24
9	Indonesia	15
10	Turkey	13

2.5.6 Quality of groundwater

Water quality is dependent on its chemical and biological properties. In most of the cases the quality of groundwater is pretty much acceptable. The quality of groundwater especially in shallow aquifers faces the chance of contamination with other natural and anthropogenic factors that can make an impact on the quality of groundwater. Groundwater is relatively safe from the effect of bacteria than surface water as effect of bacteria mostly limited in some specific environment. These characteristic does not define the purity of groundwater. Chance of contamination observed through different dissolved particles that can proved to be harmful. Water is solvent and it dissolves minerals which contacts with water. Groundwater can consume different types of particles from rocks and minerals and gasses also. Primarily groundwater can hold the particles of calcium, magnesium, potassium, sodium, chloride, bicarbonates etc. Different type of trace materials can also be mixed with groundwater even presence radioactive molecules has been observed in groundwater. According to availability of calcium and magnesium water can be called as hard. It can form scaly deposits with time, whereas with excessive amount of iron it can be termed as acidic water. This test of acidity in water can be identified by pH scale. Usually, neutral groundwater holds the value of 7.

2.6 Conclusion

Urbanisation is manmade concept that has definite land use properties. Urban area has distinct physical entity along with quality. Social scientists have identified several reasons behind the formation of an urban area. Urbanisation is the counterpart of the term urban. It is a process related to an urban area. Urbanisation can be observed from different levels from neighbourhood to world city. Historical shreds of evidence have been found about the formation of an urban area in the distant past. In the contemporary world, overall urban population is increasing and the increasing rate is comparatively higher in Asia and Africa. The process of urbanisation is already saturated in developed countries but there is a lot of scope in developing countries. From small urban agglomerations to large megacities all are increasing in number. It is expected

shortly three fourth of the world will be covered by the progress of urbanisation.
Groundwater is a natural resource and it is the most prior source of freshwater. Groundwater is sufficiently available in aquifers in the subsurface environment but groundwater is not equally distributed around the world. Geographical distribution and geological structures underneath are uneven. Also, groundwater recharge capacity varies with space. Nowadays, a huge amount of groundwater abstraction is a serious concern from a global perspective. Mainly populated regions in the world consume groundwater in a non-replenishable manner. The quality of groundwater is relatively pure than surface water resources but due to continuous pressure from anthropogenic activities, groundwater is also getting contaminated.

References

Burgess, E. W. (2008). The Growth of the City: An Introduction to a Research Project. In *Urban ecology* (pp. 71–78). Boston, MA: Springer US. Retrieved from https://link.springer.com/chapter/10.1007/978-0-387-73412-5{_}5http://link.springer.com/10.1007/978-0-387-73412-5{_}5 doi: 10.1007/978-0-387-73412-5_5

Carter, H. (1981). *The study of urban geography; third edition.* Edward Arnold.

Carter, H. (2016). Urban origins: a review.

Childe, V. G. (1950). The Urban Revolution. *The Town Planning Review*, *21*(1), 3–17.

Di Clemente, R., Strano, E., & Batty, M. (2021, dec). Urbanization and economic complexity. *Scientific Reports*, *11*(1), 3952. Retrieved from http://www.nature.com/articles/s41598-021-83238-5 doi: 10.1038/s41598-021-83238-5

Katznelson, I. (1993, sep). Marxism and the City? In *Marxism and the city* (pp. 1–42). Oxford University PressOxford. Retrieved from https://academic.oup.com/book/10906/chapter/159153085 doi: 10.1093/0198279248.003.0001

Manella, F. L., & Sjoberg, G. (1961). The Preindustrial City: Past and Present. *The American Catholic Sociological Review*, *22*(2), 181. Retrieved from https://www.jstor.org/stable/3708952?origin=crossref doi: 10.2307/3708952

Meyer, W. B. (2020). Environmental Determinism. In *International encyclopedia of human geography* (pp. 175–181). Elsevier. Retrieved from https://linkinghub.elsevier.com/retrieve/pii/B9780081022955107437 doi: 10.1016/b978-0-08-102295-5.10743-7

Pacione, M. (2013). *Urban Geography*. Routledge. Retrieved from https://www.taylorfrancis.com/books/9781134291038 doi: 10.4324/9780203023525

Richts, A., Struckmeier, W. F., & Zaepke, M. (2011). WHYMAP and the Groundwater Resources Map of the World 1:25,000,000. In *Sustaining groundwater resources* (pp. 159–173). Dordrecht: Springer Netherlands. Retrieved from http://link.springer.com/10.1007/978-90-481-3426-7{_}10 doi: 10.1007/978-90-481-3426-7_10

Shiklomanov, I. A., & Rodda, J. C. (2004, mar). World water resources at the beginning of the twenty-first century. *Choice Reviews Online*, *41*(07), 41–4063–41–4063. Retrieved from http://choicereviews.org/review/10.5860/CHOICE.41-4063 doi: 10.5860/CHOICE.41-4063

United Nations, Department of Economic and Social Affairs, P. D. (2005). *World Urbanization Prospect* (Tech. Rep.). New York: United Nations. Retrieved from https://www.un.org/development/desa/pd/content/publications

United Nations/DESA. (2019). *World Urbanization Prospects - Population Division.* Retrieved from https://population.un.org/wup/General/FAQs.aspxhttps://population.un.org/wup/Country-Profiles/{%}0Ahttps://population.un.org/wup/DataQuery/{%}0Ahttps://population.un.org/wup/Publications/{%}0Ahttps://population.un.org/wup/{%}0Ahttps://population.un.org/wup/{%}0Aht

Vance, J. E. (1978, sep). Geography and the Study of Cities. *American Behavioral Scientist*, *22*(1), 131–149. Retrieved from http://journals.sagepub.com/doi/10.1177/000276427802200108 doi: 10.1177/000276427802200108

WHYMAP. (2015). *BGR - WHYMAP network.* Retrieved 2022-10-17, from https://www.whymap.org/whymap/EN/About/Network/network{_}node{_}en.html

Woolley, L. (1957). Vol. I, Part 2, Chapter 2. The Urbanization of Society. "(Extract from History of the Scientific and Cultural Development of Mankind)" - ProQuest. *Journal of World History*, *4*(1). Retrieved from https://www.proquest.com/openview/fa98334bce4ff6ef56efe1133fe15ed6/1?pq-origsite=gscholar{&}cbl=1821331

Chapter 3

Interaction between Urban Area and Groundwater Resources

3.1 Introduction

Groundwater under the city is a needful resource. It is an important source of freshwater to serve domestic activities. Anthropogenic activities play a crucial role in urban groundwater environment. Groundwater is consumed publicly or privately to meet the need for water. Local administration uses this source for water supply. Groundwater conditions may be directly affected by the function of cities but this factor gets neglected for a long time (Akker et al., 2003). Understanding of urban groundwater is comparatively complex in nature (Lancia et al., 2020).

Morris et al. (2002) depicted that, uncontrolled groundwater development and inappropriate waste disposal often instigate within urban extension that ultimately creates water scarcity and groundwater quality degradation.

Akker et al. (2003) described that functions of the city are directly related to land use that ultimately affects the groundwater. They have emphasised on functions of cities like housing, cultivation (allotments, gardening), manufacturing, recreation, transport, and commercial and social facilities which exploit groundwater. Usually, the water cycle of the cities is balanced by a sufficient amount of water supplies from a sustainable source. Pressure in groundwater is inevitable as it gets imbalanced because it is the most reliable source of freshwater that can be utlised easily in the cities. According to Barrett (2003), the process of urbanisation changes the characteristics of the land surface into impermeable in nature that modifies the amount of recharge in a long run. According to Marsalek et al. (2008), urbanisation create certain impacts on the environment not only on groundwater but also on surface water, atmosphere, wetlands, soil, and biota gets affected.

3.2 Objectives

In this chapter the main objective is to identify interaction between urban area and groundwater resources in details. Another objective is to recognise the cities in the world which are dependent on groundwater resources.

3.3 Historical evidences of groundwater usage in urban area

Water is the ultimate resource for the civilisation. The use of groundwater in urban areas started in the historic ages (Smith, 2013). Already several societies had been destructed because of floods and water-related diseases, and from that experience, some civilisations started to locate where alternative resources are available. Ancient Greeks avoided riverine settlements and depended on groundwater mostly. In bronze age, significant evidences are available where wells has been discovered (Angelakis et al., 2016). These wells were in streets, in houses and other common places. Except from wells another aqueduct like quanats[1] also been discovered in ancient Persian civilisation. Later this practice has been found among Egyptians, Moroccans, Algerians and Indians also (Deming, 2020; Smith, 2013; Voudouris et al., 2019).

3.4 General idea about interaction

Digging for water is a common practice all over the world. There were ancient engineering techniques to dig out the water from the ground; even knowledge of aquifers and their related advantages helped with the site selection of a city in ancient times. Cities located in the water-scarce area were dependent on groundwater resources heavily. It has been a tradition for a long time.

Growth in population and related development of cities and industries started after the 17th century. Demands for new water supplies increased immensely. Groundwater resources proved to be easy to use as freshwater resources.

Conventionally, groundwater exploitation is mainly done by hand-dug wells or by drilled boreholes. Hand-dug wells are appropriate for shallow aquifers. Hand-dug wells create a depth from 1 meter to 20 meters, it varies according to the local subsurface environment. Boreholes are deeper than dug wells. It creates a depth from 20 meters to 200 meters depending on the aquifer. It is comparatively smaller in diameter than dug wells, a mechanical process used for drilling a borehole. It remains covered with steel or plastic pipes under the ground. Generally, electric pumps are used to abstract groundwater from these above-mentioned structures. The amount of abstraction varies with time and the impact of machinery tools. Tube wells can also be seen in developing countries, from where water can be abstracted manually, it can be seen in public places; it is used and maintained by a local community. Basic advantages of groundwater resource are listed below:

[1] A qanat or kārīz is a system for transporting water from an aquifer or water well to the surface, through an underground aqueduct; the system originated approximately 3,000 BC; Source: Wikipedia

- Groundwater is climate resilient source for water supply
- It is relatively low cost and this resource can be used directly without any further processing
- It is covered under the ground and that reduces the chance of direct contamination with hazardous materials compared to any surface water source
- Due to uncontaminated situation, generally it is pure than other water resources
- As it is an ubiquitous resource, it facilitates stepwise distribution. It can be fetched according to need

Despite effective advantages, it has been observed that uncontrolled access by private user decline the water level drastically and the deterioration of groundwater happens at the same time without proper management of land use, providing industrial wastage to the ground, waste water seepage, on site sanitation and leaking sewers.
Dependence on groundwater in urban areas creates a negative impact on developing countries. It is hard to quantify the actual usage of groundwater in an urban area but highly qualified research related to this subject indicates a trend of degradation in groundwater resources with further urbanisation.
Groundwater can rarely handle the total demand for water for a city. In most cases the imbalance between recharge and discharge proportion is prominent. Economically an urban area is more developed than its surrounding lands. So, willingness to pay more for resources directly impacts on local resources of the surrounding area, and it applies to groundwater also.
In the long run, modification of the urban groundwater cycle due to urbanisation seriously affects the urban area. Uncontrolled urbanisation and industrialisation highly mark an impact on groundwater storage levels within a short time and in turn- groundwater resources face unreformable consequences against the urban area. The schematic diagram has been presented here for a better understanding (Figure 3.1) where urban water supply sources, urban water demand and urban wastewater have been acknowledged. Uses of water in the urban area have been divided according to three major usages (residential, commercial and industrial). Surface water and groundwater are used as the source of freshwater resources for an urbanised area and where public and private sources are acknowledged also. After utilisation of water in the urban area, utilised water is identified as exploited and contaminated from polluting sources through sewers, drains and sanitation channels that ultimately infiltrate the subsurface environment. Utility losses from the freshwater source and the chance of contamination are also recognised in this diagram.

3.5 Stages of urban evolution and subsequent changes in groundwater resources

With changes in landuse, a city is created from a small settlement. This evolution process of urban land goes through certain internal process like urban sprawling or urban agglomeration thus changes observed in the morphology of that city. Evolution of a city from its early settlement stage to ultimate expansion has been highlighted in figure 3.2. In these stages of development,

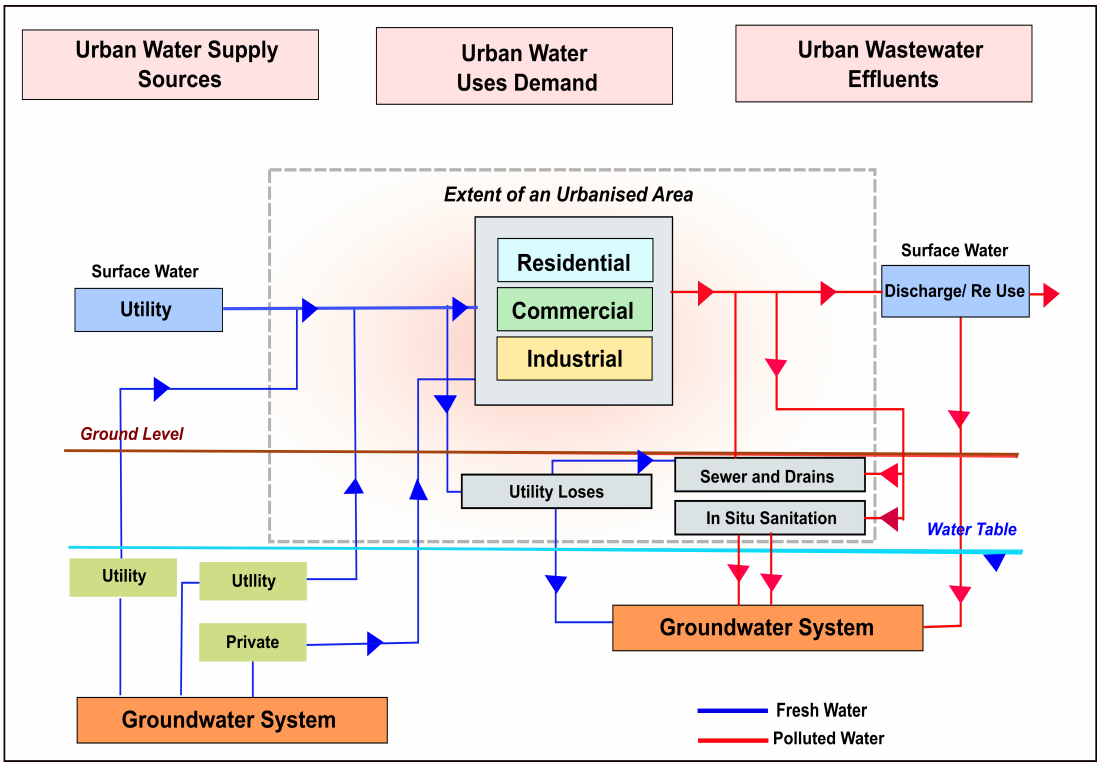


Figure 3.1. Schematic diagram of urban water cycle focusing on groundwater system; adopted from (Foster, 2020)

prominent changes in groundwater level can be observed generally for a city. Static level of groundwater usually breaks the balance between recharge and discharge after huge abstraction to meet the supply for a city. Water level declines abruptly from its surroundings. Chance of contamination also gets created with contaminated recharge from polluted urban sources. Further as the city grows in depth and in area, other adverse consequences observed for subsurface environment. Possibility of positive change in water table can also be observed locally but that at cost of contaminated water for excessive pumping from other adjacent areas (Table 3.1)

Table 3.1. Stages of a city and related groundwater scenario (Source: Foster. et al 1998)

Evolution of a city	Urban groundwater situation
Early settlement	Supply comes from shallow wells and other boreholes Wastewater disposed in the land that ultimately infiltrates in subsurface environment Surface runoff increase
Town becomes city	Water table decline beneath, wells further deepened Pollution captures the groundwater of the city centre Unconsolidated aquifers can lead the cause of subsidence Surface runoff increase further and that creates waterlogging situation
	Water table rise as an effect excessive pumping
City expands	

Table 3.1 continued from previous page

	Abruptly groundwater level decline in the periphery than core area Aquifer gets contaminated and become unsafe to use
City expands further	Excessive demand is created and water abstracted in non-replenishable manner Permanent damage in urban water cycle Increase in waste water disposal Scope of recharge from runoff further decrease with increase in impervious surface

3.6 Function of subsurface water in urban area

Water supply process

Groundwater supply is the ultimate option for those cities where other surface water resources are not available. Groundwater abstraction process utilise minimum amount of preliminary cost and it can be utilised over the years with low-cost maintenance. Climatic effects are minimum in this process. It can be utilised privately also local government can maintain balance in storage for subsurface water according to need. Conventional methods with local implications can be applied in groundwater abstraction.

Sanitation process

Sanitation process creates a direct impact on groundwater. City based sewage, drainage pipes usually not maintained properly, old conventional methods are used in this process. Groundwater gets contaminated with polluted waters through leaks from such pipes. Low income-based settlement lags in maintaining proper infrastructure for sewage and drainage, that areas get effected severely.

Pluvial drainage

Open permeable space is the place of recharge for groundwater. Built-up environment creates impermeability in land surface for sure; not only it obstructs recharge also surface runoff after rainfall gets increased. It creates more runoff than before and losses the capability to hold the retaining water in soil. This consequential process detaches the connection between rainfall and recharge of groundwater.

Industrial discharge process

Industrial discharge influenced with polluted materials directly disposed in grounds or rivers and canals that directly or indirectly encounters groundwater through seepage or leakage. Hydro-

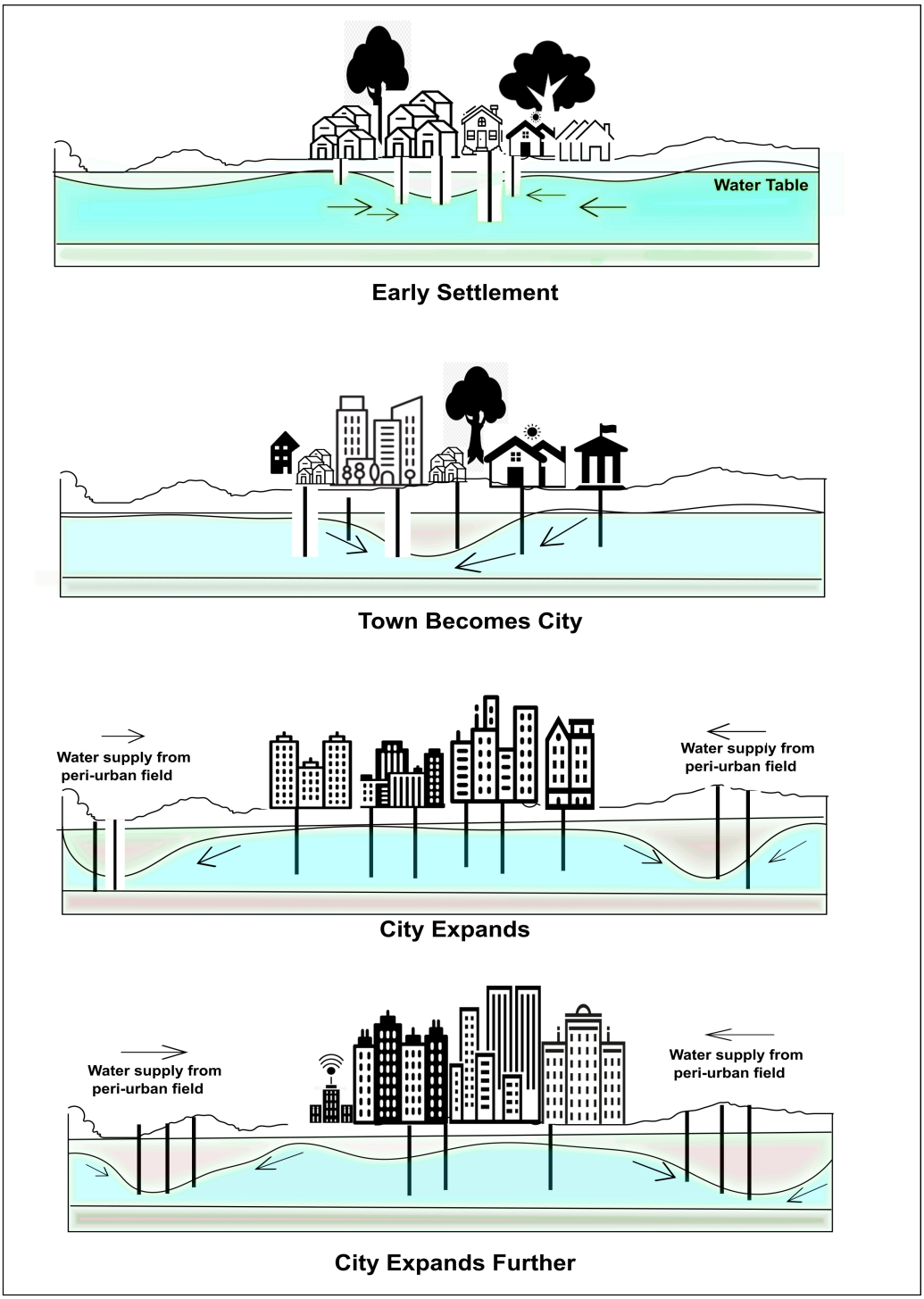


Figure 3.2. Evolution stages of a city and related changes in subsurface environment; (Source: Foster et al., 1998)

carbon fuels storage in every local area (Petrol stations/pumps) also influence the groundwater resources.

Solid waste disposal

Solid waste is an inevitable consequence of daily life in cities. Local municipalities select local and principal landfill area where disposed materials are dumped. Most of disposed objects carry polluted materials. This unprecedented objects get contaminated with local groundwater storage through seepage and infiltration. A table (3.2) has been created for a better understanding on urban use of subsurface environment and initial benefits from it and possible consequences eventually.

Table 3.2. Usage of urban groundwater: initial benefits and long-tem effects

Function of subsurface	Initial benefits	Long term costs
Water supply source	Water can be consumed according to need Quality of water is better at initial stage of abstraction Individually private consumption is possible	Excessive consumption degrades the condition of the wells Creates a risk of salinity especially in coastal area Creates the risk of land subsidence in vulnerable landforms
On-site sanitation receptor	Provides capacity to expand sanitary infrastructure Utilises natural capability of the soil underneath the process is economic Integrate water sources	Aquifer assimilation efficiency is reduced because of excessive amount of contamination load Sustainability is affected because of disproportionate groundwater abstraction
Pluvial drainage receptor	Minimise flood risk in downstream of the watercourse Dilution of materials that comes from urban environment after surface runoff	Contaminated materials increase more than dilution capacity and its degrade groundwater quality
Industrial waste and solid waste disposal	Low down treatment cost	Groundwater quality deteriorate continuously and that ultimately pollute local hydrological cycle

3.7 Effects of urbanisation on groundwater resources

Urbanisation process has a long-term effect on land use and it indirectly influences climate and groundwater. The need for cities and its growth started after 18th century industrial revolution in western part of the world but in 20th century after independence from colonisation, developing countries observed rapid growth in many cities. The reason was mainly economic development. Most of the cities were unplanned and concept of sustainability was overlooked at the time of development. Urban dwellers exploited the lands and transformed most of the open space into impermeable surfaces through heavy construction. Thus, chance of infiltration and the process of recharge got obstructed. Process of urbanisation modified soil moisture holding capacity as land surface temperature increased. High amount of groundwater abstraction in a short time span modified the water table negatively in most cases.
Groundwater quality was changed by the influence of industrial development also wastewater disposal and sewage negatively influenced the subsurface environment. Continuous increases in the amount of nitrogen and sulphur made water highly salty, pH levels changed with contamination, and electrical conductivity negatively made an impact on groundwater. The presence of hydrocarbon sources with affluent amounts in urban area directly created an impact on groundwater quality.

3.7.1 Consequences of groundwater abstraction

Continuous groundwater abstraction from a specific location creates decline in water level. Regular abstraction of water make changes in groundwater storage. Continuous increasing process makes an imbalance in groundwater recharge and discharge; later part surpasses the former. As a result, height of the hydraulic head changes in local aquifer. This repetitive process can reverse the flow direction also. This situation creates provision to intrude sea water into freshwater specifically in coastal area.
Subsidence of land can also be a consequence of the process. Differential subsidence in roads, buildings, parks, damage the constructions and that may lead to a disaster for the city.

3.7.2 Impact of groundwater on urban infrastructure

Rapid urbanisation tends to change in subsurface infiltration process, that leads to direct change in groundwater recharge (Mishra & Singh, 2019). In long run it may be possible that groundwater level can rise because of abnormality in recharge. This situation creates absurd changes in groundwater flow and noticeably groundwater quality also changes. Ultimately it generates a negative impact on groundwater resources and canals and wetlands related to it. Water quality changes lead to several negative effects on subsurface environment and ultimately in long run groundwater affects whole urban scenario definitely.

3.7.3 Urban influence on groundwater recharge

Land surface permeability

Urbanisation makes direct impact on landuse pattern of a city. Concentrated construction increases impermeable land and it reduces the direct infiltration of excess rainfall. Possibility of groundwater recharge also decrease and with this process amount of evaporation also decrease. Consequently, rate of surface runoff increases in an urban area. Cemented buildings, roofs, concrete roads reduce the permeable capability where as tile, brick, porous asphalt increase the chance of permeability in surface.

Pluvial drainage

Impermeabilisation in urban surface reduce the chance of infiltration from pluvial drainage. Urban planners usually, plans to pass the excess amount of water from the city with minimum time, that minimise the opportunity to infiltration and recharge.

Local groundwater abstraction

Groundwater abstraction from a specific location contributes minimum in groundwater recharge. Open Dug wells, faulty bore holes sometimes make contribution to groundwater recharge due to poor maintenance of the infrastructure.

Water supply system

Water demand increases with the growth of the city. Need of water is managed by public water supply from local municipalities. Water supply is provided throughout the city with large diameter pipes submerged under the city. Initial cost is high for this process and scope of maintenance of these pipes is limited as consequence, leakages and spills from pipes make contribution to groundwater recharge in urban setup.

On-site sanitation

Especially in developing countries, poor sanitation system unload sewage to open areas and that remains there for a long time, it increases the chance of infiltration to subsurface environment. Septic tank leakages also a prior issue in urban areas. Septic tanks are related with every residence and building. Number of septic tanks are more in dense urban area that consequently increase the chance of leakages from this and this process is directly related to subsurface environment. Disposal grounds and landfill areas generates the same problem in urban area. Unplanned infrastructure related to this rise the possibility of infiltration.

3.7.4 Water quality problems in urban area

Water quality in urban area may inclined towards degradation due to various reason. Effect of agricultural activities is negligible for an urban area but dense industrial activities and domestic

activities are very prominent within a small area. Seepage from neglected sanitation system, like septic tanks, underground holding tanks and latrines, usually contributes mostly for degradation of urban water quality. Pathogenic bacteria from an on-site location can directly percolate to subsurface environment and it raise high chance of contamination with groundwater. Cities under karst topography are most vulnerable for groundwater pollution.

Pathogens and other heavy metals might directly infiltrate due to poor borehole construction

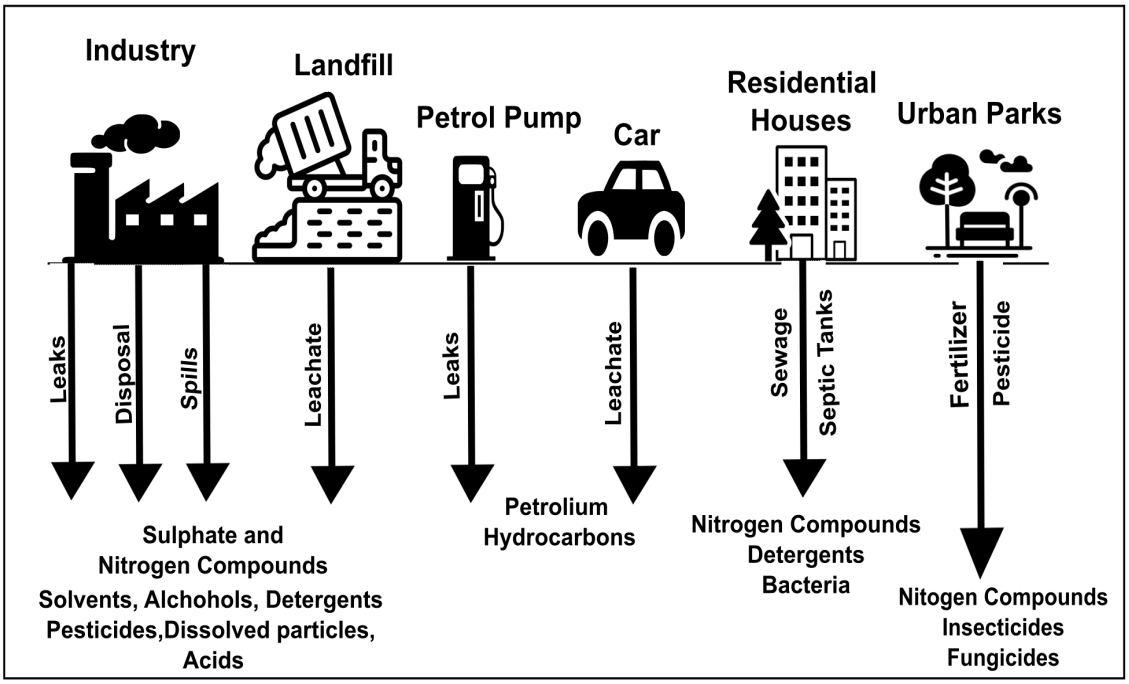


Figure 3.3. Polluting sources, process to pollute and pollutants in urban groundwater

designs. Additionally, contaminated surface water can immediately percolate from land surfaces to shallow aquifers. This process contaminates groundwater with various bacteria, protozoa, and viruses. Long-term availability of nitrogen compounds through excreta materials in groundwater can be a severe problem. The subsurface hydrological environment can change when nitrogenous elements are present in different concentrations. Accidental spills, leaks, and incorrect disposal of industrial outflow also create serious, although more localised groundwater pollution.

Presence of semi confined (deeper) aquifers is observed in many cities, those underlie in shallow aquifer. Poor quality of groundwater in shallow aquifer can contaminate the underlying aquifer in a long run and exploitation results permanent change in aquifer.

Pollution of alluvial aquifers also occur in downstream of cities. In different cities, waste water is deposited in surface watercourses without or with minimal treatment. It is a prevalent practise, particularly in developing countries. These processes have a negative impact on alluvial aquifers.

Table 3.3. Major groundwater quality related issues in urban area

Type of Problem	Causes	Concerns
Anthropogenic pollution	Urban and industrial activities	Pathogens, NO_3, Cl, SO_4, Heavy metals, aromatic, and halogenated hydrocarbons
	Intensification of agricultural and plantation activities	NO_3, Cl, Pesticides
Nature based contamination	Related to increase in pH level in groundwater and dilution of minerals	Mainly Iron, Fluoride sometimes Arsenic, Al, Mg, SO_4, Nitrate
Wellhead contamination	Inadequate well design and construction allowing direct admittance of polluted water from the land or shallow groundwater	Mainly pathogens

3.8 Groundwater dependent cities over the world

It has been prominently observed that, as population has grown in cities, the water demand increased proportionately. As urban water supply generally depends on local municipal supply, water demand pressurised supply systems. Economic infrastructure led to a force in demand for water also. Supply systems inclined to find alternative resources and groundwater always proved to be beneficial in such situations. In such cities without a proper source of surface water, groundwater is the ultimate resource there. Dependency on groundwater thus became an inevitable factor for a city. Further, it has been projected that in near future, population density in an urban areas will be more than in rural areas. Dependency on groundwater will increase also.

Usually, city represents a unit of an urban area. It is observed that, with the development of a city, groundwater has played a crucial role. WHYMAP (2015) produced a worldwide description about groundwater dependencies of cities (Appendix. Table 6). From that spatial dataset, it has been found that more than 10 cities with greater than 5 million population are deliberately dependent on groundwater. There are area more than 66 cities in the world with 1 to 5 million people that rely on groundwater resources for urban water demand. Worldwide, 33 cities with a population of between 5 lakh to 1 million (10 lakh) people rely on groundwater. Other cities with lower than 5 lakh people also depend on groundwater for their needs. Groundwater dependency is certainly determined by local hydrogeological proponents and surface water supply.

A detailed table 3.4 has been produced from the spatial dataset, showing the countries with number of cities that depend on groundwater. Few of the important countries have been enlisted. In a large part of the world, where cities are dependent on groundwater. Most populated countries have most cities which are dependent on groundwater. China, USA and India are the top three countries where most populated cities are dependent on groundwater resources for urban water supply. Apart from this dataset, it has been also found that there are several other countries in

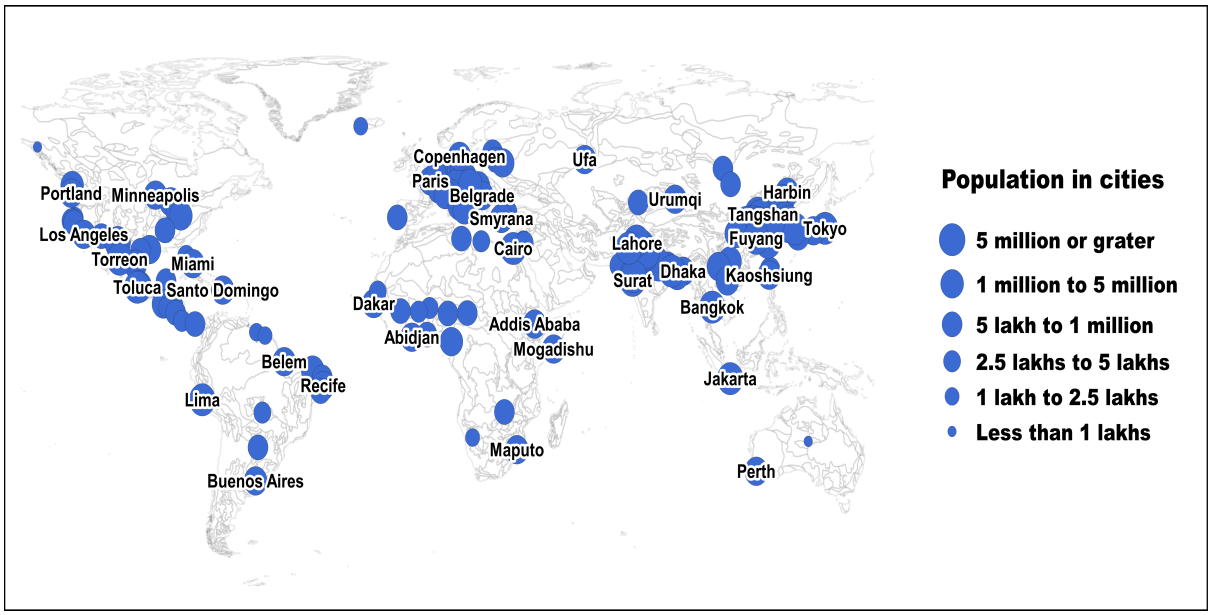


Figure 3.4. Cities that partly or solely dependent on groundwater, size of the cities in circle representing the population (Source: WHYMAP, 2015)

every continent that are solely dependent on groundwater.

Several researchers have concentrated on groundwater usage in urban area. Focusing on

Table 3.4. Country wise groundwater dependent cities with examples

Country	No. of Cities	City Name
China	22	Beijing, Tianjin, Harbin, Taiyuan, Jinan and others
USA	19	San Francisco, Los Angeles, Cincinnati, Miami, Memphis, Houston and others
India	15	Calcutta (Kolkata), Jaipur, Lucknow, Surat, Amritsar and others
Brazil	6	Recife, Cuiaba, Belem, Natal and others
Mexico	6	Mexico City, Merida, Monterrey and others
Italy	4	Milan, Turin, Rome, Naples
Germany	3	Hamburg, Berlin, Munich
France	3	Paris, Lyon, Lille
Japan	3	Tokyo, Kyoto, Fukuoka
Russia	2	Irkutsk, Ufa
Egypt	1	Cairo
Portugal	1	Lisbon

cities they have identified mostly populated and densely urbanised cities either solely depend on groundwater or partly depend on groundwater sources along with surface water supply. Serious issues like groundwater level depletion, groundwater contamination and other fearful consequences have been observed for such cities also (Ahmed et al., 2019; Edmunds et al., 2002; Hayashi et al., 2009; Hernández-Espriú et al., 2014; Mohieldeen & Al-Marri, 2016; Murad, 2010; Sekhar et al., 2017).

Worldwide urban groundwater had been a major concern for researchers and policymakers. Different types of reports and documents have already been published to maintain a sustainable urban environment with appropriate use of groundwater (Foster et al., 2010; IGRAC, 2015, 2018; La Vigna, 2022). World Bank (2010) published a report on sustainable groundwater management in urban areas that report provided details on urban groundwater use policy to maintain sustainability. They observed groundwater scenarios of most concerning continents about groundwater like South America, Asia and Africa. The study was focused on cities related to respective continents. Different types of policy and management issues have been identified for these cities. It has been identified that unplanned municipal water supply, private water supply, negligence about the condition of aquifers, and high amounts of pollutants on the urban surface are the reason behind groundwater exploitation. Institutional management has been applied for these cities but general awareness among citizens is not satisfactory. Details description of 10 cities from the above-mentioned continents has been enlisted to understand the reason behind groundwater exploitation in urban scenarios (Table 3.5).

Table 3.5. Summary of 10 cities that use groundwater and their related concerns, (Source: Foster, 2020)

Sl No.	**City/ Country**	**Groundwater Suuply (Population) [approx..]**	**Main issues and concerns**
1	Bangkok/ Thailand	5% to 10% (8 million)	Massive private water well construction
2	Lucknow/ India	50% (3 million)	Declining water table; uncontrolled privatewater well drilling, High nitrate level in shallow aquifers
3	Aurangabad / India	0% (1 million)	Excessive private water well, drilling in an limited storage aquifer
4	Lima/ Peru	30 % (8 million)	Declining groundwater level; increasing saline intrusion; industrial abstraction

Table 3.5. Summary of 10 cities that use groundwater and their related concerns, (Source: Foster, 2020)

Sl No.	City/ Country	Groundwater Suuply (Population) [approx..]	Main issues and concerns
5	Buenos Aires / Argentina	20 % (4 million)	Industrial water well use reduction after 1980s. Strong water table rebound caused groundwaterflooding
6	Natal/ Brazil	100% (1 million)	In situ nitrate pollution; sea water intrusion
7	Ribeirao Preto/ Brazil	100 % (1 million)	Groundwater level fallen about 50m after 1970s
8	Addis Ababa / Ethiopia	50% (3 million)	Water supply storage merged with well field
9	Dar- es-Salem/ Tanzania	10% (5 million)	Surface water source decrease and more reliability in groundwater/ polluted groundwater due to in situ sanitation
10	Nairobi	10% (4 million)	Decrease in surface water sources, private drilling

United Nations (2022) published a book on the visibility and invisibility of groundwater resources. It has been reported in that book that, about 50% of the urban population depends on groundwater as the primary resource. Here, world cities have been identified according to their countries and proportional usage of urban groundwater has been identified (Table 3.6). However, it has been acknowledged that specific groundwater abstraction data is really limited. From the available data, it can be identified that Denmark (100%) is a country where all cities are solely dependent on groundwater resources. Hungary (95%) is another example. Coastal country Indonesia is also dependent on groundwater in urban areas. Costa Rica, Paraguay, and Bangladesh are other countries where groundwater is a crucial resource to meet up the demand for urban water supply. With time, the situation of urban groundwater is degrading throughout the world.

Table 3.6. Selected cities from selected countries with urban groundwater usage data; (Source: United Nations, 2022)

Country	**Population (Million)**	**Urban population (Million)**	**Utility water supply (mm3/year)**	**Utility groundwater supply (mm3/year)**	**Selected cities with major groundwater use**
Brazil	209.3	178.2	16 740 **	3 164 (19%)	Natal,Ribeirão Preto, São Luis do Maranhão
Chile	16.4	14.7	1 267	498 (39%)	Santiago,Coquimbo, Concepcion
Costa Rica	4.9	4	652	522 (80%)	San Jose, Puntarenas, Liberia
Mexico	129.2	102.1	14 230 *	7 000 (49%)	Mexico City, Merida, San Luis Potosi, Leon
Paraguay	6.4	3.9	362 *	272 (75%)	Asuncion, Villarica
USA	324.5	270.7	58 390 *	21 001 (36%)	Miami, Tampa, Phoenix, Oklahoma
Cote d'Ivoire	24.3	12.2	321 **	n/a	Abidjan, Bouake
Ethiopia	105	21.3	810 *	n/a	Addis Ababa, Dire Dawa
Kenya	49.7	13.2	495 **	n/a	Mombasa, Nakuru
Senegal	15.9	7.4	98 *	n/a	Dakar, St. Louis

Table 3.6. Selected cities from selected countries with urban groundwater usage data; (Source: United Nations, 2022)

Country	Population (Million)	Urban population (Million)	Utility water supply (mm3/year)	Utility groundwater supply (mm3/year)	Selected cities with major groundwater use
Tanzania	42.9	9.9	328 **	n/a	Dodoma, Arusha, Tanga
Zambia	17.1	7.3	290 **	60 (21%)	Lusaka, Kabwe
India	1 339.2	455.3	56 000 **	13 328 (24%)	Lucknow, Chennai, Chandigarh, Indore
Pakistan	197	70.9	9 650 **	2 934 (30%)	Islamabad, Lahore, Rawalpindi, Multan
China	1 409.5	817.5	79 400 *	7861 (10%)	Tianjin, Beijing, Handan, Shenyang
Indonesia	964	145.2	23 800 **	21 420 (90%)	Jakarta, Semarang, Yogyakarta
Viet Nam	95.5	33.4	1 206 *	555 (46%)	Ho Chi Minh City, Da Nang, Hanoi
Bangladesh	164.7	59.3	3 600 **	2 603 (72%)	Dhaka, Khulna, Chattogram
Denmark	5.8	5.1	230	230 (100%)	Copenhagen, Odense, Aarhus, Aalborg

Table 3.6. Selected cities from selected countries with urban groundwater usage data; (Source: United Nations, 2022)

Country	**Population (Million)**	**Urban population (Million)**	**Utility water supply (mm3/year)**	**Utility groundwater supply (mm3/year)**	**Selected cities with major groundwater use**
France	67	53.9	1 774	1 064 (60%)	Paris, Caen, Limoges, Le Mans, Poitiers
Germany	83.1	64.1	1 606	1 188 (74%)	Hamburg, Berlin, Munich, Hanover
Hungary	9.7	7	257	244 (95%)	Budapest, Miskolc
Italy	60.3	42.6	1 391	1 210 (87%)	Rome, Milan, Turin, Perugia
Netherlands	17.4	15.8	489	298 (61%)	Utrecht, Eindhoven, The Hague
Poland	37.2	22.8	576	357 (62%)	Warsaw, Wrocl,aw, Poznan, Cracow
UK	66.8	55.5	3 558	1 245 (35%)	Portsmouth, Hull, Cambridge, Brighton

3.9 Conclusion

The interaction between groundwater and urban area has been highlighted in this chapter. Urban area reflects the high amount of concentrated population density in a comparatively smaller area than rural settlement so, the need for water is much higher here. Heterogeneity in terms of the consumption of water is also a fact for the city. Hydrogeological characteristics often decide the scenario of groundwater generally but in urban area, often it is altered by rigorous anthropogenic activities. Local governments or municipalities prepare a management plan to serve water to a certain amount of consumers but increasing population and other urban infrastructure create a gap between demand and supply. Groundwater is also used for industrial purposes in cities. Private usage of groundwater by residents is a common practice. It has been observed that uncontrolled groundwater abstraction is a common problem for cities. Urbanisation creates long-term effects, with impermeabilisation on the surface and the increasing built-up area directly effects on normal groundwater recharge process. Often, pollutants from urban sources percolate under the ground and contaminate the groundwater with time. Researchers have identified leakage and seepage from urban water supply pipes, and sewerage channels create the chance of groundwater recharge. Local influence of hydrogeology and aquifer environment beneath the city plays a major role in urban groundwater scenario.

Research in urban hydrogeology is comparatively among other core subjects and recently it focused as a separate subject to discuss. Awareness among public was limited and governmental policies were not fruitful from the initiation of urbanisation; recently it is developing to conserve groundwater resources. It is worthwhile to mention that, there are limited details available to generate the actual picture of an urban area and its interaction with the groundwater environment. Along with this, there are numerous factors are exploiting the urban groundwater scenario which is unknown yet.

It has been observed from the various worldwide survey most the large cities are partially dependent on groundwater. Without proper source of surface water, some cities rely on groundwater. Previously importance of groundwater was not defined among the people, so heavy usage of groundwater already created a deep impact in certain cities. Recently, developed countries already started the procedure to check the exploitation of groundwater and it has become successful in certain cities. *'Less use to Reuse'* has already started. Whereas in developing countries groundwater exploitation is continuing and impact of urbanisation creating an impeccable effect on the subsurface environment.

References

Ahmed, I., Tariq, N., & Al Muhery, A. (2019, jan). Hydrochemical characterization of groundwater to align with sustainable development goals in the Emirate of Dubai, UAE. *Environmental Earth Sciences*, *78*(1), 44. Retrieved from http://link.springer.com/10.1007/s12665-018-8030-1 doi: 10.1007/s12665-018-8030-1

Angelakis, A. N., Voudouris, K. S., & Mariolakos, I. (2016, aug). Groundwater utilization

through the centuries focusing n the Hellenic civilizations. *Hydrogeology Journal*, *24*(5), 1311–1324. Retrieved from https://link.springer.com/article/10.1007/s10040-016-1392-0http://link.springer.com/10.1007/s10040-016-1392-0 doi: 10.1007/s10040-016-1392-0

Deming, D. (2020, jan). The Aqueducts and Water Supply of Ancient Rome. *Groundwater*, *58*(1), 152–161. Retrieved from https://onlinelibrary.wiley.com/doi/10.1111/gwat.12958 doi: 10.1111/gwat.12958

Edmunds, W., Carrillo-Rivera, J., & Cardona, A. (2002, feb). Geochemical evolution of groundwater beneath Mexico City. *Journal of Hydrology*, *258*(1-4), 1–24. Retrieved from https://linkinghub.elsevier.com/retrieve/pii/S0022169401004619 doi: 10.1016/S0022-1694(01)00461-9

Foster, S., Hirata, R., Misra, S., & Garduño, H. (2010). *Urban groundwater use policy: balancing the benefits and risks in developing nations* (Vol. 3). Retrieved 2022-10-22, from https://documents.worldbank.org/pt/publication/documents-reports/documentdetail/471001468159609056/urban-groundwater-use-policy-balancing-the-benefits-and-risks-in-developing-nations

Hayashi, T., Tokunaga, T., Aichi, M., Shimada, J., & Taniguchi, M. (2009, apr). Effects of human activities and urbanization on groundwater environments: An example from the aquifer system of Tokyo and the surrounding area. *Science of The Total Environment*, *407*(9), 3165–3172. doi: 10.1016/J.SCITOTENV.2008.07.012

Hernández-Espriú, A., Reyna-Gutiérrez, J. A., Sánchez-León, E., Cabral-Cano, E., Carrera-Hernández, J., Martínez-Santos, P., ... Colombo, D. (2014, sep). The DRASTIC-Sg model: an extension to the DRASTIC approach for mapping groundwater vulnerability in aquifers subject to differential land subsidence, with application to Mexico City. *Hydrogeology Journal*, *22*(6), 1469–1485. Retrieved from http://link.springer.com/10.1007/s10040-014-1130-4 doi: 10.1007/s10040-014-1130-4

IGRAC. (2015). *International Groundwater Resources Assessment Centre.* Retrieved 2022-10-22, from https://www.un-igrac.org/download-topics/urban-groundwaterhttp://www.un-igrac.org/

IGRAC. (2018). *Groundwater Overview, Making the invisible visible* (Tech. Rep.). Retrieved from https://www.un-igrac.org/special-project/gw-mate

La Vigna, F. (2022, sep). Review: Urban groundwater issues and resource management, and their roles in the resilience of cities. *Hydrogeology Journal*, *30*(6), 1657–1683. Retrieved from https://link.springer.com/10.1007/s10040-022-02517-1 doi: 10.1007/s10040-022-02517-1

Lancia, M., Zheng, C., He, X., Lerner, D. N., & Andrews, C. (2020, may). Groundwater Complexity in Urban Catchments: Shenzhen, Southern China. *Groundwater*, *58*(3), 470–481. Retrieved from https://onlinelibrary.wiley.com/doi/10.1111/gwat.12935 doi: 10.1111/gwat.12935

Mishra, D., & Singh, B. N. (2019). Identification of Groundwater Prospect in Bara Region of Allahabad District Based on Hydro-Geomorphological Analysis Using Satellite Imagery.

Journal of the Indian Society of Remote Sensing, *47*(7), 1257–1273. Retrieved from https://doi.org/10.1007/s12524-019-00984-w doi: 10.1007/s12524-019-00984-w

Mohieldeen, Y. E., & Al-Marri, A. (2016). Using GIS to Quantify Change in the Groundwater Levels in Qatar Between 1980 & 2009. In *Qatar foundation annual research conference proceedings volume 2016 issue 1*. Hamad bin Khalifa University Press (HBKU Press). Retrieved from https://www.qscience.com/content/papers/10.5339/qfarc.2016.EEPP1685 doi: 10.5339/qfarc.2016.EEPP1685

Morris, B. L., Litvak, R. G., & Ahmed, K. M. (2002). Urban Groundwater Protection and Management: Lessons from Developing Cities in Bangladesh and Kyrghyzstan. In *Current problems of hydrogeology in urban areas, urban agglomerates and industrial centres* (pp. 77–102). Dordrecht: Springer Netherlands. Retrieved from http://link.springer.com/10.1007/978-94-010-0409-1{_}5 doi: 10.1007/978-94-010-0409-1_5

Murad, A. A. (2010). An Overview of Conventional and Non-Conventional Water Resources in Arid Region: Assessment and Constrains of the United Arab Emirates (UAE). *Journal of Water Resource and Protection*, *02*(02), 181–190. Retrieved from http://www.scirp.org/journal/doi.aspx?DOI=10.4236/jwarp.2010.22020 doi: 10.4236/jwarp.2010.22020

Sekhar, M., Tomer, S., Thiyaku, S., Giriraj, P., Murthy, S., & Mehta, V. (2017, dec). Groundwater Level Dynamics in Bengaluru City, India. *Sustainability*, *10*(2), 26. Retrieved from http://www.mdpi.com/2071-1050/10/1/26 doi: 10.3390/su10010026

Smith, R. (2013). *Drought Led to Collapse of Civilizations, Study Says.* Retrieved 2022-10-18, from https://www.nationalgeographic.com/culture/article/131024-drought-bronze-age-pollen-archaeology

Voudouris, K., Valipour, M., Kaiafa, A., Zheng, X. Y., Kumar, R., Zanier, K., … Angelakis, A. (2019, mar). Evolution of water wells focusing on Balkan and Asian civilizations. *Water Supply*, *19*(2), 347–364. Retrieved from https://iwaponline.com/ws/article/19/2/347/40849/Evolution-of-water-wells-focusing-on-Balkan-and doi: 10.2166/ws.2018.114

Chapter 4

Literature Review on Impact of Urbanisation on Groundwater Resources

4.1 Introduction

Urbanisation results increase in population that ultimately exploits natural resources to maintain economic and social well-being. It has been observed that urban water cycle is complex and interesting. Researchers from the perspective of sustainability understood the importance of groundwater as resource.The dichotomy about its actual reuse has been under topic of discussion. Polarity has been developed among researchers about treatment of groundwater as renewable or non-renewable resource. According to FAO[1], groundwater must be counted as non-renewable resource as negligible rate of recharge has been observed relating to human time scale. Whereas, in the discussion about the sustainability of groundwater resources, a report published by USGS[2], it has been mentioned that, groundwater should be treated as a renewable resource but completely blind in believing about renewing ability should not be inferred. Understanding the importance of groundwater and it is specifically in urban areas is a serious step towards sustainability.

4.2 Objectives

In this chapter, urbanisation and groundwater related research documents have been included in chronological manner to understand the research trend towards urban groundwater studies. Main objective of this particular chapter is to incorporate such crucial and valuable studies that already published and created an impact in this research sector. Chronological order has been maintained to realise the path that researchers have fallowed already. Another objective of this study is to select important methodologies that are ideal for groundwater analysis in urban scenario.

[1]Food and Agricultural Association
[2]United States Geological Survey

4.3 Methodology and data collection

For literature review, use of bibliographic database is the ultimate method in the research field. In this chapter, search for urban groundwater studies have been proceeded using the largest bibliographic database, Scopus[3]. Different types of keywords have been used to collect bibliographic data related to subject, the temporal search remained limited within 1990 to 2020 to get the research viewpoint for last three decades. Mainly the search tried to identify research trend in groundwater for the last three decades. Also, another open database like Google Scholar[4] has been used. It has been observed that nearly 3000 documents have been published in last three decade that mainly focused on urban groundwater studies. Outcome is mixed with journal articles, books, book section, conference proceedings, report etc. In this chapter, mainly knowledge gathered from peer reviewed journal articles for its authenticity and global acceptance. According to their appearance in high impact journals and acclamation through citations, mostly two hundred documents served the purpose of this thesis.

4.4 Significant urban groundwater studies

4.4.1 Before the year 1990

Hollis (1974) observed that, in Essex Harlow, New Town where urbanisation has increased the water yield rate. Urban flood has increased about 200% that was unaffected before the urbanisation. His doctoral thesis have shown that, impact of urbanisation on floods oppositely related to the recurrence frequency of the floods.
Williams (1976) in his paper, has described in Wairau creek, Auckland a small catchment area that mostly changed with time into urban area, hydrological changes occurred therefore, a consisted change draws an opposite relation with flood interval increase and depth of flood. Floods stroked frequently as consequence of urbanisation.
McFarlane (1981) worked on Perth, Western Australia. He identified three factors that obstructs to rise the groundwater level, a) removal of water by boring, b) flood mitigation drains, c) swearing areas by septic tanks. According to him, housing density, quantity of water extracted by bores and sewerage and drainage system mainly reflects the equilibrium of the water level. Housing density affects the recharge and discharge both. Socio-economic factors make changes on quantity of water extraction, and sewerage and drainage capacity are dependent upon local governing body. He concluded with the perception that, input, and output of the hydrological cycle changes with urbanisation. He also included that, groundwater salinity, iron content and hardness may be changed due to urbanisation.
Australian Water Resources Council. et al. (1987) showed that at Perth, Western Australia, level of nitrate increased in urban area due to seepage from septic tanks and nitrogenous fertilizers. that affected mostly the unconfined aquifers.
Marsh & Davies (1983) described in their paper about Chalk area of London that, industrial

[3] https://www.scopus.com/search/
[4] https://scholar.google.com/

development in London certainly increased the demand of water with this the possibility of pollution in water increased. Ground water level dominated by ground water pumping. Burgeoning growth of urbanisation reduced the potential growth of natural recharge. Falling water level made change on ground settlement.

4.4.2 The period between 1990 to 2000

Foster & Foster (1990) published a paper related to impact of urbanisation on groundwater. He depicted about profound importance of urbanisation on hydrological cycle. Regime of groundwater recharge changes with rapid urbanisation.This article was concluded with certain perceptions like urbanisation creates definite negative impact on groundwater. Without proper planning and implications for sewage and drainage, these negatively affect the groundwater. Groundwater supply should be checked and controlled specially where it is under industrial belt, Nitrate is one of the most concerned elements that may be contaminate with groundwater in urbanised area. proper planning and precaution can prevent the deterioration of public health that caused due to use of groundwater.

D. N. Lerner (1990) described on groundwater recharge in urban areas. According to him, water does not follow a definite cycle in the urban environment. Hydrological cycle gets altered by urbanisation. He divided the recharge of groundwater in an urban area by natural network and water supply network. However, he depicted that it is difficult to calculate the net effect of recharge in a certain area. He identified potential threats for groundwater, those area waste disposal activities, industrial premises, chemical stockpiles, sewers, and surface drainage. He also prescribed certain methods to calculate the recharge in groundwater in urban area.

A report published on 1993 about south east Asian city Hat Yai, Thailand. This report published on the perspective of Urbanisation and its impact on groundwater. The assessment described that, rate of recharge increased with time due to leaking from the pipes and sewage. Increase in recharge could not made any effective change in water level, because abstraction rate of groundwater was more than recharge. Chance of infiltration decreased with increase in impervious layer. Quality of groundwater deteriorated because of poor quality of urban recharge. Ammonia, Chloride and Nitrate contaminated in the water (Unesco, 2000).

Barber et al. (1996), in Western Australia, near Perth city, 11 groundwater wells were analysed by GIS technology for the time span of twenty years. This study concluded with result that, there is considerable change in nitrate concentration and VOC [5] due to rise in urban area and industry.

British Geological Survey on their technical report, published that, groundwater is the principal source of water supply in Hanoi, Vietnam. Abstraction of groundwater increased with increasing population and rapid urbanisation. This report suggested that, groundwater has been replaced by modern recharge, this recharge slightly increased the chloride and bicarbonate and these are associate with urban waste disposal. Proportion of ammonia also increased. (Trafford et al., 1996).

D. N. Lerner & Tellam (1999) applied the concept of quantification for groundwater recharge in

[5] Volatile Organic Compound

Nottingham, a city from United Kingdom. They identified three major urban recharge sources like, rainfall, supply leakage and sewers. They provided a calibrated groundwater flow model to quantify the recharge.
Kittu (1999) has also been investigated impact of urbanisation on coastal city like Madras, India. He identified the gap between supply and demand making stress on groundwater. This consequence led to the effect of sea water ingress in the aquifer and shallow groundwater contaminated by sea water.

4.4.3 The period between 2000 to 2010

Rao & Pardhasaradhi (2000) analysed the groundwater regime in Visakhapatnam urban area in paper in early 2000. A gap was created in water supply by municipal authority and water demand that was fulfilled by subsurface water in fastest growing city. Demand from domestic need and industrial demand made a stress on urban groundwater and with increasing rate of decline rate in water level, that also made change in groundwater quality. They focused on rapidly increasing population in urban area and change in demand of water. They specified about industrialisation and consequent increase in water demand. Dense built up area and disappearing small water bodies consequently made increased runoff. They described that due to construction of building for housing, commercial spaces, laying asphalt roads for transportation made change in impermeability of the land and resulting of reduction in groundwater recharge and enhancement of surface runoff.
Foster (2001) published a paper on the co-relation of groundwater and urbanisation for cities developing rapidly. He described the role of subsurface water in urban development. Worldwide, 50% of the urban area used subsurface water as a source of drinking water around 2000; specially in major part of Asia, Latin America. He identified relevant function of subsurface water. It can be used as water supply source, it could be the onsite sanitation receptor, pluvial drainage receptor, and location for dumping industrial waste. He summarised the process that made an impact because of urbanisation in groundwater. Uncontrolled aquifer exploitation can lead up to fall in water table. Urbanisation generally decreases subsurface infiltration rate, depending upon, recharge rate, and upon permeability.
Jeong (2001) studied effect of urbanisation on groundwater contamination. His study was concentrated in urban area of Korea. He found groundwater quality is highly influenced by effect of urbanisation. Comparatively lower urbanised places showed low amount of electrical conductance.
D. N. Lerner (2002) identified that quantification of urban recharge is a more complex than rural environment. Recharge depends on impervious surface mainly. Permeability is different for different objects in urban location. Identification of urban recharge area and their potentiality identification is difficult. He advised for application of empirical method. He mentioned about piezometry process to identify the constant source of recharge and applied this process on a part of Hong Kong Island. He also mentioned some case studies related to it.
Daji Limaye (2006) mentioned about urban groundwater situation in India in his paper. According to him, investment and infrastructure built up in sanitation usually lags water supply facility.

Old and unmaintained sewer channels leaks polluted water. Pollution also takes place due to percolation of such water. Petrol pumps, stormwater drainage, chemical usage contaminate the water with pollutants. Newly formed cities that are suburban of the main city those lags from upgraded infrastructure, so that makes change in groundwater. Urban residents especially from bungalows and apartments prefer their own source of water rather than municipal supply. They use private borewells due to huge demand in small area. This process make change in water level also. He mentioned about the picture of Kolkata on his paper to a give brief of the situation.it is in alluvial deltaic region. Water comes from the municipal supply is not adequate to drink, and available for certain time in a day. people here, prefer private digging to meet up the demand of water.

Paliwal (2007) described about the ascend in groundwater level in the Jodhpur city in India. It is a city which is under Thar Desert, very low possibility of rainfall. But the groundwater level raised because of the interaction with surface water. After 1997 the Indira Gandhi Canal made change in the supply of water on that city. Human intervention in desert area made change in water availability but poor drainage and leaking from the sewers made an impact on groundwater recharge.

D. N. Lerner & Harris (2009) reviewed the association between land use and groundwater quality. They have depicted that, anthropogenic activities mainly exploit the groundwater resources and unplanned land use may cause deterioration in groundwater quality.

Jago-on et al. (2009) attempted DPSIR model for the first time to urbanised subsurface environment to create a holistic idea about the Asian cities like Bangkok, Jakarta. Tokyo, Manila, Osaka etc.. They described detail process to apply DPSIR model on groundwater environment. It has been observed that, with change in population and economy, urbanisation process took a leap in these cities. Groundwater abstraction to meet up the demand was the obvious practise for the cities, especially industrial demand along with domestic needs abstracted the groundwater much than normal recharge. Most of the cities identified deterioration in aquifer system thus strict rules and regulations applied for abstraction. With strict implications of laws, check in groundwater abstraction was possible. Effect of urbanisation and subsurface environment in Japanese Cities like Osaka and Tokyo has been well analysed with DPSIR method.

4.4.4 The period between 2010 to 2020

Nas & Berktay (2010) produced spatial groundwater quality map using GIS. They applied geo-statistical methods to interpret spatial variation of physio chemical proponents of groundwater. Application of spatial kriging and semivarioveriogram was part of the methodology. A city-based groundwater quality exploration process was successfully developed through GIS thus it was highly acclaimed among the research sector.

Nagarajan et al. (2010a) analysed water quality parameters for an Indian city where groundwater is the ultimate resource and groundwater is utilised in domestic and irrigational purpose. They have applied descriptive statistical method to analyse water quality parameters and therefore spatial maps has been produced. They evaluated groundwater quality based on drinking water standards. It is identified that influence from surface contamination,ion exchange, evaporation,

mineral dissolution, modified the groundwater quality. Impact of nitrate and chloride on groundwater also acknowledged by the authors due to irrigational and domestic activities.
Nagarajan et al. (2010b) reviewed about emerging contaminants in groundwater of UK. In this article, nano materials, industrial compounds, pesticides, pharmaceuticals, , fragrances, water treatment by products, flame retardants and surfactants, personal care products as well as caffeine and nicotine has been addressed as emerging groundwater contaminants. Transportation of these emerging contaminants in aqueous environment has been analysed with source-pathway-receptor model, where source are the contaminants that creates a various path to infiltrate into subsurface environment and ultimately used by receptors. Authors have discussed about the risk related issues from such contaminants.
Kazi Ahmed et al, (2011) described the changes in groundwater regime of Dhaka city. It is an analysis based on historical data. They identified change in water depth due to high-rate abstraction and reduction of natural resource like groundwater. They mentioned continuous declination of water level from the eighties i.e the beginning of rapid urbanisation in Dhaka city. The abstraction rate is about 0.75 m per year and that made cone of depression at the centre of the city.
Huang et al. (2013) analysed the anthropogenic impact along with environmental impact on the evolution of groundwater quality in an urban area. Their study was based on a rapidly urbanised coastal area from South China. They have analysed the spatio temporal changes in landuse to identify urbanisation and for anthropogenic activities related to groundwater they have collected sample from different locations to analyse physio chemical parameters. They also have acknowledged the effect of hydrogeological structures of the study area. Along with descriptive statistical analysis they have applied principal component analysis to understand the effectiveness of different parameters in groundwater and produced hierarchical structural analysis to divide the study area with different clusters according to the quality. Water quality parameters also visualised with piper diagram. It is analysed that, negative impacts from anthropogenic activities can be broadly divided into three segments. Those are, industrialisation, sewage intrusion and agricultural pollution.
Menberg et al. (2013) discussed about subsurface heat environment in urban area due to anthropogenic activities. The study was conducted on six German cities. The article aims to identify man made impacts on groundwater temperature. It has been identified from the study, groundwater temperature anomaly in dense urban areas rather than other rural areas. Even heterogeneous nature of temperature has been observed within the city. Built-up area identified as the primary source for increased temperature in groundwater and sewage network, high voltage cables and district heating networks are the additional factors behind anomaly.
Schirmer et al. (2013) reviewed the contemporary research on urban hydrogeology. Authors have addressed research on urban groundwater as highly complex matter for local heterogeneous flow and different diversified parameters that directly or indirectly influence groundwater regime. They have acknowledged some crucial factors to analyse an urban groundwater environment. Water balance method, contamination, amount of concentration and distribution over space and time, implementation of holistic modelling approach, empirical GIS methods are the most emerging concepts.

Remondi et al. (2016) described the paper on effect of urbanisation on tropical river catchment in Indonesia published on 2015. It is Suggested that noticeable increase in flood events caused by uncontrollable rapid urbanisation. That changes the base flow and as a result that making an adverse effect on hydrological budget. They used Topkapi-ETH model for hydrological analysis.
Boken (2016) identified the groundwater crisis on the capital of India, Delhi. In his book chapter, he mentioned with 4 years of data analysis from different wells, He identified fluctuation in groundwater table. He identified increase in depth of groundwater except northeastern part. With his assumption he predicted massive groundwater crisis in Delhi. He also mentioned about the impact of population density on several groundwater condition.
Locatelli et al. (2017) prepared a novel modelling for stormwater infiltration with the impact of urbanisation. The study discussed that, urban area after storm water infiltration with increasing rate much affect the water balance of the catchment. Effect reflects through increase in recharge amount and decrease in evapotranspiration. Authors assumed that it may change into quantity of groundwater and as a result level rise in groundwater can be observed.
Wakode et al. (2018) discussed about groundwater recharge scenario in urban area. The study was developed on Hyderabad city, India. Authors estimated the recharge amount of water into the subsurface. They also tried to identify the proportion of supply leaks and its influence on groundwater recharge. They identified this estimation is a very complex approach as different kind of unknown and uncountable factors related to it. Ultimately, they followed water balance method and individually calculated amount of surface runoff using SCS-CN method.
Minnig et al. (2018) attempted an effort to analyse urbanisation driven factor that changes the amount of recharge in groundwater. They identified prediction of groundwater recharge is difficult to predict as several complex climatological factors affects the whole system. Simple water balance method has been applied to identify the recharge ratio in the study area. The study was applied on city on Switzerland. Through their study it has been identified that, a strong positive correlation exists between amount of groundwater recharge with extension in urban area.
Kalhor & Emaminejad (2019) studied the relationship between urbanisation process and consequential groundwater quantity using remote sensing data. They have identified that, with advancement in space science, observation from satellite on related data like, Landuse, water mass storage, precipitation, temperature is easily available. Using these GRACE data, they analysed the correlation between landcover changes and consequential changes in groundwater level. They have identified undeniable relation between urbanisation process and groundwater level anomality. They have applied this study on Atalanta, a city from USA at the same time authors mentioned its appropriate applicability in fast growing countries like China and India also.
Foster (2020) has addressed urbanisation as predominant global phenomenon. He shared experience from World Bank organised survey on World's 10 cities about private and public water supply from groundwater. They study was collected data in between 2001 to 2012. A strategic assessment has been described here about those cities and other cities that are dependent on groundwater. This article analysed the risk based on resource sustainability, built infrastructure, groundwater pollution and economic distortion with institutional investments

Urbanisation and related groundwater studies findings not only limits within generalised impact of urbanisation on subsurface environment. From elaborated studies it have been identified that, each of the city represents a specific characteristic on its own and that creates the complexity to gather a generalised concept about city environment in term of groundwater management.

4.5 Conclusion

From the above mentioned observations, it is realised that researchers highlighted urban-related issues to analyse groundwater related problems. Groundwater studies broadly focused on two subdivisions, groundwater quantity analysis and groundwater quality analysis. In some research, both have been covered. Serious issues have been identified for groundwater recharge due to the impervious nature of urban areas. Increased surface runoff indirectly affects groundwater regime. Groundwater quality is a serious concern for researchers and policymakers. Hydrogeological characteristics remained a crucial factor also various anthropogenic factors have been identified behind groundwater pollution in urban areas. Generally, it has been identified that groundwater in highly intensified urban areas gets contaminated with pollutants mostly outsourced from the surface of that urban land. Excessive groundwater abstraction from domestic and industrial sites both are the major concern for almost every urban land. In most cases, high yield in groundwater already modified the groundwater flow in urban water cycle and made permanent damage in subsurface environment. In the past, awareness about the importance of groundwater was not adequate among citizens but recently local governments and policymakers already amended strict rules to check groundwater exploitation; awareness is being created. Cities without another adequate water source strongly depend on subsurface water and further process of urbanisation affects additionally. Analysing the research trend it has been observed that, previously groundwater research broadly focused on the identification of anthropogenic factors behind groundwater quality and quantity change. After technical development in the identification of urban factors, researchers mainly concentrated on finding spatial variation in groundwater scenarios within an urban area. Apart from general factors, minor yet crucial factors have been identified which is particularly crucial for a city. Previously, researchers used to depend on rigours field surveys with rudimentary appliances and techniques. Recently, advanced, scientific and highly accurate instruments are being applied in fields also. Glorious advancements in remote sensing technology and the use of GIS already expanded research sphere, especially for urban groundwater analysis. Multidisciplinary approach has already been initiated by researchers to agglomerate knowledge from different fields. Recently application of machine learning, deep learning, cloud based data collection, and advanced internet of things along with complex computing technology enriched the analysis of urban groundwater studies. Nowadays, urban groundwater studies are concentrating more on the specific location-based investigation.

References

Australian Water Resources Council., International Association of Hydrogeologists., & Institution of Engineers Australia. (1987). Proceedings of the International Conference on Groundwater Systems Under Stress : Brisbane, Australia, 11 to 16 May 1986. , 648.

Barber, C., Otto, C. J., Bates, L. E., & Taylor, K. J. (1996, jan). Evaluation of the relationship between land-use changes and ground water quality in a water-supply catchment, using gis technology: The gwelup wellfield, Western Australia. *Hydrogeology Journal*, *4*(1), 6–19. Retrieved from https://link.springer.com/article/10.1007/s100400050078http://link.springer.com/10.1007/s100400050078 doi: 10.1007/s100400050078

Boken, V. K. (2016). Groundwater Crisis of a Mega City: A Case Study of New Delhi, India. In *Balanced urban development: Options and strategies for liveable cities* (pp. 211–219). Retrieved from http://link.springer.com/10.1007/978-3-319-28112-4{_}14 doi: 10.1007/978-3-319-28112-4_14

Daji Limaye, S. (2006, dec). Aspects of urban groundwater management and use in India. In *Urban groundwater, meeting the challenge* (pp. 189–194). Taylor & Francis. Retrieved from http://www.crcnetbase.com/doi/10.1201/9780203947050.ch14 doi: 10.1201/9780203947050.ch14

Foster, S. (2001, sep). The interdependence of groundwater and urbanisation in rapidly developing cities. *Urban Water*, *3*(3), 185–192. Retrieved from https://linkinghub.elsevier.com/retrieve/pii/S1462075801000437 doi: 10.1016/S1462-0758(01)00043-7

Foster, S. (2020, feb). Global Policy Overview of Groundwater in Urban Development—A Tale of 10 Cities! *Water*, *12*(2), 456. Retrieved from https://www.mdpi.com/2073-4441/12/2/456 doi: 10.3390/w12020456

Foster, S., & Foster, S. S. D. (1990). Impacts of urbanisation on groundwater IMPACTS OF URBANIZATION ON GROUNDWATER Chairman'Commission on Hydrogeology for Developing Nations'International Association of Hydrogeologists. *Article in Hydrological Sciences Journal/Journal des Sciences Hydrologiques*(198). Retrieved from https://www.researchgate.net/publication/237480481

Hollis, G. (1974). The Hydrological Effects of Urbanisation in the Canon's Brook Catchement, Harlow New Town, Essex. *Doctoral thesis, University of London.*. Retrieved from https://discovery.ucl.ac.uk/id/eprint/1349346/

Huang, G., Sun, J., Zhang, Y., Chen, Z., & Liu, F. (2013, oct). Impact of anthropogenic and natural processes on the evolution of groundwater chemistry in a rapidly urbanized coastal area, South China. *Science of the Total Environment*, *463-464*, 209–221. Retrieved from https://linkinghub.elsevier.com/retrieve/pii/S0048969713006293 doi: 10.1016/j.scitotenv.2013.05.078

Jago-on, K. A. B., Kaneko, S., Fujikura, R., Fujiwara, A., Imai, T., Matsumoto, T., ... Taniguchi, M. (2009, apr). Urbanization and subsurface environmental issues: An attempt at DPSIR model application in Asian cities. *Science of The Total Environment*, *407*(9), 3089–3104.

Retrieved from https://linkinghub.elsevier.com/retrieve/pii/S0048969708008176 doi: 10 .1016/j.scitotenv.2008.08.004

Jeong, C. H. (2001, nov). Effect of land use and urbanization on hydrochemistry and contamination of groundwater from Taejon area, Korea. *Journal of Hydrology*, *253*(1-4), 194–210. Retrieved from https://linkinghub.elsevier.com/retrieve/pii/S0022169401004814 doi: 10.1016/S0022-1694(01)00481-4

Kalhor, K., & Emaminejad, N. (2019). Sustainable development in cities: Studying the relationship between groundwater level and urbanization using remote sensing data. *Groundwater for Sustainable Development*, *9*(May), 100243. Retrieved from https://doi.org/10.1016/j.gsd.2019.100243 doi: 10.1016/j.gsd.2019.100243

Lerner, D. N. (1990). Groundwater recharge in urban areas. *Atmospheric Environment. Part B, Urban Atmosphere*, *24*(1), 29–33. doi: 10.1016/0957-1272(90)90006-G

Lerner, D. N. (2002, feb). Identifying and quantifying urban recharge: A review. *Hydrogeology Journal*, *10*(1), 143–152. Retrieved from https://link.springer.com/article/10.1007/s10040-001-0177-1http://link.springer.com/10.1007/s10040-001-0177-1 doi: 10.1007/s10040-001-0177-1

Lerner, D. N., & Harris, B. (2009). The relationship between land use and groundwater resources and quality. *Land Use Policy*, *26*(SUPPL. 1). doi: 10.1016/j.landusepol.2009.09.005

Lerner, D. N., & Tellam, J. H. (1999). Quantification of groundwater recharge in the city of Nottingham , UK. , *38*(September), 183–198.

Locatelli, L., Mark, O., Mikkelsen, P. S., Arnbjerg-Nielsen, K., Deletic, A., Roldin, M., & Binning, P. J. (2017, jan). Hydrologic impact of urbanization with extensive stormwater infiltration. *Journal of Hydrology*, *544*, 524–537. Retrieved from https://linkinghub.elsevier.com/retrieve/pii/S0022169416307363 doi: 10.1016/j.jhydrol.2016.11.030

Marsh, T. J., & Davies, P. A. (1983, may). The decline and partial recovery of groundwater levels below London. *Proceedings - Institution of Civil Engineers, Part 1*, *74*(May), 263–276. Retrieved from https://www.icevirtuallibrary.com/doi/10.1680/iicep.1983.1468 doi: 10.1680/iicep.1983.1468

McFarlane, D. J. (1981). The effects of urbanization on groundwater levels and chemistry in Perth, Western Australia. In *Groundwater resources of the swan coastal plain (1981). proceedings of symposium organized by csiro and water research foundation of autralia* (pp. 243–262).

Menberg, K., Bayer, P., Zosseder, K., Rumohr, S., & Blum, P. (2013, jan). Subsurface urban heat islands in German cities. *Science of The Total Environment*, *442*, 123–133. Retrieved from https://linkinghub.elsevier.com/retrieve/pii/S0048969712013253 doi: 10.1016/j.scitotenv.2012.10.043

Minnig, M., Moeck, C., Radny, D., & Schirmer, M. (2018, aug). Impact of urbanization on groundwater recharge rates in Dübendorf, Switzerland. *Journal of Hydrology*, *563*, 1135–1146. Retrieved from https://linkinghub.elsevier.com/retrieve/pii/S0022169417306625 doi: 10.1016/j.jhydrol.2017.09.058

Nagarajan, R., Rajmohan, N., Mahendran, U., & Senthamilkumar, S. (2010a, dec). Evaluation of groundwater quality and its suitability for drinking and agricultural use in Thanjavur city, Tamil Nadu, India. *Environmental Monitoring and Assessment*, *171*(1-4), 289–308. Retrieved from http://link.springer.com/10.1007/s10661-009-1279-9 doi: 10.1007/s10661-009-1279-9

Nagarajan, R., Rajmohan, N., Mahendran, U., & Senthamilkumar, S. (2010b, dec). Evaluation of groundwater quality and its suitability for drinking and agricultural use in Thanjavur city, Tamil Nadu, India. *Environmental Monitoring and Assessment*, *171*(1-4), 289–308. Retrieved from https://linkinghub.elsevier.com/retrieve/pii/S0048969711013908http://link.springer.com/10.1007/s10661-009-1279-9 doi: 10.1007/s10661-009-1279-9

Nas, B., & Berktay, A. (2010, jan). Groundwater quality mapping in urban groundwater using GIS. *Environmental Monitoring and Assessment*, *160*(1-4), 215–227. Retrieved from http://link.springer.com/10.1007/s10661-008-0689-4 doi: 10.1007/s10661-008-0689-4

Rao, P. N., & Pardhasaradhi, Y. J. (2000). 17.-Impact of urbanisation on groundwater regime in Vishakhapatnam Urban area, Andhra Pradesh, India. Retrieved from http://117.252.14.250:8080/jspui/handle/123456789/4371

Remondi, F., Burlando, P., & Vollmer, D. (2016, jan). Exploring the hydrological impact of increasing urbanisation on a tropical river catchment of the metropolitan Jakarta, Indonesia. *Sustainable Cities and Society*, *20*, 210–221. Retrieved from https://linkinghub.elsevier.com/retrieve/pii/S2210670715300408 doi: 10.1016/j.scs.2015.10.001

Schirmer, M., Leschik, S., & Musolff, A. (2013, jan). Current research in urban hydrogeology – A review. *Advances in Water Resources*, *51*, 280–291. Retrieved from https://linkinghub.elsevier.com/retrieve/pii/S0309170812001790 doi: 10.1016/j.advwatres.2012.06.015

Trafford, J. M., Lawrence, A. R., Macdonald, D. M. J., Nguyen, V. D., Dang, N. T., & Nguyen, T. H. (1996). *The effect of urbanisation on the groundwater quality, beneath the city of Hanoi, Vietnam* (Tech. Rep.). Hanoi, Vietnam: British Geological Survey. Retrieved from http://nora.nerc.ac.uk/id/eprint/21403/1/WC{_}96{_}22.pdfhttp://nora.nerc.ac.uk/21403/1/WC{_}96{_}22.pdf{%}5Cnpapers2://publication/uuid/99697943-3315-4EA5-A981-512E3EC36D9C

UNESCO. (2000). 4 - Impact of Urbanisation on Groundwater. *City*(May), 55–64. Retrieved from http://cidbimena.desastres.hn/pdf/eng/doc5925/doc5925-indice.pdf

Wakode, H. B., Baier, K., Jha, R., & Azzam, R. (2018). Impact of urbanization on groundwater recharge and urban water balance for the city of Hyderabad, India. *International Soil and Water Conservation Research*, *6*(1), 51–62. doi: 10.1016/j.iswcr.2017.10.003

Williams, P. W. (1976). *Impact of urbanization on the hydrology of Wairau Creek, North Shore, Auckland* (Vol. 15) (No. 2). Retrieved from https://www.jstor.org/stable/43944404

Part II

A Case Study on Kolkata

Chapter 5

Evolution of Kolkata

5.1 Introduction

Kolkata is an imperial city; it embraces a glorious history of urbanisation. It is one of the cities in India, that still holds the influence of the British Empire. It was the capital of the country until 1911. *Calcutta* as a city is presumed to begun its journey in 1690 with its founder Job Charnock, an Englishman. But historical evidence from Indian ancient literature strongly supports existence of this geographical land from the medieval period. Without any ambiguity regarding the origins of this metropolis, this chapter highlights historical perspectives on urbanisation that have been drawn from the literature currently available.

5.2 Objectives

Kolkata as a city created its importance by its own. It holds a strong significance in Asian continent. It is a megacity and also a capital of an Indian state. This city is treated as the gateway of Eastern India from economic perspective. This chapter aims to recollect the evidences from the journey of this city from a uninhabitable place to a renowned megacity in the world map.This chapter also tried to clear concept about position of Kolkata, as a city as a megacity, as a capital or as an urban agglomeration. Locational aspect and specific details of the study area clearly described in this chapter.

5.3 Data and methodology

Significant evidences about Kolkata and its development through urbanisation have been recapitulated by collecting historical maps and literature. Detailed census data have been curated for quantitative data and relevant maps and figures. GIS software has been used to recreate the maps. Detailed data about the boundary of Kolkata have been collected from the official website

of KMC[1]. Extract of extensive literature review has been reflected in this chapter.

5.4 Evolution of an urban area from Calcutta to Kolkata

In 1690, Job Charnock established Kolkata with a mind of business and expand colonisation in India. According to historians, the real foundation day of Kolkata as an urban land is 24th August, 1690 (Deb Roy, 1989a). Starting from that time urban growth in Calcutta was the most prosperous still 1911 under British rule, later Kolkata maintained its prosperity with indigenous urban revolution of India.

In writing of Deb Roy (1989b), it has been described that total 1678.2 acres of land were demarcated for and as 'Calcutta' in 1690. Out of which Sutanuty was with 559.5 acres, Govindapur with 389.4 acres and town Calcutta was selected with 567.8 acres also Bazar Calcutta was established within 161.5 acres of land. Houses were scattered and clustered within 10 to 12 acres area. Most lands were covered with dense forest and wetlands were here and there. The initiation of urbanisation was concentrated around Fort William and its adjoining areas.

Deb Roy (1989) enumerated about the demographic status of Calcutta from the extensive literature review. There were around 8,703 residents in 1696. As it was selected as a town, Within next eight years in 1704 population increased to 51,600, and in next four years population was 108,700. A large number of floating populations remained a factor for Kolkata. The growth of Calcutta as an urban area (1700-1800) can be realised from the table 5.1 below:

Table 5.1. Growth of Calcutta from 1706 to 1794

Year	Urban (acre[a])	Total Area (acre)	Pucka House	Streets	Tanks
1706	216	1692	8	2	17
1726	332	2350	40	4	27
1756	704	3229	498	27	13
1794	3714	4997	1114	163	61

[a]1 acre=0.004 sq.km

According to the writing of Sen (1989), urbanisation of Calcutta in eighteenth century can be defined from two perspectives. First was *market-oriented* town growth and other was hectic *building activities* in the city. The development scenario of Kolkata was limited as it was restricted by strict governance. Concept of *White Town* and *Black Town* was prominently existential in urban morphology also. Existence of white Brits was limited to the white town while native Indians mainly those who were rich, they used to be the inhabitants of 'Black Town'. Apart from social segregation, imbalance in civil construction planning and execution was prominent in the city.

Describing the growth of the city in nineteenth century, census report from 1951, described

[1]https://www.kmcgov.in/KMCPortal/jsp/KMCPortalHome1.jsp

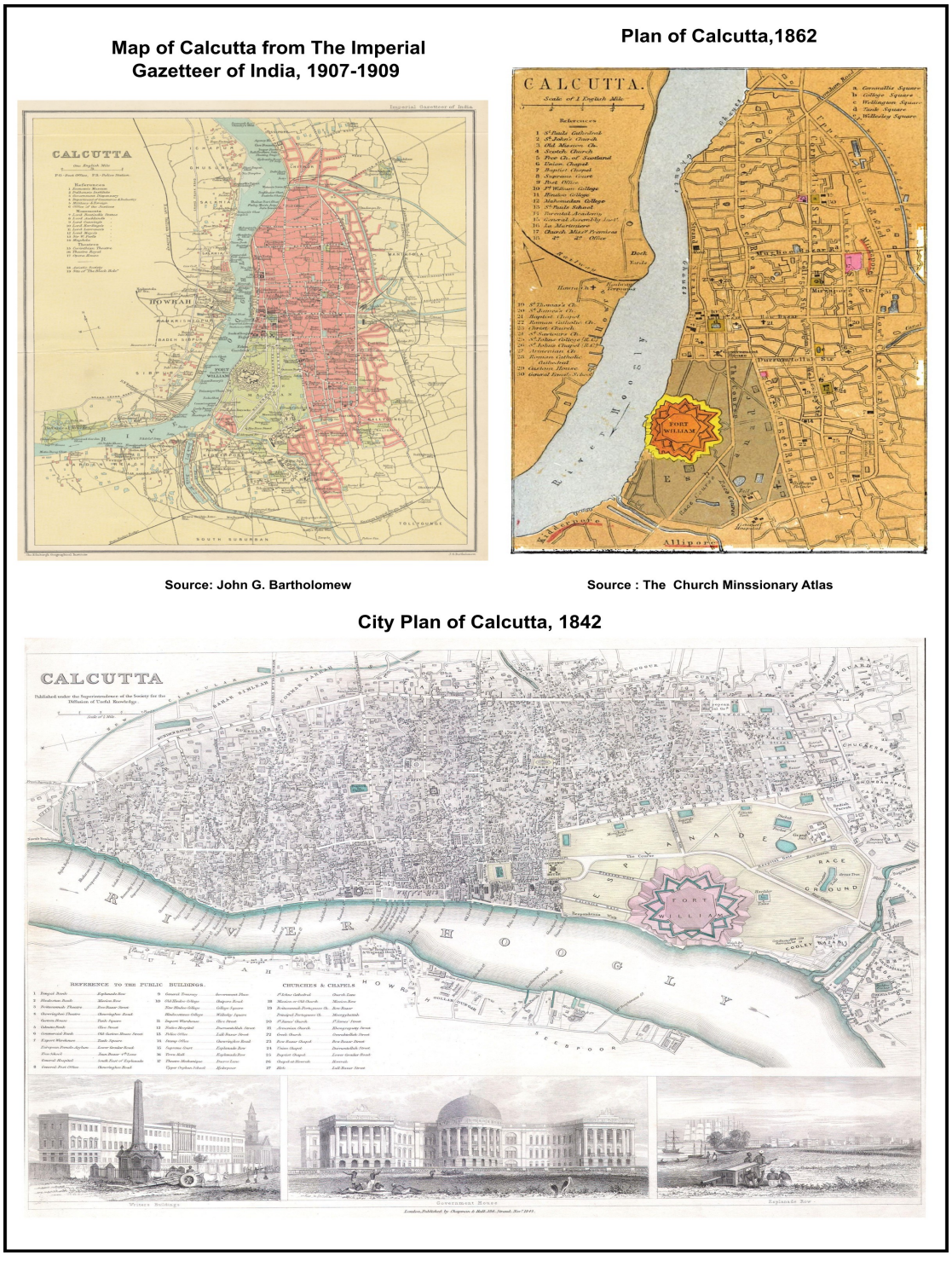


Figure 5.1. Picture of Kolkata through old maps. created and published in between (1800-1910)

the effect of lottery committee that was created for the development of the city in around 1817. This committee was termed as *Committee of Improvement*. This committee was constructed mainly to develop the city by digging new tanks for water supply, creating new streets or roads, constructing bridges, new ghats and other improvements for health regarding issues from the profit of selling lottery tickets to residents of Calcutta. After the establishment of municipal corporation, proper sewerage, drainage and water supply was constructed throughout the city. More than three hundred oil lamps were allotted to lighten up the city at night. Repairing, cleansing and lighting for roads were then implemented around 1847. Along with the increase in house rent, taxes were imposed for having vehicles and animals in 1856 (Figure 5.1).
According to *Calcutta Municipal Consolidation Act, 1876*, proper administration was created with establishment of corporation in Calcutta with 72 commissioners, a vice chairman and a chairman. In 1888, the boundary of the city was revised and extended towards southern part of the city. Democracy in municipal corporation began after 1923. After independence from British rule, with *Calcutta Municipal Act,1951*, wards in Calcutta increased in number (KMC, 2022b).
We can get a detailed view of earlier urbanisation process of the city from census report published with a gap of a decade. According to census report published for 1921 (Thompson, 1923), it has been reported that Calcutta was abruptly extended up to Manicktala and Tollygunge to the east. The city was constructed with five suburban municipalities like Cossipore-Chitpore, Manicktala and Tollygunge. Very large amount of to-and-fro workers has been addressed in Calcutta as floating population. Total area was calculated as 62 sq.km and population was about 13,27,547 in 1921. Population of Calcutta was higher than any of the major cities in India like Bombay (Mumbai), Delhi, Madras (Chennai) etc. Calcutta was then divided into 25 wards. Areas like Bowbazar, Beniapukur and Ballygunge with highest population density of 1.8 pesons per acre. After the independence as the report published by census for 1951, average density of Kolkata was 88,953 persons per square mile or 139 persons per acre whereas in places like Jorabagan, Jorasanko, Colootola, the population density was 3 to 4 times greater than average. Northern part of Kolkata was highly populated then. Suburban rail and road services and ferry services helped people to commute to Kolkata daily. After immediate independence with the immigration of refugees, the structure of the city was much distressed with slums here and there. Then Calcutta was divided into 32 wards.
After extending, mainly towards south, in 1981, area of Calcutta was 104 sq.km. and the population density was 31,799 with 69% literacy rate. Calcutta was divided into 100 wards with around six lakh occupied residential houses. According to the census town dictionary, Calcutta was termed as Class I city with population of far more than one lakh.
In 2001, Calcutta was renamed Kolkata. It was a decision from state government that was taken for proper pronunciation of this city in Bengali language and to establish it for the world. Englishmen gave the name of the city as 'Cal-cutta' but for Bengalis, it is more comfortable to call the city as *'Kol-kata'*.

5.5 Different identities of Kolkata

Kolkata is undoubtedly a proper urban area with defined boundaries and administration. Although, it has been observed that, mental mapping about Kolkata is sometimes confusing to common people as different geographical and administrative boundaries co-exist parallelly and are often conceived by a singular name 'Kolkata'. In this chapter, an effort has been given to clear the confusion acknowledging that different identities coexist but at some point it is different from others.

5.5.1 Kolkata as a District

At the time of independence (1947), after demarcation of East Pakistan, a state named West Bengal was formed in the eastern part of India. The state then divided into 14 districts out of which Calcutta was a selected as a district. Still Kolkata holds the status of a district. As a part of administrative structure every district is divided into subdivision, but this is not applicable for Kolkata. As, total land of Kolkata demarcated as urban land, this district is governed by the local administration i.e.,KMC.

5.5.2 Kolkata as a Capital

In time of British rule, Kolkata was selected as a capital of the undivided India from 1772 to 1911 for definite political and economic reasons. Calcutta was termed as jewel in the crown of British India (Ganesan, 2014). After partition of India, in 1947, India was divided into several states and Calcutta was selected as the capital of the state West Bengal. From then Kolkata, is a capital of a state.

5.5.3 Kolkata as a Megacity

Kolkata is one of the most important cities in India, since the time of independence due to its long history and geopolitical advantages. Population density is certainly higher than in any other districts in the state or for many other cities in the country. Due to the limited boundary of this district and limitations from the administration, the scope of development was getting reduced for the city. It was impossible for Calcutta to maintain qualities and amenities like other developed cities in the world. So, an act was passed by government of India, in 1972, Calcutta corporation and its adjoining municipal boundaries merged within Calcutta metropolitan district (CMD) is to be administered by Calcutta metropolitan development authority (CMDA). According to the last census publication, cities of India have been classified by certain parameters and population has been chosen as one of the most important parameters. From the perspective of the population in city, with more than a million population, Kolkata Metropolitan Area (termed as Kolkata UA) is the third largest megacity in India from the other two megacities Mumbai and Delhi. The total area of KMA is about 1451 sq. km in area (Bhatta, 2012)

5.5.4 Kolkata as a Municipal Corporation

Already, brief history of the establishment of Municipal corporation has been mentioned. From the past to present Kolkata Municipal Corporation holds an autonomous prestigious position as an administrative body. From centuries ago, it is serving for the development of Kolkata. At the beginning, British people used to hold the position of chairman before independence; Indians took charge of it lately. With the development of municipal corporation, boundary of Kolkata was properly defined for administration purpose. It has been modified and extended with time. Total area further divided into wards. Recently KMC has been divided into boroughs merging adjoining wards. The table 5.2 showing modification in wards and area of KMC.

Table 5.2. Changes in ward number and area in KMC

Year	No. of Wards	Area (sq.km)
1921	25	62
1951	32	83
1961	80+	103
1981	100	104
1991	141	186
2012	144	207

Administrative boundary of Kolkata increased to maintain its population growth and related urbanisation pressure. Before independence, administration concept was different, mainly it replicated the concepts already generated in U.K. After independence it was changed according to Government of India and local government started their work. In 1951, Kolkata was divided into 32 wards with other special wards but within ten years for betterment of administration Kolkata was divided into 80 wards and other special wards. Fort William (A military Base), Ports, Canals were treated as part of special wards and remained excluded from general wards. In 1986, Kolkata extended its southern boundary, adjoining municipals area from south were merged with KMC and then further 41 wards were added with Kolkata. Area of Kolkata increased from 104 sq. km to 186 sq.km. For the next twenty years administrative division remain unchanged. In 2012, Further 3 wards added, merging the lands from panchayat area of Joka. Presently administration of KMC is divided into 144 wards and area is limited within 206.8 sq.km (Figure 5.3).

5.6 Locational perspective of Kolkata

According to basic statistics acknowledged by KMC, the description of Kolkata has been demarcated with boundary locations or areas (Table 5.3). Presently Kolkata is the 7th biggest city in India in the area and population KMC (2022a). It is the smallest district in West Bengal. River Hoogly is on the western side and East Kolkata Wetland in the eastern side. Howrah,

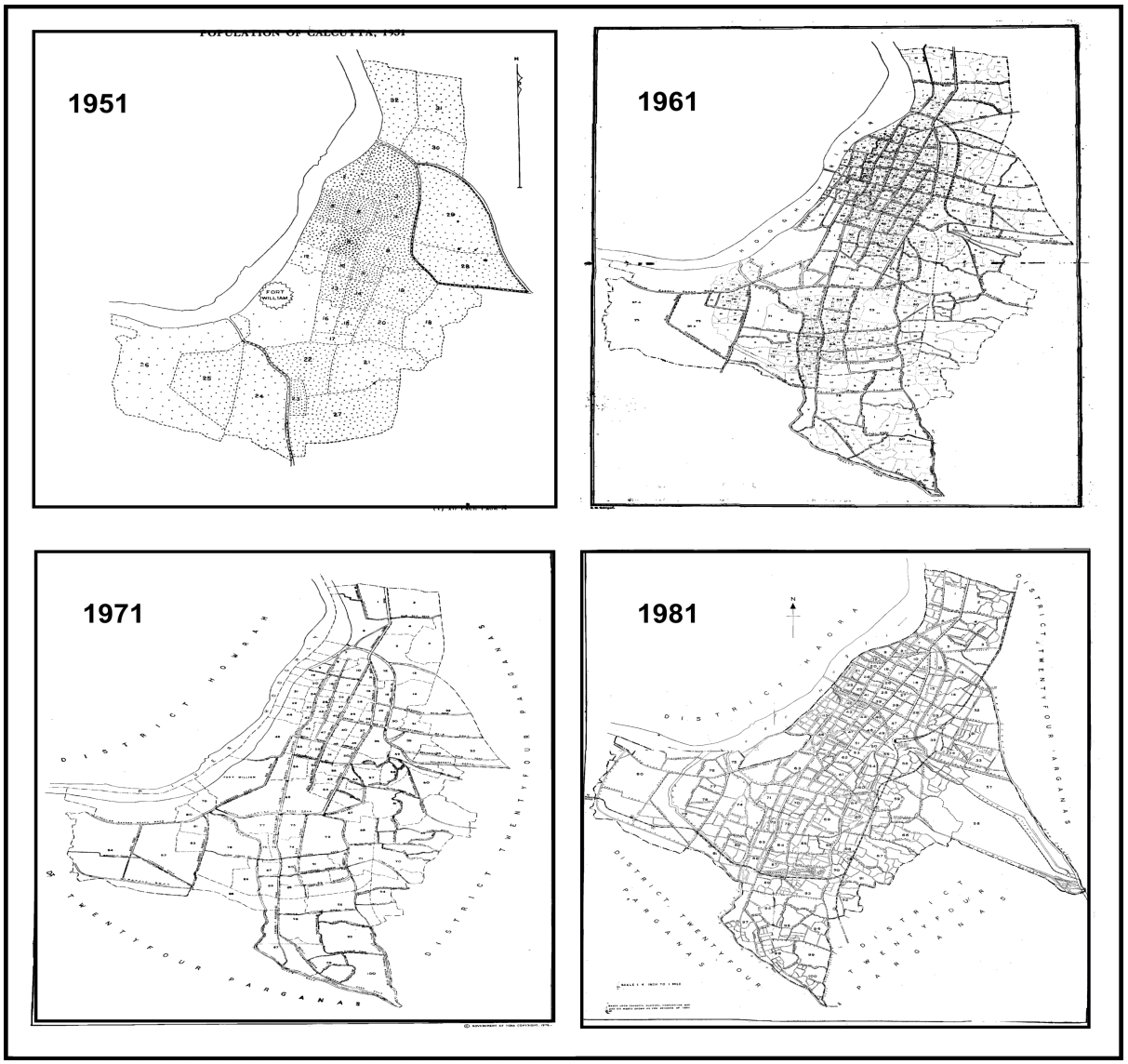


Figure 5.2. Expansion of Kolkata in between 1951 to 1981; Source: District statistical handbook

Table 5.3. Locational demarcation for identification of boundary for Kolkata

Category	Location/Area[a]
Old Kolkata	Shutanuti - Chitpur, Bagbajar, Sovaabajar & Hathkhola. Kolkata - Dharmatala, Bowbajar, Simla, Janbajar. Gobindapur - Hastings, Maidan & Bhowanipore
New Kolkata	North - Sinthi, Cossipore & Dum Dum South - Tollygunge, Khiddepur & Behala East - Salt Lake, Beleghata & Topsia West-Hooghly River
Grater Kolkata	Baruipore to Bansberia & Kalyani to Budge Budge

[a]Source: KMC website, 2022

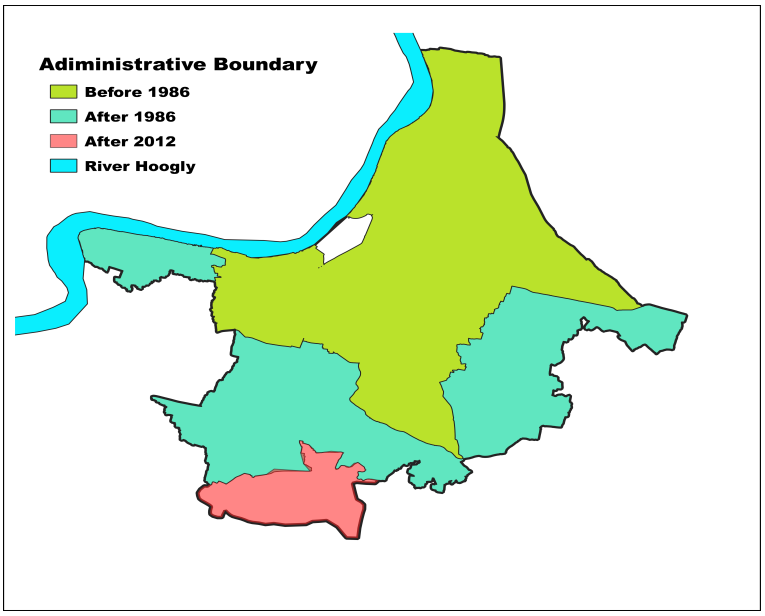


Figure 5.3. Change in administrative area of KMC

Table 5.4. Cordinate limits of KMC

Latitude		Longitude	
North	South	East	West
22º37' N	22º30' N	88º23' E	88º18' E

North 24 Parganas and South 24 Parganas are its adjoining districts. Census data after every ten years is maintained to produce a map for this district. From 1921 to 1981, northern and western boundaries remained unchanged for Kolkata, minimum amount of change has been observed in the eastern side whereas, a significant extension of the district has been observed in the southern part, specifically the south-eastern part. Till 1951, the numbering of wards was modified accordingly, but after 1961, ward numbers remain unchanged till now.

5.7 Conclusion

Calcutta, presently Kolkata holds its importance in the global scenario as it holds a long history of urbanisation. It is a capital of a state and an economic centre point for other East India. Various business organisations and governmental headquarters run from this city. This city was the brainchild of Brits, but Indians inherited the legacy of British rulers and made this city like any other global city with eminent amenities and facilities. The city matured itself with an evident process of urbanisation. For its elegance, it used to be termed as 'London from the east'. It is one of the safest cities in India in terms of security. People over the world bear a soulful engagement after visiting the city; they called it a *City of Joy*. For cultural supremacy it is termed as *Cultural capital of India*.

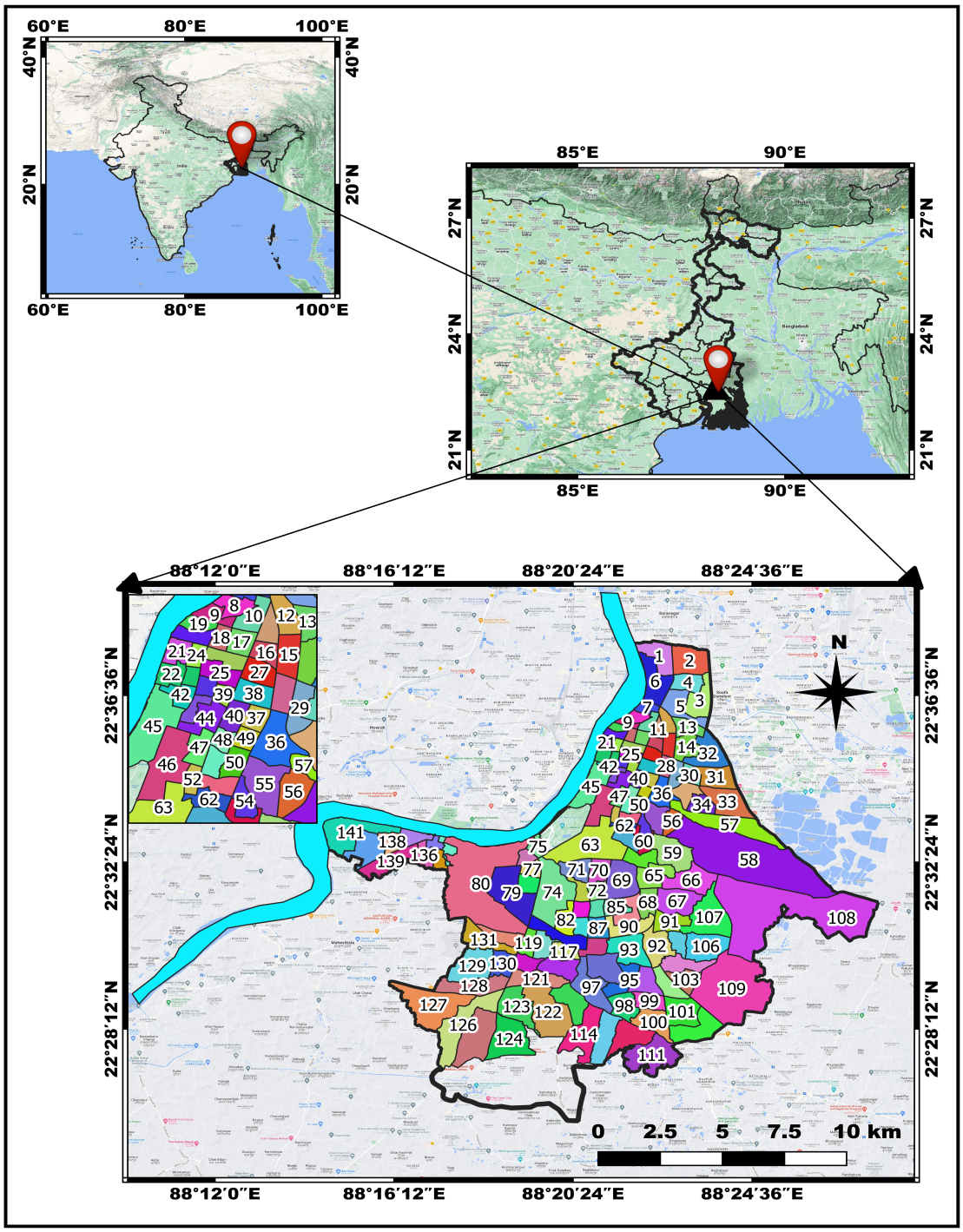


Figure 5.4. Location map of the study area highlighting 141 wards; congested wards of northern western side (inset)

References

Bhatta, B. (2012). Urban Growth Analysis and Remote Sensing: A Case Study of Kolkata, India 1980–2010. *Springer Briefs in Geography*, 1–112. Retrieved from https://link.springer.com/book/10.1007/978-94-007-4698-5

Deb Roy, R. (1989a). Glimpses on the history of Calcutta, 1600-1800. *Annales de démographie historique*, *1988*(1), 243–257. Retrieved from https://www.persee.fr/doc/adh{_}0066-2062{_}1989{_}num{_}1988{_}1{_}1718 doi: 10.3406/adh.1989.1718

Deb Roy, R. (1989b). Glimpses on the history of Calcutta, 1600-1800. *Annales de démographie historique*, *1988*(1), 243–257. doi: 10.3406/adh.1989.1718

KMC. (2022a). *Basic Statistics Of Kolkata.* Retrieved 2022-10-29, from https://www.kmcgov.in/KMCPortal/jsp/KolkataStatistics.jsp

KMC. (2022b). *Kolkata-A Municipal History.* Retrieved 2022-10-28, from https://www.kmcgov.in/KMCPortal/jsp/MunicipalHistoryHome.jsp

Sen, R. (1989, nov). A NOTE ON THE URBANISATION OF CALCUTTA IN THE 18th CENTURY. *Proceedings of the Indian History Congress*, *50*, 564–570. Retrieved from http://www.jstor.org/stable/44146098

Thompson, W. H. (1923). *City of Calcutta, Report, Part I, Vol-VI, Bengal - Census 1921* (Tech. Rep.). Calcutta: Office of the Registrar General, India. Retrieved from https://censusindia.gov.in/nada/index.php/catalog/28359

Chapter 6

Physical Setup of Kolkata

6.1 Introduction

The physical properties of any urban area define the natural characteristics of any land. Economical and socio-political conditions are also dependent upon the physical features of the urban area to some extent. Knowledge about the physical features of any land helps to establish an integrated idea about its physical and historical existence in nature. In this chapter, the study area has been evaluated based on its significant physical properties. Here, the physical properties of the study area have been assessed based on its geographical, geomorphological, geological, pedological lithological and climatological characteristics.
The elevation profile defines the altitudinal situation of the study area. Geomorphology represents details about the formation of landforms and their evolutional chronology. Geological characteristics of landforms represent their physical structure, historical evolution and processes related to it. Whereas, pedology represents soil characteristics of the surface or beneath the surface of the earth. Physical properties do not limit to surface studies, identification of the subsurface environment is equally important specifically where groundwater studies are related. Further detailed climatological characteristics are needed for a better understanding of the effect of rainfall and temperature over the study area. Land surface temperature (LST) identifies the condition of the surface within two meters. Urbanisation conditions can be estimated from this physical property of the land also as it reflects the condition of soil moisture. Aquifer properties of the study area and layers beneath the surface are also important to understand the groundwater environment. Details about the physical properties of the study area depend on literature review, secondary data and primary observation. After studying literature related to Kolkata and following eminent researchers regarding the specified field, physical background of Kolkata has been highlighted in this chapter.

6.2 Objectives

Identification of physical properties of Kolkata as an urban area is the main objective of this chapter. Focus has been given to understand such physical properties that directly correlates with process of urbanisation and groundwater resources. For this process some objectives have been followed:

- To understand about elevation and slope profile.
- To identify the canals and local waterbodies.
- To identify geomorphological characteristics.
- To identify the geological scenario.
- To understand the soil characteristics and soil profile.
- To identify runoff and recharge capabilities of the land.
- To understand the condition of the local aquifer in details.
- To identify the position of groundwater table.
- To analyse land surface temperature and its soil moisture condition.
- To observe climatic condition of the study area.

6.3 Data sources and methods

In this chapter, identification of elevation profile has been initiated using SRTM (Version 3.0) generated data. NASA initiated a global satellite mission for generating elevation profile of the land globally. Global 01 arc second (nearly 30m spatial resolution) obtained for elevation data using radar radiometry (USGS, 2015). This data is freely available and easy to use in GIS platform. Obtained data represents elevation of Kolkata from 2014. It has been processed and visualised with QGIS 3.16 software. After analysing the dataset, further slope of Kolkata has been identified from the elevation data.
Details about geomorphology and geology have been collected from GSI. Aquifer exploration and mapping process is very expensive for developing countries like India. There are limited scope about vast and detailed study on aquifers. With minimum available data, governmental institutes and independent researchers have explored the aquifers of India. A generalised idea can be adopted from, those study. For Kolkata, aquifer study further narrows due to insufficient data. Recently, India-WRIS developed an web based application where aquifers of India have been represented in 2D format where, certain details have been mentioned regarding the characteristics and properties of aquifer. Details regarding aquifer structure has been exported from the website to visually represent and get a brief idea about the aquifer beneath the study area. Soil related data and litholog data also collected from WRIS.
Based on rainfall, runoff and infiltration factors USDA[1] has classified the global soil into different groups. Soil scientist termed this classification as Hydrological Soil Group (HSG). Broadly HSG has been divided into four groups named as A, B, C and D. Where A group soils represents minimum runoff potential and D represents high runoff potential. (Ross et al., 2018)

[1] https://www.usda.gov/

represented a global dataset of HSG. The dataset has a spatial resolution of 250 meter. HSG map has been produced for Kolkata obtaining that dataset. Data represent soil runoff potential from 1900 to 2015. Curve Number based runoff modelling has been followed for this dataset. From the global dataset, soil runoff potentiality has been extracted for the study area.

Litholog data also an important aspect of subsurface environment study. Litholog data is the most needful details for that case but details exploration regarding the study area is very limited, proper exploration about lithological data are missing in literature. For that matter, a brief idea about exploration details or detailed lithology data have been collected from recently published India-WRIS[2]. Data insufficiency reflected here with minimum details but it represented a perception about the study area from its locational data within its boundary and adjoining places

Anthropogenic activities related to energy generation reflects in LST. Areas with dense built up, generate more heat compared to any other green or blue space and it reflects on surface temperature. It is identified that value of LST is higher in urban area than its adjoining rural areas. Satellites are being used to calculate the LST. It has a direct relationship with LULC; researchers have identified its negativity with vegetation (Feizizadeh et al., 2013).Apart from climatological knowledge, LST is a crucial factor to understand the condition of soil moisture specially for urban area (Wang et al., 2021). LST modifies the amount of soil moisture and ultimately it creates an impact upon shallow groundwater level (Ashwini & Sil, 2022; M. S. Malik et al., 2021; Sun & Pinker, 2004). Researchers have already identified the seasonal variation of LST for Kolkata (Bera et al., 2022). In this chapter, LST has been calculated for Kolkata in Google Earth Engine using MODIS. GEE is an web based platform where, available 20 years (2000-2020) of data has been collected for the study Area from medium resolution satellite data i.e. MODIS. Due to its course spatial resolution (1 km× 1 km), data is less accurate location wise but analysing 20 years, an average scenario has been represented to get an idea about the LST in day and night.

Primary characteristics of Climate i.e., temperature and rainfall have been associated for thirty years (1990-2020) of time span. Due to insufficiency of data from local observational weather station, globally acclaimed satellite data *WorldClim* have been used to gather knowledge about climate of the study area. Monthly minimum and maximum temperature data and rainfall data have been collected. Further a linear trend line has been created to identify changing patterns with time. Aquifer and soil related data have been collected from India Water Ressources Information System. For other phsyical properties this study mainly relied on secondary data and other published articles from reputed journals.Further deatils about data sources have been mentioned along with individual observation.

[2]https://indiawris.gov.in/wris/Litholog

6.4 Physical features

6.4.1 Elevation and Slope

Kolkata is a riverine city. It is situated on the west bank of river Hooghly. The city is a part of the deltaic plain. Significant amount of wetlands observed in the eastern and south-eastern boundary. For the case of Kolkata, several researchers have already analysed the elevation profile of Kolkata with remote sensing techniques. They have identified that Kolkata is basically, a low-lying area with an average elevation of 12 meters above the sea level (Mohanty & Walling, 2008).

After generating the result, it has been identified that the average elevation of Kolkata is between 5 to 10 meters (Figure 6.1). The western part of the Kolkata is comparatively higher than the eastern part which reflects the levee formation of the river. Most of the eastern and southeastern parts of Kolkata merged with wetlands nearby. The central part of Kolkata is comparatively higher than the boundary area. It can be observed that the core part of Kolkata is relatively higher in elevation. More than 10 or above 25-meter elevation is reflecting the high-rise buildings in the city, not the actual surface area. Usually, high-rise buildings created a bias in elevation, but broadly it can be easily enumerated that the average surface elevation of Kolkata is between 9 to 12 meters above sea level where land is equal with sea level representing the waterbodies and characteristics of wetlands.

After visualising the slope analysis. It has been identified that general slope of Kolkata varies

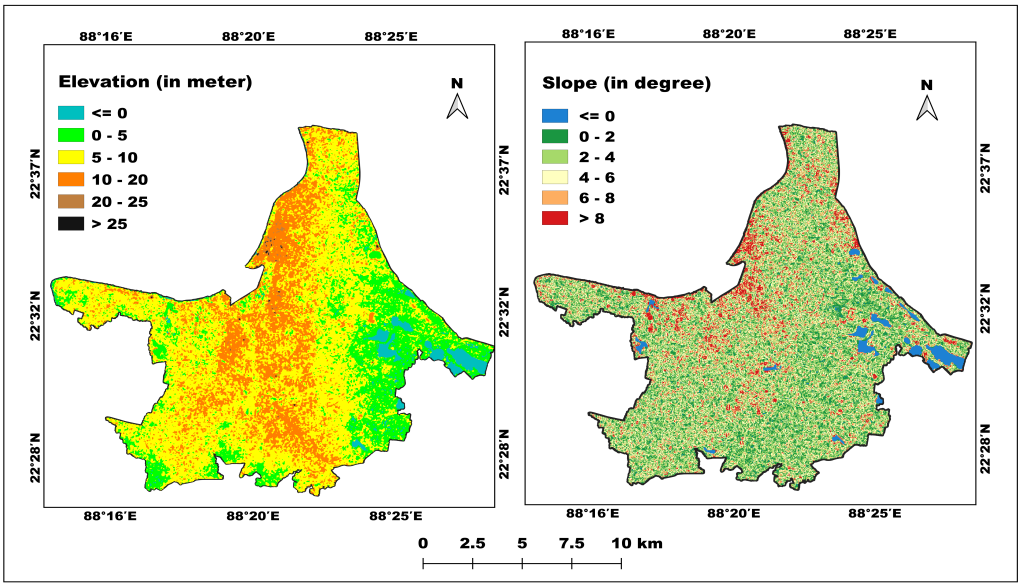


Figure 6.1. Elevation and Slope profile of Kolkata (Source: SRTM,2014)

by location and it is obvious for a reason as modification of land use according to local needs is common practise in densely populated cities like Kolkata (Figure 6.1). From overall observation, it can be said that general slope of Kolkata stands between 0 to 4 degrees which represent Kolkata as an extremely flat plain land but near the canals and drainage channels the slope has

increased abruptly. Geographical characteristics of this city created this kind of land surface near the mouth of the river. The overall slope of the land is towards the eastern and south-eastern boundaries.
After analysing the elevation and slope of the study area, it can be clarified that the land is generally flat, with negligible undulation and differences in elevation and slope between locations that are certainly modified by anthropogenic activities.

6.4.2 Canals

British rulers applied several strategies to develop economy using trade routes. For Kolkata, due to nearness with Bay of Bengal and deltaic landform they took the opportunity to prosper in trade using multiple riverine routes. Then, numerous canals were utilised as riverine routes to create a transport network with the sea and major rivers. River branches, tributaries and creeks were dredged. These canals were used for irrigation also. Further modification on canals were done using modern engineering techniques. Evolution of canals, its application and its use usefulness has been documented by several researchers (Dutta et al., 2021; Gangopadhyay & Patra, 2020; IWD, 2020; Singh, 2022).
Presently these canals are highly silted with deposition, mainly with urban disposals. Transport routes and interlinking condition has been detached. These canals now treated as surplus water flow channel, as drainage and as sewage channel.
In this chapter, Canals have been highlighted for its application in and as sewage and drainage channels (Figure 6.2). In the northern part, there is a portion of Keshtopur Canal, Circular Canal is in the northern part also Beliaghata Canal also merged with these canals. Storm Water Flow Channel and Dry Water Flow Channel are on the eastern side of the Kolkata, which are solely dedicated to treat excess runoff that generates from the city. Tallygunge-Panchanangram Canals also transports the excess water from the south-eastern part of Kolkata. Above mentioned canals transports towards the eastern part of Kolkata and ends in East Kolkata Wetlands. Whereas Tolly's Nallah dissected Kolkata from west to east and connected with river Bidyadhari and Hoogly. It flows from east to west. Other small canals like, Suti Canal, Churiyal Canal, Chetla Boat Canal, Kalgachia Canal presently serves as drainage channels and transport towards river Hooghly.
Kolkata regularly observes serious waterlogging situation after an hour of intense rainfall. Situation becomes much more serious without proper channelisation of excess runoff. Then canals are mainly utilised to channelise the water, pumping stations all over the city provide waters to these canals. Present health of these canals is not up to the mark. Drainage congestion, encroachment of canal land, excessive siltation and contamination of polluted materials are the major problems for the canals.

6.4.3 Geomorphology

Kolkata is situated upon Bengal Basin. It is in the eastern part of the Asian subcontinent. It is a vast pericratonic tertiary basin that composed with enormous amount of fluvio-marine sediments

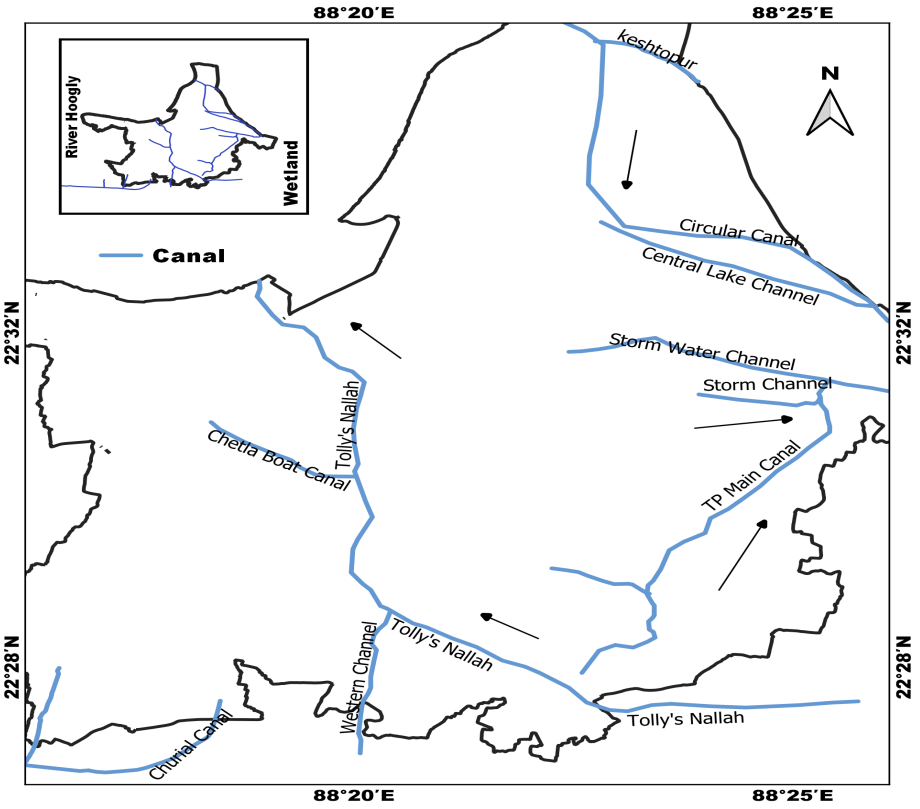


Figure 6.2. Canals in Kolkata, (Source: Chatterjee, 2017)

(Dasgupta, 2015). Kolkata is near to NE-SW trending, Eocene Hinge Zone (EHZ), also known as Calcutta Mymensingh Hinge Zone (Nath et al., 2015).
Kolkata situated on the low-lying bank of river Hooghly. Bay of Bengal is about 160 kilometres away from Kolkata. It was established as a city about 400 years ago as a hinterland of river port. Quaternary alluvium has made the base of the Kolkata which is deposited with time by the near river. Narrow natural levee has formed because of the river but it is limited to the side of the river. Low lying area has been created automatically after the levee. Slope is away from the river. Kolkata faces high tidal influences because of the vicinity of the sea. Swamps and other types of marshy lands are prominent in Kolkata specifically in the eastern side. Main components of geomorphology can be divided into the following types:

Deltaic Plain The lower deltaic plain of West Bengal is in southward extension of the Bengal Basin, resulting from the process of delta building (Bagchi, 1944). Kolkata is a part of the deltaic plain. It is typically floodplain with low lying areas of swamps, marshs, ponds, small lakes. General elevation of the land in between 3 to 7 meters (Mukhopadhyay, 2004). This plain is covered by quaternary sediments which holds the groundwater for Kolkata. Constantly growing impervious layer directly obstructs the natural recharge of groundwater here. This situation precluding the recharge to deep aquifer. Sediments concentrations are relatively recent, and it is

loosely distributed and having homogeneity in nature. Human dominance and their modification turning natural properties of the land to concrete.

Interdistributary Marsh Marshy land can be found on the eastern part of the Kolkata. The lands have capability to hold water through all seasons, it gets increased in time of monsoon and excess rainfall, turns to surface runoff and it gets more wet than ever and releases water through small channels towards the river.

Distributary Levee Hooghly is a meandering river and it deposited alluvial silts through time over both side of the lower part of the river. This natural levee has given a height which comparatively high from the place which is far from river. So the part of the surface runoff moves from west to east part of the Kolkata. the distance between the bank of the river and East Kolkata marshy land is wide about 6 km. (Mukhopadhyay, 2004).

According to GSI, geomorphic origin of Kolkata is distributed within coastal and local water

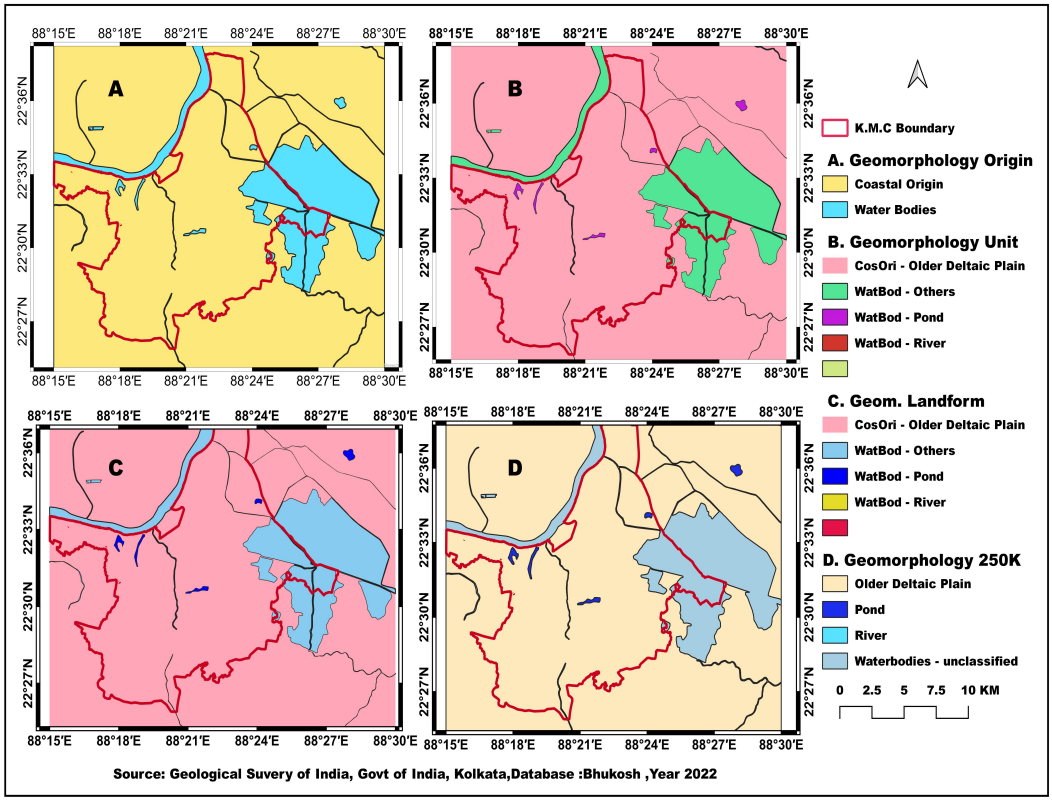


Figure 6.3. Geomorphological details about the study area (Source: GSI, 2022)

bodies (Figure 6.3). Nearness to the Bay of Bengal reflects this type of origin. Classification wise Kolkata is situated between older deltaic plain and different kind of water bodies. Dominance of waterbodies can be observed in the eastern and western side. According to geomorphological characteristics, Kolkata represents the properties of older delta plain which signifies maturity and antiquity in landforms.

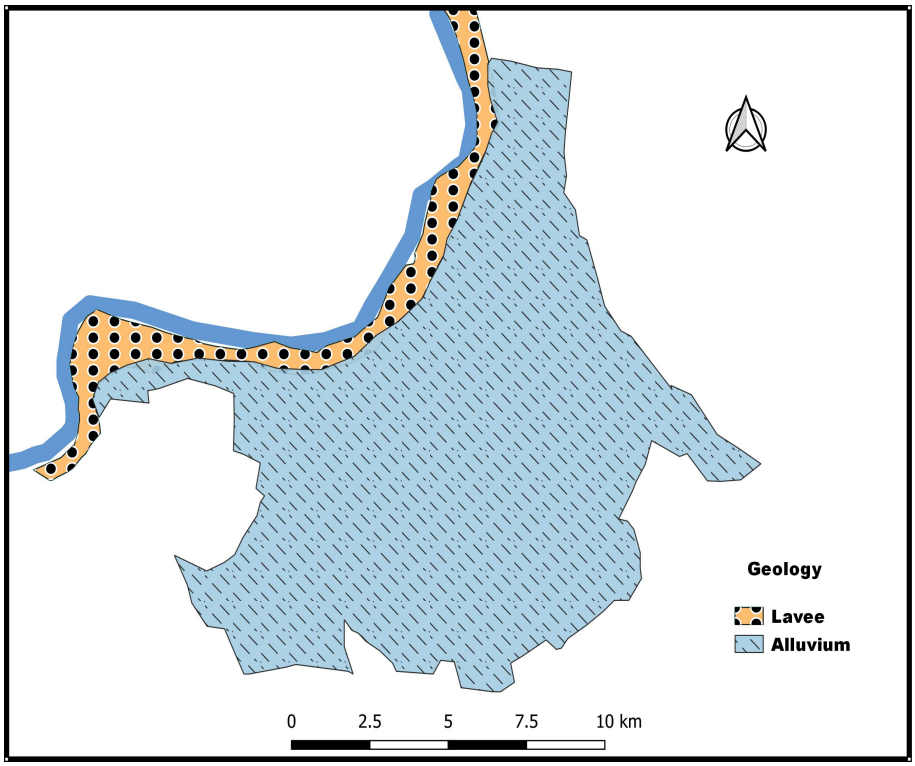


Figure 6.4. Geological condition of the study area based on 1: 1 million scale (Source: G.S.I , 2022)

6.4.4 Geology

Kolkata is situated upon the Bengal basin that is expanded upto the Amphibolite-Granulite facies basement of the Shillong plateau in the north and tertiary rock of the Himalaya (J. Roy & Saha, 2018). Lateritic uplands and Rajmahal Hill is in the west and folded Indo-Burmese belt is in the east. The Bengal basin mainly formed due to deposition of Ganga, Brahmaputra, and its tributaries. Around, 75% of the entire region is covered by alluvium deposits. Difference in sedimentation properties can be observed in the both side of the Hinge zone. It is revealed through subsurface mapping that, base of the city Kolkata is made of marine and riverine sediments, mainly composed of carbonaceous shale with organic peat layer. It is enormously thick fluvio marine sediments in pericratonic Bengal Basin and thickness of sediment varies from shelf area in the west to Barisal region in the east. Total thickness of sediment is about 7500 m above crystalline basement. Formation of recent Quaternary sediment depths upto 350-450 m from the ground level whereas tertiary sediment reaches up to 4500-5500 m after the former layer (Nath et al., 2015; A. B. Roy & Chatterjee, 2015). Geological variation is uniform in Kolkata (Figure 6.4) . There is thick grey sticky clay layer up to 30 m. to 60 m. from ground level and after that a relatively coarser sediment layer can be observed that consist of silt to mediums and or coarse sand with or without pebbles/cobbles. Liquification is quite obvious here due to man-made landfills and poor consolidated or unconsolidated water charged sediments.
Detailed stratigraphy model for Kolkata has been published in a report by WBDMD [3]. According

[3]W.B Disaster Management Civil Defence Department

to the report, deposits from Pleistocene and Holocene can be easily identified here; mainly constructed after last glacial maximum. Sand, silt, and clay are the main components of this deposit. Evidence of sedimentation from Holocene and Pleistocene period has been identified through bore hole drilling and radiocarbon dating also a distinct layer made of peat/wood has also identified at various depth. These wood/peat layers are intermixed with clay and it has been estimated that, it is a product from Holocene and Pleistocene period (Umitsu, 1993).

Lithostratography

Lithostratigraphy of Kolkata depicts that, the city is covered with thick quaternary alluvium sediment up to 450 m. It has been found analysing the literatures related to it that, in 1840, at the time when British came to Kolkata and they dig upon a bore well to understand the lithological characteristics of the location. From that report, it is found out that, decayed wood /peat layer is in 10 m to 15 m below the ground.
According to Smith (1841), at the time of interference of Brits at 1717, that time, dense vegetation was destructed and lakes were filled for spreading the boundary of Kolkata. The wood/peat layer can be result of that process. A layer of conglomerate has been found out after the wood layer, a thin layer of Kankar, limestone has also been observed.
Lithostratigraphy related study has also been published by (WBDMD, 2015). In this recently published report detailed study has been done to understand the actual scenario underneath the city (Figure 6.5). According to that report, a cross section profile between Howrah and Newton, defining west to east direction showing greyish clayey silt with layer of decomposed wood identified at a depth range of 1 to 10 meter. Kankar layer has been residing in fragmented way. Dominance of silt and clay can be clearly observed here. The Last glacial maximum boundary can be observed at a depth 8 to 15 meters along the profile. Another cross-section line staring from Dum Dum airport in the north and ending at Bijoygarh in the south of Kolkata showing mainly silty clay and silt along the profile. Decomposed wood layer can be observed between 5 to 11 meters below the ground. Stratigraphic line within 10-12 meters divided the Holocene and Pleistocene period. Lithologies of Kolkata can be majorly divided into ten parts viz.1) clay layer, 2) coarse Sand layer, 3) medium Sand layer, 3) fine Sand layer, 4) sandy silt/silty sand layer 5) gravel, 6) kankar, 7) silty clay/clayey silt, 8) decomposed wood/peat. 9) clay layer. In major portion of Kolkata clay later can be recognised ubiquitously.

6.4.5 Soil profile

Kolkata has profound history of urbanisation from the eighteenth century. But before the process of urbanisation it was more of an abandoned land, with minimum agricultural activities and human settlements. Mainly the land of Kolkata and its vicinity was covered with dense jungle. The land was mainly swampy and boggy. With encroachment process through urbanisation, top soil of Kolkata started to reduce rapidly. Nowadays, few fragmented open lands are here and there where topsoil of Kolkata can be observed. There has been limited scope for extensive research about Kolkata's soil profile. Detailed study was initiated at the time of metro rail excavation. Soil profile of Kolkata has been recognised then. It has been found that, as geology

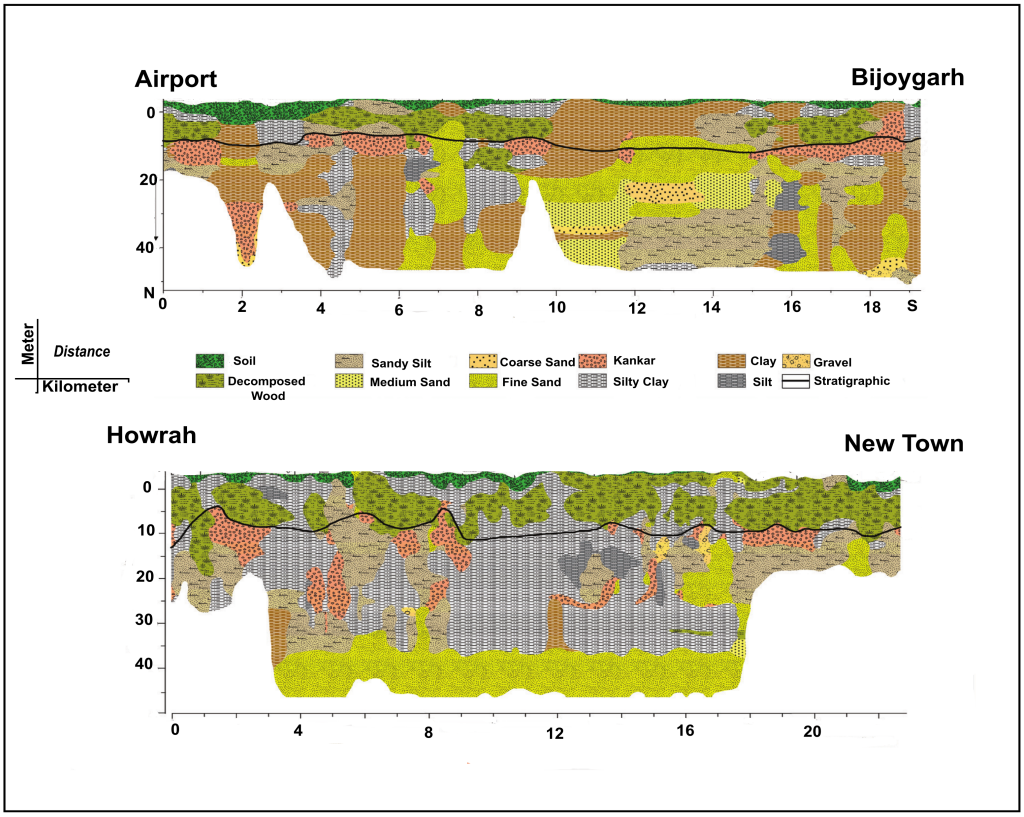


Figure 6.5. Two cross section profile showing lithostrography of Kolkata from north to south (up) and east to west (down), (Source: WBDMD, 2015)

of Kolkata totally composed of sediment deposition, soil below the ground is very erratic in nature (Diptendra & Chattopadhyay, 2009). The soil profile of Kolkata indicates a large variation in soil layers (Table 6.1). Recently in 2015, one of the few studies demarcated soil profile of Kolkata through piling process. Three locations from Kolkata was selected e.g. (Park Circus, Dum Dum, Belghoria expressway) for the study. It has been found from the study that in Park Circus area, soil strata is mainly composed of silt clay with clayey silt for a depth of 19 m. Medium to dense grey silty fine sand can be found after the upper layer up to 28 m. Similar kind of soil profile can also be found in Belghoria expressway i.e.in the north eastern part of Kolkata. However a change can be observed for the location of Dum Dum. Deep grey medium stiff silty clay with fine sand can be found upto level of 6 m. depth. The colour of soil changes in 12 m. depth and after this layer it turns into whitish grey medium to dense silty sand and that extends up to 33 to 40 m (Chatterjee et al., 2015).

Table 6.1. Deatils about soil profile of Park Circus and Dumdum

Stratum	Thickness of Layer	Soil Description
Location: Park Circus		
I	0.5	Fill of rubbish with brick pieces
II	2.5	Medium brownish grey clayey silt
III	9	Soft to very soft grey silty clay
IV	3	Medium to stiff grey silty clay
V	4	Very stiff yellowish clayey silt
VI	11	Medium to dense grey sandy silt / silty fine sand
Location: Dum Dum		
I	1	Filling with mixed soil
II	6	Grey loose silty sand with clay binders
III	6	Dark grey medium stiff silty clay with fine sand
IV	7	Dark grey medium silty sand with clay binder
V	14	Whitish grey medium to dense silty sand
VI	4	Dark grey fine to medium grained dense silty sand
VII	3	Yellowish grey very dense silty sand

Subsoil

Main subsoil exploration was executed in the time of metro rail construction in early seventies. The experience of this process can be found in writing on Prof. N.N. Som. It has been found from his study that; soil exploration was done up to 50 meters from the surface level with interval of 100 m. The soil is mainly made of silty clay/clayey silt, particularly soft in the top 12-14 m., having a high organic content and decayed vegetation. After that stiff silty clay layer has been found up to 50 m. with alteration in layer. Silty clay/clayey silt strata with laminations and occasional lenses of silt and fine sand below 20-25 m. depth can be found till the depth of 30 m. at an interval of 100 m. This generalised pattern has broken in Tollygunj, Maidan and Belgachia. Here riverine channel deposit has been found that consists if fine sand going down to some depth. The deeper sand layer in Kolkata is generally golden brown with varying size in different location (Figure 6.6).

Recently WRIS providing soil related data[4] it provide needed details about soil depth, soil

[4]https://indiawris.gov.in/wris/soil

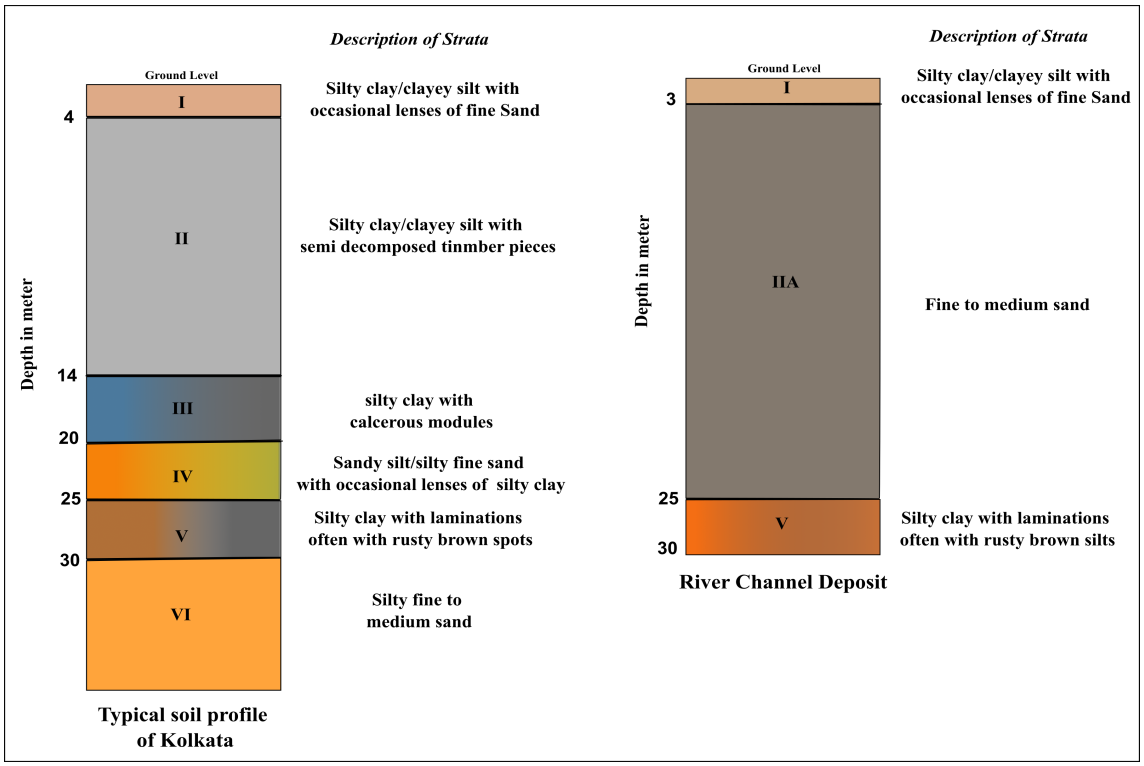


Figure 6.6. Subsoil profile of Kolkata (Source: WBDMD)

texture and soil slope. For Kolkata, soil characteristics is uniformly distributed and minimum spatial variation can be observed throughout the study area (Figure 6.7). Depth of soil is more than 50 cm all over the Kolkata except in the eastern part. Landfill site of Kolkata in the eastern side residing with wetland nearby, where soil depth is extremely low (<10 cm). Most part of the Kolkata is covered with soil texture of loam, silt loam, silt, sandy loam. Loam is mixture of sand, silt and clay and silt loam consist more of silt in its properties where as sandy loam majorly composed of sand with loamy properties. It is quite common for Kolkata, where the geology is made of recent alluvium. Presence of clayey soil can be observed in the extreme eastern part of Kolkata where dominance of wetlands is significant. Kolkata is based on properties of Bengal basin, which typically holds flat topographical characteristics. It is obvious for Kolkata, that soil is nearly levelled all over the area, but extreme eastern part of Kolkata holds characteristics of steep slope in terms soil properties. Mainly accumulation of soild waste in the open land forced that part of land to be undulating.

Hydrological soil

Broadly the study area can be classified with two HSG. i.e., Group C and Group D. Group D soil has covered maximum area of the study area where soil is composed of more than 40% of clay materials and less than 50% of sand (Figure 6.8). High clay component reflects comparatively high runoff potential of the soil in most of the part in the study area. Other than, Group D soil, Group C soil covered the rest of the study area. HSG C represent comparatively less potential than Group D soil, but it reflects moderately high runoff potential among the group. HSG D is

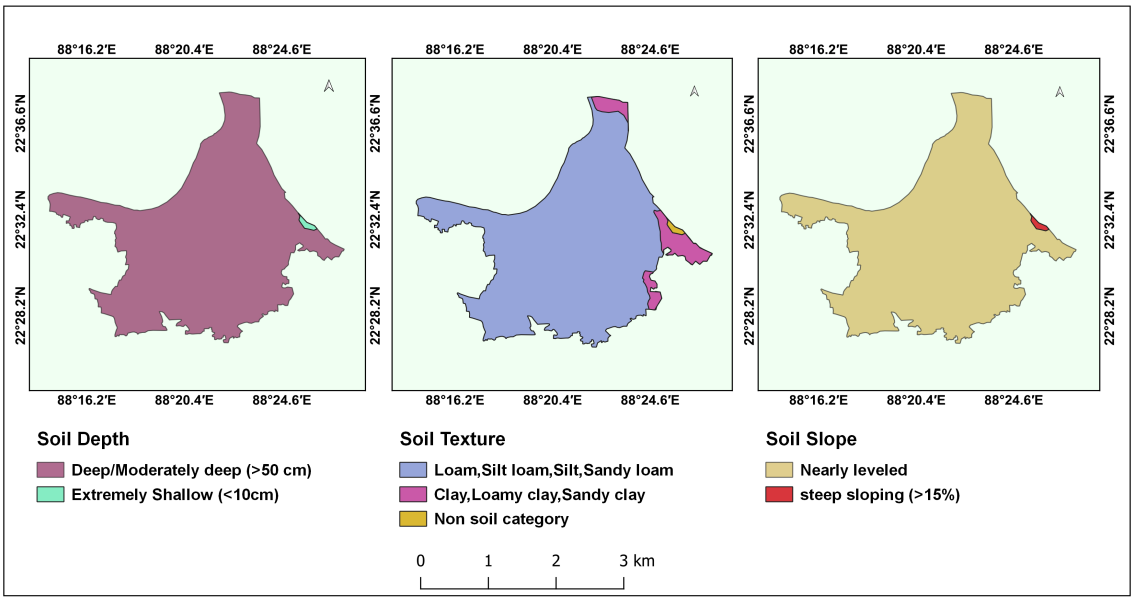


Figure 6.7. Soil properties of Kolkata (Source: WRIS, 2022)

mainly composed of less than 50% of sand and 20- 40% of clay component. Mostly presence of clay content in soil created high runoff potential of soil in Kolkata. A map has been visualised to represent HSG profile Kolkata (Figure 6.8). It can be observed that, Group D is soil is observed around the waterbodies like canals and wetlands. Otherwise, rest of the Kolkata is covered with Group C soil.

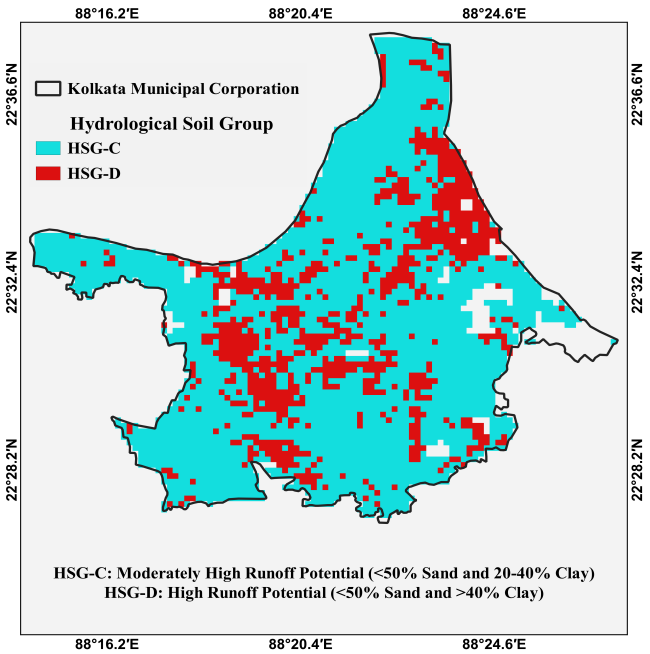


Figure 6.8. Hydrological soil properties of Kolkata, (Source: Ross et al. 2018)

6.4.6 Aquifer status

Kolkata is the capital city of the state West Bengal. In this state, geology and geomorphology are diverse in nature. In case of the aquifer, West Bengal has several principal aquifer systems those are made of alluvium, laterite, basalt, sandstone, shale, limestone, granite, etc. A large part of this state is under the alluvium aquifer system precisely in the southern part of West Bengal. This principal alluvial aquifer system is subdivided into six parts. An Alluvium aquifer system has been identified underneath the Kolkata that is made of comparatively younger alluvium. Formation of this aquifer started since the quaternary age. Depth to water level of 5 to 10 m. can be identified by decadal average. Thickness of the aquifer is between 50 to 700 m. The yield capacity of this aquifer is within 200 to 1500 m^3/day on average (Figure 6.9).
The aquifer under Kolkata is made of alluvium. This aquifer is semi-confined to confined in nature. It is mainly formed by unconsolidated sediment from the quaternary age. The thickness of the aquifer is mainly moderate in comparison with other thick aquifers in India. In the Central part of Kolkata, a thin layer of the aquifer is circled by a thick layer of aquifer. Abrupt changes can be only found in the central part of Kolkata. Aquifer or saturated groundwater table can be found 100 meters below the ground. On average. Central to the southern part of Kolkata has a very deep aquifer layer with a depth greater than 150 m. This deep aquifer can be found in the northeastern part also. Rest of the Kolkata has a homogeneous aquifer scenario with a depth of 90 to 150 m. below the ground.

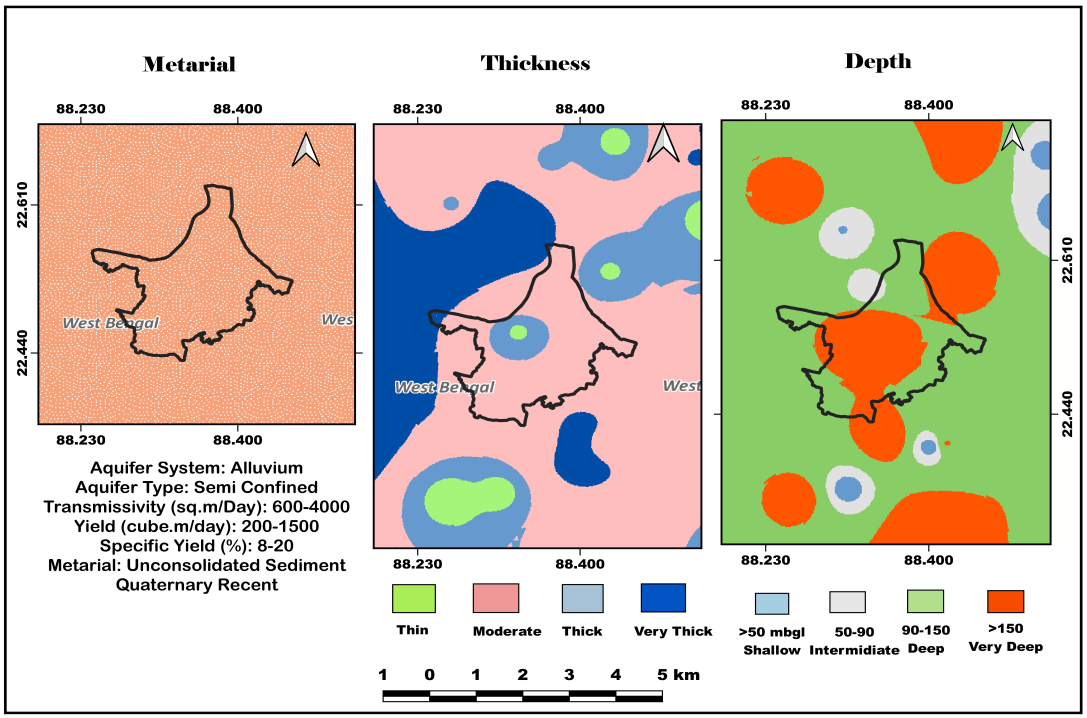


Figure 6.9. Details about the aquifer enevironment (Source: WRIS, 2022)

Litholog data

From the collected lithologic data, it has been identified that the first water table is below 200 meters from the ground level and the next water table can be observed between 300 to 400 m. below the ground level (Figure 6.10). From the lithology data of adjoining areas, it can be found that on the extreme northern side about 20 km. away from the boundary of KMC, the water table nearly starts from 100 m. below the ground level. There is another water table also beneath it within 300 m. below the ground. On the northeastern side water table is 200 m. below the ground level. The scenario is the same for the eastern side beyond the KMC boundary. Beyond the southern part of the boundary, the water table can be found after 150 m. and up to 230 m. below the ground.
It can be found that on average, the water table is 150 m. below the ground for the region. It can be roughly estimated that the possible availability of a water table for the study area also can be found 150 m. to 200 m. below the surface.

6.4.7 Land surface temperature

According to its landuse characteristics, Kolkata is totally urbanised. Land is either covered with built up area or open with bare soil, minimum area is left behind with greenery and waterbodies. It is clear from the figure 6.11 that, in daytime, surface temperature of Kolkata ranges between 23°C to 27°C on an average where, LST in adjoining areas are much lesser than Kolkata. A difference of 2°C to 3°C is prominent. Within Kolkata, temperature varies between 4°C. Core part of Kolkata reflects relatively higher temperature than its boundary area. Specifically in daytime, LST in southwestern part of Kolkata is higher than other areas .
Temperature usually low down after sunset. It is observed that, difference in temperature is minimum in case of Kolkata. whereas in adjoining rural areas, range of temperature is higher. From the figure it can be identified that, average temperature in Kolkata and its adjoining districts at night ranges between 9°C to 22°C and for Kolkata LST ranges between 13°C to 17°C. Temperature relatively higher in locations like Ballygunge, Tollygunge, and Jadavpur area. Highly urbanised areas reflect higher amount of LST than comparatively less dense areas.

6.4.8 Climatic condition

Kolkata is in the north hemisphere. Mean co-ordinates of Kolkata are, 22.5726°N, 88. 3639°E. Kolkata is very near to tropic of cancer, climatic experiences are familiar with tropical type. According to classification of Koppen, Kolkata is part of *'Am' / Tropical Monsoon Climate*. This type of climatic condition defines at the driest month minimum precipitation will be less than 60 mm. Moonsoonal wind create a definite impact upon the city. It is a seasonal wind; it brings rainfall. Tropical cyclone is a common phenomenon for the city. Tropical cyclone usually affects Kolkata in the month of April and May. Effect of land wind and sea wind can be also experienced in Kolkata, as it near to coast. After detailed observation, it has been found that, in peak season of rainfall storm events occurs 2 to 3 times a day with a span of 15 to 180 minutes.Researchers have studied in details about climatic condition of Kolkata and identified



Figure 6.10. Lithologocal log of borehole data for Kolkata and its surrounding areas (Source: WRIS, 2022)

its effects on physical and socio-economic properties (Dasgupta et al., 2013; S. Malik et al., 2020; Mitra et al., 2012; Saha et al., 2014). After extensive literature review, climatic condition has been analysed for this study.

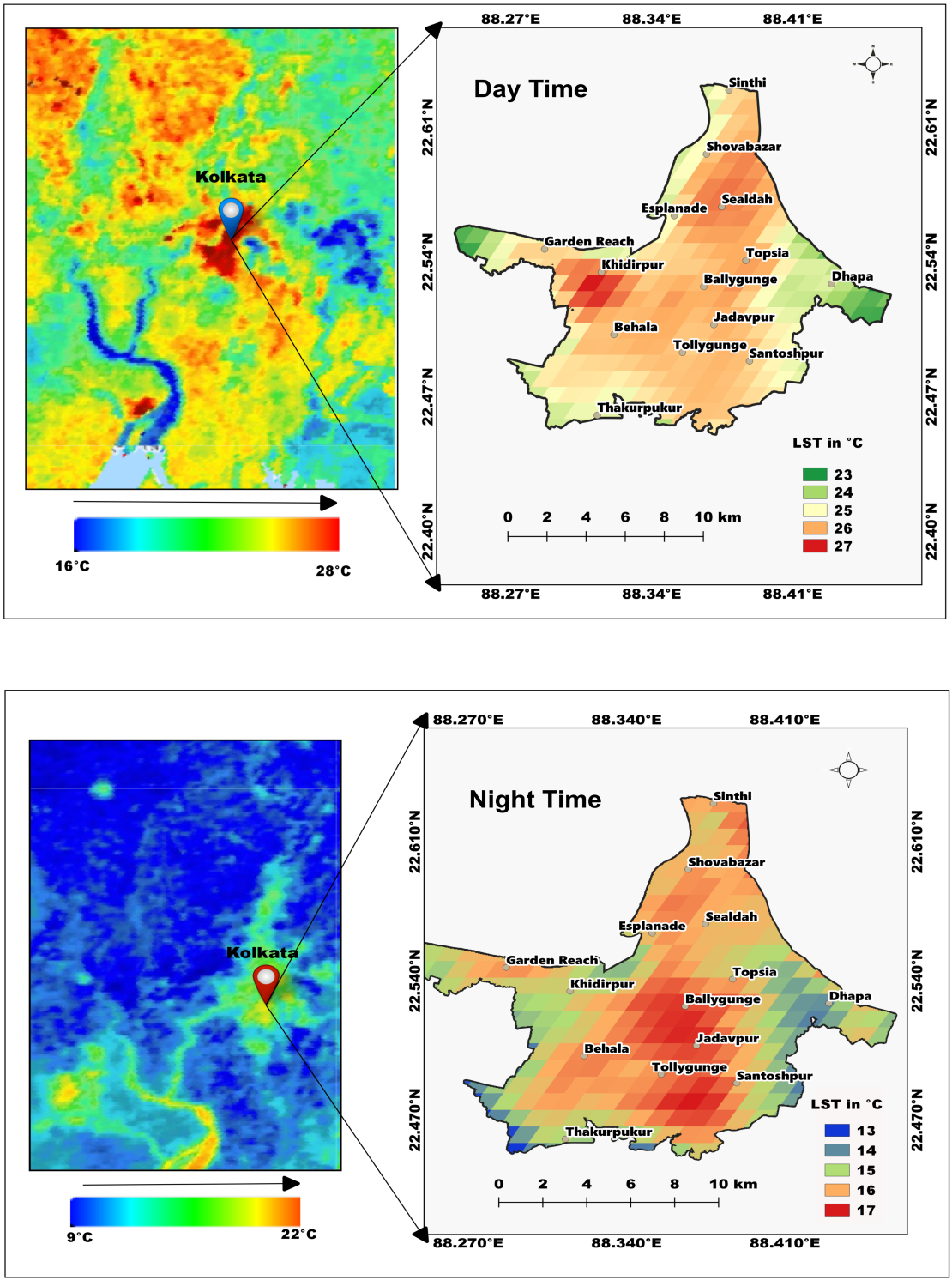


Figure 6.11. Average day and night land surface temperature, (Source : MODIS, 2000-2020)

Kolkata experience tropical type of temperature throughout the year. Maximum temperature can be observed more than 40°C for certain days in a year, where minimum temperature lowers up to 10°C certain days in year. Mostly Kolkata experiences the warm kind of feelings in



Figure 6.12. Temperature condition from 1990 to 2020, (Source: TerraClimate)

most the months and at that time humidity remains high. In monthly temperature analysis it can be seen that, January experience usual temperature within 25°C-30°C at maximum level and 10°C-15°C at minimum level. There is a gap of 15°C to 20°C in a day betwen max. and min. temperature. February also experiences the same kind of temperature range. January and February are treated as winter season in Kolkata. A change can be observed from the month of march. The maximum temperature increases up to 5°C from former months and this happens for the minimum temperature also. Effect of summer starts from April, maximum temperature exceeds the level of 35°C and for minimum it is exceeds 25°C. Daily range of temperature starts to decrease it consists under 10°C to 12°C. May experience the effect of scorching heat. The effect of summer solstice is prominent in this month. Maximum temperature reaches up to 40°C or more and minimum temperature rises up to 28°C. Daily range reduce to 5°C-8°C. April and May experiences a soothing southern wind in the evening time, as it comes from the sea side. June also experiences the same as May but rainfall frequency starts to increase from this month. These are treated as summer months it experiences warm temperature and due to continued warmness in atmospheres torrential thunderstorm occurs in the evening or night time. Effect of wet monsoonal wind starts to cover the area of Kolkata from the end of June, and it is prominent

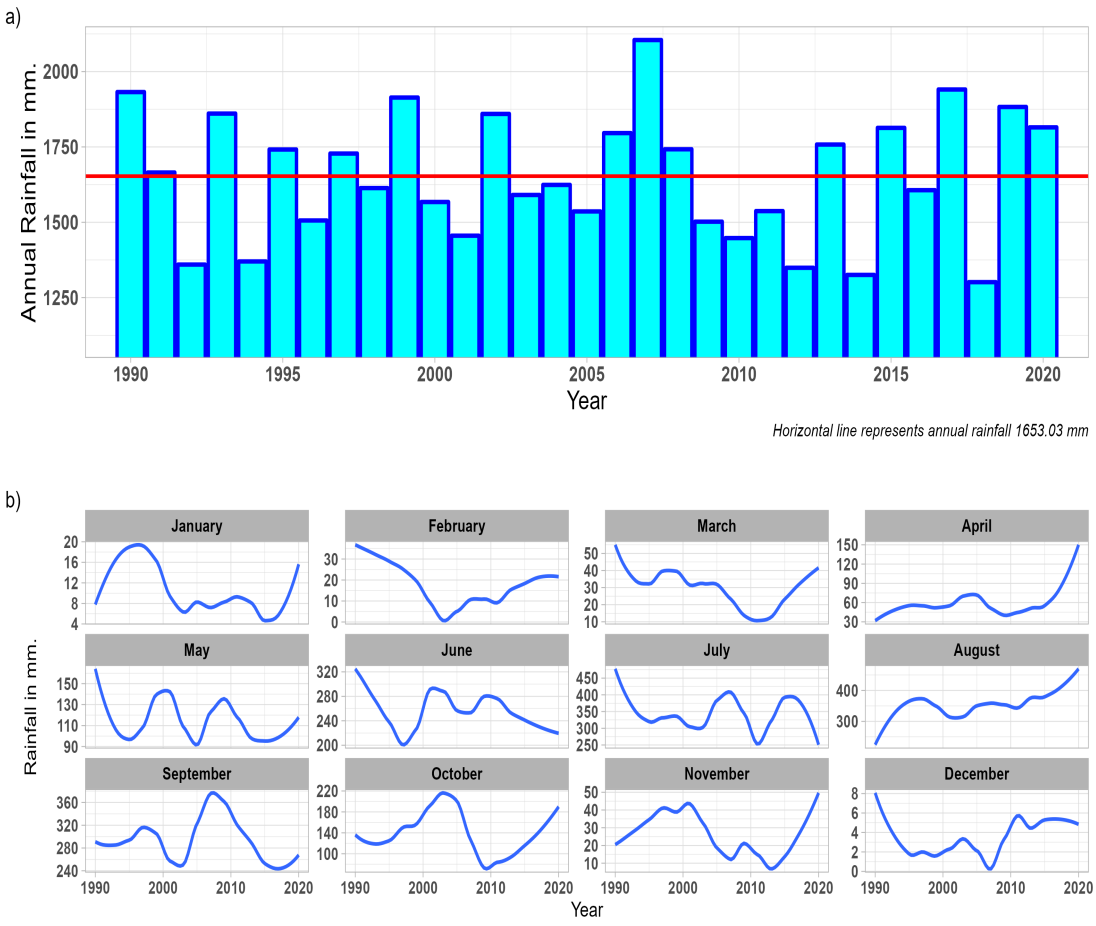


Figure 6.13. Rainfall condition from 1990 to 2020, (Source: TerraClimate)

in July and August and beginning of the September. Daily difference of temperature turns to minimum and temperature ranges within 25°C-30°C for the three months. October experience a change in weather, effect of winter solstice reflects in local weather. Maximum temperature starts to decrease.This time of the year is recognised as the end of southwest monsoon. November and December treated as the beginning of winter season, the range of temperature starts to decrease, and change in maximum and minimum temperature can be spotted also, December is realised as the most comfortable month from the year.

Observing thirty years (1990-2020) of monthly data and yearly data has been represented through graphical representation (Figure 6.12a). It is identified that maximum temperature of Kolkata in a month ranges between 31°C to 33°C. From 1990 to 2010, mean maximum temperature increased continuously but after 2010, a sharp fall has been observed in maximum temperature, In recent years overall temperature increased also. whereas, for mean maximum temperature, chronological pattern is more or less stagnant but, significant positive trend observed for mean minimum temperature. Usually minimum temperature is observed in night time. Increasing pattern in minimum temperature signifying warmness in night in recent years (Figure 6.12b). Generally, minimum and maximum temperature varies in different month. It is minimum in

rainy season i.e., July and August. Difference between two temperature parameter reaches its limit in end the of the winter season i.e., February and March.
Rainfall in Kolkata depends on monsoonal winds. Kolkata also faces the effect of tropical cyclone also. Dependency on monsoonal wind made the rainfall pattern very erroneous. Observing thirty years of data, it has been identified that, average rainfall in a year is about 1653 mm, and amount of rainfall in a year is very irregular (Figure 6.13a). Analysing mean monthly data, it is observed that, in certain months in year showing clear trend of increasing rainfall pattern, parallelly rest of the months showing a negative trend (Figure 6.13b). Rainfall is increasing from the month of January to April and same trend applicable for August, October and November also. Usually, extreme rainfall events occur in between June to September but in recent years it is changing in pattern shifting towards August to October and potentiality is also increasing in winter months.

6.5 Conclusion

The physical properties of the land define its existential circumstance on the earth. In this chapter, the physical properties of the land have been highlighted supporting the main motive of the study. It has been observed that Kolkata is a part of an older deltaic plain, comparatively nearer to the mouth of the river. A homogeneous surface has been observed with minimum undulation. The geomorphology of this study area is influenced by the river on its western side and wetland on its eastern side. Geology also supports geomorphology with quaternary alluvium deposit which is comparatively recent in the geological timeframe. The Landforms of Kolkata are extensively plain and the meandering characteristics of the river near the mouth created a levee on its eastern bank, which created a comparatively highland than the eastern part of Kolkata, as this part is mostly covered with a wetland. Rivers and wetlands also formed the soil as clayey in nature with the existence of sand and loam in limited amounts. The high amount of clay made the soil, runoff friendly that ultimately preventing the percolation of water beneath the surface. The aquifer of Kolkata is mainly confined to semi-confined nature. Aquifer thickness is mainly moderate, and water table can be observed mostly 150 meters below the ground level but distant from the central part of the study area aquifer can be observed between 100 meters to 150 meters below the ground level. Land surface temperature is high in the core area of the city as that is mostly covered with the built-up area, whereas in the periphery, the surface temperature is relatively low specifically near greenery and water bodies. Rainfall is dependent upon the monsoonal wind and average rainfall is above 160 cm per year. Only in the winter season, the effect of rainfall is minimum. Temperature is relatively higher in summer but as it is a core urban area, anthropogenic activities reflect in the diurnal temperature range. Ultimately urbanisation modified the physical status of the land and as it is a continuous process ultimately creating an impact on the subsurface environment also.

References

Sumi,A., Rajendran,T., Ramamurthy,T, Krishnan.T., Nair,G., & Kobayshi.,N. (2013).

Effect of temperature, relative humidity and rainfall on rotavirus infections in Kolkata, India. *Epidemiology and Infection*, *141*(8), 1652–1661. Retrieved from http://www.embase.com/search/results?subaction=viewrecord{&}from=export{&}id=L369350644{%}0Ahttp://dx.doi.org/10.1017/S0950268812002208

Ashwini, K., & Sil, B. S. (2022, oct). Impacts of Land Use and Land Cover Changes on Land Surface Temperature over Cachar Region, Northeast India—A Case Study. *Sustainability*, *14*(21), 14087. Retrieved from https://www.mdpi.com/2071-1050/14/21/14087 doi: 10.3390/su142114087

Bagchi, K. (1944). *The Ganges Delta : Bagchi,kanangopal : Free Download, Borrow, and Streaming : Internet Archive*. Kolkata: University of Calcutta. Retrieved from https://archive.org/details/in.ernet.dli.2015.21183

Bera, D., Das Chatterjee, N., Mumtaz, F., Dinda, S., Ghosh, S., Zhao, N., ... Tariq, A. (2022, sep). Integrated Influencing Mechanism of Potential Drivers on Seasonal Variability of LST in Kolkata Municipal Corporation, India. *Land*, *11*(9), 1461. Retrieved from https://www.mdpi.com/2073-445X/11/9/1461 doi: 10.3390/land11091461

Chatterjee, K., Choudhury, D., Rao, V. D., & S.P, M. (2015, mar). Dynamic analyses and field observations on piles in kolkata city. *Geomechanics and Engineering*, *8*(3), 415–440. Retrieved from http://koreascience.or.kr/journal/view.jsp?kj=TPTPHF{&}py=2015{&}vnc=v8n3{&}sp=415 doi: 10.12989/gae.2015.8.3.415

Dasgupta, S., Gosain, A. K., Rao, S., Roy, S., & Sarraf, M. (2013, feb). A megacity in a changing climate: The case of Kolkata. *Climatic Change*, *116*(3-4), 747–766. Retrieved from https://link.springer.com/article/10.1007/s10584-012-0516-3http://link.springer.com/10.1007/s10584-012-0516-3 doi: 10.1007/s10584-012-0516-3

Diptendra, D., & Chattopadhyay, B. C. (2009). Characterization of Soil over Kolkata Municipal Area. In *Indian geotechnical society.* Retrieved from https://gndec.ac.in/{~}igs/ldh/conf/2009/articles/T01{_}03.pdf

Dutta, K., Basu, D., & Agrawal, S. (2021, apr). Synergetic interaction between spatial land cover dynamics and expanding urban heat islands. *Environmental Monitoring and Assessment*, *193*(4), 184. Retrieved from https://link.springer.com/article/10.1007/s10661-021-08969-4https://link.springer.com/10.1007/s10661-021-08969-4 doi: 10.1007/s10661-021-08969-4

Feizizadeh, B., Blaschke, T., Nazmfar, H., Akbari, E., & Kohbanani, H. R. (2013, nov). Monitoring land surface temperature relationship to land use/land cover from satellite imagery in Maraqeh County, Iran. *Journal of Environmental Planning and Management*, *56*(9), 1290–1315. Retrieved from http://www.tandfonline.com/doi/abs/10.1080/09640568.2012.717888 doi: 10.1080/09640568.2012.717888

Gangopadhyay, A., & Patra, P. (2020, aug). The historical background of the canal system in Calcutta, India, and its contribution to development. *Proceedings of the Institution of Civil Engineers - Engineering History and Heritage*, *173*(3), 80–91. Retrieved from https://www.icevirtuallibrary.com/doi/10.1680/jenhh.19.00024 doi: 10.1680/jenhh.19.00024

IWD. (2020). *Irrigation & Waterways Department.* Retrieved 2022-11-04, from https://wbiwd.gov.in/index.php/applications/kolkata{_}drainage

Malik, M. S., Shukla, J. P., & Mishra, S. (2021, sep). Effect of Groundwater Level on Soil Moisture, Soil Temperature and Surface Temperature. *Journal of the Indian Society of Remote Sensing*, *49*(9), 2143–2161. Retrieved from https://link.springer.com/10.1007/s12524-021-01379-6 doi: 10.1007/s12524-021-01379-6

Malik, S., Pal, S. C., Sattar, A., Singh, S. K., Das, B., Chakrabortty, R., & Mohammad, P. (2020, jun). Trend of extreme rainfall events using suitable Global Circulation Model to combat the water logging condition in Kolkata Metropolitan Area. *Urban Climate*, *32*, 100599. Retrieved from https://linkinghub.elsevier.com/retrieve/pii/S2212095519300872 doi: 10.1016/j.uclim.2020.100599

Mitra, C., Marshall Shepherd, J., & Jordan, T. R. (2012). Assessment and dynamics of urban growth in the City of Kolkata. *Facets of Social Geography: Facets of Social Geography International and Indian Perspectives*, 541–555. doi: 10.1017/UPO9788175969360.031

Mohanty, W. K., & Walling, M. Y. (2008). Seismic hazard in mega city Kolkata, India. *Natural Hazards*, *47*(1), 39–54. doi: 10.1007/s11069-007-9195-1

Mukhopadhyay, A. (2004). *Geomorphology of Kolkata municipal corporation KMC its impact on urban functions* (Doctoral dissertation, University of Calcutta). Retrieved from http://hdl.handle.net/10603/159507https://shodhganga.inflibnet.ac.in:8443/jspui/handle/10603/159507

Nath, S. K., Adhikari, M. D., Devaraj, N., & Maiti, S. K. (2015, jun). Seismic vulnerability and risk assessment of Kolkata City, India. *Natural Hazards and Earth System Sciences*, *15*(6), 1103–1121. Retrieved from https://nhess.copernicus.org/articles/15/1103/2015/ doi: 10.5194/nhess-15-1103-2015

Ross, C. W., Prihodko, L., Anchang, J., Kumar, S., Ji, W., & Hanan, N. P. (2018, may). HYSOGs250m, global gridded hydrologic soil groups for curve-number-based runoff modeling. *Scientific data*, *5*(1), 180091. Retrieved from http://www.nature.com/articles/sdata201891http://www.ncbi.nlm.nih.gov/pubmed/29762550http://www.pubmedcentral.nih.gov/articlerender.fcgi?artid=PMC5952866 doi: 10.1038/sdata.2018.91

Roy, A. B., & Chatterjee, A. (2015). Tectonic framework and evolutionary history of the Bengal Basin in the Indian subcontinent. *CURRENT SCIENCE*, *109*(2).

Roy, J., & Saha, S. (2018). Assessment of land suitability for the paddy cultivation using analytical hierarchical process (AHP): a study on Hinglo river basin, Eastern India. *Modeling Earth Systems and Environment*, *4*(2), 601–618. Retrieved from http://dx.doi.org/10.1007/s40808-018-0467-4 doi: 10.1007/s40808-018-0467-4

Saha, U., Maitra, A., Midya, S. K., & Das, G. K. (2014). Association of thunderstorm frequency with rainfall occurrences over an Indian urban metropolis. *Atmospheric Research*, *138*, 240–252. doi: 10.1016/j.atmosres.2013.11.021

Singh, S. S. (2022). *Killing of a canal- why environmentalists are opposing a multi-crore drainage project in Kolkata - The Hindu.* Retrieved 2022-11-04, from https://www.thehindu.com/news/cities/kolkata/killing-of-a-canal-why-environmentalists-are-opposing-a-multi-crore-drainage-project-in-kolkata/article66044442.ece

Sun, D., & Pinker, R. (2004, apr). Case Study of Soil Moisture Effect on Land Surface Temperature Retrieval. *IEEE Geoscience and Remote Sensing Letters*, *1*(2), 127–130. Retrieved from http://ieeexplore.ieee.org/document/1291396/ doi: 10.1109/LGRS.2004.824749

Umitsu, M. (1993, mar). Late quaternary sedimentary environments and landforms in the Ganges Delta. *Sedimentary Geology*, *83*(3-4), 177–186. Retrieved from https://linkinghub.elsevier.com/retrieve/pii/003707389390011S doi: 10.1016/0037-0738(93)90011-S

USGS (2015). *NASA Shuttle Radar Topography Mission (SRTM) Version 3.0 Global 1 arc second Data Released over Asia and Australia.* Retrieved from https://earthdata.nasa.gov/learn/articles/nasa-shuttle-radar-topography-mission-srtm-version-3-0-global-1-arc-second-data-released-over-asia-and-australia

Wang, D., Chen, Y., Hu, L., Voogt, J. A., Gastellu-Etchegorry, J.-P., & Krayenhoff, E. S. (2021, may). Modeling the angular effect of MODIS LST in urban areas: A case study of Toulouse, France. *Remote Sensing of Environment*, *257*, 112361. Retrieved from https://linkinghub.elsevier.com/retrieve/pii/S0034425721000791 doi: 10.1016/j.rse.2021.112361

WBDMD. (2015). Geology, Geomorphology and Seismotectonics of Bengal Basin with special emphasis on Kolkata and its adjoining region. , 31–83. Retrieved from http://wbdmd.gov.in/writereaddata/chapter-2A.pdf

Chapter 7

Socio-economic Status of Kolkata

7.1 Introduction

Urbanisation is an artificial process. Synthetic changes in the urban area describe the quality of the city towards development. Economic growth and social changes define the urban status of a city. Several factors are related to the identification process of the socio-economic prospect of a city. Population and households reflect the effect of urbanisation most prominently. Typical landuse and landcover patterns differentiate an urban area from other regions. Available urban amenities also prove to be a crucial factor to evaluate the prospect of an urban area. Transport networks are also an important part to identify the growth of urbanisation. The foremost important factor is its water supply system. In this chapter, the socio-economic perspective has been captured for the study area of Kolkata. The main aim behind the chapter lies in the identification of the urban status of Kolkata through socio-economic factors that truly define the magnitude of urbanisation. Focus has been given to such socioeconomic parameters that are relevant to this study.

7.2 Objectives

This chapter has been processed further based on such objectives that have been mentioned below:

- To identify the landuse status of Kolkata compared with other adjoining areas.
- To identify changes in population growth and household pattern to understand the urbanisation scenario.
- To observe urban amenities to identify the depth of urbanisation.
- To observe transport network of Kolkata to identify urban growth pattern.
- To analyse water supply system in densely populated urban area.

7.3 Land use and land cover

Land use and land cover pattern of an area define the usage of lands and its physical coverage respectively for a different land. Broadly, West Bengal is a state of India that is under the Indo-Gangetic plain. Most of the land is plain, except the extreme northern part and the extreme western portion of the state. Due to its physical advantages most of the land of West Bengal is used as agricultural land. In the northern and western parts, lands are covered by forest. The southern part of the land is dominated by waterbodies or wetlands as it is part of an active delta region with numerous rivers and tributaries. Wasteland and barren land are minimum as most of the lands are either converted into agricultural land or for purpose of living.

Kolkata is in the southern part of West Bengal. The land of this district is mostly dominated by

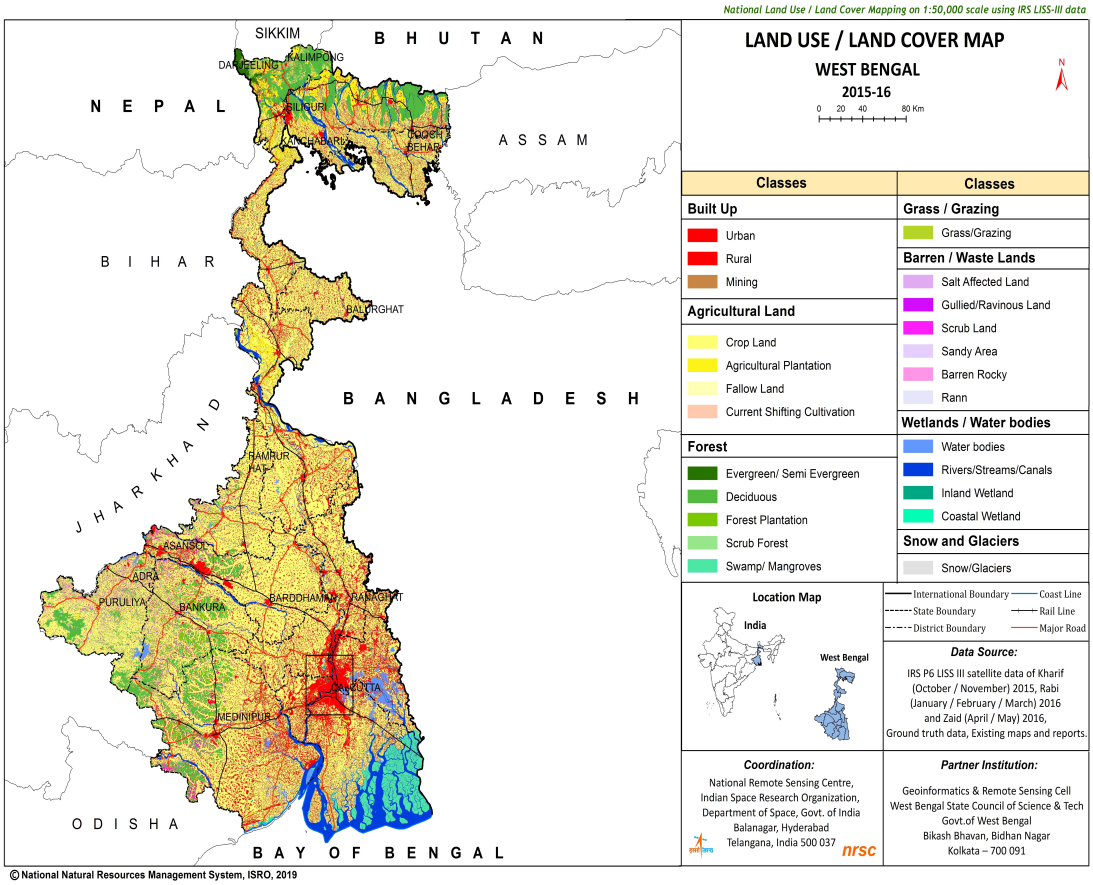


Figure 7.1. Land use/ land cover map of West Bengal where black rectangle highlighting Kolkata; (Source :ISRO, Bhuvan)

its landuse pattern and landcover holds minimum importance as this district is densely urbanised. With time, anthropogenic activities transformed the landcover and it has been used in different land use patterns. Distinct agricultural land is absent in this district so as forest. Mainly the district is dominated by dense built-up. Kolkata is the capital of the state, West Bengal. The land of this district served economical, administrative and residential purposes and the practise of primary activities is in negligible amount. Landuse is developed based on secondary and tertiary

activities.
Researchers have already recognised the importance of different land use patterns for Kolkata and published secondary data that provides details about the LULC pattern of the district. It has been identified that Kolkata is the most urbanised district in terms of its land use pattern in this state. In this chapter, the landuse and landcover map of West Bengal has been added to the study (Figure 7.1). NRSC produced LULC maps using remote sensing technology. LULC map has been utilised here to study the situation of this study area comparing it to other districts of West Bengal. According to the LULC map produced by NRSC where the dominance of agricultural land is prominent throughout the state but for the district of Kolkata and its adjoining area, the scenario is different. Kolkata is covered with a densely built-up area. Calculating the statistical part, it has been identified that, around 95% of this district is covered with urban built-up area whereas, for other districts, the ratio between total surface area and urban built-up hardly crosses 10%. Kolkata is the primate city of West Bengal. The urban land ratio in Kolkata must be compared with urban areas on a logarithmic scale in this state.

7.4 Demographic profile

7.4.1 Demographic scenario between 1901-1981

Urbanisation is perpetual for a city, and Kolkata is not an exception. This city holds a vast history of development. Population influx in a city depends upon the rule of migration from a rural to an urban area; pull factors are prominent here. Kolkata evidenced the addition in population not only from the rural part of west Bengal it is also faced a flow of population from the neighbour country Bangladesh, which was just built in 1971 due to political turmoil (Ghosh, 2015). Before 2001, the city was called Calcutta. Detailed census data provides a clear vision of the accumulation of population in Calcutta. This historical perspective on population shows the evolution of population with time (Figure 7.3).
In 1901, Kolkata was the capital of India and the population in this census just crossed 1 million. Politically Kolkata was the most important city in India.
About 1911, Calcutta was a part of eastern Bengal and totally under British territories.1921 it was holding an area of 62 km^2 with its suburbs and its population was more than 13 lakhs, At that time Kolkata was comparatively much higher in population than other glorious cities like Bombay, Delhi, and Madras.
Due to a severe famine and socio-political issues, a huge influx in population was observed specifically in Calcutta. It is estimated that about 80% population increased between 1931 and 1941 (Ray, 2017).
After the independence from British rulers, Calcutta was on the eastern side of India, certain adjoining part of Bengal was then divided and called East Pakistan which was created as a neighbouring country. Religious conflict in both countries affected on population. It was not limited to the state West Bengal, it made an impact on Calcutta also. According to census data, in 1951, the population of Calcutta was more than 26 lakhs that time administrative boundary of Calcutta was about 83.7 km^2. After a decade the population increased to 29 lakhs (Mitra.A,

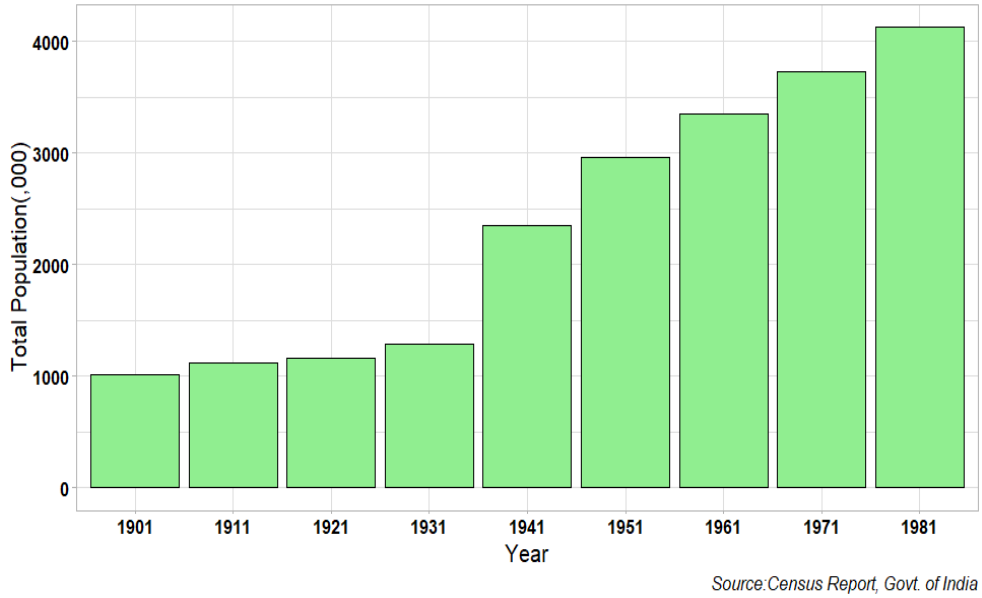


Figure 7.2. Total population of Kolkata from 1901 to 1981

1951). In 1971, the population increased to 31 lakhs and at that time total urban population in West Bengal was about 1 crore. Kolkata was filled up with 100% of the urban population then. Decadal growth was about 7.57% at that time and the density of population was about 30,000 people per sq. km. area. The administrative boundary of municipal corporations was then divided into 100 wards.
In 1981, after the published data from the census, it was observed that decadal population growth increased to 4.96% with a total population of more than 33 lakhs in Kolkata. The administrative area of Calcutta was 104 km^2 then. The average population density was increased to 31,779 person/ sq.km.

7.4.2 Detailed demographic scenario between 1991 to 2011

Overall demographic situation

According to census data, the total population increased between 1991 to 2001 but in the next decade population decreased in the case of Kolkata where overall urban population growth was at a rapid pace before 2011. The decreasing trend of population reflected in population density also, in between 1991 to 2001 population density increased slightly but ultimately it decreased in 2011. Calculating decadal growth, it has been observed that, between 1991 to 2001 the population increased by 3.9% but in the next ten years the population decreased by 1.7%. However, population density is always highly dense in Kolkata. Analysing 2011 census data, it has been observed that, the population density was 308 in India whereas in West Bengal as a state it was 912 and in Kolkata as a district or as a city it was more than 24000. The sex ratio between 1991 to 2011 improved constantly.in 2011, the female population was near to the male population. Further, growth has been observed in the working population in 2011 about 40% of the total population in between working age. As it is a developed urban area, this

advantage reflects in literacy rate and it is continuously growing with time. Overall, the number of households increased with time and as per the latest data, more than 1 million households are in Kolkata (Table 7.1).

Table 7.1. Demographic characteristics of Kolkata from 1991 to 2011

Year	1991	2001	2011
Total population	4399819	4572876	4496694
Population density	23783	24718	24306
Decadal growth rate	-	3.9	(-)1.7
Sex ratio	799	829	908
Working population	33	37.6	39.9
Literacty rate	77.6	80.9	86.3
Total household	853337	929586	1024928

Population Scenario

The total population was divided by the area of an ward to calculate population density for each census year between 1991 to 2011(Appendix, Table 7). Population density is always higher in Kolkata than in any other district of West Bengal. Calculated data reflects inequality in ward-wise population data also. It can be observed from Figure 7.3 that, mainly northern to the central part of Kolkata where the population in some wards exceeded more than 1 lakh population per km^2.whereas from the central portion to central southern part, population density is in between 20000 to 50000. In the boundary or peripheral part of Kolkata, population density is limited to 20000 people in km^2. The scenario of population density changed with time. In Ward No. 19, 18, 23, 41, 43, 48, and 54 where the population density is more than one lakh. In 2001, Ward no. 52 and 62 adjoined with 54 were added along with other wards but in 2011, only Ward no, 23 and 39 were holding population density of more than a lakh. Bara Bazaar and College street area remained densely populated over years. The peripheral part of Kolkata where population was much below twenty thousand in sq, km area. Especially, the southeastern part of Kolkata was less populated than all other wards. Calculating changes between two the census year 1991 and 2011, it has been observed that population density either decreased or remain unchanged in the northern and central parts of Kolkata. These wards were extremely populated and saturated and further scope of the increasing population were limited. Up to 50% positive change has been observed in adjoining areas and further positive change has been observed towards southern and specifically the south-eastern part of Kolkata. In a few wards population density increased more than two times in just twenty years. From the figure, it can be analysed that, from Ward No. 1 to 100, where overall population density decreased except in a few wards. But from Ward no.101 to 141 which were newly added to Kolkata after 1986, the population increased significantly and it is observed that in Ward no. 108 and 109 population density increased more than 200% within two decades.

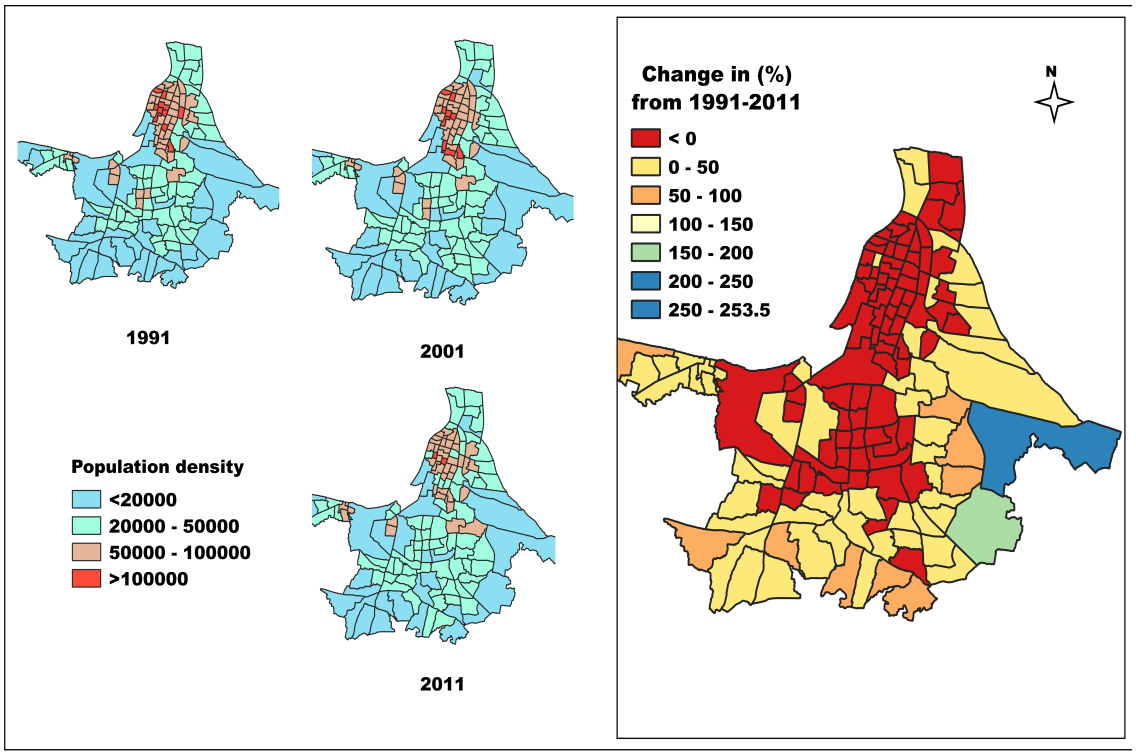


Figure 7.3. Population density (people/km^2) in census year 1991, 2001 and 2011 (left) and change in population density between 1991 and 2011 (right), (Source: Census data)

Household scenario

A household defines a place which is constructed and the number of people live jointly and take their meals from a common kitchen. The household can be of a singular member or with multi members. In this chapter, household density has been calculated ward-wise individually for each census year between 1991 to 2011 (Figure 7.4). It has been observed that in the northern part of Kolkata which is treated as an economic zone of Kolkata, there are most of the households consist within a small area. The number of households is inversely proportional to the distance from the central business district of Kolkata. The scenario remained more or less the same in every census year except in 2011, household density increased towards the southern part of Kolkata. After calculating, the difference in household density between 1991 and 2011, it has been revealed that household density remained unchanged or decreased due to restructuring in the northwestern and central part of Kolkata but household density increased gradually from west to east intending for the southern part. In the peripheral area of Kolkata, household density increased by more than 50%, and a specifically significant change has been observed in southeastern part of Kolkata. From the figure, it can be understood that From Ward no 1 to 91, household density decreased between 1991 to 2011, but after Ward no. 91, household density increased significantly, up to Ward no.141. Extreme change has been observed for Ward no. 106,107,108,109,111,114 and 141 where household density increased more over 100% in twenty years.

Changes in population density and household density have been analysed above. It has been

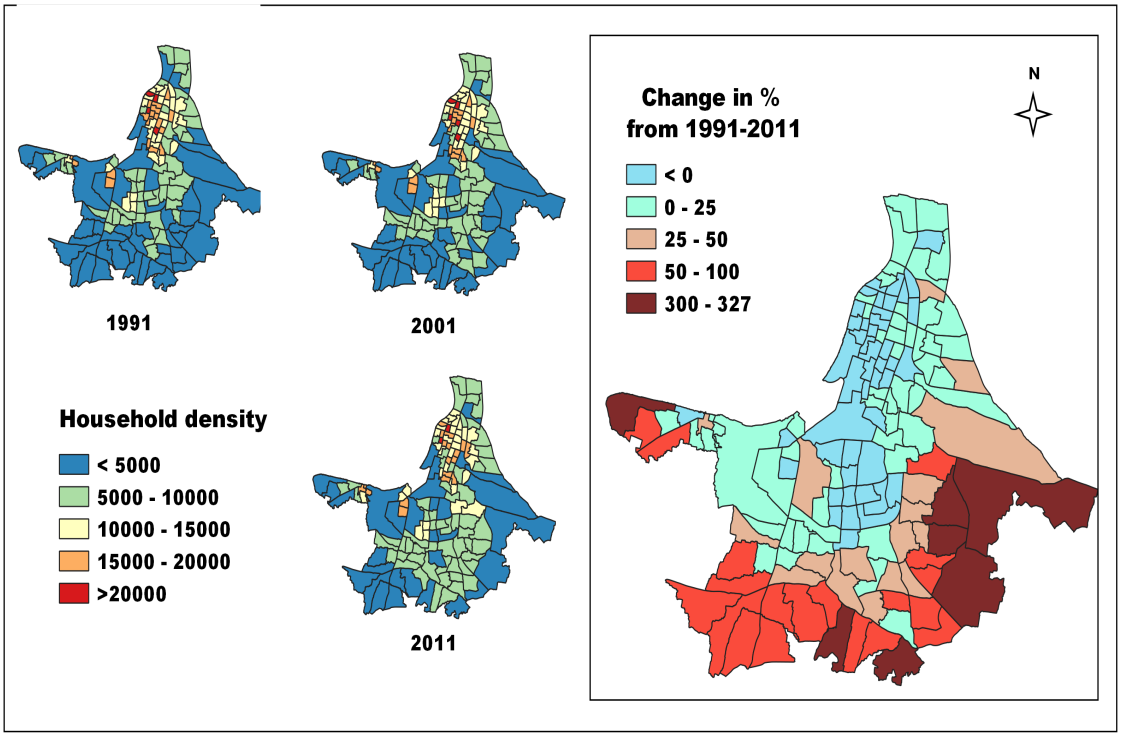


Figure 7.4. Household density (people/km^2) in census year 1991, 2001 and 2011 (left) and change in household density between 1991 and 2011 (right), (Source: Census data)

recognised that, Changes in population density and household density positively correlated with each other (Figure 7.5). In the first ninety wards, population density decreased significantly than household density whereas the growth rate in population density and household density is extremely high in wards from southeastern part of Kolkata, where household density increased much more than population density. Overall it has been observed that households increased at a much faster rate than the population in Kolkata.

Sex composition

The sex composition of a region also reflects socio-economic structure of the society. It proves to be an important factor to understand the demographic and socio-economic development aspects. At the beginning of 20th century, the male population was dominant in Kolkata and social structure was the main reason behind it. India was not independent then, residents were mainly residing in Kolkata for either business purposes or as administrative workers. In 1911, two third of the total population was led by males. The percentage difference increased up to 1941.At that time, political scenarios, and economical conditions were not suitable for a woman to reside in this city. In 1951 after independence, the difference between the male and female populations started to reduce gradually. The female population in Kolkata is increasing continuously since 1951 that time it was only 37% and in 2011, it was 45%. The growth of the female population is slow but gradual because of its importance. Usually, most of the population lives in this city mainly for work purposes. As per local traditional social values, the male population from a

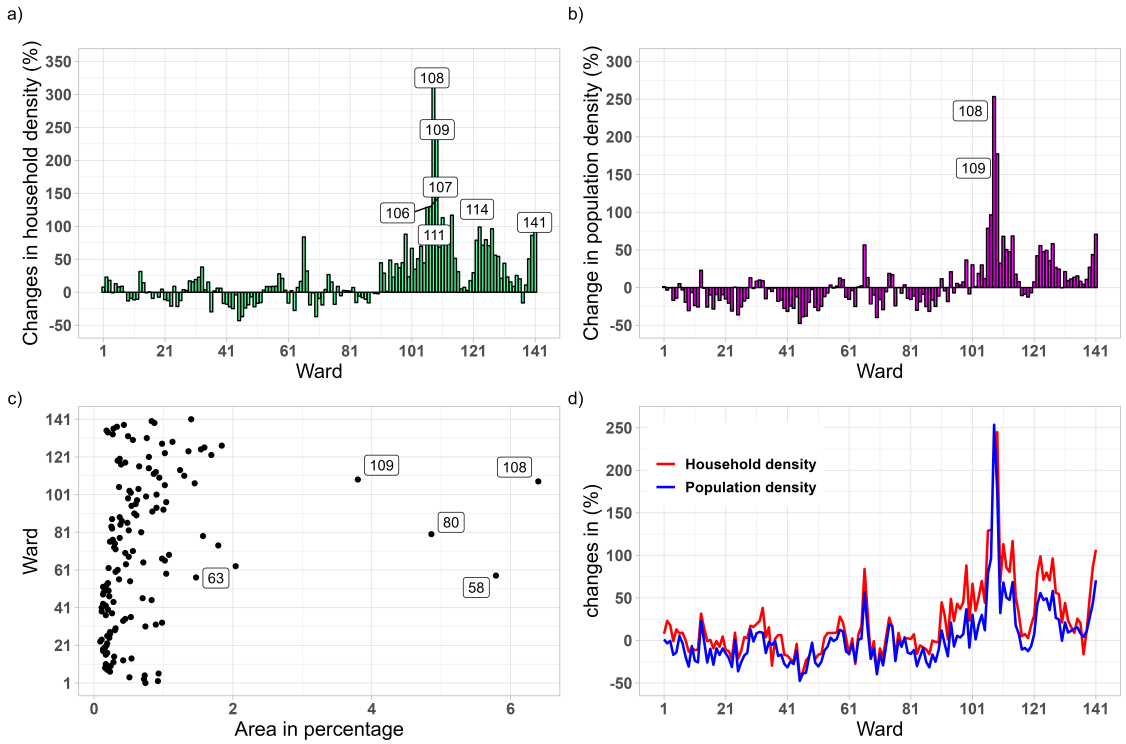


Figure 7.5. Wardwise changes in population density and household density between 1991 to 2011

family usually came to this city for work and went back to their hometown after service or business period. These traditional social values are diminishing with overall socio-economic development and as a result female population is increasing in Kolkata and upcoming years ratio will be equalised (Figure 7.6).

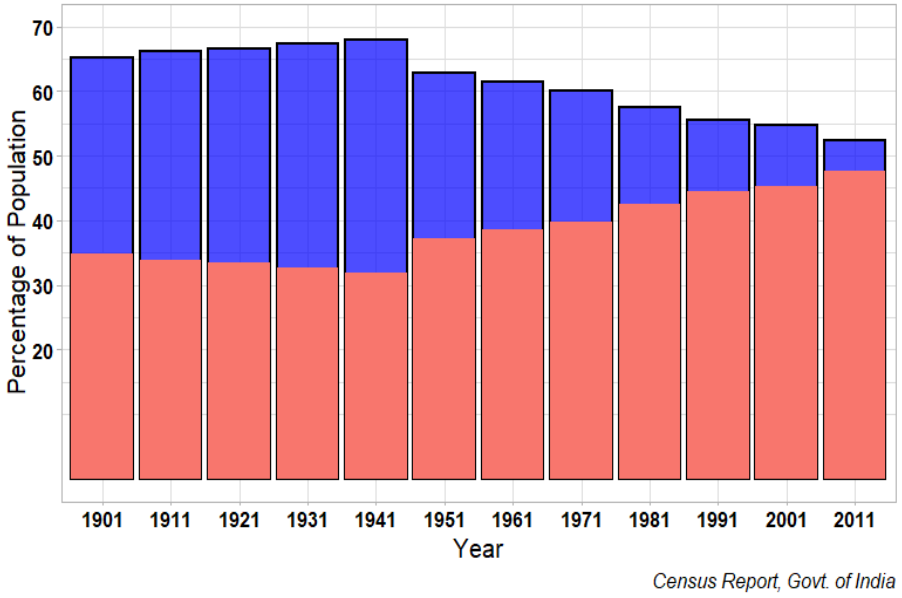


Figure 7.6. Ratio of male (blue) and female (red) population in Kolkata from 1901 to 2011; Source: Census data (1901-2011)

7.5 Urban amenities

Marans & Stimson (2011) stated that amenities reflect available facilities in a place. Quality of life can be replicated by the availability of amenities. Effluent amenities of a place attract people for living or working where effectiveness proves to be a pulling factor when other places are lacking in it. Urban amenities are described in this chapter as definite urban facilities that contemplate a better urban living experience for city dwellers. Urban amenities can be broadly divided into public sector amenities as well as the private sector. Government-aided health facilities (hospitals, blood banks etc.) educational institutions, parks, recreational lands etc are generally provided by the public sector and restaurants, hotels, cinema halls, etc facilities are provided by the private sector. Kolkata is the capital city, all possible facilities are available here that can be compared with other urban amenities provided in world-class cities. Needful urban amenities were already being provided from the British era and after independence development process continued further. In the last thirty years after the era of globalisation, almost all modern amenities are available in Kolkata (Figure 7.7).

World class treatment facilities are available in the hospitals that are run by the public sector. All the Govt. hospitals also provide efficient medical training facilities through colleges along with integrated treatment facilities. These medical institutions are concentrated mainly in the central part of Kolkata. In recent years, improved private health facilities concentrated in the southeastern part (Chingrighata, Anandapur, Mukundapur) of Kolkata.

Kolkata is also famous for its educational institutions, as it was a capital city, British rulers then established promising educational facilities in Kolkata. Those educational institutions still hold the glory of the past in the present time also. University of Calcutta, Presidency College, Hindu School, and Bethune College are among these. With time schools and colleges developed in every infamous location from them St. Xavier's College, to Jadavpur University enlightening the educational sphere at the world level. Several libraries along with museums are here to promote learning. Along with traditional educational facilities Kolkata also nurtures abstract ideas and promotes technical skills with different types of training institutions.

Kolkata is also called the cultural capital of India. People of Kolkata are typically inclined to different cultural practices like music, dance, art and cinema. Every year international-level cultural festivals are organised and promoted by the local government and their reflection reaches up to distant parts of the World. Several art galleries, music academy, and dance academy is in Kolkata. Even Rabindra Bharati university is there to promote a different indigenous form of arts.

British in their ruling period constructed different architectures to celebrate their imperialism. Those prolific structures are now being treated as historical monuments and memorials. Victoria memorial, the Ochterlony monument are the most celebrated one.

British rulers also constructed different types of administrative buildings for official works. Those buildings are still in Kolkata. Those buildings are mainly concentrated in the central part of Kolkata. Later different types of administrative buildings were constructed in different locations. Nowadays different types of administrative buildings are placed in Alipur, Camac street, Bhawanipore area. Recently to reduce pressure most administrative offices are being

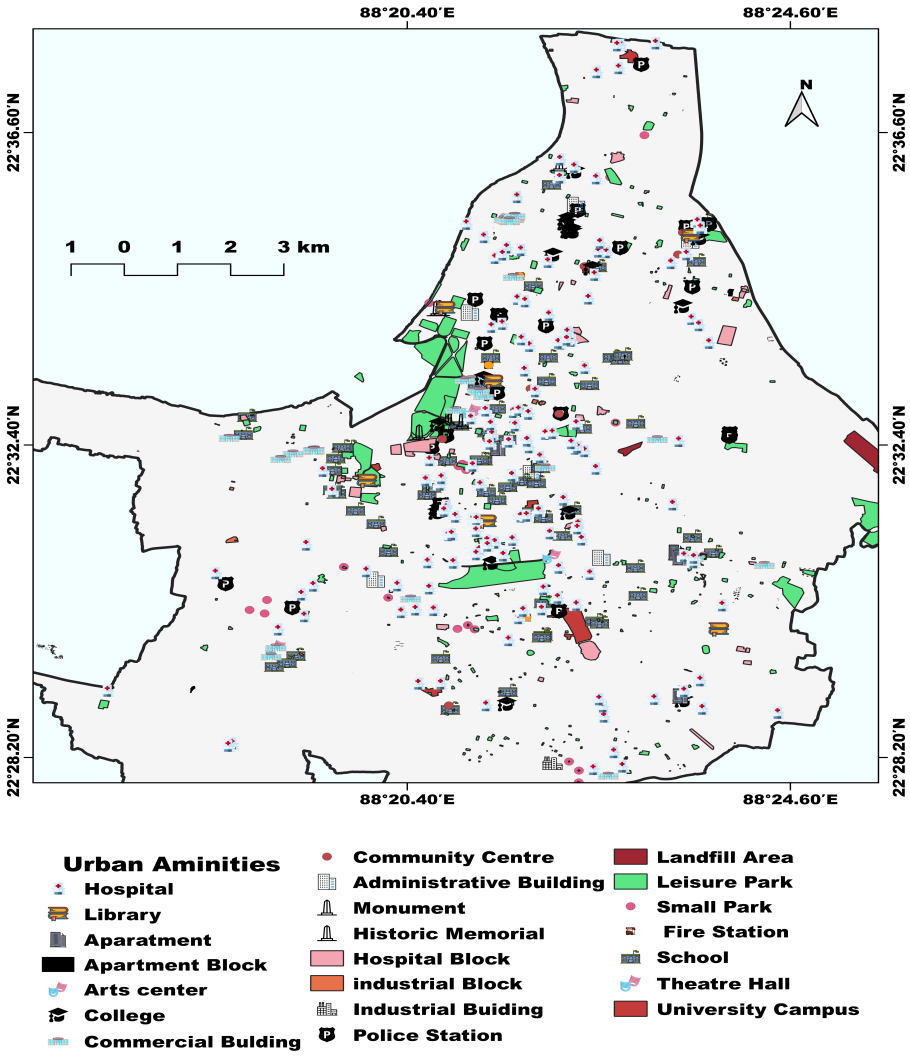


Figure 7.7. Urban aminities in Kolkata, (Source: OpenStreetMap, 2021)

shifted to their satellite town Salt Lake and New Town.

In the past century, commercial buildings were mainly concentrated in the business district of Kolkata i.e based in the central western part of Kolkata. Commercial offices in high skyscrapers nowadays can be observed in the heart of Kolkata. Parallelly, in the southern part and the eastern boundary of Kolkata technically integrated commercial buildings are being created to cope with world-class infrastructures. Decentralisation from central Kolkata has already been started in urban amenities.

In every neighbourhood, there are small markets. These markets mainly reflect the inclusive sector of the economy. Locally it is called a Bazaar. Along with local initiatives, KMC also fixed markets to serve people in their land. Recently, the concept of a departmental store, and shopping mall, the supermarket also has been introduced to the people of Kolkata.

In terms of security and service, Kolkata Police earned its name globally. More than 80 police

stations covered the whole area of Kolkata among them, several women police stations are also there.
Along with other basic amenities leisure parks, lakes, and children's parks are also there in Kolkata.At Maidan, where a large amount of greenery and openness can be observed in the heart of the city like 'Central Park' in New York. Rabindra Sarobar is one example where, leisure parks, recreational communities, sports complexes and ample small green parks can be found encircling the lake. Park can also be found in Kolkata rounding the pond or waterbodies. Football grounds and indoor sports complexes are all available in Kolkata.
Kolkata is populated with more than 4 million people and the floating population is a major component of the city, as a result, it huge amount of wastage is produced every day dumping infrastructure of such wastage is already facilitated in every corner of the city and large dumping landfill site has been dedicated only for Kolkata. Dhapa is the main dumping ground for Kolkata the eastern boundary of Kolkata. 95% of total wastage is being dumped here.
Kolkata is equipped with all kinds of possible amenities but extreme population density in several parts of the city creates a disbalance in service infrastructure sometimes.

7.6 Transport network

The road network of Kolkata is divided into state highways, district roads, service roads and pedestal streets. Roads are highly interconnected with each other and the traffic system in Kolkata is efficiently equipped with modern technology and well appreciated. Primary roads are broad and connect the north-south stretch and secondary roads are interconnected with primary roads. Whereas, tertiary roads mainly connect the adjoining neighbourhoods and ultimately join with secondary or primary roads. Footpaths and pedestrian lanes are dedicated to walking and cycling. There are some famous roads in Kolkata, that still holds historical importance and economic importance. Those are Acharya Jagadish Chandra Bose Road and Acharaya Prafullya Chandra Road, Amherst Street, Bidhan Sarani, Camac Street, Chowringee Road, College Street, Gray Street, Hare Street, Lindsay Street, Mahatma Gandhi Road, Mirza Galib Street, Park Street, Prince Anwar Shah Road, Rabindra Sarani, Raja Subodh Chandra Mullick Road, Rashbehari Avenue also Shakespeare Sarani, Strand Road, Sudder Street, Vivekananda Road and Zakaria Street. It is noteworthy to mention that, after the construction of the Eastern Metropolitan Bypass Road, in the eastern part of Kolkata, a significant change has been observed in the urban growth pattern in the case of Kolkata. Along with this recently constructed flyovers, underpasses, bridges and road connectors significantly developed the perspective of urbanisation in Kolkata. Kolkata is connected with other adjoining districts through highways. Even the international road transport system is maintained from Kolkata
The railway infrastructure in Kolkata is commendable. Sealdah, the busiest station in India is in Kolkata, further, a station has been constructed named Kolkata in the northeast part of Kolkata. Local trains from adjoining districts travel up to Kolkata, and every day more than 12 lakh people avail of the railway facilities only from Sealdah stations. Circular railway track also serves the communicational purpose. It is dedicated to urban commuters but with time its importance has

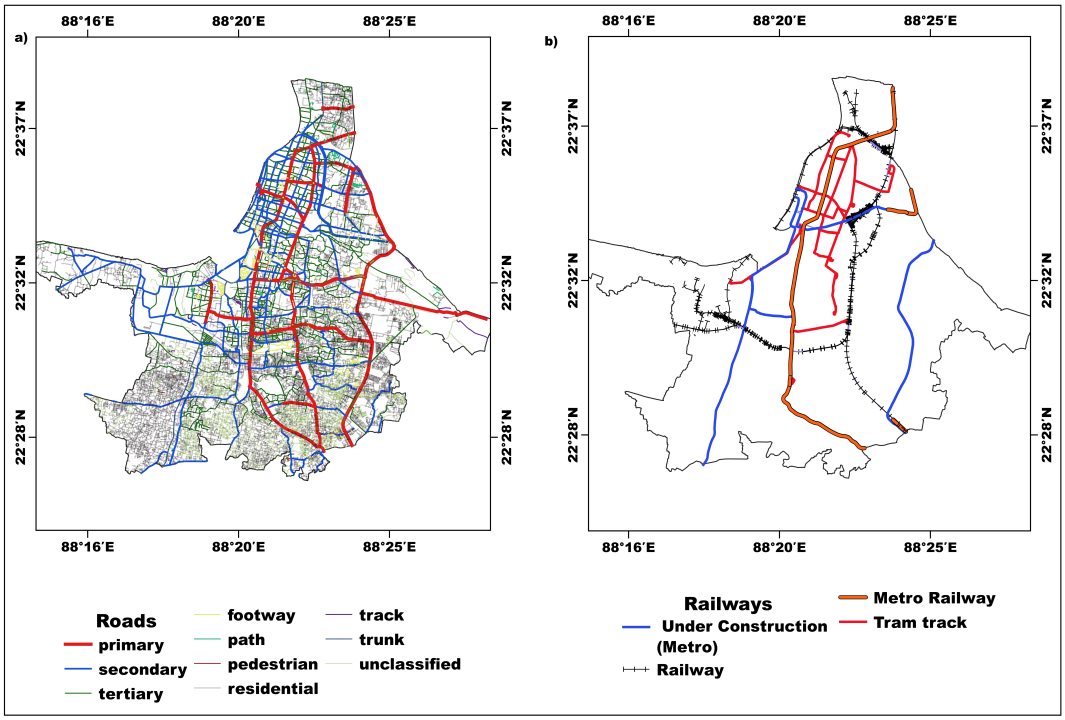


Figure 7.8. Road network of Kolkata (Left) and Rail network of Kolkata (right); (Source: OpenstreetMap, 2021)

faded. In the last thirty years, urban commuters majorly depend on the metro railway. Kolkata got its metro railway facilities in around the nineties first time in India. Metro rail facilities were grounded and then mainly targeted to serve north-south stretch of Kolkata. Metro railway is the most smooth public transport medium and because of its advantages further, it stretched its wing from east to west and other parts of the city. By developing a well-connected network in the near future metro railway will be the easiest and budget-friendly transport medium in Kolkata. It is note worth mentioning that, like other imperial cities Kolkata also had tram lines to support urban transportation. The network was densely distributed in the core part of Kolkata but with time, it could not cope with other transport facilities. In recent days, most tram routes have been removed from roads. Only a few routes are there to maintain its heritage value.

7.7 Water supply system

Kolkata is situated on the west bank of River Hooghly and East Kolkata Wetland is on the eastern boundary of Kolkata. From the initiation of this city, fresh drinking water was in demand. In the beginning, the water supply was dependent on ponds and water tanks created by British rulers. Infectious waterborne diseases were a serious concern for the local governing bodies then. The water supply system was first commissioned by British rulers in 1865. With time, the water supply system developed and extended to meet up the demand of the increasing population. KMC holds the responsibility to supply water in every part of the city. The source of freshwater

supply is collected from River Hooghly. Now, there are five water treatment plants to treat the water into drinkable freshwater.

Table 7.2. Water supply situation in 1990

Source	Average supply (mgd)
Palta	160
Garden Reach	35
Surface Water	195
Groundwater	25

In this case study, as per the time frame (1990-2020), it can be observed from the table 7.2 that, previously in 1990, water supply was mainly from two major water treatment sources i.e., Palta and Garden Reach. Water supply from these two sources was not sufficient to meet up the demand of the increasing population of Kolkata, then other surface water sources were used for water supply. Mainly, booster pumping stations were used to provide water supply directly to the household. Along with this groundwater abstraction and supply was a common practice for KMC.

Table 7.3. Groundwater supply system maintained by KMC; (Source: KMC, 2015)

Year	Big diameter tubewells	Small diameter tubewells
1991	285	10500
1993	308	11877
1998	335	12000
2001	351	12000
2012	358	10000

Before the era of the 90s, Kolkata has observed a significant amount of growth in population due to migration and other socio-political issues. Public water supply was not sufficient at all to cater to such a huge increasing population, especially in the southern and southeastern parts of Kolkata. Water supply planning did not match up with the short span of the population diaspora. Groundwater abstraction was a common practice for such areas where public water supply was not provided. LUBs also took support from groundwater resources for water supply in Kolkata. It can be observed from that table 7.3 that, the use of big diameter tube wells and small diameter tube wells also increased until 2001. Afterwards, groundwater abstraction was reduced from the KMC water supply system.

Table 7.4. Water supply situation in 2011

Service area	Area coverage (km^2)	Perc capita supply (lpcd)
Palta	62.75	144
Garden Reach	67.20	136
Jorabagan	1.85	140
Wattgunge	4.84	139
Groundwater	44.32	

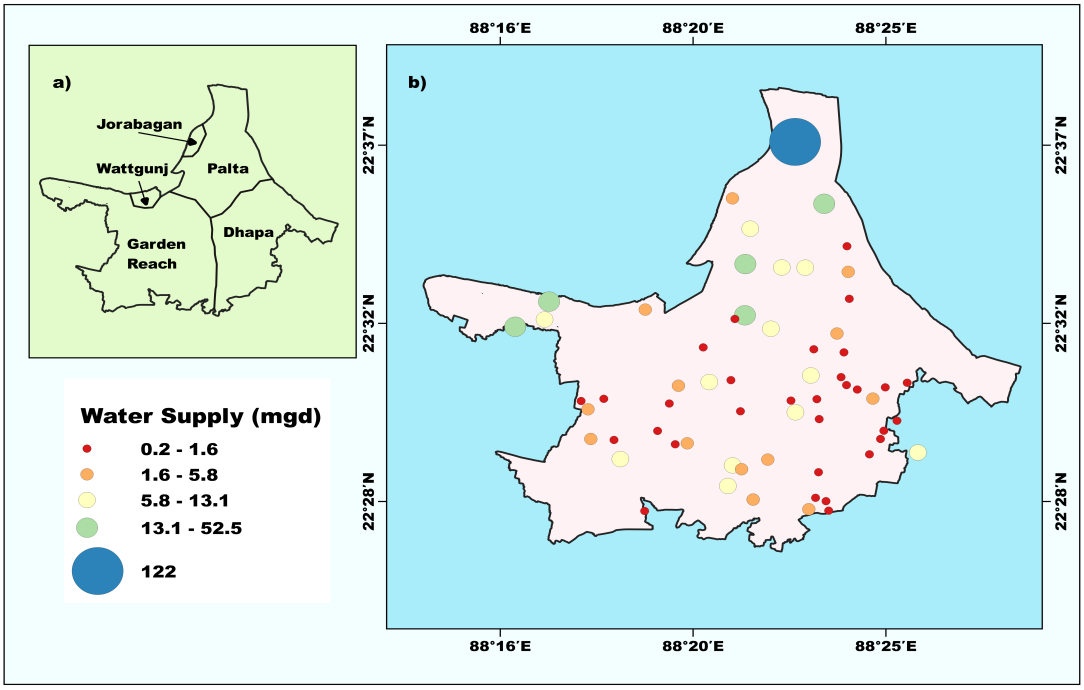


Figure 7.9. Water supply sources in Kolkata; Zones divided into water works for supply (inset); (Source: KMC, 2018)

After 2011, it can be observed from the table 7.4 that, with increasing population demand for water supply infrastructure also increased at a higher pace to meet up the demand KMC created more sources to meet up the demand. Within 2011, Jorabagan and Wattgunge water treatment plants were created to supply water in the CBD and western boundary area of Kolkata respectively where population density is at the highest level. These minor water treatment plants covered minimum areas but that was not still sufficient to provide water to every corner of the city. Till that time groundwater abstraction was persisting in the south and southeastern part of Kolkata where water supply was not available. From the table, it can be observed that about 44 km^2 was dependent on groundwater resources. Also, it needs to be mentioned that, the benchmark for urban water supply per person is 150 litre of water in a day in India whereas till

2011, most portions of Kolkata did not match up to this level, water supply was limited to 80% of the total area and at an average 134 lpcd was provided to people for their daily usage which was not sufficient at all and an as result groundwater abstraction was inevitable in Kolkata. Water supply was a major concern for this study area from the beginning but with efficient planning and major financial support from state and national governments, *Jai hind Jal Prakalpa* was developed in the southeastern part of the city with about 30 mgd capacity around 2014. Now groundwater abstraction is also reduced extensively from the KMC supply system but the private groundwater abstraction process is continuing in almost every part of Kolkata without any further intimation to authority. It is also noteworthy to be mentioned that, most of the southern and southwestern part lacks sufficient water supply according to the benchmark of the Indian government. The water supply is free from any tax for the residents and the water supply is not measured by any meter, so exact consumption is a difficult measure. Water loss through pipes and reservoirs is a common problem here in this city (approx. 30% water loss from the supply system) and misuse of supplied water can be observed here and there all over the city.

7.8 Conclusion

Kolkata is a densely populated urban area where significant imprints of urbanisation are prominent through well-developed socio-economic infrastructure. In the last three decades, Kolkata developed mostly with the wave of globalisation. Urban built-up areas captured most of Kolkata and it is the most urbanised land compared to other districts. The population of Kolkata increased continuously throughout the last century and within a small period it multi-folded. Population growth slowed down recently. Population density is excessively high in the economic zone of Kolkata. Minimum discrimination in the sex ratio describes social equality. The highly educated proportion in Kolkata defines its intellectual exuberance. Urban amenities are affluent. Every kind of world-class facility is available within the vicinity. The developed transport network, world-class medical facilities, developed higher education system, commercial conglomerates, business hub and other several integrated facilities depict the depth of urbanisation in Kolkata. The water supply system provides treated surface water along with groundwater as a source but usage of groundwater has been reduced. The water supply facility system is not up to the mark in Kolkata. As population density and household density are quite high in Kolkata that ultimately affects on demand supply of water. Increasing number of slums is also a major concern in Kolkata.

References

Ghosh, G. (2015). An 'infiltration' of time? Hindu Chauvinism and Bangladeshi migration in/to Kolkata, India. *Journal of Comparative Research in Anthropology and Sociology*, *6*(1), 263–288. Retrieved from http://sfx.scholarsportal.info/guelph/docview/1712852312?accountid=11233{%}0Ahttps://sfx.scholarsportal.info/guelph?url{_}ver=Z39

.88-2004{&}rft{_}val{_}fmt=info:ofi/fmt:kev:mtx:journal{&}genre=article{&}sid=ProQ:ProQ{%}3Asociology{&}atitle=An+{%}27infiltration{%}27+of+time{%}3F+Hi

Marans, R. W., & Stimson, R. J. (Eds.). (2011). *Investigating Quality of Urban Life* (Vol. 45). Dordrecht: Springer Netherlands. Retrieved from https://link.springer.com/10.1007/978-94-007-1742-8 doi: 10.1007/978-94-007-1742-8

Mitra.A. (1951). *District Census Handbook Calcutta* (Tech. Rep.). Deputy Superintendent of Census Operations. Retrieved from https://censusindia.gov.in/census.website/

Ray, B. (2017, mar). Quality of life in selected slums of Kolkata: a step forward in the era of pseudo-urbanisation. *Local Environment*, *22*(3), 365–387. Retrieved from https://www.tandfonline.com/doi/full/10.1080/13549839.2016.1205571 doi: 10.1080/13549839.2016.1205571

Chapter 8

Urbanisation in Kolkata

8.1 Introduction

Urbanisation defines the change of land into urban area. It can be best understood by analysing changes in land conversion. Usually, the identification of an urban area and its magnitude of urbanisation depends on several factors. Physical, economic, social, cultural and political factors are factors among them. Urbanisation can be realised both with quantitative and qualitative approaches. Boundary or extension of an urban area not only depends on its land conversion from rural to urban; but other variables like property valuation, daily commuter transportation, newspaper circulation, social wellbeing, urban mindset etc. create an impact upon it. In this chapter, urbanisation has been explored with credentials of urban lands following different approaches leading to detailed analysis.

Classification of land is generally, termed Land use and Land Cover (LULC). Both terms often create confusion in the literature and daily particle also. The observed biotic and abiotic assemblage of the earth's surface and immediate subsurface are part of land cover. Forests, grasslands, agricultural lands, waterbodies, urban areas, barren lands, and wetlands are examples of land cover (Meyer & Turner, 1992). Whereas, land use defines, how land is occupied by humans. In brief, land cover is observed as physical cover, whereas land use is based on function or the socio-economic purpose for which the land is being used (Giri & Chandra P., 2012). Land cover change defines the modification and conversion of land from one type to another. The change remains within the land cover category. Whereas, when land is modified or changed purposefully by humans for their use then it is called Land Use change. LULC is used for spatial analysis and LULCC helps to understand spatiotemporal analysis, where spatial and temporal changes both are covered. LULC changes are treated as one of the important environmental issues that lead to global concern (Veldkamp & Lambin, 2001). The evolution of a study area can be clearly understood with LULCC. LULCC in urban areas differs from the rural area. LULCC in the urban area certainly differs from other landscapes. Also, the pace of LULCC is not the same for every urban area, various social, economic, political even physical factors modify the rate of change. Human innervation is the major reason behind LULC change in

urban areas that is replicated through urbanisation.
Following the changes in LULC, researchers identify the magnitude of urbanisation also urban expansion ratio calculation is an appropriate index related to LULCC that helps to measure the expansion ratio over the years.
Built-up area defines an area which is covered by buildings and other related constructed structures. It replicates the dominance of urban land. The built-up area not only represents the buildings but also represents the overall area with other available facilities surrounding buildings like roads, parking space etc. An increase in the built-up area directly reflects the process of urbanisation.
Urbanisation is an anthropogenic intervention to nature. This process affects the land surface. Different kinds of construction materials (cement, rock, iron, steel, brick, different kind of metals, several chemical components etc.) are involved in urbanisation that directly or indirectly creates an impact on the land surface. As urbanisation is a permanent, persisting and continuous process, it obstructs the infiltration capability of the surface and increases surface runoff, reduces the possibility of groundwater recharge, and chance of water purification and even degrades water quality of the subsurface environment (Strohbach et al., 2019). Ultimately, urbanisation in the local and regional environment directly affects the hydrological cycle. Biochemical and physical changes in the hydrological system of the city particularly degrade the water balance. The impervious surface reflects the consequences of urbanisation in a city. Condition of urbanisation can be calculated by identifying the extent of the impervious surface over urban land. Apart from the impervious surface, urban land represents a permeable surface within a boundary of an urban area. Calculating its declining condition, also the process of urbanisation can be calculated alternatively.
Primarily, it has been recognised that the identification of LULC defines the land characteristics of an urban area and separates it from other land categories. A positive relationship between urbanisation through urban land use change is already a proven fact. Next, the identification of the Builtup area in a certain land directly represents the proportion of land with urban qualities. Further, the concrete material of an urban area mostly reflects the nature of the surface as impervious. Identification of impervious surfaces directly or indirectly represents the amount of land under the process of urbanisation. Above said three properties of land certainly related to each other, a schematic diagram is given here for a better understanding (Figure8.1) Above mentioned three properties are comparatively more accurate factors for the estimation of urban land area and its spatio-temporal changes within the boundary. Further analysis process needs a detailed field survey with the huge expense and humongous manpower. Years ago, it was a laborious process but with advancements in science and technology, now it has become the most comfortable way to identify and analyse the result with minimum expense and effort. Recently, remote sensing technology with the huge advancement in geospatial techniques, satellite-driven data help to remotely serve the previously mentioned purposes. Satellite images cover the land from a certain high altitude that creates a holistic view of the study area and further statistical techniques along with a machine learning process that differentiates different land types most accurately. Spatio-temporal changes within a specific timeframe accurately define the urbanisation process at its best. In this chapter, all the efforts have been concentrated

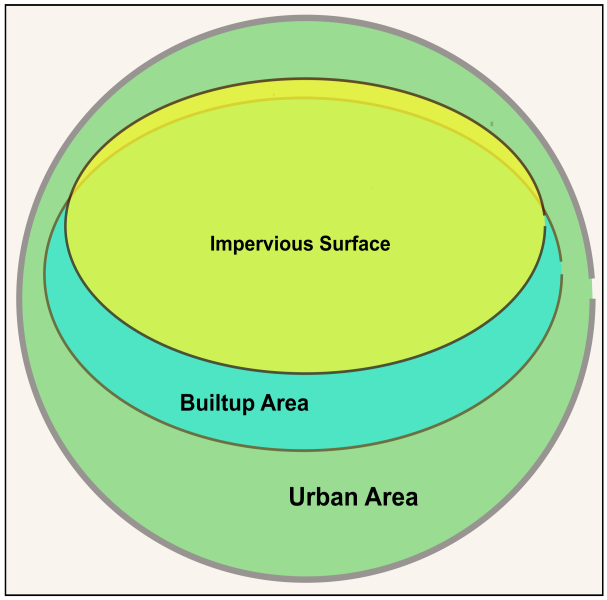


Figure 8.1. Co-relation between urban area, built-up land and impervious surface

based on the application of remote sensing technology to identify the exact amount of urban land use and landcover change. Also, the impervious surface has been analysed along with the identification of a built-up area that reflects the situation of an urban area. Further, temporal changes have been identified to recognise the process of urbanisation.
All the above-mentioned processes applied for the study area Kolkata. It is naming a city, district and municipal corporation over the years. Spatial analysis has remained within the KMC area on 141 wards that are consistent for over three decades. Temporal changes have been analysed from 1990 to 2020. Three decades have been covered in the study to identify the long-term change in urbanisation and the last three decades have been chosen to address the contemporary situation.

8.1.1 Overview of urbanisation in Kolkata through literature review

Latest condition of a city describes about the present time but the present condition certainly reflects the impact of the past. For a better understanding about the past, researchers have already produced significant number of details through their research works. It has been culminated in this section to understand the urbanisation scenario of Kolkata according to other researchers and clear the concept before further analysis.
Munsi (1990) described about the genesis of Kolkata. Kolkata is based upon three villages *Sutanuti, Gobindapur* and *Kolikata*. Subsequently it changed into a *port city*. He mentioned about early morphological structure of the city that, is helpful to understand the landuse structure in the beginning. In 1757, Gobindapur village was cleared for development of English military departments, named as Fort William. Large buildings were built around the vicinity of English residential houses. Earlier settlements intermingled with small commerce. Northern part of Kolkata was crowded with native peoples, households were congested along with markets. At the beginning, Kolkata was unhealthy and filthy because of wetlands around the city. So, new

roads and infrastructures were developed at the cost of encroaching the wetland and cutting down enormous number of trees.

Dasgupta (1990) discussed about landuse pattern in Kolkata on around 1960s. Kolkata municipal corporation was limited to 100 sq.km area. At that time 42.7% of lands were occupied by residential areas but most the lands were unplanned. Transportation was limited to 11.82% of the total land. Commercial and industrial land was limited to 13%. Whereas, non-developed areas were around 16%. These derelict lands were mainly located in eastern and southern part of Kolkata. Most of the land were part of *sine qua non*[1]. So further development was limited on that place. From the beginning, Kolkata was being treated as service-oriented city. Small industries like hosiery, tailoring, printing, confectionary, bakery, repairing shops are placed here and there in between residential areas. In the extreme eastern part, there was few tanneries that produced pollutants so only that part of the land was limited with settlements.

Nath & Acharjee (2013) monitored the landuse change for KMC area using satellite imagery and secondary data. They found that, through time Kolkata changed from commercial and business oriented urban area to centre of social, cultural and educational activities. They identified some localities in the northern and central part of Kolkata with minimum of residential houses and concentrated urban infrastructure in between 1793-1856. Educational institutes, medical facilities, recreational parks, markets, and other transformational infrastructures was started to develop after 1856.They identified Kolkata was mainly treated as service-oriented city after independence. Small scale industries were built up within residential areas. Mainly they focused on identification of landuse and landcover through satellite images, they used Landsat TM data and with application of GIS software they identified landuse and landcover pattern of Kolkata from 1990 to 2014.

Mukherjee et al. (2018) produced LULCC in KMC from 1980 to 2014 to understand LULCC and water scarcity in the study area. LULC classes was broadly divided into urban settlement, vegetation patches and wetlands. The methodology was focused on supervised classification. The result shows, in 1980, urban settlement covered 49% of the total land and in 2014 it increased up to 79%. Vegetation patches increased from 1980 to 1990 but after that period of time vegetation started to decrease and in 2014 it was about 17% of the total land. Amount of wetlands also decreased but that did not directly transformed into urban settlement rather wetlands were desiccated and overgrown by vegetation.

Mandal et al. (2019) discovered urban growth dynamics with changing landuse and landcover for Kolkata. They have taken time frame from 1991 to 2018 and produced result with multi-temporal Landsat data. This study followed unsupervised classification method. According to their analysis, urbanisation growth was 19% in 1990 and it changed up to 57% in 2018. Significant loss has been observed within this time LULC other than Urban/built-up area. Radical LULC change has been observed in sparse vegetation and fallow land. North-north west part has been identified as most urbanised area. It has been projected through their study that, further landuse will change and it will be built-up area based and will encroach water bodies, vegetation, and fallow lands further.

A. B. Mukherjee & Bardhan (2021) focused the study on Kolkata and its surrounding wetland

[1]Noun| an essential condition; a thing that is absolutely necessary.

about LULCC. This study period was limited within a time span of ten years (2009-2019). They have taken Landsat images to understand the situation. They have applied maximum likelihood technique (MLC) to analyse through satellite images with five broad classes for LULC representing, urban settlement, vegetated areas, lakes, inland wetlands, open space, and agricultural lands. They have reported 89% overall accuracy in their result. It is observed that, urban settlement has increased about 3-4% within ten years. And consequently, open spaces have been reduced near about a percent.
Dinda et al. (2021) initiated an approach to identify loss of urban green space(UGS) analysing the LULCC for Kolkata. They have limited their study within 1980 to 2018.They have approached three different classifier (SVM, ANN and MLC) for supervised classification methods to identify LULC and compared between these methods. It has been identified that, SVM (Support Vector Machine) produced the most accurate result. They have taken eight classes to describe LULC for Kolkata. Those are 1. High dense built-up land, 2. Low dense and fragmented built-up land, 3.Vegetation, 4. Grass land, 5. Cropland, 6. Waterbodies, 7. Wetland, 8. Bare land. In spatio-temporal change analysis it has been found that, from 1980 to 2018, High dense built-up has increased upto 31% and low dense built-up has increased about 95%. Rest of the classes all have decreased about 50% within this period, singularly bare land has been decreased about 74%. It has been also analysed that, low dense built-up is increasing annually at the rate of more than 3% whereas, bare land and vegetated land is decreasing at the rate of more than 2%.

8.2 Objectives

In this chapter, the main aim is to spatio-temporally analyse the process of urbanisation in Kolkata for the last three decades (1990-2020) with the help of geo-informatics. For a better understanding about the process of urbanisation, major objectives have been followed that are mentioned below:

- To Identify LULC changes and its magnitude over the years.
- To calculate urbanisation level for every decade.
- To examine the ratio of urban expansion over the years.
- To analyse built-up area over the study area and ward wise analysis of built-up area also its magnitude of changes over the years.
- To identify impervious surface in the study area also with vegetation cover and bare soil as the permeable surface and its change over the time.

8.3 Data sources and methodology

Analysis for the process of urbanisation has been majorly divided into three parts. At first, process of urbanisation has been identified observing LULC maps. Based on this result, urbanisation level has been identified for each decade and estimation of urban expansion has been calculated. Next, average built-up area has been identified from the study area for every year, further impervious layers have been identified for the study area in different decades. For observation

regarding LULC and impervious surface a decadal difference have been evaluated because distinct changes in urbanisation can be best identified with a definite gap. Further average built-up area has been calculated yearly to understand the gradual changes. Analysis of these above mentioned process follows distinct internal processes while working with geospatial remote sensing techniques that has been applied in this study and results has been visualised. Further descriptive statistical methods are also needful for identification of changes and interpretation of results. Those processes briefly discussed below:

8.3.1 LULC classification

Secondary data regarding LULC maps are limited in India, published maps from the governmental organisation are not updated and applied scales on those maps are sometimes not useful for study in detail. After realising such facts, geoinformatics has been applied in this study. LULC analysis has been processed using high-resolution satellite imageries, which are easily accessible and free of cost.

Satellite data are readily accessible and free, from the Landsat satellite data are most appropriate as it has a long temporal range in the dataset. United States Geological Survey (https://www.usgs.gov/landsat-missions) has initiated satellite missions since 1972. They have produced continuous images of the earth's land surface for the study of natural resources and the environment. Researchers have applied these satellite data in various ways to understand the land surface. Understanding LULC is the most prior one. Several appropriate usages of Landsat data for LULC analysis already have proven its reliability and usefulness (AlDousari et al., 2022; Amiri et al., 2009; Dewan & Yamaguchi, 2009; Silva et al., 2018; Tan et al., 2010; Wu et al., 2013). A spatio-temporal analysis is the most required process to understand the LULCC. So, in this chapter, spatio-temporal analysis has been done by taking data from four different years. Understanding urbanisation primarily depends on the identification of built-up land change. Change in built-up land is a comparatively slow and continuous process. A gap of the decade has been taken to understand a significant amount of changes. Analysis has been initiated from the year 1990 and a consecutive ten years gap has been maintained to identify significant changes in LULC. As the objective was to identify the decadal growth in urbanisation, possible seasonal variation has been overlooked consciously and collected images have been taken maintaining the same season (winter[2]).

LULC classification creates individual classes with different Landuse and Land Cover characteristics. Generally, the LULC classification process follows two classifiers: Parametric and Non-Parametric. It is believed that data are normally distributed in individual classes in parametric analysis (Seto & Kaufmann, 2005). The Maximum Likelihood Classifier (MLC) is the mostly used parametric classifier. This creates a class based on mean and covariance values (Richards, 2013). Artificial Neural Network (ANN) can be used as a non-parametric classifier and it identifies classes based on statistical data. Another important non-parametric classifier is Support Vector Machine (SVM) which is mainly used for classification and regression. These

[2]Usually in winter, the sky of Kolkata remains clear from clouds and vegetation cover and grasslands can be separated along with wetland in this season.

three classifiers are widely used in LULC analysis (Dingle Robertson & King, 2011; Kumar et al., 2013; Omeer et al., 2019).All these classifiers have relatively different accuracy in every study area. Several researchers have also compared these classifiers to get the most accurate result (Jozdani et al., 2019; Nery et al., 2016; Talukdar et al., 2020).
Analysis of LULC in this study focused on Kolkata. It has been found that Dinda et al.(2021) have provided a detailed comparison of these classifiers and they have proved with accuracy assessment, that the SVM classifier is most suitable and appropriate for LULC analysis on Kolkata. In this paper, SVM classifier has been used for classification. Details about the SVM algorithm have been mentioned below:

Support Vector Machine (SVM)

SVM is treated as non-parametric machine learning technique. Main advantages over MLC are, Gaussian distribution is not required for SVM as it is needful for MLC and it is not sensitive to Hughes trends (Zhou et al., 2017). SVM reflects the concept of *'Structural risk minimisation'* and support multiple continuous and categorical variables in various class memberships and reach a higher accuracy than other conventional techniques with comparatively less number of samples (Shih et al., 2019). A hyper-plane is created with SVM that separates two classes by minimising controlled quadratic programming problem. It can be applied followed the equations

$$Maximize \sum_{i=1}^{n} S_i \frac{1}{2} \sum_{i=1}^{n} s_i s_j p_i q_i K(p_i q_i) \tag{8.1}$$

$$Subjectto \sum_{i=1}^{n} s_i q_j = 0, \;\; 0 \leq s_i \leq \in \tag{8.2}$$

Where,p_i, q_j, $K(p_i q_i)$, s_i and $\in$ denotes the training samples, class label, kernel function Lagrange multiplier and penalty, respectively. About class selection, it has been observed from literature review, that authors have classified LULC classes according to their purpose of the study. General rule cannot be established from such studies. So, after observing Kolkata from actual ground and through high resolution satellite images, distinct seven classes have been identified to analyse LULC. A handheld GPS has been used to collect sample points from the study area. Total 180 points has been collected to understand the LULC of Kolkata and apply it for further process.
Seven LULC classes has been listed in Table 8.1 for a better understanding through actual images, figure 8.2 has been incorporated here.

Table 8.1. Deatils about major LULC classes observed in Kolkata

LULC Class	Description
High Density Built-up	Densely populated settlements including residential and commercial land, high rise buildings, transport and other socio-economic infrastructure

Table 8.1. Deatils about major LULC classes observed in Kolkata

LULC Class	Description
Low Density Built-up	Comparatively less dense and fragmented settlements including residential and commercial land and transport and other socio-economic infrastructure
Vegetation	Lands where trees are available also with deep dense bushes and shrubs in residential green space, parks, organized green space also road side vegetation
Grassland	Open green space available with grass,and fragmented bushesand shrubs, crop land or agricultural land
Waterbody	Lakes, canals, ponds
Wetland	Wetlands and open water spaces area either permanently or seasonally covered by water
Bare land	Open spaces where trees. grasses, bushes, shrubs are not available and mainly occupied for constructions or other purpose, fallow land, dumping ground

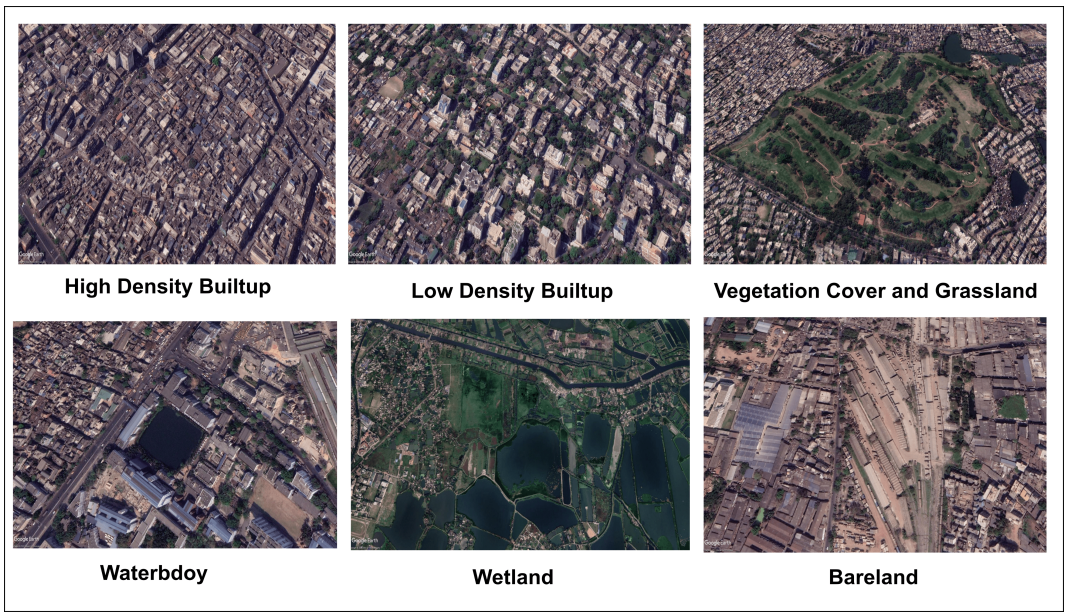


Figure 8.2. Google earth images representing different LULC classes; Source: Google Earth Pro, 2022

Urbanisation Indices

Urbanisation process is directly related with changes in LULC. Recognition of urbanisation can be best identified with changes in land use classification. Previously researchers used to adapt different type of socio economic measures to identify process of urbanisation but after the

development of advanced remote sensing technology, it reduced the rigours effort and money. Different type urbanisation indices have been developed to understand the urbanisation process with the help of remote sensing and GIS technology.

Urbanisation Level Index (UI) Previously calculation for level of urbanisation was dependent on change in urban population and other economic parameters but along with GIS and RS technology, much more efficient method has been established based on landuse classification that are more accurate and less time consuming.

$$UL = (HDB + LDB + UGS) \tag{8.3}$$

$$UI = \frac{UL}{TL} \times 100 \tag{8.4}$$

Where, UI represents urbanisation level index in percentage, UL represents Urban Land (Km^2) which is the summation of High Density Builtup, Low Density Builtup and Urban Green Space (Vegetation and grassland) and TL represents Total Land Area (Km^2) (Chan Vu, 2017; Hu Jiyuan, 2009).

Urban Expansion Index (UX) Urban expansion defines the dynamics of land between selected time periods. It is the yearly ratio of expansion of an urban area.

$$UX = \frac{UL_j - UL_i}{T} \tag{8.5}$$

Where, UX defines yearly urban expansion ratio between stipulated time period and UL_j and UL_irepresents two different years with a selected time gap signifying with T. Urban expansion can also be identified with relative change in urban land between a selected time gap. Basically, it is a ratio of the urban expansion from the original land area.

$$UX_r = \frac{UL_j - UL_i}{UL_i} \times 100\% \tag{8.6}$$

8.3.2 Built-up area identification

Normalised Built-up Index (NDBI)

NDBI index majorly used in identification of built-up area from a selected land within a boundary. It is the most used and a simple technique to identify built-up land from an urban area. This index primarily works on the principle of spectral difference of two consecutive bands. From the multi spectral satellite image dataset, specific two bands i.e., SWIR and NIR are used for the calculation of this index. SWIR band represents short wave infrared and NIR represents near infrared. These bands most accurately identifies the properties of built-up from the satellite sensors.
(Zha et al., 2003) used normalised difference technique to extract the built-up land from an

urban area. The equation clarifies further:

$$NDBI = \frac{(SWIR - NIR)}{(SWIR + NIR)} \tag{8.7}$$

$NDBI$ values ranges within -1 to +1 where, positive value (>0) defines built-up. It can be observed that, higher positive value depicts high density built-up and low density built-up reflected in comparatively low positive values and negative values shows other than built-up land. It is to be mentioned that, in different multispectral satellites (Landsat, Sentinel, Cartosat) bands carrying values of SWIR and NIR are sometimes different in names. As example for Landsat TM, band 5 and band 4 represents SWIR (1.55-1.75 μm) and NIR (0.76-0.90μm) but for Sentinel-2, SWIR and NIR represented by B11 and B8.

8.3.3 Impervious surface

An urban area mainly covered with major three components in terms of water penetrating nature. Vegetation and bare soil represents permeable nature of the surface and artificially constructed land properties represent impervious nature of the surface. Characteristics of urban area can be identified based on three above mentioned components in perspective of hydrogeology.
Ridd (1995) developed an advanced ternary diagram to understand the uban cover through observed ratio between Vegetation (V), Impervious (I) and Soil (S). Application of the this model is mostly justified with remote sensing technique Linear Spectral Mixture Analysis (LSMA). There are also different methods to extract impervious surface like Maximum likelihood classification (MLC), Exponential Method (EM). Recently serveal upgraded machine learning techniuqes like Random Forest (RF) and ANN also being used (Feng & Fan, 2021; Powell et al., 2008; Sekertekin et al., 2018; Strohbach et al., 2019). In this chapter, following V-I-S model, impervious surface has been identified. A spatio temporal analysis has been processed to understand change in impervious surface and other landuse type with change in time.
Abdikan et. al (2018) identified that MLC is the optimal method for identification of impervious surface. MLC has been applied to analyse impervious surface repeated times for the years from 1990 to 2020 maintaining a gap of ten years.
Details about satellites data already mentioned previously, all that dataset has been pan sharpened for further analysis. Here, different types of samples have been collected for this classification. Any area having more than 30% of impervious surface quality according to Ridds definition, has been selected as impervious surface sample points and vegetation cover in between 10% to 50% has been selected for vegetation cover sample and soil percentage in between 10% to 80% has been selected as soil sample as pre-defined values for the classification (Figure 8.3). Here brief about MLC have been given below:

Maximum Likelihood Classification (MLC)

MLC is a form of supervised classification, where, decision primarily depends on classifier itself. It is based on two principles (Richards & Jia, 1999):

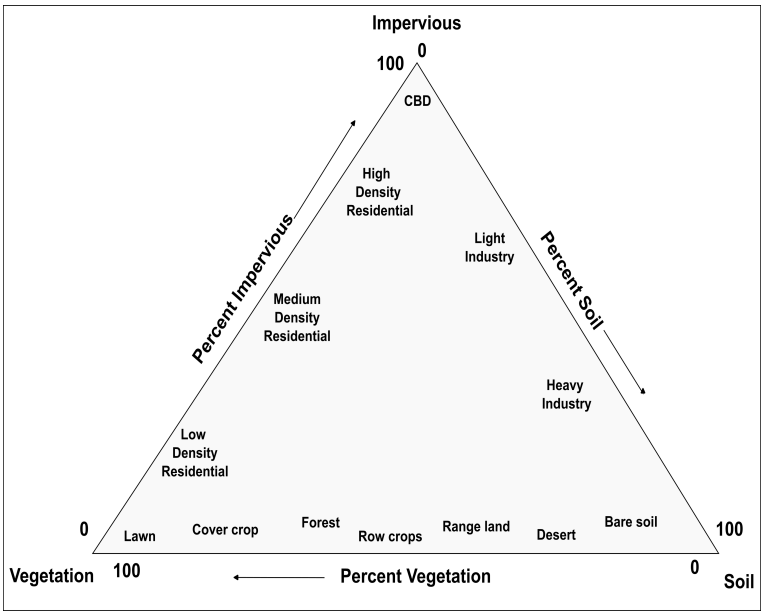


Figure 8.3. Ridd's V-I-S model for remotely sensed data

- The cells in each class sample in the multidimensional space being normally distributed
- Bayes' theorem of decision making

The tool considers both the variances and covariances of the class signatures when assigning each cell to one of the classes represented in the signature file. With the assumption that the distribution of a class sample is normal, a class can be characterized by the mean vector and the covariance matrix. Given these two characteristics for each cell value, the statistical probability is computed for each class to determine the membership of the cells to the class. When the default EQUAL option for A priori probability weighting is specified, each cell is assigned to the class to which it has the highest probability of being a member.

8.3.4 Accuracy assessment

It is noteworthy to mention that, application of remote sensing in geospatial analysis is less time consuming and all most free from any charges but precision of this process relies on accuracy assessment. Classified images must be compared with secondary referenced data. In this chapter, applied process has been assessed by three different methods. More than 200 points has been collected from the images and that has been compared with high resolution google earth images (2010 and 2020), for other years selected points has been compared with available toposheets (79A/7 and 79B/6) and other secondary data. Error matrices has been generated to calculate user's accuracy, producer's accuracy, overall accuracy, and kappa's coefficient (K). The user's accuracy and producer's accuracy are derived as:

$$A = \frac{\hat{R}_{diagonal}}{R_{total}} \tag{8.8}$$

$$A = \frac{\hat{C}_{diagonal}}{C_{total}} \tag{8.9}$$

Where $\hat{R}$ and $\hat{C}$ are the row elements and column elements of correctly classified pixels and R and C are the total number of pixels of row and column, respectively.
The Kappa statistics are calculated using the formula:

$$K = \frac{N \sum_{k=1}^{q} n_{kk} - \sum_{k=1}^{q} (G_k C_k)}{N^2 - \sum_{k=1}^{q} (G_k C_k)} \tag{8.10}$$

Where K is the Kappa coefficient,k is the class number, N is the number of classified values to references data,n_{kk} is the values related to class K, C_k is the total no of predicted pixels related to class k and G_k is the total number of truth values related to class k.
From above three processes, two geospatial analyses has been done on renowned geospatial software ArcMap 10.5. Further open-source software QGIS 3.16 has been used for further visualisation. Already discussed process NDBI, has been performed for the study area on web-based cloud computing technique. For this purpose, Google Earth Engine has been utilised. It is comparatively an easy method in web-based platform where worldwide data are available with extensive temporal range. For calculation of NDBI for the study area, more than 500 satellite dataset have been utilised. For every statistical analysis R programming language has been used for a better interpretation and visualisation of derived data from the utilised satellite images. Further calculation of urbanisation indices and urban expansion ratio has been calculated from the LULC data. For understanding the process of urbanisation applied in this study, it has been presented through a flow chart (Figure 8.4)

8.4 Urbanisation scenario in between 1990-2020

8.4.1 Land use and land cover

1990

After the change in administrative boundary in 1986, KMC extended its boundary. It can be easily identified from the LULC map (Figure 8.5) that, in 1990, most of Kolkata was urbanised along with a significant amount of green space. Dense urban concentration with HDB was limited between Ward 1 to 100. The northern part of Kolkata was highly urbanised, especially dense urbanisation intensified in and around central Kolkata. HDB covered that part of the surface and a very limited amount of land covered with vegetation, grassland and waterbodies in a scattered way. Grassland, vegetation cover and bare soils are concentrated only around the Maidan area. The concentration of HDB decreased towards the south direction. Mainly, clustered HDB concentration was limited to a few wards that were already a part of Kolkata from long ago. In the southern part, linear urban settlements were observed along with roads.

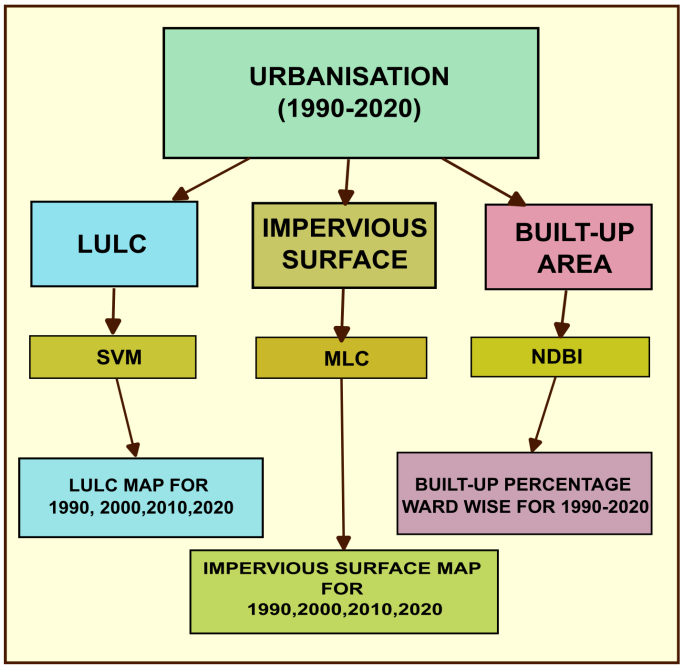


Figure 8.4. Flow chart showing process to identify urbanisation for the study area

HDB was limited to that places only. From the central eastern part to southeastern part, there was dominance of grassland, wetland and waterbodies and domination of built-up was minimum there. In the extreme western part, the existence of LDB was prominent also with a significant amount of vegetation cover, grassland and water bodies. In the southern part of Kolkata, urban characteristics were majorly LDB type with a significant amount of vegetation cover and grasslands. A significant amount of grassland observed in southeastern part of Kolkata. Mostly, large natural waterbodies observed near the boundary area of Kolkata, and also moderate number of man-made lakes and ponds were observed all over Kolkata.

From the extreme northern boundary to the central part of Kolkata was concentrated dense urbanisation, especially in the northwestern part. Commercial buildings along with residential buildings, a dense road network and other urban amenities already covered most of the land, saturation in urbanisation almost reached its edge in 1990, specifically in that part of Kolkata, further scope was really limited for further new construction. But the southern part of Kolkata was not overfilled in the nineties, at that time that lands[3] (Figure 5.3) were recently added as part of KMC. A significant amount of natural environment was available in the southern and southeastern parts. From Shyambazar to Dharmatala, Kolkata was densely covered with commercial and residential buildings. In the extreme western part, Garden Reach was also densely populated with concentrated HDB. After the Tollygunge area, green space and other natural land cover were dominantly present in 1990 near Naktala, New Garia, and Nayabad. The situation was also similar for the southern part of Behala specifically near Sarsuna and Thakurpukur.

[3]Wards from 101 to 141 added to Kolkata municipal corporation after 1986

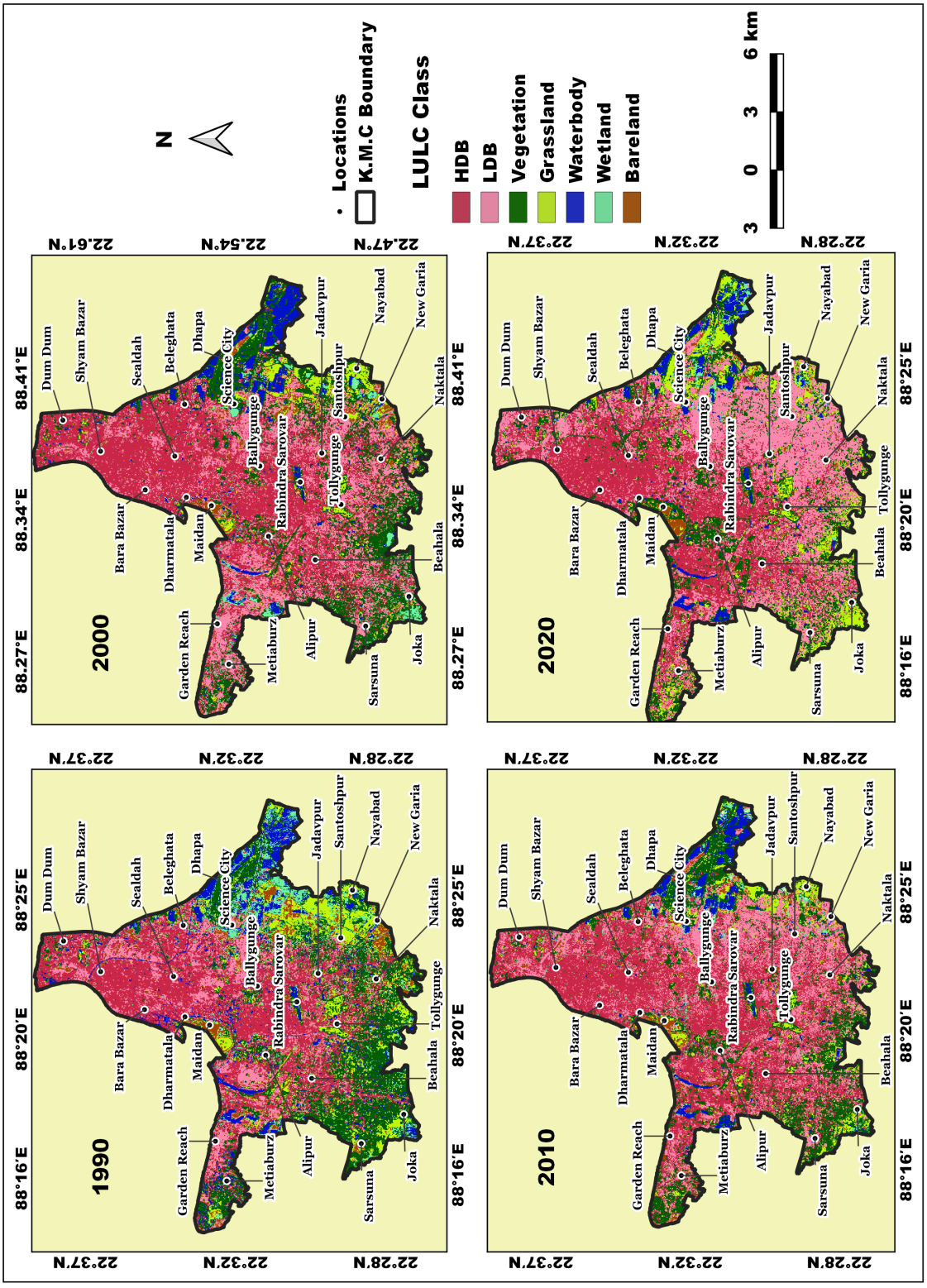


Figure 8.5. LULC maps of Kolkata for different years between 1990 to 2020

2000

In 2000, the northern and core central part of Kolkata was saturated with HDB and LDB. Maximum area was covered by HDB in commercial and administrative zones like Shovabazar, Barabazar, Sealdah, and Dharmatala (Esplanade). Certain patches of location were observed with HDB in the southern part. In between Maidan, Bullygunge and Alipur and rest of the area was covered with LDB. In the western part, most of the land in between Garden Reach and Metiaburz was covered with LDB, also vegetation cover and grassland were prominent along the riverside.
It is observed compared to the situation of 1990 that, in a decade, continuous and sharp changes happened in the southern part with the process of urbanisation. Swift changes were observed in the southeastern part of Kolkata also. After Rabindra Sarobar, urbanisation was leading with LDB. In the extreme southern part between Naktala and Sarsuna, a significant change in landuse was observed also. Till 2000, the eastern part of Kolkata was dominated by green space and waterbodies but in a decade portion of the wetland decreased drastically.

2010

It can be observed from figure 8.5 that around 2010, most of the land areas were covered by HDB and LDB from the northern to the southern extent. Vegetation cover and grasslands were limited to the peripheral portion of Kolkata expect a few patches of greenery in a fragmented way. With a change in a decade, it can be observed that LDB increased continuously towards the southeastern part of Kolkata. The eastern portion of Science City, Bullygunge, Rabindra Sarovar, and Jadavpur built-up encroached on the natural vegetation cover, even grassland. This process was also prominent in the southern part, especially in the southwestern part of Behala. Also. The area between Garden Reach and Metiaburz was also covered with HDB in 2010. Proper vegetation cover and a significant amount of natural waterbodies were present only in the extreme eastern side of Kolkata near Dhapa.

2020

In 2020, it is observed that HDB remained clustered within the central portion focusing on the western side. Whereas, the major part of Kolkata was already covered by LDB in 2020 and significant dominance of LDB was observed in the southeastern part of Kolkata. Dense distribution of LDB was observed for Kolkata in 2020 from Science City to New Garia. Southeastern part of Kolkata is now mostly covered up with LDB by a significant amount of encroachment of vegetation and grassland. Bare land was only available in an open area near Maidan. Grassland is only observed in the extreme southern and eastern parts.

LULC change

With a gap of every decade, total area wise changes in LULC classes have been analysed for the study area (Figure8.6). It has been observed that, in 1990, HDB covered 31.9% of the total land, after ten years in 2000, the dense settlement pattern increased up to 38.5% in Kolkata. With the

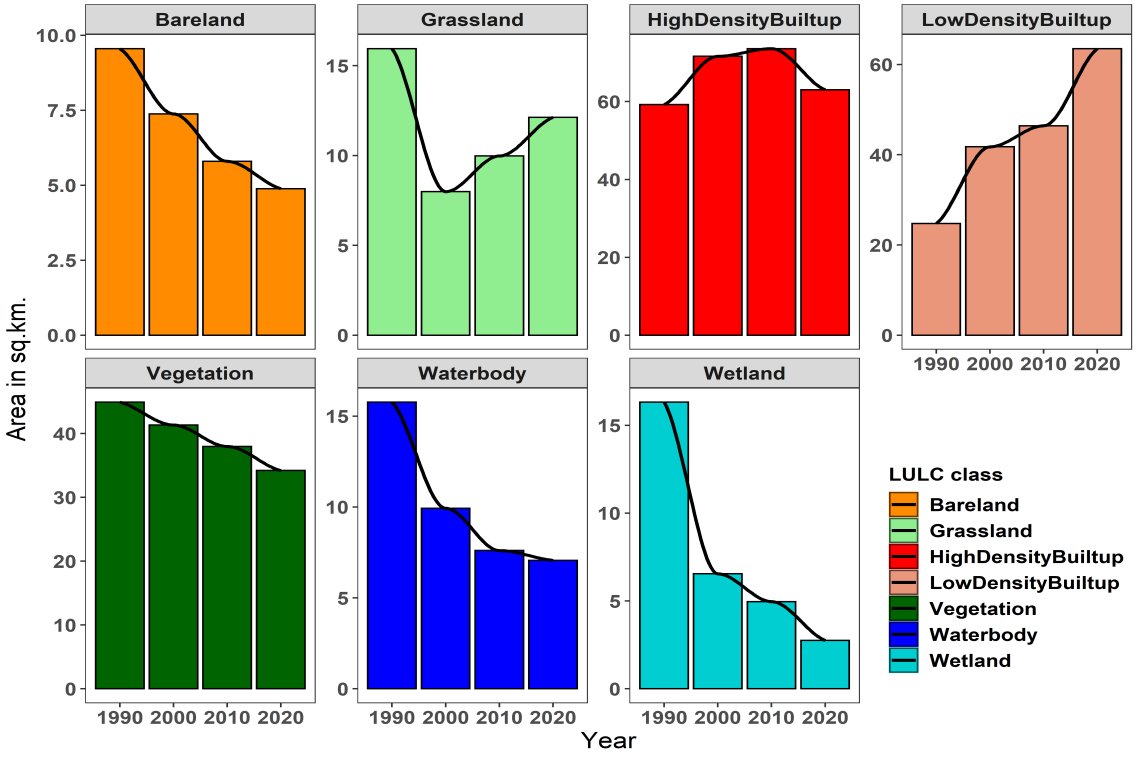


Figure 8.6. Area wise changes in different LULC classes from 1990 to 2020

beginning of the twenty-first century, the growth of HDB was checked and it was restricted to 39.6%. It is observed that in 2020, the portion of HDB was reduced to 34% of the total land of Kolkata. Landuse with HDB was checked in Kolkata but LDB continuously increased at a higher rate than other LULC classes. Only 13.3% of land was covered with LDB in 1990, whereas it increased by about 9% from the previous decade. From 2000 to 2010, the growth of LDB was limited and LDB covered 25% of the total land. Again in 2020, LDB growth was about 9% and now Kolkata covered by 34.1% with LDB.

Consistently vegetation cover has lost its position from the land of Kolkata. Vegetation covers rapidly decreased with time. About 2% of vegetation cover is deceased per decade; about 24% of land was covered with vegetation in 1990, but in 2020, only 18% of the land has been left with trees. About 8.57% of land was covered with grassland in 1990, but drastically it reduced to 4.29% in 2000. After 2000, it increased at a rate of 1% with every decade and in 2020, only 6.52% of the land was part of grassland.

Kolkata is situated extremely close to East Kolkata Wetland (EKW), along with this fact, soil properties of the land within the vicinity hold the characteristics to be a wetland, in 1990, about 8.77% of the land was part of wetland in Kolkata, but in 2000, it significantly reduced and more than 50% of the land covered with wetland as it was encroached by other Land-use class. From 2000, a constant negative change has been observed for wetlands, about 50% of the wetland vanished from the total land of Kolkata with every decade.

Kolkata is situated on the east bank of river Hooghly and in the eastern part, EKW is situated. Several canals, lakes and ponds are also there. About 9% of the land was covered with different

types of waterbodies in 1990, after a decade total area of waterbodies reduced to 5.34% of the total land; about 40% the land with waterbodies were compromised with other Landuse type. From 2000, the area of waterbodies constantly decreased and in 2020, only 3.80% of the land was covered by water bodies. From 1990, the total portion of bare land decreased with every decade. About 5.14% of the land was part of bare land in 1990 but in 2020, it was only 2.63%. Near about 50% bare land was utilised in the process of urbanisation in thirty years.
In LULC change, the process of urbanisation holds the main theme in a city like Kolkata. From 1990 to 2020, urban growth is prominent in this study area. The distinctive nature of urbanisation has been visualised in Figure 8.7 for a better understanding specifically for Kolkata. Three grids

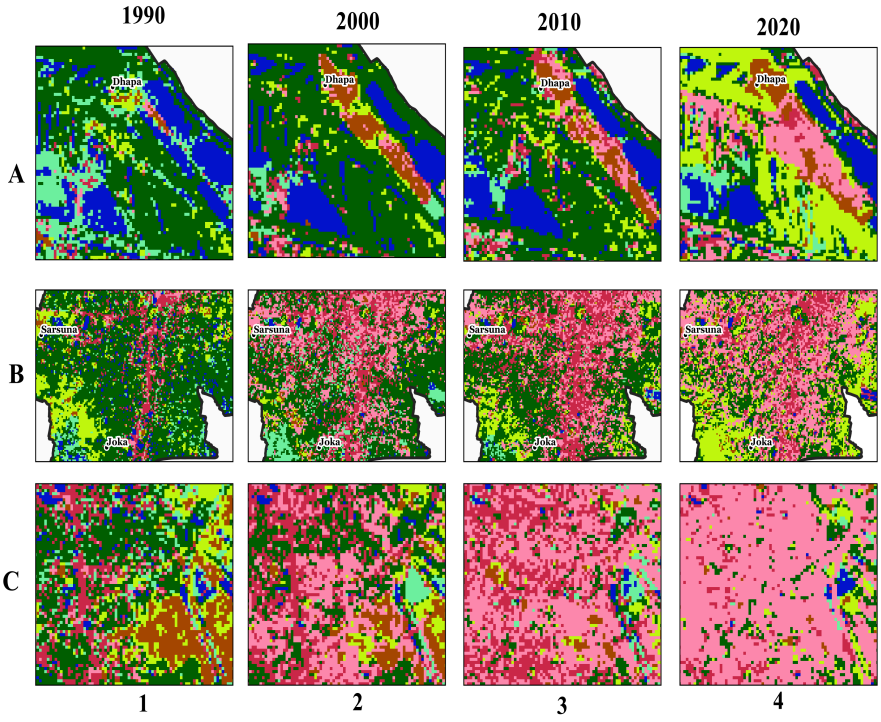


Figure 8.7. Temporal changes (1990-2020) in three different area (2 km^2) where A. showing area around Dhapa, B. showing the stretch from Sarsuna to Joka and C. represents Snatoshpur to Garia

have been selected purposefully (*2 km* × *2 km*) to demarcate urbanisation. Group A represents the Dhapa dumping ground and its adjoining areas, Group B represents a region between Sarsuna and Joka and Group C defines as near the area between Santoshpur to Garia. Group A clearly defines that, the portion of built-up has increased encroaching on bare land. Here for Dhapa, the built-up area is made by dumped waste material that is collected from all over the city. In 1990, there was the dominance of vegetation and waterbodies along with a prominent percentage of wetlands but next thirty years a significant amount of land has been transformed into a built-up area; trees and waterbodies reduced significantly but still, the dominance of grassland can be observed in Dhapa. Now the land is dedicated as a landfill site for Kolkata. Group B represents the most transformed area from the observed timespan. In 1990, built-up was limited surrounding state highway D.H. Road in that area, Households formed a line pattern

from Sarsuna to Joka. In the next ten years, in 2000 process of Landuse change was increasingly focused on the highway and ultimately with time it covered the whole region with HDB and LDB. A huge portion of greenspace and waterbodies were reduced through the process of urbanisation. In group C, that part of the land was highly diversified with all classes of land. The proportion of soil was prominent in the nineties along with a significant amount of vegetation cover and water bodies. The urban settlement only followed a linear pattern on the western side only with HDB. In the next ten years, the scenario was changed totally, waterbodies and green spaces were encroached on by LDB but the proportion of soil was prominent on the extreme southeastern side. Within the next ten years, with the rapid pace of urbanisation, the total area was covered with LDB. Built-up encroached all other land types, and only 5% to 10% lands were left behind with characteristics of grassland and waterbody.

8.4.2 Urbanisation Indices

Observing the LULC pattern of Kolkata, urbanisation indices has been calculated and represented in this study (Figure 8.8). Kolkata was already urbanised before the observation period. Applying

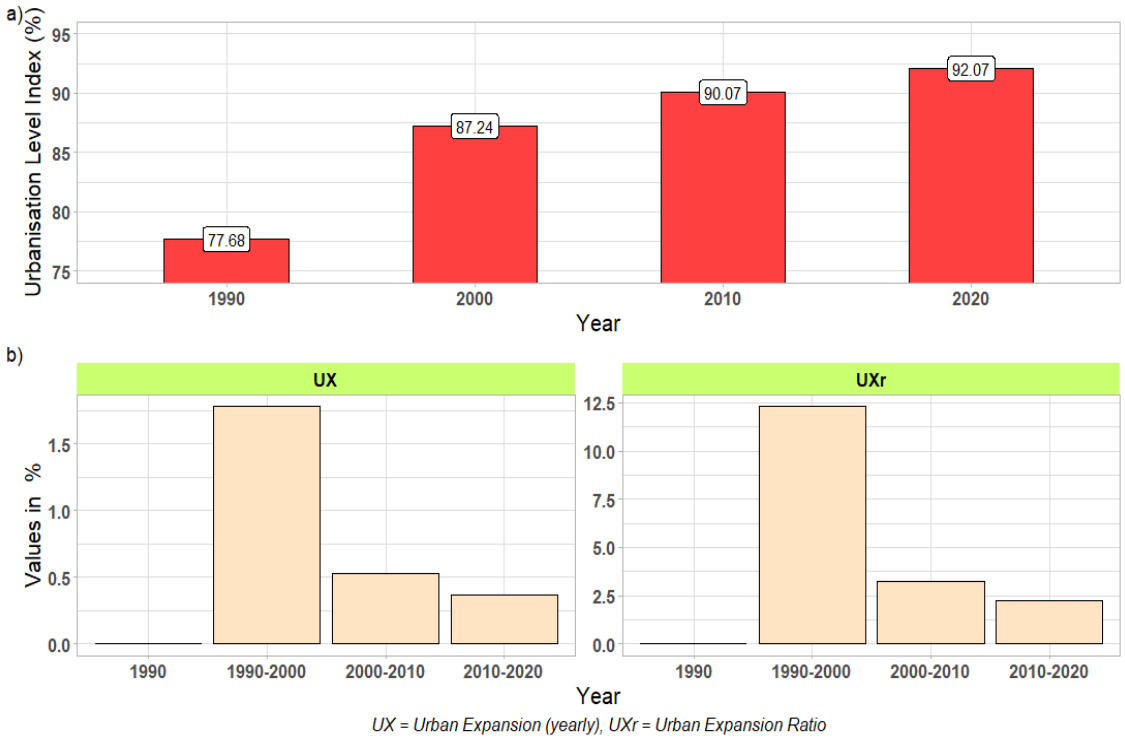


Figure 8.8. a) Urbanisation level, b) yearly urban expansion, c) urban expansion ratio from 1990 to 2020

the equation (Equation. 8.3, 8.4 and 8.5), it has been observed that, in 1990, already urbanisation level of Kolkata was about 78%; more than three forth lands of Kolkata was urbanised. With a change of decade (1990-2000) further 10% land was converted into urban land. Through the process of urbanisation and in the next ten years (2000-2010) urbanisation process slowed down

and changed only 3% in these years. In 2020, the urbanisation level of Kolkata was about 92% with just 2% increase from the year 2010. It can be observed that the urbanisation process was comparatively rapid between 1990 to 2000 but further urbanisation process slowed down. The minimum scope of modification in the already saturated urbanised area was the primary reason behind the sluggishness.
The urban expansion rate was 1.78% for every year between 1990 to 2000, which decreased in the next ten years. Between 2000 to 2010 urban expansion rate was 0.53% for every year. Further, it slowed down between 2010 to 2020. At that time urban expansion rate was only 0.43% per year.
Additionally, the urban expansion ratio was calculated for Kolkata. It has been observed that, within the observation period, urban expansion was about 12.3% in the first ten years (1990-2000) and in the next ten years (2000-2010), it was only 3.24% and further reduced to 2.23%. Urbanisation expansion took a slow growth gradually and the limited scope for further land modification was the ultimate reason behind it.

8.4.3 Built-up area

Concentration of built-up genuinely reflects the condition of an urban area or its urbanisation scenario. From figure 8.10, a clear picture of urbanisation can be easily conceptualised through the proportion of the built-up area. The condition of built-up has been visualised from 1990 up to 2020. It can be observed that, in 1990, mainly built-up was densely clustered in the northern, specifically northwestern part of Kolkata and it was extended up to the central and western parts of Kolkata. The proportion of Built-up was moderate in the southeastern part. The built-up area was comparatively less in South Kolkata than in the north and it was minimum in the southwestern part. The increasing tendency of built-up area in 1996 was reasonable with concentrated built-up area in the northern part only but with time, it is observed that in 2002, built-up area extended up to the southern boundary, expansion of built-up area was mainly towards the southeastern direction from the northern part of Kolkata. In the southern part built-up was fragmented and scattered way. In 2008, further expansion of built-up was continued mainly in the southern part and from 2014, continuous built-up area extension was observed towards the eastern part of Kolkata. Majorly all parts of Kolkata concentrated with built-up area in 2020. It is identified that a continuous expansion process of built-up areas was slow but prominent for the last three decades. The tendency to the expansion of built-up area was from the northern to the south-eastern part and from the central portion of Kolkata to the southwestern portion of Kolkata.
Further, wardwise percentage of urban built-up area has been calculated from its total available land (Figure 8.9). It has been observed that, in 1990, wards from northwestern and Central Kolkata where built-up areas covering more than 50% of the total land. Wards from the southeastern part of Kolkata where wards were covered with less than 25% of built-up. But In 1996, about one third of wards from the total of 141 wards in Kolkata, where 50% or more proportion of built-up covered the rest of the land. Built-up covered 75% of the total land in 23 wards. A portion of built-up increased within the ward mainly in the northern and central parts

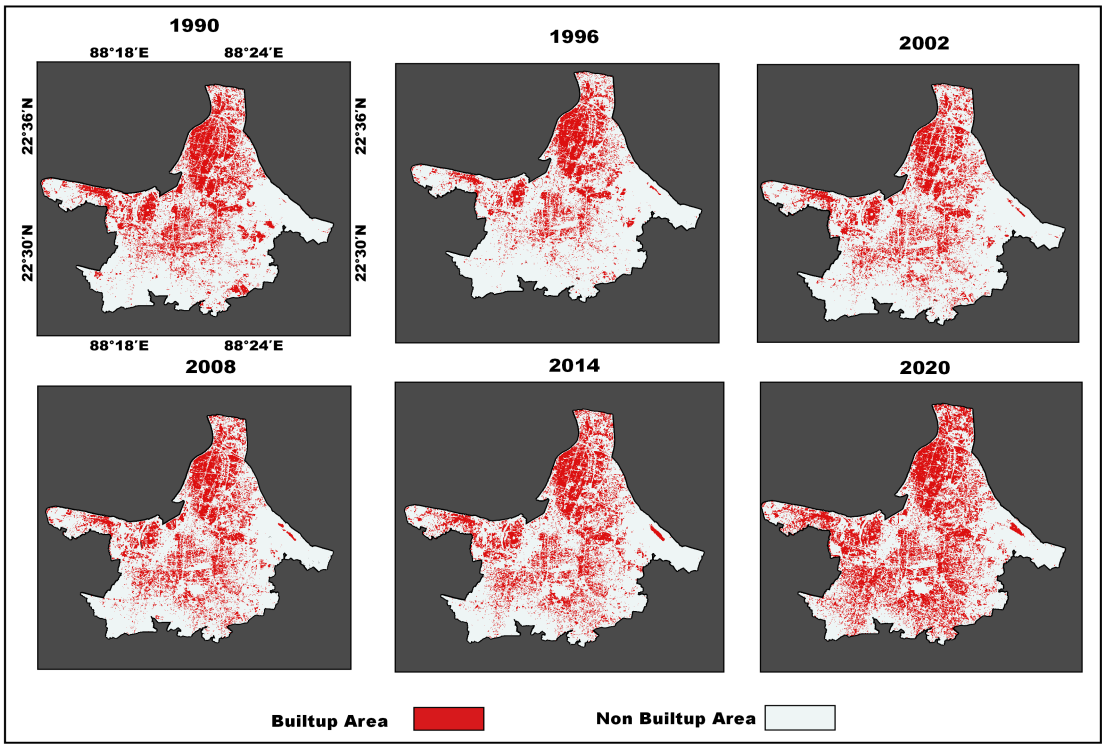


Figure 8.9. Built-up area maps of Kolkata with a gap of 5 years from 1990 to 2020

of Kolkata. After a gap of five years in 2002, the situation was almost the same except for wards in the southeastern part where increase in built-up area was significant. A gradual growth also persisted in 2008. From 1990 to 2008 an inclined pattern in the proportion of built-up area can be observed for the wards from 81 to 121 but from 2014 that inclined pattern started to reduce and in 2020, half of the wards were covered with more than 50% built-up land. In the figure 8.10, changes in between years have been calculated and it has been observed that the increasing tendency of each ward was not the same over the years. It has been analysed that, between 1990 and 1996, the increasing rate was comparatively high with about 5% to 7% on average for wards in the Northern and central part of Kolkata and it was minimum for south eastern part of Kolkata. The scenario changed with time and in between 2014 to 2020, a significant increase has been observed for south eastern part of Kolkata, whereas a significant decreasing tendency was observed for wards in the northern part of Kolkata. On a whole, inequality in proportion to the built-up area got reduced with time. Broadly, it has been identified that the average proportion of built-up area in wards increased gradually in Kolkata as in 1990, the average built-up area in a ward was 26%, in 2002, it was 37%, in 2014, it was 42% and in 2020, it was more than 50%. Changes in the built-up area were not equal for every ward, it changed with time.From the figure 8.10b) it can be easily enumerated that, for wards up to 101, the increasing rate was high before 2000 whereas it was minimum for wards after 101. The scenario was the opposite in the last six years of observation where in wards after 101, the built-up area increased at high pace than in wards within 81. The proportion of built-up area increased for every ward but the expansion rate differed with time.

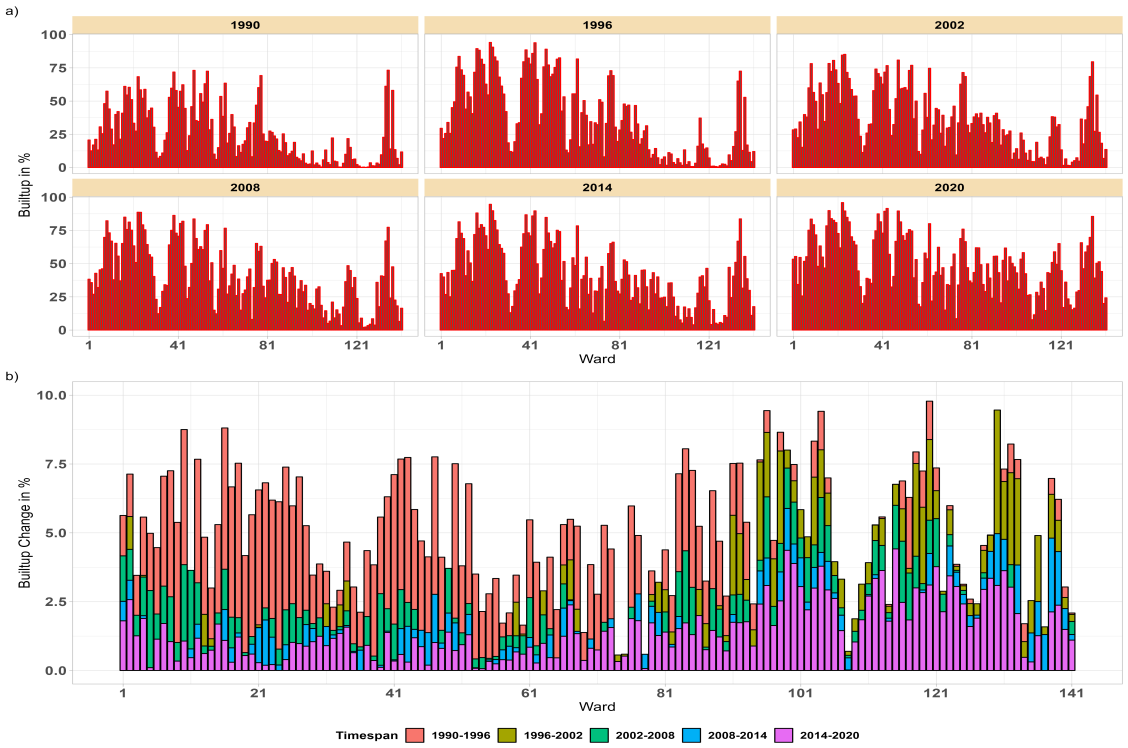


Figure 8.10. Wardwise a) percentage of built-up area, b) percentage of change with a gap of 5 years in between 1990 to 2020

8.4.4 Impervious surface

The impervious nature of a surface certainly depends upon the process of urbanisation. It has been distinguished for the study area also. Different types of construction materials and infrastructure related to an urban area prevent surface water to percolate directly in the form of recharge to the subsurface environment. From the generated result, it can be observed that water percolation scope has already been reduced for this city over time as an effect of urbanisation. In this study, within the stipulated time frame, a significant change has been observed for the study area on the impervious surface (Figure 8.11). In 1990, the dense impervious surface was clustered up to the northern and central part of Kolkata whereas the southern and eastern part was not covered with dense impervious surface and that part of the land was covered mostly with the permeable surface; the scope of infiltration was moderate here. With time impervious surfaces increased as an outcome of urbanisation. In 2000, a noteworthy change has been observed in the central part to the southeastern part. Even the land of the south-western part also turned into an impervious surface at a higher pace at a cost of altering the permeable surface. Further encroachment of impervious surface was observed towards the boundary area of Kolkata and it was continuous in upcoming years. In 2010 a drastic growth of impervious surface was observed in the southeastern part of Kolkata that covered most of the land. The situation was almost the same for the extreme western part also. As already northern and central part of Kolkata was covered up with impervious surface and further scope of expansion was very limited from that part. After ten years (2020), it can be observed that the total southern part of Kolkata is also

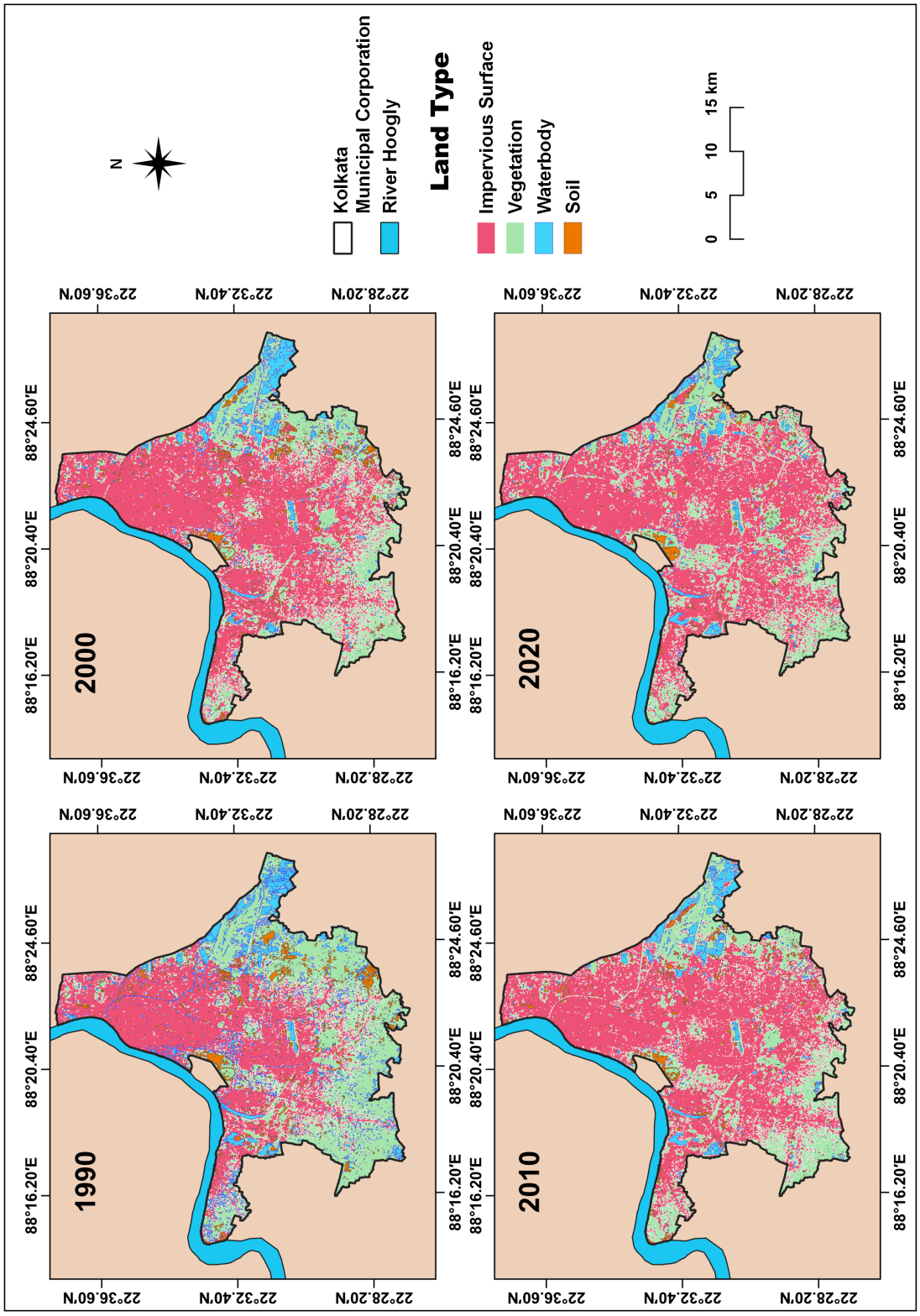


Figure 8.11. Impervious surface maps of Kolkata from 1990 to 2020

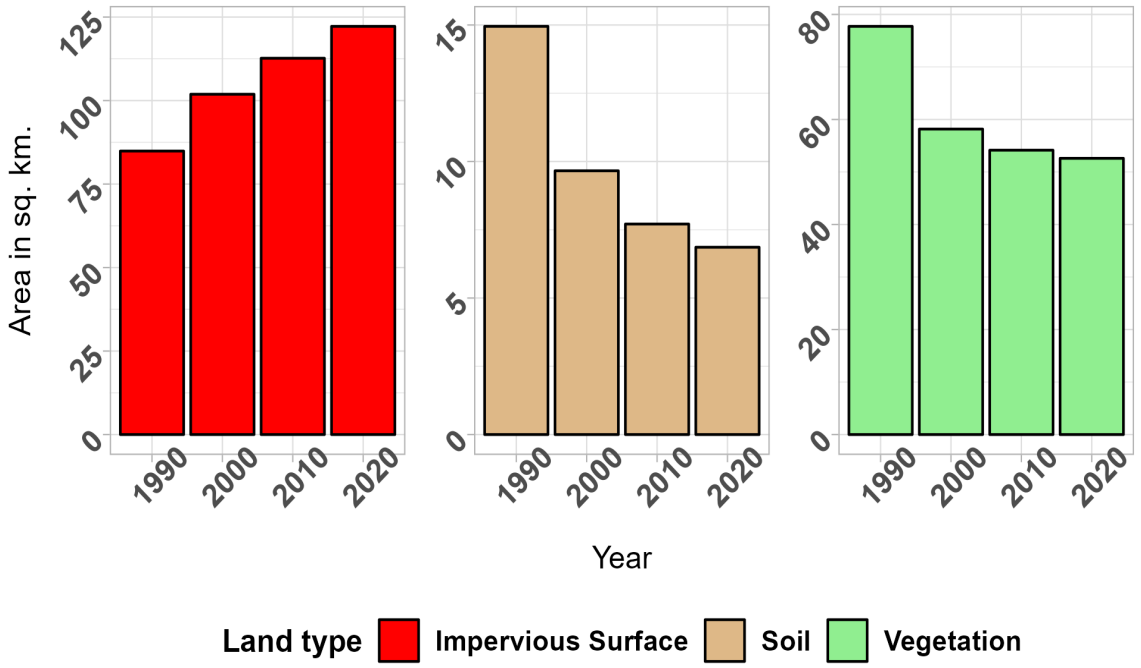


Figure 8.12. Area wise change in impervious surface along with vegetation and soil over the decades (1990-2020)

concealed with a layer of impervious surface except for areas extremely close to the boundary. A significant amount of open soil surface remained mainly near the Maidan area. In the meantime, vegetation cover and grassland were reduced abruptly. Consequently, the scope of infiltration got reduced with time by the encroaching nature of urbanisation.

From figure 8.12 it can be decided that the overall impervious surface has increased at a cost of encroaching the permeable surface in this study area. The impervious surface has expanded its area constantly over the decades and the parallel proportion of soil and vegetation cover decreased gradually. From the result, it can be calculated that from 1990 to 2020, impervious surface increased by about 43%. At the beginning of the observation period about 45% of the total land was covered with the impervious surface in the next thirty years about 65% land was impervious in nature from the total land of Kolkata. The growth percentage of impervious surfaces was about 20% in between the first ten years. In the next twenty years, the growth percentage was 12% in every decade. In 1990, the land sharing a percentage of impervious surface and vegetation cover was almost equal. In that year, 43% of the total land of Kolkata was covered with vegetation but vegetation covers with trees and grasses decreased by about 31% within thirty years and in 2020, vegetation cover was spread only 30% of the total land. The reduction rate was comparatively high between 1990 to 2000, reduction of vegetation cover was checked in the next twenty years. Open soil covered only 8% of the total land in Kolkata in 1990, which was further decreased to 5.3% in 2000. After 2000, open soil conversion was restricted somehow and it was checked and in the next twenty years soil proportion of Kolkata, was reduced at a nominal rate. Overall in thirty years, about 54% soil land was compromised with other landuse.

Analysing the result, it has been observed that, Impervious surfaces increased by 14% every decade on average. The growth of impervious surfaces was highest between 1990-2000. In 1990, the land sharing percentage of vegetation cover and the impervious surface was equal. Gap increased up to 20% in 2000, further that gap increased by 7% and in 2020, the gap increased to 33.1%. Within 30 years, impervious surface increased by 19% by land area at a reduction of vegetation cover by more than 1% yearly. The overall permeable surface was reduced 41% and the impervious surface expanded 43% in the study area.

8.5 Overall observation about urbanisation

After the spatio temporal analysis of Kolkata, it is revealed that, as Kolkata had a prominent history of urbanisation at least for the last two hundred years. North Kolkata and Central Kolkata was already saturated with prominent urban influence before the observation period. From the beginning, area around Dharmatala (Esplanade) was demarcated as central business district for the city. Administrative and commercial spaces were concentrated in the central part only.After the era of globalisation, scope for further development was only left towards the southern part of Kolkata. With the opening up of world economy for this city, urbanisation process started with rapid growth and this scenario was almost same for other important cities like Kolkata. Urbanisation was mainly focused in northern and central part. Southern part of Kolkata was uninhibited in time of British rule as it was counted as extended coastal part of South 24 paragana but after the 1971 Bangladesh war, mainly a portion of migratory people from Bnagladesh took shelter in south eastern part of the city specifically, in Kasba, Jadavpur, Santoshpur and areas near to Tollygunge. Population in southern part of Kolkata started to increase from the middle part of the twentieth century and it continuously increased afterwards. Another reason has been identified that, Kolkata is the primate city in West Bengal and also it is the prime city in eastern part of India. So in search of opportunity, people from other district and from other adjoining states started to focus on the rest portion of the Kolkata. North Kolkata was already concentrated with dense built-up and with minimum amount of green space in nintees era. Scope was open for further built-up in southern and western part as the land price was comparatively low there. After 2000, Eastern Kolkata was more accessible with development of Eastern Metropolitan Bypass Road that stretched from north to south. With this initiation, eastern part of Kolkata now got well connected to the other part of the city and as a consequence in next twenty years urbanisation was mainly concentrated on the eastern part of the Kolkata. This situation was similar for south western part also. With the development of Diamond Harbour Road and James Long Srani, Behala was well connected with the main central business district of Kolkata and concentrated urban growth was prominent there. After 2010, total area within Kolkata was almost covered up with built-up but further concentration of HDB started to decrease compared with LDB. It is worthwhile to mention that, extreme burden of population, built-up density, congestion and other urban dependencies on northern and central part of the city deteriorated the quality of urban life there eventually it was realised by local administrative bodies. As a result, major economic and administrative departments were transferred to Kolkata's own satellite town

Saltlake which is situated beyond the eastern boundary of Kolkata. Even principal administrative building which runs by state government that was transferred to the adjoining district Howrah to reduce burden from this city. Along with this process, another satellite city was initiated in the north eastern part beyond the boundary of Kolkata, naming New Town Kolkata where further 'sustainable' and 'smart' urbanisation is being initiated there from 2010. For the above mentioned reasons, unprecedented growth of urbanisation certainly slowed down in Kolkata. From 2010 to 2020, different kinds of environment friendly schemes have been implemented for this city. As result vegetation cover increased for the city and HDB gradually transformed in to LDB in core part of the city. In these thirty years of observational period, drastically wetland has been encroached along with bare soil for the sake of urbanisation. Surprisingly, significant number waterbodies has been changed into land for further construction. Trees and grasslands deducted from the land ruthlessly for urbanisation process in last three decades.

Urbanisation and built-up are co-related to each other. Usually urbanisation proceeds with increase in urban built-up and related infrastructure. As, already mentioned about built-up in land-use classes, it can be easily assumed that change in built up was continuous in stipulated years. In between thirty years of timespan, built-up was continuously increasing but growth rate was not same for all the wards and it varied with time. Mostly, in the beginning of the mentioned time period, growth rate of built-up area was high in such wards that located in North Kolkata but at the end of the mentioned time period, recently growth of built-up is limited in South Kolkata. It can be easily deducted from this observation that scope of further expansion of built up was only possible in southern part of Kolkata. It is to be mentioned that in last decade (2010-2020) built-up growth rate definitely decreased but gradual growth is divided in all of the 141 wards. Wardwise inequality in proportion of built-up area got balanced with time and average proportion of built-up increased in thirty years.

Urbanisation process positively brings economic independence, developed infrastructure, affluent amenities, improved social well-being, modern thought process, and cultural assimilation but at the cost of damage to the natural ecosystem. From the perspective of hydrogeology, an impervious surface increase prevents percolating water after rainfall and the corresponding amount of runoff increase automatically as a consequence of urbanisation. This situation is very consequential at least for Kolkata. Due to dense urbanisation, the impervious surface has increased abruptly here. After a few hours of rainfall, due to the huge runoff amount, water logging in a densely populated place is common every year. Due to unplanned urban growth impervious layer has almost covered the whole city swiftly. Further scope of direct water recharge to the subsurface environment has become nearly impossible in the last few years further scope of recharge also getting obstructed due to the constantly decreasing amount of vegetation cover and soil from the total land.

8.6 Conclusion

Kolkata has a long history of urbanisation process through proper urban planning was not implemented properly, this city erratically expanded with time. In this chapter, thirty years of

urbanisation has taken into account. Three different aspects have been applied separately to capture the main theme of urbanisation more accurately. A comparatively modern approach has been taken with the help of remote sensing technology to analyse the process of urbanisation. Remote sensing is comparatively economic and covers the area in detail, further statistical analysis has been applied to calculate the process of urbanisation quantitatively. This approach creates mostly advantages along with minor disadvantages of accuracy. From the investigation, it has been found that Kolkata was mostly saturated with dense urban land in the northern and central parts at the beginning of the observation period but with time, unoccupied spaces in the southern part of Kolkata have covered up also with built-up areas. Most of the land with vegetation cover, grassland, and water bodies all changed into built-up land gradually. Urbanisation continuously created built-up areas and thus imperviousness on the surface also increased within a short period of time. In the end, observational period it has been observed that most of Kolkata is now covered up with the impact of urbanisation and further possibility of horizontal growth within the boundary is limited and vertical growth of the city will be the ultimate option in future.

References

AlDousari, A. E., Kafy, A. ., Saha, M., Fattah, M. A., Almulhim, A. I., Faisal, A.-A., … Rahman, M. M. (2022, nov). Modelling the impacts of land use/land cover changing pattern on urban thermal characteristics in Kuwait. *Sustainable Cities and Society*, *86*, 104107. Retrieved from https://linkinghub.elsevier.com/retrieve/pii/S221067072200422X doi: 10.1016/j.scs.2022.104107

Amiri, R., Weng, Q., Alimohammadi, A., & Alavipanah, S. K. (2009, dec). Spatial–temporal dynamics of land surface temperature in relation to fractional vegetation cover and land use/cover in the Tabriz urban area, Iran. *Remote Sensing of Environment*, *113*(12), 2606–2617. Retrieved from https://linkinghub.elsevier.com/retrieve/pii/S0034425709002405 doi: 10.1016/j.rse.2009.07.021

Dasgupta, S. (1990, apr). 5. The Structure of Calcutta. In *Calcutta 1981* (pp. 131–150). Institut Français de Pondichéry. Retrieved from http://books.openedition.org/ifp/5254 doi: 10.4000/books.ifp.5254

Dewan, A. M., & Yamaguchi, Y. (2009, jul). Land use and land cover change in Greater Dhaka, Bangladesh: Using remote sensing to promote sustainable urbanization. *Applied Geography*, *29*(3), 390–401. Retrieved from https://linkinghub.elsevier.com/retrieve/pii/S0143622809000058 doi: 10.1016/j.apgeog.2008.12.005

Dinda, S., Das Chatterjee, N., & Ghosh, S. (2021, feb). An integrated simulation approach to the assessment of urban growth pattern and loss in urban green space in Kolkata, India: A GIS-based analysis. *Ecological Indicators*, *121*, 107178. Retrieved from https://linkinghub.elsevier.com/retrieve/pii/S1470160X20311171 doi: 10.1016/j.ecolind.2020.107178

Dingle Robertson, L., & King, D. J. (2011, mar). Comparison of pixel- and object-based classification in land cover change mapping. *International Journal of Remote Sensing*, *32*(6), 1505–1529. Retrieved from https://www.tandfonline.com/doi/full/10.1080/01431160903571791 doi: 10.1080/01431160903571791

Feng, S., & Fan, F. (2021). Impervious surface extraction based on different methods from multiple spatial resolution images: a comprehensive comparison. *International Journal of Digital Earth*, *0*(0), 1–27. Retrieved from https://doi.org/10.1080/17538947.2021.1936227 doi: 10.1080/17538947.2021.1936227

Giri, & Chandra P. (2012, apr). Brief Overview of Remote Sensing of Land Cover. In *Remote sensing of land use and land cover* (pp. 24–33). CRC Press. Retrieved from https://www.taylorfrancis.com/books/9781420070750/chapters/10.1201/b11964-7 doi: 10.1201/b11964-7

Jozdani, S. E., Johnson, B. A., & Chen, D. (2019, jul). Comparing Deep Neural Networks, Ensemble Classifiers, and Support Vector Machine Algorithms for Object-Based Urban Land Use/Land Cover Classification. *Remote Sensing*, *11*(14), 1713. Retrieved from https://www.mdpi.com/2072-4292/11/14/1713 doi: 10.3390/rs11141713

Kumar, R. S., Menaka, C., & Cutler, M. E. J. (2013, sep). Ann Based Robust LULC Classification Technique Using Spectral, Texture and Elevation Data. *Journal of the Indian Society of Remote Sensing*, *41*(3), 477–486. Retrieved from http://link.springer.com/10.1007/s12524-012-0247-y doi: 10.1007/s12524-012-0247-y

Mandal, J., Ghosh, N., & Mukhopadhyay, A. (2019). Urban Growth Dynamics and Changing Land-Use Land-Cover of Megacity Kolkata and Its Environs. *Journal of the Indian Society of Remote Sensing*, *47*(10), 1707–1725. Retrieved from https://doi.org/10.1007/s12524-019-01020-7 doi: 10.1007/s12524-019-01020-7

Meyer, W. B., & Turner, B. L. (1992). Human population growth and global land-use/cover change. *Annual Review of Ecology and Systematics*, *23*(1), 39–61. Retrieved from https://www.jstor.org/stable/2097281 doi: 10.1146/annurev.es.23.110192.000351

Mukherjee, A. B., & Bardhan, S. (2021, jan). Flood vulnerability and slum concentration mapping in Indian city of Kolkata: A post Amphan analysis. *Water Science*, *35*(1), 109–126. Retrieved from https://www.tandfonline.com/doi/abs/10.1080/23570008.2021.1957641https://www.tandfonline.com/doi/full/10.1080/23570008.2021.1957641 doi: 10.1080/23570008.2021.1957641

Mukherjee, S., Bebermeier, W., & Schütt, B. (2018, jul). An Overview of the Impacts of Land Use Land Cover Changes (1980–2014) on Urban Water Security of Kolkata. *Land*, *7*(3), 91. Retrieved from http://www.mdpi.com/2073-445X/7/3/91 doi: 10.3390/land7030091

Munsi, S. K. (1990, apr). 2. Genesis of the Metropolis. In *Calcutta 1981* (pp. 29–49). Institut Français de Pondichéry. Retrieved from http://books.openedition.org/ifp/5221 doi: 10.4000/books.ifp.5221

Nath, B., & Acharjee, S. (2013). Urban Municipal Growth and Landuse Change Monitoring Using High Resolution Satellite Imageries and Secondary Data A Geospatial Study on Kolkata Municipal Corporation, India. *Studies in Surveying and Mapping Science*, *1*(3). Retrieved from www.as-se.org/ssms

Nery, T., Sadler, R., Solis-Aulestia, M., White, B., Polyakov, M., & Chalak, M. (2016, jul). Comparing supervised algorithms in Land Use and Land Cover classification of a Landsat time-series. In *2016 ieee international geoscience and remote sensing symposium (igarss)* (pp. 5165–5168). IEEE. Retrieved from http://ieeexplore.ieee.org/document/7730346/ doi: 10.1109/IGARSS.2016.7730346

Omeer, A. A., Deshmukh, R. R., Gupta, R. S., & Kayte, J. N. (2019). Land Use and Cover Mapping Using SVM and MLC Classifiers: A Case Study of Aurangabad City, Maharashtra, India. In (pp. 482–492). Retrieved from http://link.springer.com/10.1007/978-981-13-9187-3{_}43 doi: 10.1007/978-981-13-9187-3_43

Powell, S. L., Cohen, W. B., Yang, Z., Pierce, J. D., & Alberti, M. (2008). Quantification of impervious surface in the Snohomish Water Resources Inventory Area of Western Washington from 1972-2006. *Remote Sensing of Environment*, *112*(4), 1895–1908. doi: 10.1016/j.rse.2007.09.010

Ramankutty, N., & Foley, J. A. (1998, dec). Characterizing patterns of global land use: An analysis of global croplands data. *Global Biogeochemical Cycles*, *12*(4), 667–685. Retrieved from https://onlinelibrary.wiley.com/doi/full/10.1029/98GB02512https://onlinelibrary.wiley.com/doi/abs/10.1029/98GB02512http://doi.wiley.com/10.1029/98GB02512 doi: 10.1029/98GB02512

Richards, J. A. (2013). *Remote sensing digital image analysis: An introduction* (Vol. 9783642300). Springer-Verlag Berlin Heidelberg. doi: 10.1007/978-3-642-30062-2

Richards, J. A., & Jia, X. (1999). *Remote Sensing Digital Image Analysis*. Berlin, Heidelberg: Springer Berlin Heidelberg. Retrieved from http://link.springer.com/10.1007/978-3-662-03978-6 doi: 10.1007/978-3-662-03978-6

Sekertekin, A., Abdikan, S., & Marangoz, A. M. (2018, jul). The acquisition of impervious surface area from LANDSAT 8 satellite sensor data using urban indices: a comparative analysis. *Environmental Monitoring and Assessment*, *190*(7), 381. Retrieved from http://link.springer.com/10.1007/s10661-018-6767-3 doi: 10.1007/s10661-018-6767-3

Seto, K. C., & Kaufmann, R. K. (2005, feb). Using logit models to classify land cover and land-cover change from Landsat Thematic Mapper. *International Journal of Remote Sensing*, *26*(3), 563–577. Retrieved from https://www.tandfonline.com/doi/full/10.1080/01431160512331299270 doi: 10.1080/01431160512331299270

Shih, H.-c., Stow, D. A., & Tsai, Y. H. (2019, feb). Guidance on and comparison of machine learning classifiers for Landsat-based land cover and land use mapping. *International Journal of Remote Sensing*, *40*(4), 1248–1274. Retrieved from https://www.tandfonline.com/doi/full/10.1080/01431161.2018.1524179 doi: 10.1080/01431161.2018.1524179

Silva, J. S., da Silva, R. M., & Santos, C. A. G. (2018, may). Spatiotemporal impact of land use/land cover changes on urban heat islands: A case study of Paço do Lumiar, Brazil. *Building and Environment*, *136*, 279–292. Retrieved from https://linkinghub.elsevier.com/retrieve/pii/S0360132318301768 doi: 10.1016/j.buildenv.2018.03.041

Strohbach, M. W., Döring, A. O., Möck, M., Sedrez, M., Mumm, O., Schneider, A. K., ... Schröder, B. (2019). The "hidden urbanization": Trends of impervious surface in low-density housing developments and resulting impacts on the water balance. *Frontiers in Environmental Science*, *7*(MAR). doi: 10.3389/fenvs.2019.00029

Talukdar, S., Singha, P., Mahato, S., Shahfahad, Pal, S., Liou, Y.-A., & Rahman, A. (2020, apr). Land-Use Land-Cover Classification by Machine Learning Classifiers for Satellite Observations—A Review. *Remote Sensing*, *12*(7), 1135. Retrieved from https://www.mdpi.com/2072-4292/12/7/1135 doi: 10.3390/rs12071135

Tan, K. C., Lim, H. S., MatJafri, M. Z., & Abdullah, K. (2010, jun). Landsat data to evaluate urban expansion and determine land use/land cover changes in Penang Island, Malaysia. *Environmental Earth Sciences*, *60*(7), 1509–1521. Retrieved from http://link.springer.com/10.1007/s12665-009-0286-z doi: 10.1007/s12665-009-0286-z

Veldkamp, A., & Lambin, E. (2001, jun). Predicting land-use change. *Agriculture, Ecosystems & Environment*, *85*(1-3), 1–6. Retrieved from https://linkinghub.elsevier.com/retrieve/pii/S0167880901001992 doi: 10.1016/S0167-8809(01)00199-2

Wu, K.-y., Ye, X.-y., Qi, Z.-f., & Zhang, H. (2013, apr). Impacts of land use/land cover change and socioeconomic development on regional ecosystem services: The case of fast-growing Hangzhou metropolitan area, China. *Cities*, *31*, 276–284. Retrieved from https://linkinghub.elsevier.com/retrieve/pii/S0264275112001424 doi: 10.1016/j.cities.2012.08.003

Zha, Y., Gao, J., & Ni, S. (2003). Use of normalized difference built-up index in automatically mapping urban areas from TM imagery. *International Journal of Remote Sensing*, *24*(3), 583–594. doi: 10.1080/01431160304987

Zhou, W., Wang, J., & Cadenasso, M. L. (2017, jun). Effects of the spatial configuration of trees on urban heat mitigation: A comparative study. *Remote Sensing of Environment*, *195*, 1–12. Retrieved from https://linkinghub.elsevier.com/retrieve/pii/S0034425717301463 doi: 10.1016/j.rse.2017.03.043

Chapter 9

Groundwater Resources of Kolkata

9.1 Introduction

Brief discussion about the groundwater resources of the world has been cleared already at the beginning of this study (Section 2.5). Further, this chapter focused on groundwater resources in Kolkata. This study area is situated upon quaternary alluvium which is more than 700 meters thick and composed of unconsolidated to semi-consolidated sediments. Pulses can be observed in sedimentation structures because of marine transgression and regression and tectonic uplift from Cretaceous to Pleistocene times. Mainly several cycles of sand, silt and clay composed this thick layer.
Lithological logs indicate the presence of two extensive clay beds in the study area within 400 mbgl. Within Kolkata, a thick top clay layer covered extensively just above the quaternary alluvium sequence. It holds a depth from 10 meters to up to 60 meters varying in a different locations. The aquifer below the clay blanket is made of coarse sand, also mixed with gravel. The aquifer reflects its deltaic nature and the top clay bed of it shows an evolution from aquiclude to aquitard. Presence of available freshwater ranges within 100 to 180 meters below the ground level. It is noteworthy to mention that, beneath this freshwater source another water table is identified with brackish water specifically beneath 200 meters below the surface (CGWB, 2006). In this chapter, Kolkata's groundwater resources have been analysed based on available data from different locations over the years. It has been realised from the previous chapter that, Kolkata is highly urbanised as a district but other adjoining districts are comparatively low in terms of urbanisation. Comparing the groundwater scenario with other districts it is possible to understand the impact of groundwater resources on urbanisation in a general way. In this type of study, long-term observation is also needed to understand the actual impact of urbanisation on groundwater resources. Hence, thirty years of data have been collected but from this available data but selective time frame has been used to identify different aspects of groundwater. Before analysing the consecutive situation of Kolkata, satellite data have been used to get a brief idea about the groundwater scenario of the study area. Further, groundwater resources analysis has been divided into two major parts, i.e., groundwater quantity and quality analysis.

9.2 Objectives

The main motive behind the groundwater scenario analysis of the study area lying within certain objectives that have been mentioned below:

- To realise the overall groundwater condition of Kolkata through pervious studies
- To identify the groundwater scenario of the study area comparing with other adjoining districts.
- To observe groundwater level spatially and identify changes in every decade within the timespan of 1990 to 2020.
- To observe yearly changes in groundwater level.
- To observe seasonal changes in groundwater level.
- To identify physiochemical parameters of groundwater resources and its concentration over the years.
- To observe seasonal changes in hydrochemical parameters.
- To identify correlation between hydrochemical parameters and observe its state over the time.
- To analyse the type of groundwater resources and observe its state over the time.
- To identify spatial changes in water quality of Kolkata over the decade.

9.3 Survey through literature review

Groundwater as a topic for research was not prioritised for years. In the past, importance of urban groundwater related studies was ignored in the research sector. Later, with increasing awareness about environmental sustainability, groundwater studies found its importance. Kolkata was an important city for the last two hundred years but groundwater resources were not properly assessed over time. Recently, after certain incidences like massive water level drops and land subsidence, the importance of groundwater has been realised. An extensive literature review of groundwater resources and their related issues focused on Kolkata have been incorporated in this section. Each of the properties of groundwater relevant to the study have been reviewed separately for better understanding. These are mentioned below:

9.3.1 Groundwater level

Bhattacharya & Kumar (2012) described about variation in piezometric level for Kolkata. Piezometric level declined maximum at Gobra, Tilajala area and the magnitude was about 8.29 m. In Kasba, Gariahat, Dhakuria zone, level declined about 6.82 m. between 1958 to 1994. In south Kolkata, piezometric level dropped about 12.93 m. in between 1958 to 1999.
Adhya (2015) depicted about vulnerability in top three megacities in India, For Kolkata. She has identified alarming depletion in piezometric level for two decades (1995-2015),also identified seasonal variation in groundwater level,a prominent phenomenon for Kolkata. She also addressed about contamination in groundwater. According to her study, contamination from road

salt, toxic substances, motor oil, that seep into subsurface and make changes in groundwater quality. Chromium, copper, cadmium and zinc contamination from landfill area contaminated groundwater of Kolkata.

Bardhan (2016) has mentioned that groundwater abstraction quantity is higher than groundwater recharge in case of Kolkata due to high demand for water supply in highly urbanised area. Permanent depletion in water level has been acknowledged by the researcher. She attempted to find out reasons behind depletion of groundwater level in Kolkata, analyse the reasons behind depleting groundwater quality and land subsidence in Kolkata. The study depended on secondary data available from authenticated governmental organisation. She observed that, number of tube wells and borewells increased in between 1986 to 2006. Amount of groundwater extraction increased due to huge demand from increasing population that depleted the groundwater level. Thick clay layer at top of the soil layer is preventing from groundwater recharge in Kolkata. Groundwater quality also degrading due to external sources that are mainly generated from anthropogenic activities. Land subsidence has been also observed in several parts of the city, it has been found that, declined groundwater level is one of the reasons behind subsidence.

Ray (2019) did a comprehensive study on groundwater resources of Kolkata. She reported that, rapid urbanisation is the reason behind,decline in groundwater level in Kolkata. She identified three risk zones for groundwater exploitation. Borough I and VIII is at high-risk zone, where declining trend of groundwater is about 0.20 m/year. Borough IX and X are part of medium risk zone with declining trend between 0.15 to 0.20 m/year. She identified unplanned urbanisation is the main reason behind it. Rest of the boroughs with declining trend less than 0.15 m/year consists under low risk zone.

Mitra (2019) described that in Kolkata Metropolitan Area, about 52% of groundwater is used in water supply. In case of Kolkata, author has found declining groundwater level of 20 cm. per annum. She analysed that huge demand from increasing population is the main reason behind groundwater depletion.

John & Das (2020a) identified areas where groundwater level dropped mostly in KMC area by spatially analysing groundwater level from 1991 to 2010. They have described that, groundwater occurs in Kolkata in two zones. Upper zone consists of clay bed as unconfined aquifer and lower zone is at much depth. Shallow water table in the upper portion is nearly close to land surface but low possibility of infiltration due to dense impervious surface prevented groundwater recharge and as a result, groundwater level was at about 9 to 10 m below the surface in 1984 where in 2010, it declined to 19 m. Heavy pumping in flat lowland of Kolkata declined the groundwater level also incessant pumping led to contamination in groundwater quality. Huge built-up cover throughout the city creates high amount of surface runoff, that prevents groundwater recharge. They have identified various kind of complexity for groundwater assessment in case of Kolkata. They have taken post monsoonal yearly data for thirty years of time span and identified water level dynamics throughout the study area. Overall analysis showed that, disproportionate groundwater recession has been found in south Kolkata due to uncontrolled amount of groundwater withdrawal to meet up the demand, as surface water supply was not adequate. Excessive groundwater recession was observed at south western part of Kolkata also. Water level depletion of groundwater is alarming in northern part of Kolkata. Highest

groundwater level depletion in Chitpur from northern Kolkata and Entally from central Kolkata. Chingrighata and Keyatala observed abrupt changes in groundwater level. In the next phase of this study, they correlated groundwater level with available amount of precipitation. Nearly 40% correlation has been established between two variables. Groundwater level has been analysed with decadal change in population density and a strong relation has been identified. At last, water supply from KMC has been acknowledged in the study to identify impact of surface water supply and groundwater extraction. Mainly focusing on the groundwater level, they have established that declined water level of Kolkata, majorly dependent upon decreasing proportion of recharge, increasing population density and water supply limitations and rainfall.
John & Das (2020b) created a comparative groundwater level study on Kolkata between 2010 and 2018, they have shown groundwater level is depleting in the city also they identified extreme spatial differences in groundwater level. Groundwater level in southern part of Kolkata is comparatively higher than northern and central part of Kolkata. They have identified that, sufficient water supply from local administration has providing water supply through surface water but some parts of Kolkata are dependent on groundwater.

9.3.2 Land subsidence

Sikdar et al. (1996) studied about land subsidence condition of Kolkata due to groundwater overdraft, they estimated that, land of Kolkata is subsiding about 7 mm/year due groundwater consumption and dropping related with it.
Chatterjee et al. (2006) identified land subsidence in 90's Kolkata. They primarily adopted that, over drafting of groundwater is the ultimate cause behind land subsidence. They defined the aquifer system beneath Kolkata as confined aquifer and recharge area of the aquifer is located 60 to 70 km distance from Kolkata in north. Recharge starts from 1st week of august and continues up to October. They have showed decline in piezometric level in Kolkata between 1992 to 1998. They have used satellite imageries to identify and quantify land subsidence and calculated that, dense urbanised cities faced the situation of land subsidence due to groundwater abstraction.The same as happened to Kolkata. Piezometric pressure declined because of groundwater withdrawal that ultimately resulted pressure loss in aquifer and increased pressure over the sand layer of subsurface environment.
Sahu & Sikdar (2011b) described the effect of groundwater abstraction on land subsidence. Their study was mainly focused on Kolkata and its surrounding wetland area. According to them, excessive pumping of groundwater made change in elastic and inelastic compression of the aquifer that caused land subsidence in Kolkata.
Suganthi & Elango (2020) studied land subsidence of Kolkata and adjoining satellite town Saltlake city, their study was limited within 2003 to 2010, they described about correlation between exploited groundwater usage and land subsidence in case of Kolkata. They identified maximum land subsidence in Saltlake and Science city area.

9.3.3 Landfill impact

Maity et al. (2002) investigated on the eastern side of the Kolkata to understand status of waste disposal related leachates and condition of groundwater quality. They found TDS, TH and Cl^- crossed the permissible limit of drinkable water quality.
Chattopadhyay et al. (2009) on their paper about solid waste management of Kolkata showed that, due to presence of solid waste management field Dhapa, leachate quality is beyond allowed level at least for COD, BOD, chloride and solid concentrations.
Sahu & Sikdar (2011a) described about groundwater potential about surroundings of Kolkata. They mentioned about Kolkata's solid waste dumping ground Dhapa where 95% of Kolkata's total solids waste are dumped. They have identified this location as one of the probable important sources for contamination in groundwater. Probably, leaching of pollutants may be advanced due to excessive withdrawal of groundwater for mainly for domestic purpose, industrial and other commercial needs from Kolkata. As it is situated in the eastern fringe, groundwater flow from east to west create a chance to contaminate groundwater of Kolkata.
Singh et al. (2013) evaluated groundwater contamination hazard rating for cities in India and Europe. They identified Dhapa as very hazardous site for groundwater contamination. They found comparatively larger landfill sites in India with no precautionary measures to prevent leaching is the cause behind percolation of hazardous materials into subsurface.

9.3.4 Canal explorations

Ghosh et al. (2019) assessed surface water and groundwater of Adi Ganga. It is a tributary of the river Hoogly. They identified, continuous disposal of wastes deteriorating surface water of the canal and consequently it is degrading the groundwater beneath it. They have analysed hydrochemical parameters of water to understand impact of surface water on groundwater. Six locations were selected for the study. They have identified surface water of the canal has a strong positive correlation with groundwater. They have further confirmed that water from the canal negatively impacted the groundwater. However geogenic contaminants like heavy metals (except Zn) and F are consistent and within legitimate limit and prominent contaminants like, oil and grease also high turbidity, total harness and alkalinity depicts anthropogenic exploitations.

9.3.5 Water quality

Banerji & Mitra (2019) assessed groundwater quality in the northern part of Kolkata with WQI index using GIS. They identified there are huge variation in pH and salinity level in groundwater and excessive TDS in supplied water erode water bearing infrastructure and water filtration systems. Available iron in groundwater mostly crossed the prescribed drinking limit, maximum it has been found 5.3 mg/l which far excessive than normal that leads to adverse effect on household products. PCA has been applied further to understand about influence of different water quality parameters. It showed that EC, TDS and Temperature have higher influence in water quality among other parameters. Water quality index shows groundwater is unfit for drinking in northern part of Kolkata.

Ali & Ahmad (2020) analysed water borne disease susceptibility in KMC using water quality index. They have taken major locations of Kolkata to understand the water quality. They identified TDS, pH and Turbidity present in groundwater are higher than permissible limit according to Indian standards. Specially groundwater quality from locations like Tangra, Topsia and Dhapa are significantly degraded.
John & Das (2020c) identified that there is a close association between groundwater level and salinity in case of Kolkata. It is also identified that, areas with lower groundwater level carrying high EC in groundwater. They depicted that, lower EC value in southern part of Kolkata due to presence of Tolly's nallah and lakes and other water bodies. It has been analysed that presence of heavy metals in groundwater due to industrial and domestic activities.

9.3.6 Groundwater recharge

Sahu et al. (2013) identified pumping effects on groundwater recharge for the megacity Kolkata. The found a pattern of increasing groundwater abstraction with time. In their study groundwater flow model estimated recharge rate is 350 m^2/s, which 8.3% of monsoonal recharge and total amount of recharge is lower than groundwater abstraction. They also depicted that, about 10% of groundwater recharge from solid waste dumping ground and possibility to contaminate groundwater of Kolkata city and that may take 16 and 40 years respectively when porosity of this aquifer is 0.2.

9.3.7 Arsenic

Pal et al. (2009) discussed about additional burden from cooked rice in West Bengal and they mentioned about the scenario of Kolkata too as rice is staple food here. They observed people of Kolkata has possibility to consume arsenic through their food as, production of rice is dependent on contaminated groundwater through arsenic.
Malakar et al. (2016) developed their research based on report of Public Health and Engineering department and through their primary sample survey for Kolkata Municipal Corporation area on 2016. They have observed about 36% wards where arsenic was above than 50 µg/l and more than 34% wards with more than 10 µg/l also less than 50 µg/l of arsenic and about 30 % of wards with less than 10 µg/L of arsenic in groundwater. Alarming situation has been found on northern and central part of Kolkata. They identified a strong positive relation between continuous groundwater withdrawal and arsenic contamination specifically in shallow water table. They have prescribed for artificial recharge and withdrawal of groundwater only from confined aquifer.
Chakraborti et al. (2017) discussed about presence of arsenic in groundwater of KMC. They presented their analysis on the basis on data collection for 23 years (1993 -2016). They observed more than 300 µg/l arsenic in groundwater in 8 wards from Kolkata, that defines about 6% of people from KMC are severely affected by arsenic by using groundwater and 37% of population are under the situation where arsenic concentration in groundwater is greater than 50 µg/l. They identified there is neutral relation between iron and arsenic in Kolkata. It is positive sign than

district Kolkata is in far better situation than other adjoining districts (Nadia, North 24 pargana, Murshidabad).

9.4 Groundwater storage estimation using satellite data

Understanding of subsurface environment is a complex part for earth science as it is not visible and various unrecognisable factors are related with it. Assessment of subsurface environment can be done with appropriate knowledge in geology, hydrology, and geomorphology. Application of remote sensing technology through observation of satellites have revolutionised this approach. Understanding of subsurface environment has become more prominent and accurate recently. Groundwater is part of subsurface environment and quantification of available groundwater is dependent on empirical mathematical calculations. Now after the application of satellite driven data, it has become possible to asses groundwater quantity. In 2002, NASA and DLR jointly launched GRACE satellite to understand about terrestrial water storage by measuring earth's gravity field anomaly. Twin satellites on geocentric orbit identifies gravity anomalies maintaining a fixed distance between them. Satellite generated data has been processed by GLDAS (Global Land data assimilation system) to understand TWS (Terrestrial Water Storage) and GWS (Groundwater Storage) data. The equation below simplifies the relation between TWS and GWS.

$$\Delta TWS = \Delta SM + \Delta SWE + \Delta GWS \tag{9.1}$$

Where, ΔTWS signify the changes in terrestrial water storage and ΔSM represent changes soil moisture, ΔSWE represent changes in snow water equivalent and ΔGWS represent changes in groundwater storage.
Area averaged data that have been collected for Kolkata, the boundary remain limited to 88.125°E to 88.375°E and 22.625°N to 22.875°N focusing the study area. Time frame has been limited to 1st January 2003 to 31st December 2020. Collected daily data have been transformed to month and year for a better understating by calculating the mean value. For this purpose, online web environment GIOVANNI data have been used which helps on obtaining data about geophysical parameters.

9.4.1 Terrestrial water storage

With terrestrial water storage anomaly, the change in water storage is identified. High value defines more availability in water storage and low value defines depletion of water storage. In 2003, TWSA value was 1173 mm. and in 2020 the value was 1130, it seems negligible change between 18 years, but high volatility observed between the time span. Clear trend has been observed by the trendline. A definite tendency of declination can be seen from 2003 to 2010. After 2010 to 2018 the recovery in TWSA is clearly visible. For the consecutive eight years (2010-2018) an alternative pattern of ups and downs in storage has happened in Kolkata. The value was minimum 2010 and value was maximum in 2003. A clear shortage of water storage has been identified from the observation. Though it has been reclaimed after 2010 with

a tendency of decline in water storage (Figure 9.1a).

Monthly terrestrial water change is clearly observed from the collected data (Figure 9.1b).

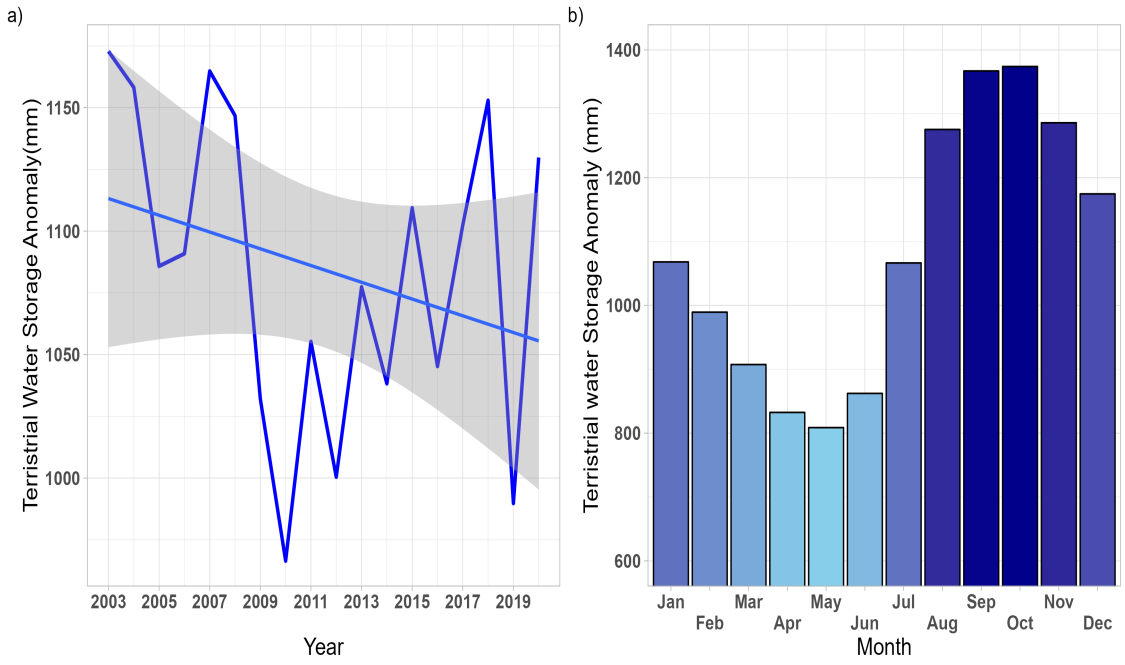


Figure 9.1. Terrestrial water storage anomaly a) yearly, b) monthly

Amount of TWSA starts to decrease in winter and it remains minimum in pre-monsoon time. Specially in the month of May. A clear pattern of decline in TWSA has been observed from the month January to May. After the beginning of monsoon in Kolkata from June, the amount of TWSA starts to increase. Significant increase can be identified between June to August. TWSA remains highest in post-monsoon period. After the October TWSA starts to decline and this trend follows up to the month of May. Effect of monsoon and its rainfall clearly makes and effect on TWSA.

9.4.2 Groundwater storage

Shallow groundwater quantified here by Groundwater storage data produced by NASA-GLDAS. For Kolkata it is seen that, in 2003, groundwater storage anomaly was about 854 mm and it has been changed to 818 mm. in 2020. It can be clearly observed that anomaly has been reduced with time. Though, fall and rise has also been observed within the time. A sharp decline has been observed from 2008 to 2010 and after 2010, GWSA has been revived. A sharp fall has been identified next in 2019 and it also revived in next year. (Figure 9.2a).

Amount of GWSA varies with season throughout the year (Figure 9.2b). In winter season, GWSA remains in declining condition. It reaches its lowest level in the summer season. With the beginning of monsoon GWSA starts to increase. It sharply increases between June to August. With available rainfall from monsoon, it reaches its highest level in September and October. With the beginning of post-monsoon GWSA starts to decline and a continuous decline ends in

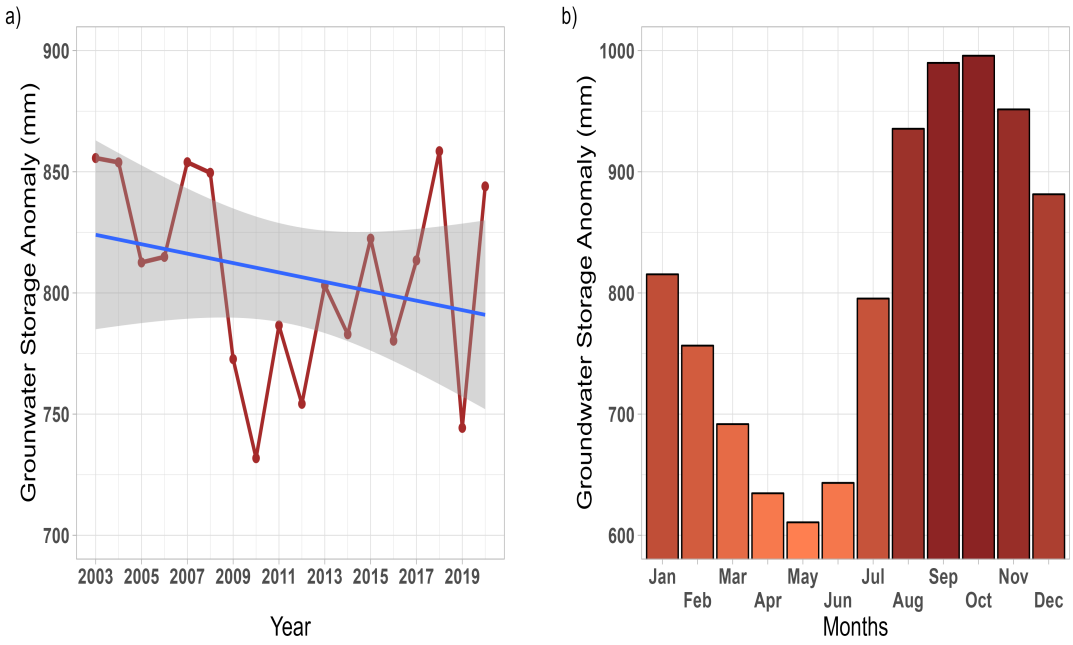


Figure 9.2. Groundwater storage anomaly a) yearly, b)monthly

April.

9.4.3 Comparative analysis

A comparative analysis has been produced to understand a temporal change between TWS and GWS (Figure 9.3). It is observed that, within 18 years, TWSA and GWSA have been altered significantly. After 2003, a sharp decline observed for both TWSA and GWSA till 2009, but rate of decline was not the same for TWSA and GWSA. TWSA sharply declined compared to GWSA. After 2009 GWSA started to increase but TWSA increased after 2012. After 2014 significant change identified for TWSA but in case of GWSA, the trend was not so satisfactory. Comparing both anomalies, It is assessed that, alteration of GWSA was less compared to TWSA but both of the variables followed mostly a common pattern with time. A clear linear trend of declination in the amount of TWSA observed within 2003 to 2020 but it is comparatively remained flat for GWSA. Observing data from preceding year changes have been identified for terrestrial water storage and groundwater storage (Figure 9.4). Distinct variation observed for the years in terms of both storage. From 2003 to 2009, both the storage declined but after 2009, increase has been observed for storage. A declining change observed afterwards till 2017 but after that year, terrestrial water storage increased but groundwater storage remained stagnant from 2015. Changes in rainfall and other surface water storage are the reason behind the change in terrestrial water storage change but groundwater storage change remained almost same for years.Overall it has been observed that terrestrial water storage anomaly decreased almost 2.52 mm every year, within it groundwater storage anomaly decreased about 2.11 mm every year on

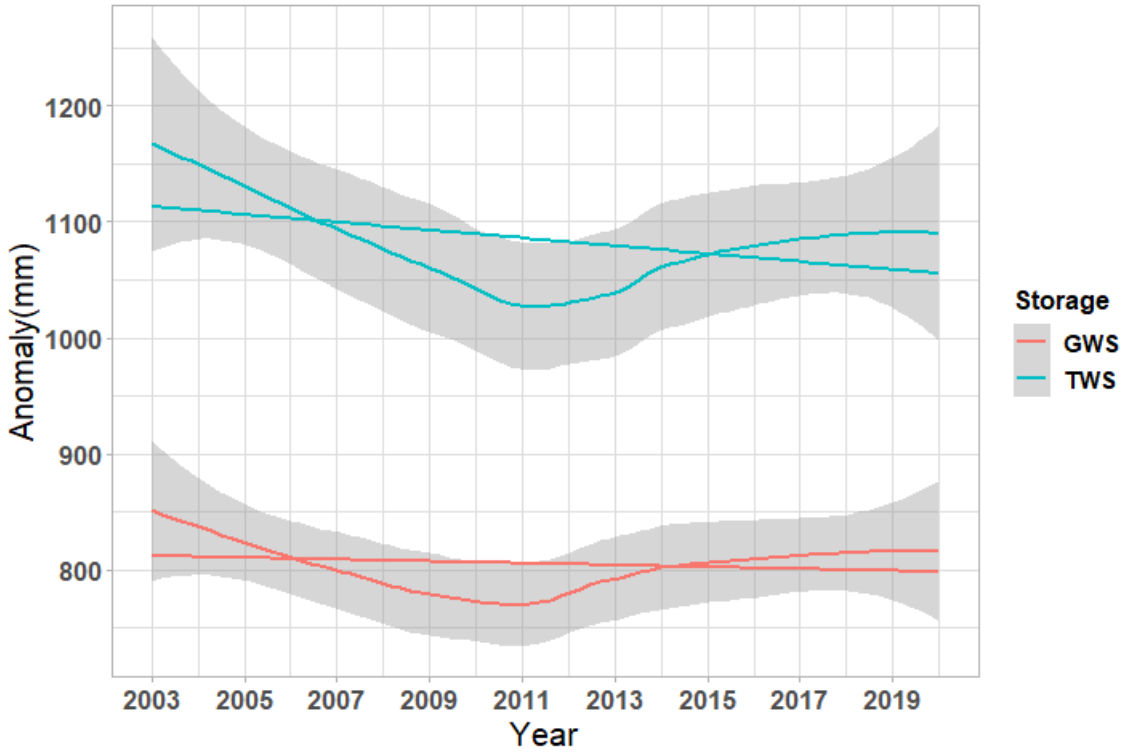


Figure 9.3. Time series analysis of Δ TWS AND Δ GWS from 2003 to 2020

an average. It can be depicted that in between the time span, negative change in groundwater storage is definite and is the prior reason behind terrestrial water storage change.

9.5 Groundwater resources analysis based on underground data

Geographical and geological advantages already favoured for the study area Kolkata in case of groundwater storage. Having this situation, groundwater usage was common from the initiation of this city. Mostly groundwater consumption here is based on domestic water usage. Calculation of exact amount of groundwater usage is next to impossible without highly defined infrastructure but governmental monitoring systems are active about monitoring the groundwater level that nearly reflects the subsurface environment. Apart from several hindrances an attempt has been made to know details about the groundwater scenario below the surface. Groundwater resource datasets are needed for a longer period of time to understand the actual impact of urbanisation process. For better understanding about the impact of urbanisation on groundwater resources total 30 years (1990-2020) of timespan have been taken for the study. So with contemporary dataset, historical data were also needed to analyse the past condition of groundwater resources in the study area. Groundwater related data have been collected from various sources. Central Ground Water Board (CGWB) collect state wise and district wise data at a regular interval, that have been collected for the study area Kolkata by directly visiting the office and also from

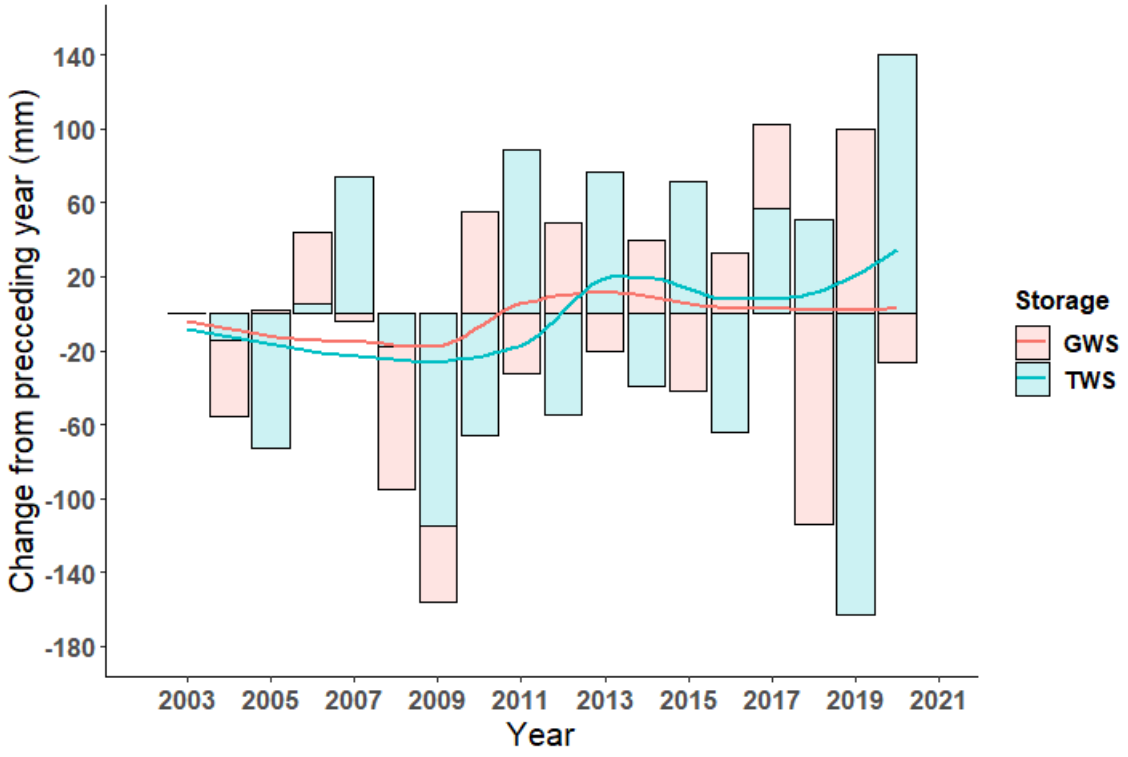


Figure 9.4. Changes in GWS and TWS every consecutive year from its preceding year from 2003 to 2020

published yearbook. State Water Investigation Directorate (SWID) also collect yearly data from different locations of Kolkata that has been collected by visiting the designated office. Groundwater level and hydrochemical properties of groundwater also collected from other published articles also. It is noteworthy, to mention that School of Water Resources Engineering at Jadavpur University, working efficiently on groundwater related issue over years. Needful data also collected from that department. Some of the datasets used here are unpublished also and collected through personal communication with the officers designated to this field. In this section, a map has been created depicting the location of observational points that has been utilised by different sources where, location data from CGWB and SWID mentioned separately and all other sources accumulated, naming as *Other* (Figure 9.5).

9.6 Groudwater level analysis

Groundwater is an *invisible* resource and quantification of groundwater is quite complex task. Availability of groundwater depends on the nature of aquifer underneath and it varies with characteristics of aquifers. Groundwater estimation in unconfined aquifer is quite difficult task but in unconfined aquifer, where groundwater is in confined condition, it can be estimated by calculating water table and potentiometric surface. Potentiometric surface in a confined aquifer, predicts the situation of water level that rise up in borehole penetrating the enclosed aquifer. With groundwater level data situation of groundwater can be easily identified. For this study,

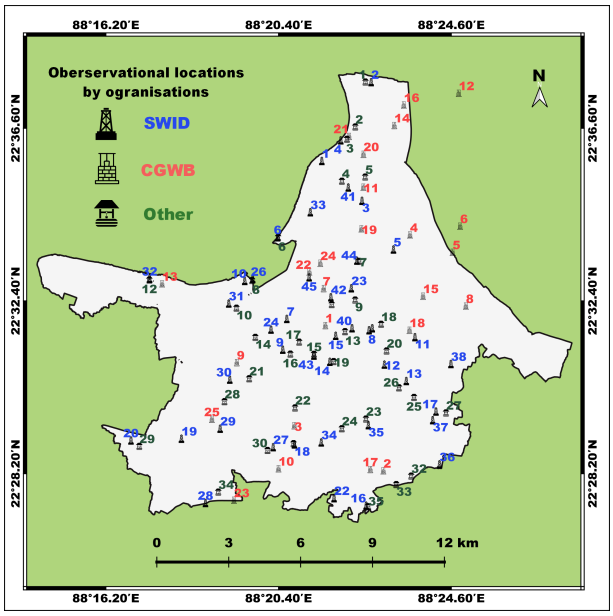


Figure 9.5. Oservational points to collect data of groundwater resources by CGWB, SWID and Other sources

different frame is needful to understand the actual change in resources, so groundwater level data have been identified for three separate time frame. Also groundwater level situation has been identified comparing the study area with other adjoining districts for a selected time frame.

9.6.1 Comparison of groundwater level with other adjoining districts

Groundwater level primarily depends on its hydrogeological characteristics but human intervention certainly modifies the groundwater level by excessive abstraction. Impact of abstraction can be better understood by comparing it with other adjoining areas. This study area, Kolkata is a comparatively much smaller district in Southern Bengal than its other adjoining districts. Hugli in the north west, Howrah in the west, North 24 Parganas in the northeast and South 24 Parganas in the south of Kolkata.Landuse pattern of Kolkata is totally different from other adjoining districts (Section 7.3). Population density of Kolkata is much higher than mentioned adjoining districts. Having the same geological characteristics in subsurface environment, Kolkata is a totally urbanised district while adjoining district's level of urbanisation is relatively much lower than Kolkata.

Comparison of groundwater levels between Kolkata and adjoining districts has been produced here to create a clear picture of groundwater level scenario. Published data from CGWB have been used for individual two years maintaining a gap of ten years i.e., 2010 and 2020 (Appnedix, Table 17). Available groundwater level data have been curated by classifying different depths and final data have been represented in percentage (Figure 9.6).

In 2010, it is visible that in pre-monsoon or post monsoon season groundwater level of Kolkata is the lowest among all other districts where the groundwater level is between 10 to 20 meters below the surface throughout the year while in other districts groundwater level are in much

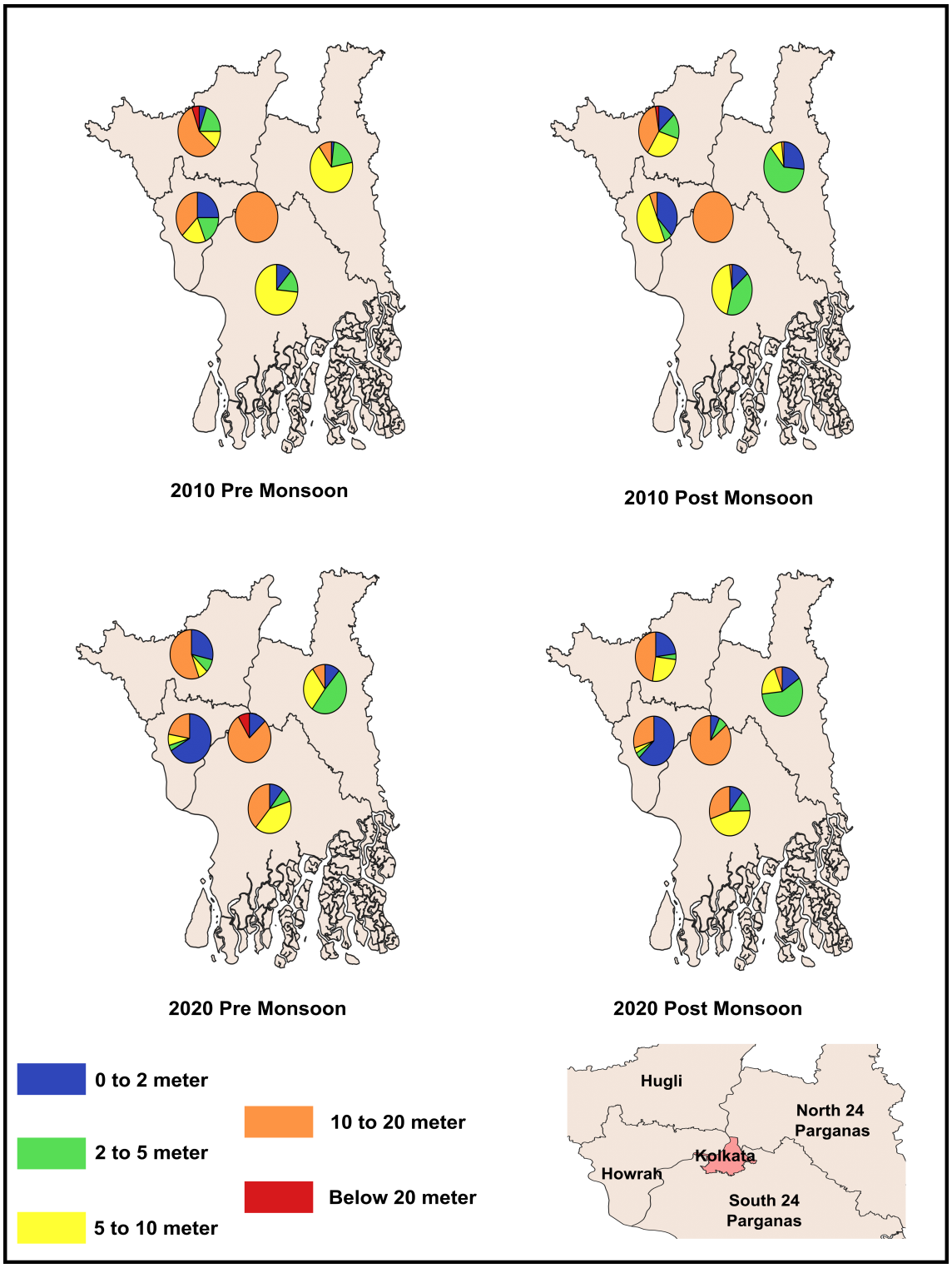


Figure 9.6. Comparison of groundwater level with other adjoining districts in pre monsoon and post monsoon for 2010 and 2020; (*source: CGWB, 2010 and 2020 yearbook*)

higher level (close to the ground level) than Kolkata. The situation is most favourable for South 24 Parganas. This year, the groundwater level is not available till 10 meters below the surface of Kolkata whereas, in all other districts minimum groundwater level is observed between 0 to 2

meters. The situation became better in post-monsoon for all the districts except for Kolkata. After ten years, in 2020, an holistic rise has been observed in groundwater level for the entire South Bengal region. Minimum level of groundwater at 0 to 2 meters below the surface observed in Kolkata also. Simultaneously groundwater below 20 meters at the maximum level also has been observed for Kolkata. The significant decline at maximum depth has been identified for Kolkata in between ten years. In post monsoon season, the situation changed and the water level rise in all the districts.
The situation of Kolkata, compared to other districts is worst and a declining tendency is observed in maximum depth. It reveals the acute pressure in groundwater resources that reflected through groundwater level. Homogeneous nature of a region in terms of groundwater resources abruptly broke in case of Kolkata.

9.6.2 Decadal changes in groundwater level

Changes in groundwater level after every decade describes the gradual and distinct characteristics of groundwater level Multi-decadal changes in groundwater level of Kolkata have been analysed here (Figure 9.7). In 1990, available groundwater was in between 11 to 14 mbgl within the boundary of Kolkata. Variation in water level ranged between only three meters. Northern portion of Kolkata was in better position except Chitpur area. Groundwater level was in better (close to the ground level) position in Hedua and Shovabazar area. In BBD Bag, Hastings area, water level ranged between 11 to 12 mbgl. In eastern side of Kolkata, groundwater level was also in better position compared to southern central part of the study area. Groundwater level was in deteriorated (distant from ground level) position after Central Kolkata. In Hazra, Deshapriya park, Kalighat, Tollygunge, Bullygunge area, groundwater level was below than 13 mbgl on an average and lower than other locations in Kolkata. Comparatively situation was better in Behala, Sarsuna and even in the south eastern part of Kolkata. Mainly a clustered trough zone was formed with most declined condition of groundwater level in the central part of Kolkata except the boundary area in both sides.
In 2000, range of groundwater level was between 10 mbgl to 15 mbgl, throughout the study area. It has been observed that after ten years from 1990, groundwater level scenario was changed. In northern part, groundwater level declined significantly about 15% to 20% from its previous level. Situation was worst for central western portion of Kolkata where groundwater level declined more than 20% in between ten years. Condition was slightly better for south eastern part of Kolkata. Significantly groundwater level increased near Panchasayar, Garia and Kamdahari area. This situation was also favourable for Sarsuna and Takurpukur area compared to previous decade. A trough observed in 1990, it was moved its position from its previous location and in 2000, now it stretched up to western boundary of the study area.
In 2010, a significant change has been observed in groundwater level pattern. From Sinthi, Chitpur, Bagbazaar and up to Babughat, groundwater level declined in the whole northern and central part of Kolkata abruptly. Groundwater level in these locations were around 16 mbgl on an average. Declining groundwater level extended up to Tollygunge and adjoining southern part of Kolkata. Groundwater level raised only in western part of Kolkata. Condition of Behala

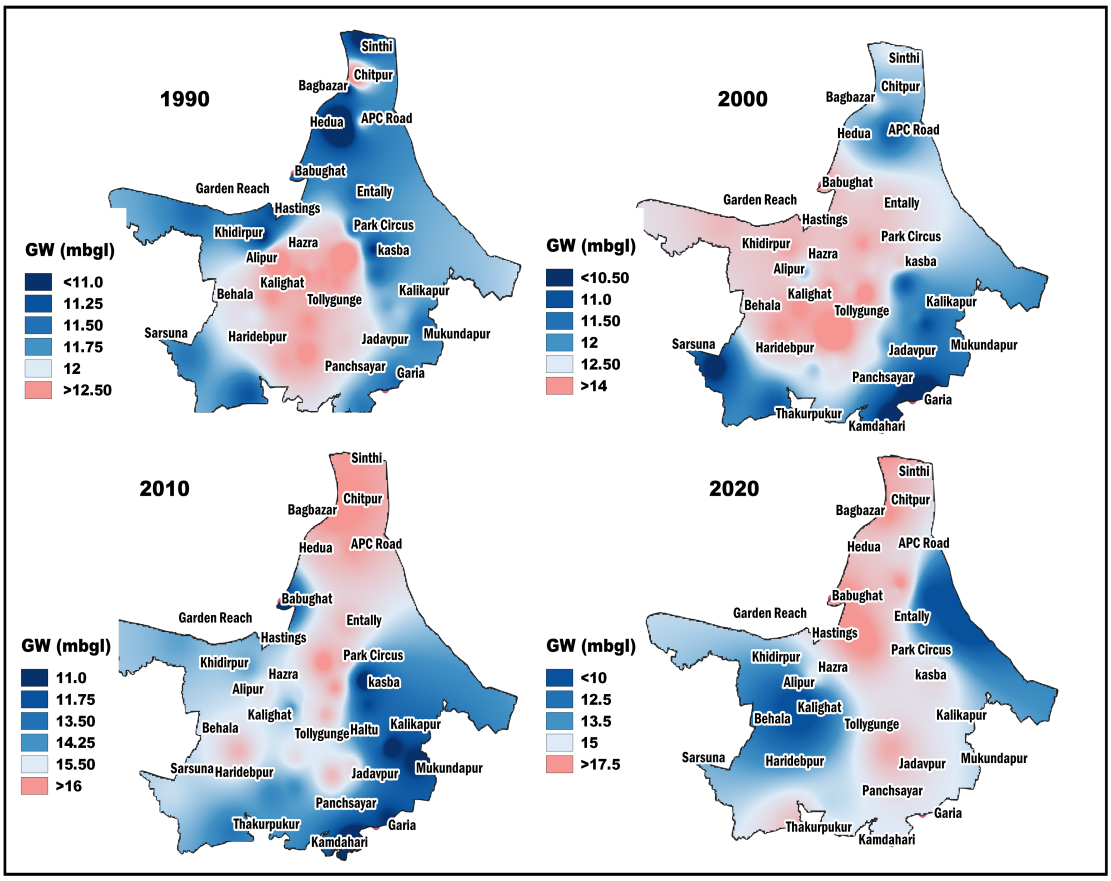


Figure 9.7. Groundwater level scenario in different decades from 1990 to 2020

deteriorated but significantly developed in south eastern part where groundwater level rose up to 11 mbgl on an average. Observed trough in previous decade changed its position pointedly towards north to south direction in 2010.

In 2020, variation in range of available groundwater level below the ground increased significantly. It has been observed that, certain places in north eastern part, groundwater level above 10 mbgl has been observed simultaneously groundwater below 20 meter has been observed also in northern part. Condition of groundwater level in south western and north eastern part slightly developed specifically in Behala, Alipur and Garden Reach but groundwater level abruptly dropped from its previous condition in north-south stretch. Particularly alarming declination has been observed in Mukundapur, Garia, Kamdahari area within timespan of ten years.

From the above observation of thirty years (1990 -2020) with a gap of ten years, it has been figured out that groundwater level consistently dropped within the study area but deterioration rate was not equal over the time. In the beginning of observation period, groundwater level deceased at high rate but with time high declining rate of groundwater level was restrained. Simultaneously it has been also observed that, groundwater declining rate varied with locations. Spatial variation in groundwater level was highly fluctuating in nature. Overall, it can be stated that, groundwater level certainly declined over the time in Kolkata, but declining trend of water level behaved differently over the time below the surface.

For better understanding about spatio temporal variation in groundwater level around the study area, a contour map has been created showing two major groundwater level with 11 mbgl and 15 mbgl (Figure 9.8). It has been observed in thirty years of the study, groundwater level of Kolkata primarily ranges between these two water levels. It has been observed that, in decade of nintees, overall groundwater level was within 11 meters to 15 meters below the groundwater level but in 2000 and afterwards it constantly decreased below 15 mbgl. In some of the locations it also increased above 11 mbgl at the same time period. A clear transformation has been observed for groundwater level at 15 mbgl, in 2010, it was north-east to south-west oriented but in 2020 it was north to south-east oriented.

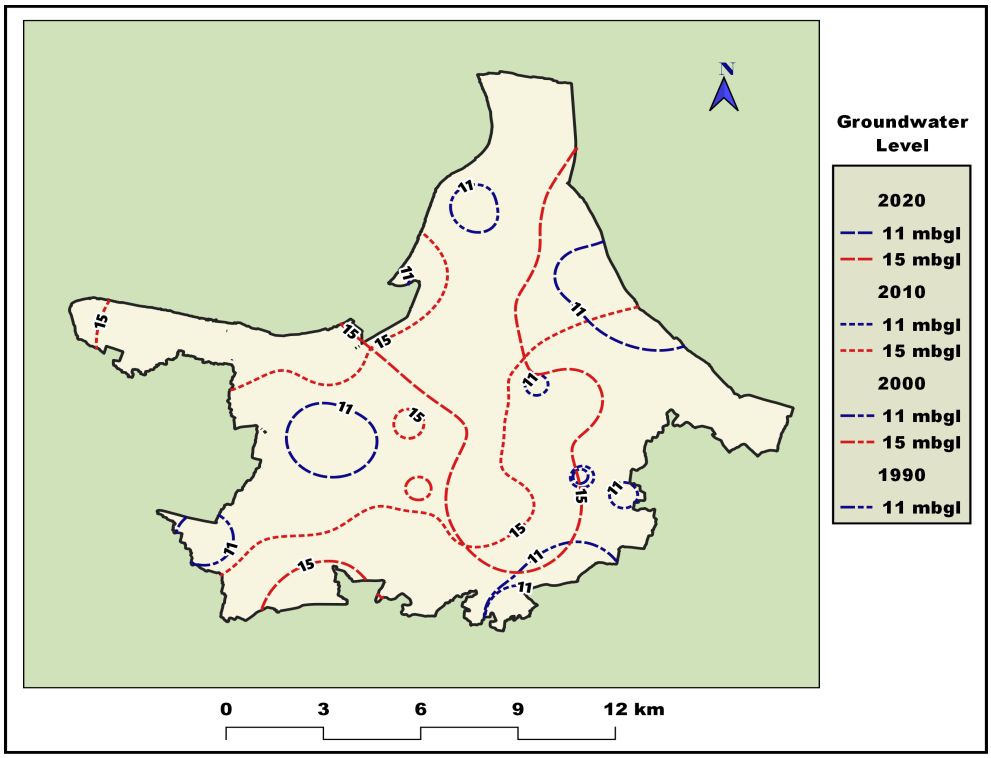


Figure 9.8. Contour map of groundwater level showing changes in position of contours with time (1990-2020)

9.6.3 Yearly changes in groundwater level

Ten years of yearly data have been collected from published data of CGWB to get an idea about the condition of groundwater level over the years for this study area.
At first, minimum and maximum water level data have been analysed to get an idea about the range of the water level. For a better understanding of the condition, it has been divided into certain categories with depth below the surface. Data from the monitored wells reflects groundwater depth from surface area to below 20 meters depth and it has been presented here in percentage form (Figure 9.9). Additionally, the year has been divided into pre monsoon and post monsoon season, where pre monsoon represents the condition of summer months till June

and post monsoon represents months after the monsoonal rainfall i.e., October or November. In 2010, all of the observed wells in Kolkata where the water level was in between 10 meters to 20 meters. After 2010, the scenario changed nominally as groundwater level was found in between 5 to 10 meters below the surface at least at a certain time of the year. The situation remained same for at least four years. After 2014, significant changes were observed in Kolkata. Certain monitoring stations (5% to 10%) were observed where the groundwater level was between 0 to 2 meters to 2 to 5 meters below the surface. Along with this observation, it can be also considered that some monitoring stations showed groundwater level below 20 meters from the ground level. After 2014, every year some portions (6% to 10%) in Kolkata where groundwater level observed below 20 meters. Parallelly groundwater level is also found relatively near the surface level. Comparing both seasons, it can be observed that, the water level declines more in pre monsoon as it face the effects of summer season. In post monsoon, situation of water level stays comparatively higher, and possibly the effect of monsoon rainfall runs behind it. Certainly impact of rainfall and recharge related is related to this condition. Effects in water level through direct groundwater recharge is negligible as the study area is covered with dense built-up area but recharge from adjoining permeable surface beyond the boundary of Kolkata, make changes in groundwater level.

It is to be mentioned that, within ten years every year certain wells have been selected for Kolkata to get an idea about the water level but the number of observation points changed from time to time. Analysing pre monsoon data, it has been observed that, from 2010 to 2014, a total of 18 wells have been monitored and minimum water level in 2010 was below 10 meters but with time minimum water level has been found just below the surface. Minimum water level rise has constantly been observed for consecutive four years. At the same time, maximum groundwater level found near 20 meters below the surface. After 2015, minimum groundwater level remained constant within 2 meters below the surface. Whereas, maximum groundwater level was observed constantly near 20 meters below the groundwater surface. From 2015 to 2020, groundwater monitoring stations were nearly double than its previous years. Situation remained the same for post monsoon season at least for minimum level of groundwater but maximum level of groundwater dropped a meter further above on average.

Analysing ten years of consecutive data, it has been revealed that, groundwater level for Kolkata remains 5 meters below the surface at minimum and maximum 19 meters below the surface level. It should be mentioned here, that change in number of observation points has possibility of altering the average data but a brief idea about the range of water level is certainly identified with these available data.

9.6.4 Seasonal changes in groundwater level

Kolkata is comparatively nearer to coastal area of the Bay of Bengal is nearly within 200 km distance. Locational existence of Kolkata also depicts its position in the flood plain, where mainland maintains a major slope tendency from north to south even from west to south is prominent as all the rivers ultimately move south to end their journey. This geographical condition creates a situation for groundwater to move towards the south also. Groundwater

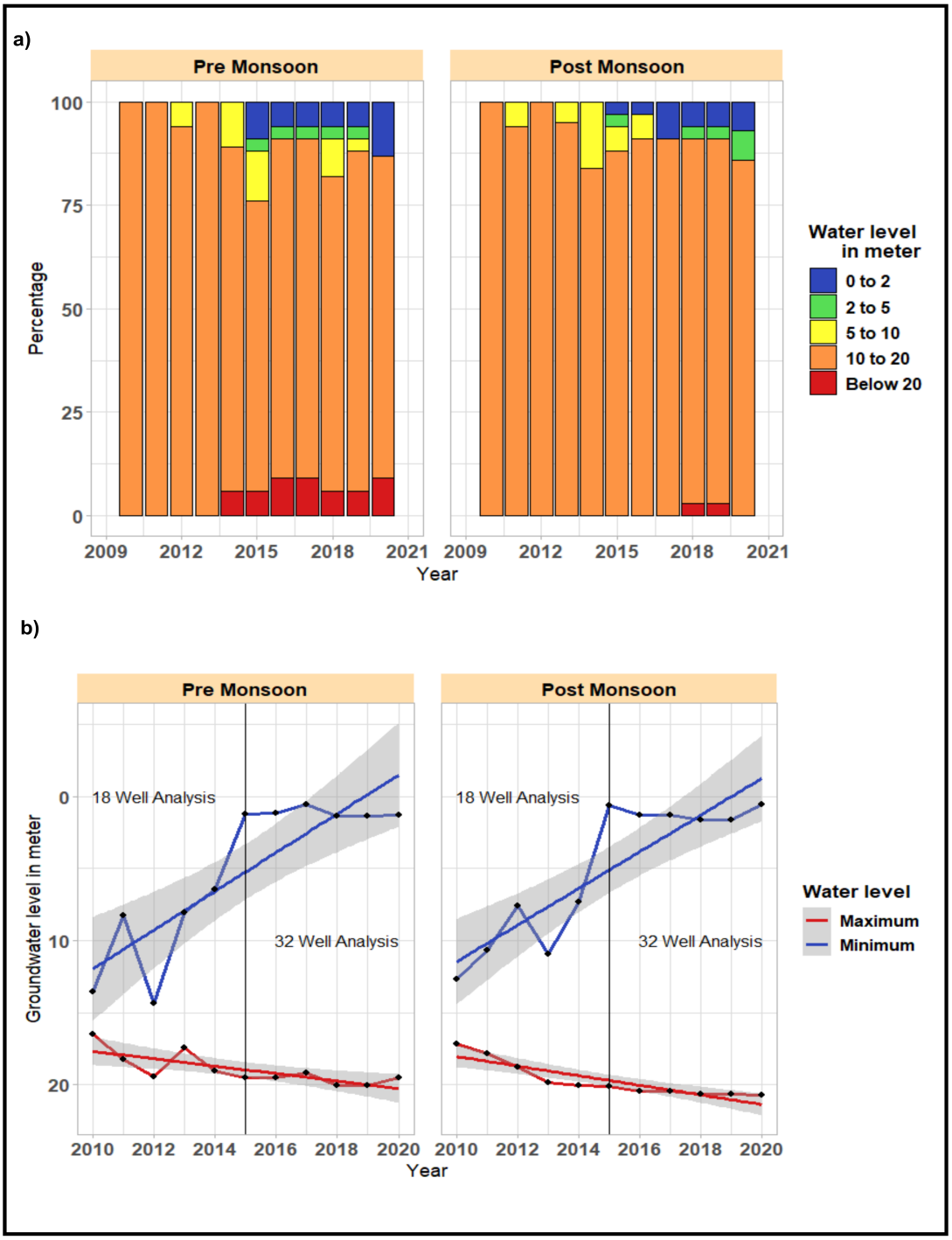


Figure 9.9. Groundwater level scenario in pre monsson and post monsoon from 2010 to 2020; a) showing percentage of groundwater level at different depth, b) showing minimum and maximum depth of groundwater level (*source: CGWB*)

majorly depends on rainfall for recharge. Scope of recharge is minimum for Kolkata and its adjoining areas because mostly it is covered up with dense built-up. A high concentration

of human intervention prevents direct recharge in the case of Kolkata. Mostly the recharge quotient is dependent on recharge from other green spaces that are far from the city. It is easily enumerable that, groundwater level change is dependent on groundwater flow in the confined aquifer. The water comes from other comparatively open spaces where the recharge scope is high. In this situation, rainfall in the Southern part of Bengal is significantly dependent on monsoonal rainfall, which usually starts from the end of June and persists up to the beginning of September. In West Bengal majorly seasons can be divided into pre-monsoon, monsoon and post-monsoon. Rainfall from monsoons certainly reflect in the scope of recharge that ultimately create changes in groundwater quantity.

Seasonal changes in groundwater level has been analysed based on monitored data that have been collected by SWID (Appendix, Table 22). Without observing the situation for every year, data have been analysed maintaining a difference between years to observe the condition of groundwater level before and after the monsoon. Data focused on selected 25 locations from all over Kolkata and years 2005, 2008, 2011 and 2013 has been finalised for the observation (Figure 9.10).

It has been observed that every year after monsoon groundwater level rises about 7% on average

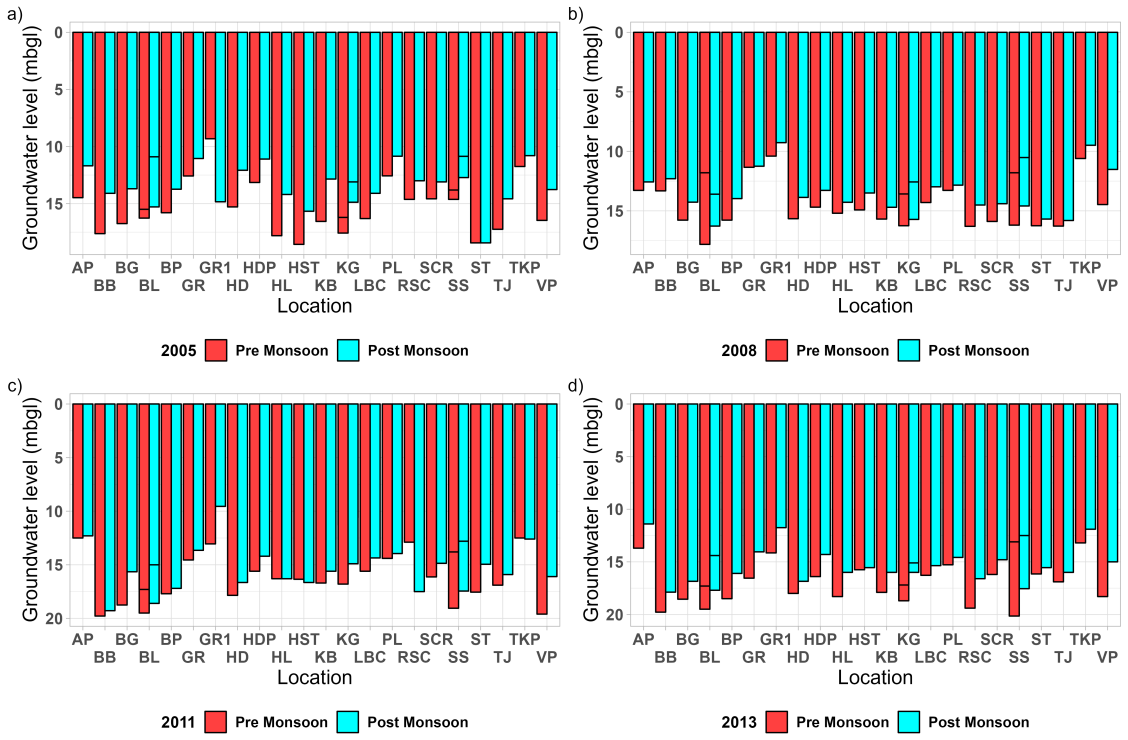


Figure 9.10. Pre monsoon and post monsoon groundwater level at different places for 2005, 2008, 2011 and 2013; (source: SWID)

from pre-monsoon level in post-monsoon season. But it varies year wise, as in 2005 the average change was about 14% rise. In 2008 it was about 8% rise. Whereas in 2011 it was 7% rise and in 2013 groundwater level rose up about 10% from pre-monsoon to post-monsoon change. The change level is comparatively high in the southern part of Kolkata compared with North Kolkata.

In 2005, the fluctuation level was comparatively high for densely populated areas like Bag bazar, Hedua, and Kalighat area. It has been observed that eventually fluctuation level in groundwater diminished with time and overall groundwater level dropped in every location with time. This is a serious concern. It can be assumed that groundwater fluctuation level is minimising that ultimately reflecting in groundwater quantity. Availability of groundwater is decreasing with time. High amount of abstraction and minimum recharge scope can be the reasons behind this situation as these observations are significant in densely populated areas.

9.7 Hydrochemical characteristics of groundwater

The study of groundwater hydrochemistry is useful to analyse hydrochemical conditions and aid decisions relating to the quality of water that is appropriate for drinking water. Polarity of the water molecule interacts with other molecules, thus chemical compositions change in groundwater also. Generally natural solutes are present in groundwater. Mostly these are inorganic solutes that are commonly available in nature. Cations like Ca, Mg, Na, K and anions like HCO_3, Cl and SO_4 are major constituents and Fe, F, CO_3 and NO_3 counted as minor constituents in groundwater. Apart from these solutes other organic solutes can be traced in groundwater. In this chapter, major physio-chemical properties of groundwater has been analysed from the chemical data collected from various secondary sources. Due to unavailability of data for long term observational period, it remained limited between 2010 to 2020.

9.7.1 Individual physio-chemical parameters of groundwater

Calcium (Ca^+)

Carbonate rocks are basically sources of calcium in groundwater. Excessive amount of calcium can cause hardness in groundwater characteristics. It is easily available component in groundwater. Repeated intake of calcium can cause osteoporosis, nervous system problems and possibility of stone formation in kidney. Calcium is affluently available in groundwater of Kolkata and its presence in groundwater varies with places.

Analysing ten years of data, it has been observed that, minimum 10 mg/l observed in Kolkata and maximum it reached up to 168 mg/l (Figure 9.11a). Average value of calcium in groundwater is about 56 mg/l for ten years but every year it deflected from average value. In 2014 and 2018, range of available calcium in groundwater was higher than every other year. Almost every year average value crossed the median values, that defines most of the locations in Kolkata had higher amount of calcium than average level. According to Indian standards [1], all of the observations are below acceptable limit (75 mg/l) and it is recommendable to use it for drinking purpose. Whereas, in 2014, 2015 and 2018 some of the observed locations crossed the acceptable limit. Wide range of diversified values have been observed for 2014 and 2018, whereas in 2010, 2011 and 2019, data remained clustered. In the observed time, none of the locations crossed the

[1]Central Ground Water Board considered the Indian standards for drinking water specification reported by Bureau of Indian Standards (IS 10500 : 2012), For details cgwb.gov.in/Documents/WQ-standards.pdf

permissible limit in case of available calcium concentration in groundwater. Some absurd values have also been identified almost every year that is uncommon in nature.

Magnesium (Mg^{+})

Magnesium is ubiquitous in groundwater environment. Basic source of magnesium are sedimentary rocks and minerals. With increasing anthropogenic activities magnesium can be found in groundwater from agricultural activities and waste materials from urban disposals. Presence of magnesium is one of the reasons behind water hardness. High amount of magnesium can be found in seawater and presence of excessive amount of magnesium in groundwater indicates the possibility of sea water intrusion in groundwater. Consuming excessive amount of hard water creates cardiovascular diseases .
Presence of magnesium in groundwater of Kolkata highly varying in nature (Figure 9.11b). Minimum 10 mg/l has been observed and maximum it observed up to 140 mg/l. Average value of magnesium is about 53 mg/l. In ten years of timespan. In most of years average values are above median value. Presence of magnesium highly varied in 2011 and 2019. According to Indian standardisation, acceptable limit is 30 mg/l, and almost every year every observed location has crossed the acceptable limit and some of the observed locations crossed the permissible limit without any alternative hydro chemical parameters in years like, 2010, 2011, 2016, 2017 and 2019. Absurd values breaking the common pattern have been identified for 2015. Available amount of magnesium in groundwater showing an increasing tendency after 2015.

Sodium (Na^{+})

Presence of sodium in groundwater can be observed due to various reasons. Mainly sedimentary rock and minerals are the ultimate resource for available sodium in groundwater. Along with these, various anthropogenic activities lead to contamination of sodium with groundwater. Excessive amount of sodium in groundwater indicates polluted nature of groundwater. Weathering characteristics of geology or it is directly defines the position of sea water intrusion. Sodium is an essential element for human body but excessive amount of intake through water can lead to hypertension which is harmful for health of the heart. Limitation has not prescribed for sodium but higher amount of sodium in water creates salty in taste and it automatically rejects the usage for drinking purpose. WHO has prescribed a limitation of Na with 200 mg/l.
From the available data, it can be observed that, maximum amount of sodium has been identified in observed location with value of 387 mg/l whereas, for minimum its value is near about 10 mg/l (Figure 9.11c). Average value in ten years is about 165 mg/l which defines a presence of significant amount of sodium in groundwater that makes groundwater of Kolkata as salty in nature. From 2010 to 2013 average amount has been consistent but after 2015 a decreasing pattern observed for consecutive years. Diversity in observed locations are highest in 2016 and minimum variation has been observed in 2010.

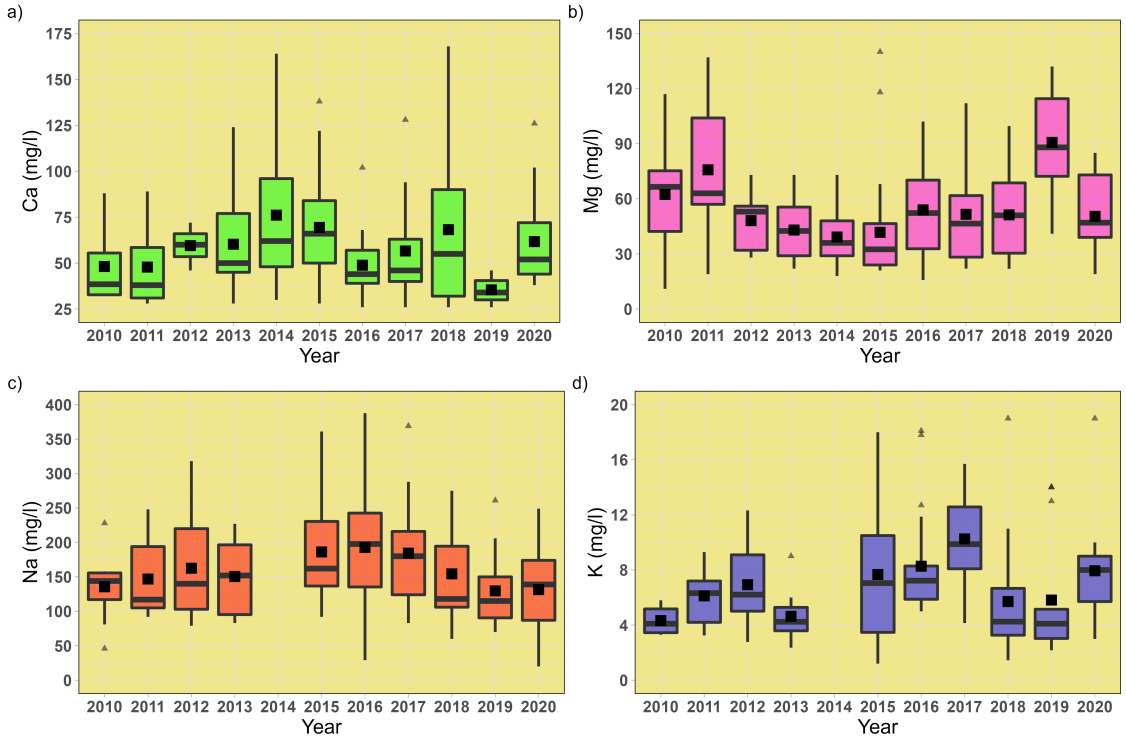


Figure 9.11. Boxplot showing cations available in groundwater of Kolkata (2010-2020), black square showing average value every year, black horizontal line with the box showing median value, boundary of the box showing 1st and 3rd quartile value respectively, extended vertical lines showing minimum and maximum values and black triangles showing absurd values observed in that year

Potassium (K^+)

Potassium is naturally available resource in groundwater. Its presence is observed due to weathering of rocks and minerals. Potassium in drinking water is not classified as in polluting or harmful substance. Usually in municipal water treatment plant, extra treatment also not applied to remove potassium from groundwater.
In ten years average value has been identified as about 8 mg/l where maximum value observed up to 19 mg/l (Figure 9.11). Parallelly minimum value was 1.20 mg/l. Most of the years showing minimum variation in values but 2015 is an exceptional year where high inequality has been observed abruptly. Contamination from groundwater recharge source those are distant from the city could be one of the reason behind high amount of concentration of magnesium in Kolkata.

Chloride (Cl^-)

Chloride is a naturally occurring ion that can be observed in freshwater and salt water. Sodium chloride and magnesium chloride are the common source of chloride in groundwater. Available Cl in fresh groundwater ranges within 1000 mg/l, whereas concentration of chloride in sea water is about 19,000 mg/l. Chloride level changes within 20 to 30 mg/l in groundwater but abrupt change in chloride level alarms the possible sign of sea water intrusion in groundwater. Nominal intake of chloride in the form of sodium chloride is harmless but consumption in excessive

amount can lead to be harmful. Chloride concentration within 250 mg/l in India as permissible for drinking purpose.
Availability of chloride in groundwater in different places are highly fluctuating and holds a wide range. Average value of chloride, almost every year crossed the permissible limit marginally. In 2011, 2014 and 2020, tendency of available Cl in groundwater reached more than 600 mg/l in certain places. Concentration range for Cl was minimum in 2015. Lately concentration of available Cl are widely varying in nature. Highly varying nature of Cl concentration in groundwater reveals the alarming possibility of sea water intrusion in groundwater of Kolkata.

Sulphate (SO_4^-)

Sulphate is a common anion found in surface water and groundwater. Along with naturally available from gypsum, sulphate is produced with combustion of fossil fuel in atmosphere and ultimately it contaminates with water resources. Local concentration of sulphate occurs from decomposition of organic matter, oxidation of sulphur bearing minerals and industrial deposition. Sulphate with minimum concentration is considered to be safe but more than 200 mg/l in drinking water proves to be really harmful as per Indian standards.
In ten years of observation, lower range of SO_4 concentration is limited within 25 to 30 mg/l parallelly higher ranges concentration reached up to 80 mg/l on an average (Figure 9.12a). Highest amount of observations have been found in 2011 and 2014. Range was minimum in 2016.

Fluoride (F^-)

Fluoride is another common substance that is available in groundwater. Usually, higher amount of fluoride concentration found in groundwater where igneous and metamorphic rocks are easily available. Volcanic eruptions are the ultimate source of fluoride but normally available amount fluoride is less compared to the other substances. According to drinking water standards prescribed by Indian government, permissible concentration should limit within 1.0 mg/l.
Very limited amount fluoride is available in groundwater of Kolkata (Figure 9.12c). Fluoride concentration in groundwater in all consecutive years remained within prescribed limits. Ranges varied highly between 2012, 2015 and 2018 and it was minimum amount for rest of the years.

Bicarbonate (HCO_3^-)

Bicarbonate is an important ingredient for human body and it is available in groundwater also. It is reported that water having pH level more than 7.5 usually consumes high amount of bicarbonate in groundwater. Weathering process is one of the important sources of available bicarbonate in groundwater. As it is good for health, no permissible measurement has been applied for it.
Available amount of bicarbonate in groundwater is 300 mg/l on an average within the observed period (Figure 9.12d). Range is minimum for bicarbonate in different locations compared with other available substances and available amount of HCO_3 is highest among other substances

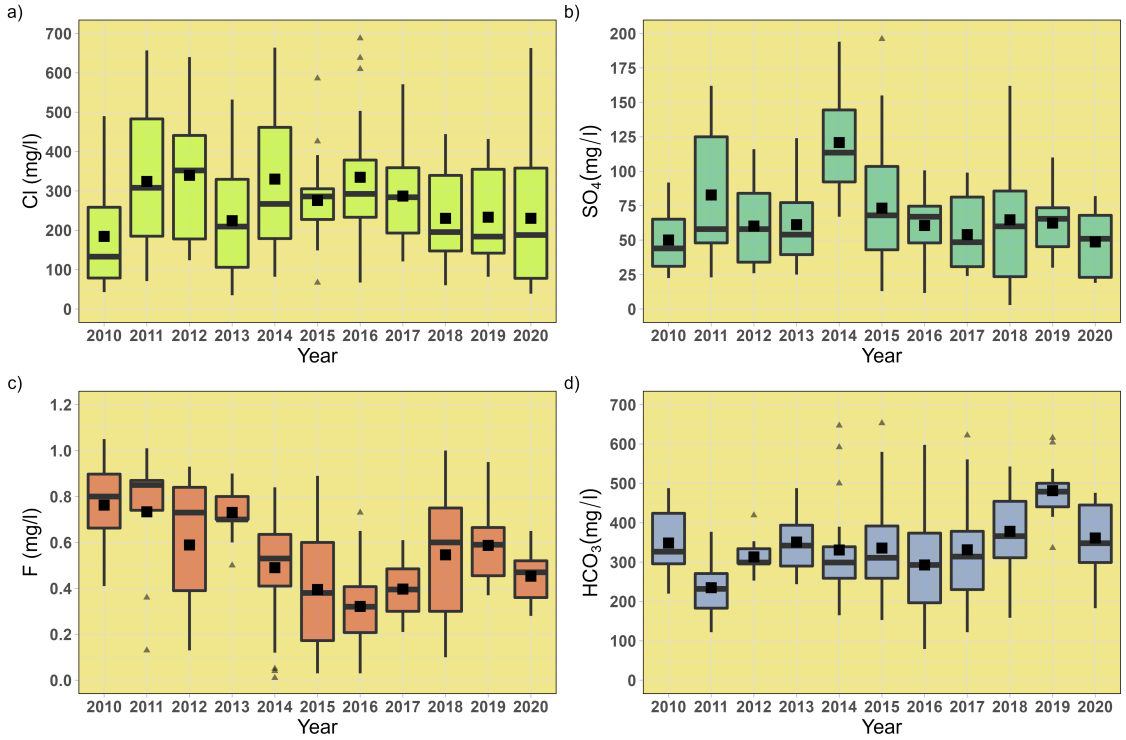


Figure 9.12. Boxplot showing anions available in groundwater of Kolkata (2010-2020), black square showing average value every year, black horizontal line with the box showing median value, boundary of the box showing 1st and 3rd quartile value respectively, extended vertical lines showing minimum and maximum values and black triangles showing absurd values observed in that year

present in groundwater of Kolkata. From 2010 to 2015, observed values were highly varying in nature but after 2015, a consistent increasing tendency has been observed till 2019. Overall, it has been observed that, concentration of bicarbonate in groundwater is increasing in Kolkata within specified observed time.

Electrical Conductivity (EC)

EC defines a physical property of groundwater quality and it measures the capability of water molecules to proceed an electrical current. The value of conductivity usually changes with availability of dissolved solids in water. Inorganic dissolved solids are anions like, Chloride, nitrate, sulphate and sodium, magnesium, iron like cations. Organic compounds like, phenol, alcohol, sugar etc. usually do not relate with conductivity. Such organic presence keeps low value of conductivity. It is usually termed as electrical conductivity. The electrical conductivity of water is the conductance per length and equals the inverse of the electrical resistivity. It usually ranges from a few tens to thousands in µS/cm in groundwater. A wide range of natural water usually holds a constant of 0.55 to 0.75 µS /cm. EC (Electrical Conductivity) mainly depends on the availability of TDS in water (Fitts 2013). Value of electrical conductivity is highly varying in nature. EC ranges between 500 µS/cm in fresh groundwater and in saline sea water value is above 6000 µS/cm at 25°C.

EC in groundwater level is generally above 1000 µS/cm. Average value of available EC varies from place to place. In 2014 and 2019, range of EC in groundwater was highly variable. A tendency of increasing pattern in EC concentration has been observed in the study area (Figure 9.13a).

Total Hardness (TH)

The term *hard* used for water applied from Hippocrates (460-354 B.C.) Divalent metallic cations present in ion of calcium and magnesium are present in groundwater that results hardness. These ions react with detergent to create precipitates and with certain anions existing in the water to form scaly deposits. Hardness in water can be caused by precipitation also.

$$H_T = Ca \times \frac{CaCO_3}{Ca} + Mg \times \frac{CaCO_3}{Ca} \tag{9.2}$$

Where, TH ,Ca and Mg are measures in milligrams (ml) per litre. Hard water is not beneficial for domestic purpose as it creates a scaly deposit on the inside pipelines and warer bearing tanks (Todd & Mays 2005). It takes huge cost to soften the hard water.
In India hardness is calculated based upon available $CaCO_3$ in groundwater and 200 mg/l has been selected as permissible limit for drinking water with hardness component. Presence of $CaCO_3$ defining the hardness of water is fluctuating in nature for Kolkata in between observation period. Average hardness in groundwater decreased consecutively in the beginning but along with time it further increased (Figure 9.13b). It is showing an increasing pattern in hardness for groundwater of Kolkata. All over the years, average value of total hardness crossed the level of permissibility. It has reached two to three times more than permissible limit in some locations. Range of available hardness was maximum in 2013 and it was minimum in 2012.

Total Dissolved Solids (TDS)

Water naturally contains mineral ions. Soil particles, rocks and sediments are the main source of it. Usually, these dissolves in water through its way. These are solids in nature and defined as dissolved solids. Precipitation can also add ions to water in the process. Dissolved materials list is large enough. Broadly it is divided into major & minor constituents, and trace elements. These mass of dissolved constituents in the water is referred to as total dissolved solids (TDS) concentration (Harter, 2003). Source of high concentration of TDS is found in groundwater because of leaching from soil and salts. Domestic sewage with long time also percolate into subsurface environment. Naturally concentration of TDS varies between 70 mg/l to 6000 mg/l. TDS concentration less than 300 mg/l is excellent for drinking purpose. It has been observed that value of TDS relate to the value of electoral conductivity. Both can be correlated using the equation

$$TDS\ (mg/l) = k_c \times EC\ (\mu S/cm) \tag{9.3}$$

Where, k_c is the correlational factor typically, ranges between 0.5 to 0.8. From the available data it has been observed that, in this study area correlation factor is about 0.6.

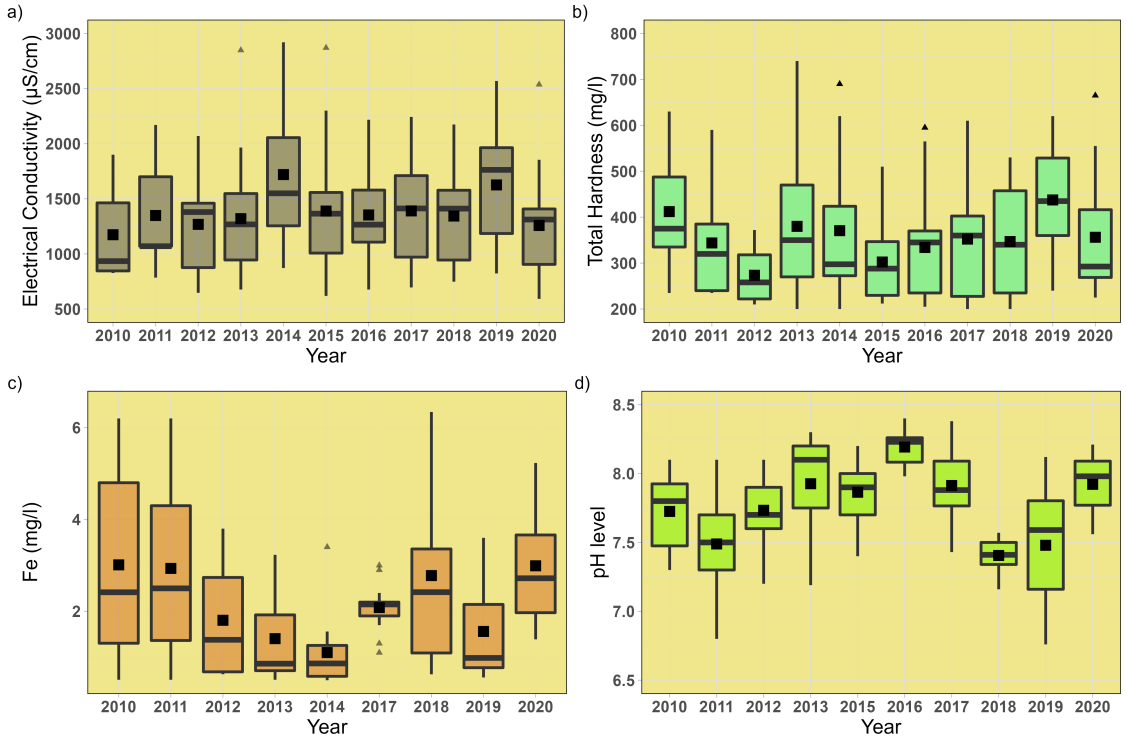


Figure 9.13. Boxplot showing chemical properties available in groundwater of Kolkata (2010-2020),black square showing average value every year, black horizontal line with the box showing median value, boundary of the box showing 1st and 3rd quartile value respectively, extended vertical lines showing minimum and maximum values and black triangles showing absurd values observed in that year

Iron (Fe)

Concentration in groundwater generally depends local rock formation. Iron usually available on groundwater in three possible forms; in non-visible ferrous form, insoluble ferric form and as iron bacteria. With the movement of groundwater some iron dissolves through erosional process. Certain amount iron is necessary for human body but excessive amount of iron can be harmful. According to Indian standards permissible limit of iron has been set within 0.3 mg/l.
It has been observed in Kolkata, excessive amount of iron is present in groundwater in various parts of Kolkata. Almost in every places under the boundary, available amount of iron in groundwater crosses the prescribed limit. It has been observed that, in 2010, iron concentration was in excessive amount with a variant range (Figure 9.13c). In next years amount of available iron reduced significantly but after 2017, it increased consecutively. In 2010, 2011 and 2018, it reached up to 6mg/l in some the locations in Kolkata which about twenty times greater than permissible limit.

pH level

The carbon dioxide-bicarbonate-carbonate equilibrium system usually controls the pH level of water, which is a gauge of the acid-base balance. In natural water, the pH is regulated by this

system. When there is a rise in the concentration of carbon dioxide, the pH level lowers, and when there is a decrease, it increases. Probably pH by far it is the most important physiochemical parameter that defines the characteristics of water quality. The hydrogen ion activity of a solution is represented by the negative common logarithm of its pH:

$$pH = -Log(H^+) \tag{9.4}$$

In dilute solutions, the hydrogen ion activity is approximately equal to the hydrogen ion concentration (W.H.O, 2007). The range of pH availability in water should range between 0-14. Value 7 represents neutrality in water. Value less than 7 represents acidic components and more than 7 represents basic components in water. Drinking water usually ranges between 6.5 to 8.5 prescribed by W.H.O. With one unit change in pH of 6 has 10 times more hydrogen ions than water with a pH of 7. Water with basic nature can form scale and water with acidic characteristics generates corrosion. In this study area, pH level is above 7 from all over the observational period (Figure 9.13d). It defines, definitely groundwater is basic in nature. Amount of pH is highly varying nature here, where in between 2015 to 2017 it reached upto 8.2 value but with time it decreased and again it increased after 2019.

9.7.2 Decadal changes in physio-chemical parameters (2010-2020)

After the detailed description on individual physio-chemical parameters for a decade a summary has been produced to understand the general characteristics of groundwater quality of Kolkata in the last decade. Descriptive statistical analysis has been produced to idealise a concept about physio-chemical properties of groundwater in Kolkata. Highly varying nature has been observed for every individual parameter. Every year concentration of chemical parameters differed for every individual location also. Establishment of a definite pattern through these limited data have been a complex task for this city at least for last decade (2010-2020) (Appendix, Table 23). Availability of Cl are highly variable with a minimum availability of 35 mg/l to maximum of 757 mg/l in ten years. Though mean of available Cl is about 275 mg/l where 50% of the observed value lies near to 265 mg/l which cross the permissible limit. Availability of F in groundwater of Kolkata is lowest among all other parameters with average of 0.50 mg/l and present within satisfactory range . Amount of SO_4 are highly variable in ten years where range is about 207 mg/l and it is cross the permissible limit in most the year which initiates an alarming situation. Same scenario has been observed for the case of HCO_3, it is signifying highly variable range with minimum value of 80 mg/l to maximum of 720 mg/l. Range of available Ca and Mg are also high but observed amount in a decade are comparatively lower than SO_4 and HCO_3. Available amount of Na are highly variable as maximum amount of Na is about 390 mg/l where minimum value is about 20 mg/l. Presence of K in groundwater is comparatively lower than any other hydro chemical parameters except F. It can observed from the descriptive statistics that in Kolkata, accumulated value of anionic components are comparatively higher than cationic components. HCO_3 is mostly available hydro chemical parameter in groundwater of Kolkata and Cl comes after it. Minimum EC in this decade was about 600 S/cm and maximum it observed

upto 2900 S/cm. TH i.e., mainly composed of Ca and Mg also highly variable like these two components. Situation available pH also varied in this decade with an average value of 7.8.

Table 9.1. Descriptive statistics of physio-chemical parameters of groundwater for Kolkata (2010-2020)

Parameters	Mean	Standard Deviation	Median	Minimum	Maximum	Range
Anions						
Cl	274.54	151.60	264.16	35	757	722
F	0.50	0.25	0.485	0.03	1.27	1.24
SO_4	64.58	38.67	57.5	2.9	210	207.1
HCO_3	346.30	125.43	329.2	79.3	720	640.7
Cations						
Ca	53.37	29.02	46	10	168	158
Mg	54.66	29.26	49.41	11	140	129
Na	164.06	71.62	149.5	20	387.6	367.6
K	7.09	3.90	6	1.2	19	17.8
EC	1364.16	483.57	1338	592	2870	2278
TH	324.70	130.70	295	110	740	630
pH	7.82	0.37	7.9	6.76	9.11	2.35
Fe	1.70	1.65	1.14	0.05	8.3	8.25

9.7.3 Correlation between individual parameters

Correlation between individual chemical and physio chemical properties has been identified based on Pearson's correlation coefficient (Eq. 9.5); where, correlation (r) between two variables can be identified within a range of -1 to +1. Within this range value of r towards -1 reflects strong negative correlation value of r towards +1, reflects positive correlation and value close to 0 reflects neutrality between two variables. It can be calculated following the equation:

$$r = \frac{\sum (x_i - \bar{x})(y_i - \bar{\bar{y}})}{\sqrt{\sum (x_i - \bar{x})^2 \sum (y_i - \bar{\bar{y}})^2}} \tag{9.5}$$

In this study, chemical properties of groundwater data have been collected for the year 2010 and 2020. Correlation between individual chemical parameters has been identified separately following the equation and correlational matrix has been created for each year. Further changes in correlation within a decade also identified (Figure 9.14) .

Scenario in 2010 It has been identified that, presence of Ca and Mg are positively correlated and both are highly correlated with TDS and TH positively. Simultaneously negatively correlated with other anions like F, HCO_3 and with pH level also. Na positively correlated with pH

level, SO_4 and Fe and negatively correlated with F and TH. and individually Na is not related with HCO_3 and TDS. Available amount of Fe is positively correlated with Na and negatively correlated with F and SO_4. Individually, Cl is high positively correlated with Ca and Mg created a highly positive correlation with TDS and TH and significantly negative correlation with HCO_3. Available F is almost negative with all other individual chemical parameters. SO_4 shares a high positive correlation with Na and pH level and strong negative relation with F. HCO_3 shares a high positive correlation with pH level and negative correlation with other parameters. TDS shares a positive correlation with cations like Ca and Mg and anions like Cl. TH level positively correlating with Ca and Mg and negative correlated with pH level. pH highly correlated with Na and SO_4.

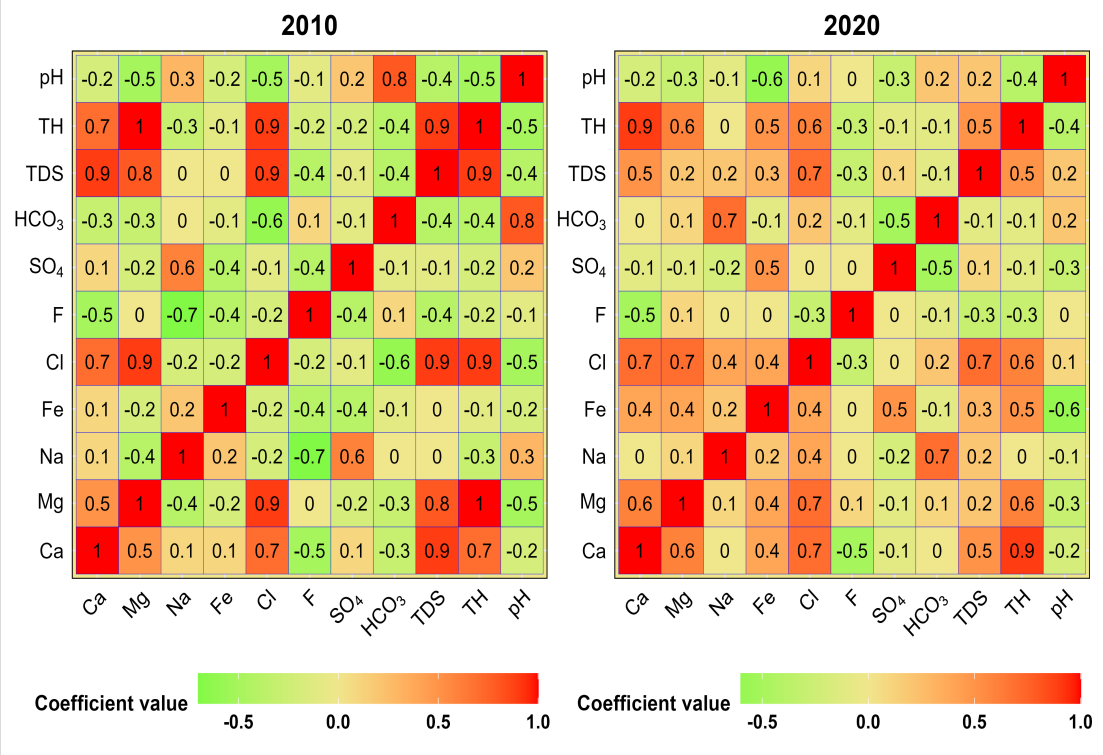


Figure 9.14. Correlation matrix showing correlation between major physio chemical parameters of groundwater of Kolkata for 2010 and 2020

Scenario in 2020 In 2020, it is observed that, Ca is highly correlated with Mg, Fe and Cl, consequently positive correlated with TDS and TH. parallelly Ca is negative with F. Correlation of Mg with other parameters are almost same like Ca except for F. Na maintained almost neutral relation with other parameters majorly but highly positive with HCO_3. Fe is positively or neutrally correlated with all other major components except pH. This situation is applicable for Cl also, it is positively correlated with Ca and Mg also with TDS and TH but negatively correlated with F. Whereas, F is either neutrally correlated or negatively correlated with other chemical components. HCO_3 is highly correlated with Na, positively but negative correlated with SO_4. TDS is negatively correlated with pH level, the situation is almost same for TH level

but for case of TH, it is negatively correlated with pH level. pH is negatively correlated with cations like Ca, mg and Na but positively correlated with anions like Cl and HCO_3.
Assessing both the years, it has been observed that, scenario of groundwater quality pointedly changed in between a decade. Positivity in correlation increased between Ca and other parameters like Na, HCO_3 and significantly decreased with Fe. In case of Mg, it has been observed that, positivity increased between Na and Mg also with SO_4, TDS and pH but hugely decreased with HCO_3. Correlation between Fe and other components like TDS, TH and pH decreased highly. Correlation of Cl with HCO_3 and pH increased sharply. Relation between Na and SO_4 increased notably. Relation became strong for HCO_3 with TDS, TH and pH level.

9.7.4 Seasonal variation in groundwater hydrochemistry

Physiochemical properties of groundwater vary with change in groundwater flow. It is also dependent on recharge and discharge process. Naturally properties of groundwater change with seasons but anthropogenic activities are crucial factor also. In this chapter, seasonal change in physiochemical properties have been identified. For this process data have been taken from SWID (Appendix, Table 25). From the provided data, 2011, has been selected to analyse seasonal changes in chemical properties of the groundwater. Data have been collected from various locations within Kolkata for the month of April and November. Primarily, rainfall is crucial factor in groundwater analysis. So, here seasonal changes have been defined with changes in individual parameter by before and after the monsoon. Both of the time frame has been renamed as pre monsoon and post monsoon. Major physiochemical parameters that create a definite impact on groundwater quality those have been selected for further analysis. Further spatial distribution of the parameters have been visualised maintaining its unit as given (Figures 9.15 and 9.16) .
It has been observed from 2011, that, pH level remains low in overall Kolkata at pre monsoon whereas after rainfall pH value increase in overall Kolkata specifically in southern part of Kolkata pH value remains high. With high value in pH level groundwater quality becomes base in nature after rainfall. Addition of Ca, Mg, Na in water after rainfall creates groundwater more basic in nature than pre monsoon.
Specific conductivity defines collective concentration of ion in groundwater. Specific conductivity highly varies in Kolkata. In the western part it remained high throughout the year. After monsoon, concentration of specific conductivity remain unchanged except in the south-eastern part of Kolkata. Collective ion concentration increased in south eastern part of Kolkata after the monsoon.
After monsoon, high variability observed in the values of HCO_3. In pre monsoon, available bicarbonate ranged within 300 to 1000 ppm all over in Kolkata. After monsoon, concentration of bicarbonate increased specifically upto 2000 ppm in specific areas of north-western part of Kolkata. Southern part of Kolkata remained unchanged after rainfall.
TDS defines total dissolved solids present in groundwater. Here in Kolkata in 2011, TDS concentration was extremely high in western part of Kolkata and TDS concentration was moderately high in northern part of Kolkata in pre monsoon. In post monsoon scenario changed for northern

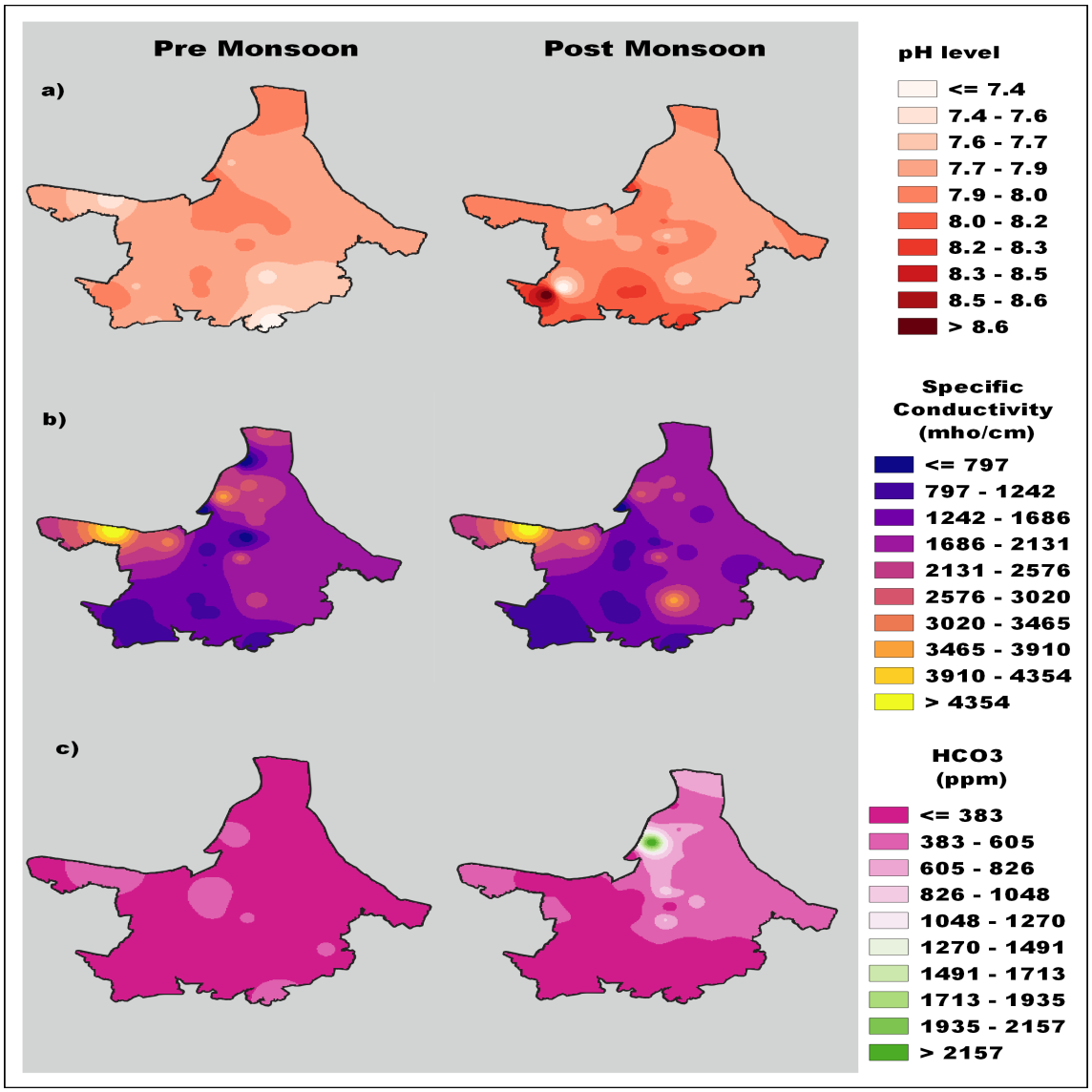


Figure 9.15. Spatial variation in hydrochemical properties of groundwater in premonsoon and postmonsoon period (2011); source: SWID

and south-eastern part of Kolkata. TDS concentration increased in south eastern part where it deceased in northern part in Kolkata after monsoon.

TH defines total hardness in water specifically it is calculated upon available amount of $CaCO_3$. It is observed that, overall situation turns better after monsoon in case of TH concentration. In pre monsoon, TH remains high in western and northern part of Kolkata, It is high also in south eastern part of Kolkata.TH level remains low only in south western part of Kolkata. Whereas in post monsoon, TH concentration turns better in whole eastern part of Kolkata. TH level remains high only in western part and specific locations of south east part of Kolkata. Throughout the year TH is concentration remains in better position compared to the other parts of Kolkata.

Available amount of Chloride changes with monsoon in Kolkata. Before the monsoon concentration of Cl remains low on an average throughout the Kolkata. After monsoon concentration of Cl increase all over the Kolkata. Western part of Kolkata remains high in Cl concentration all

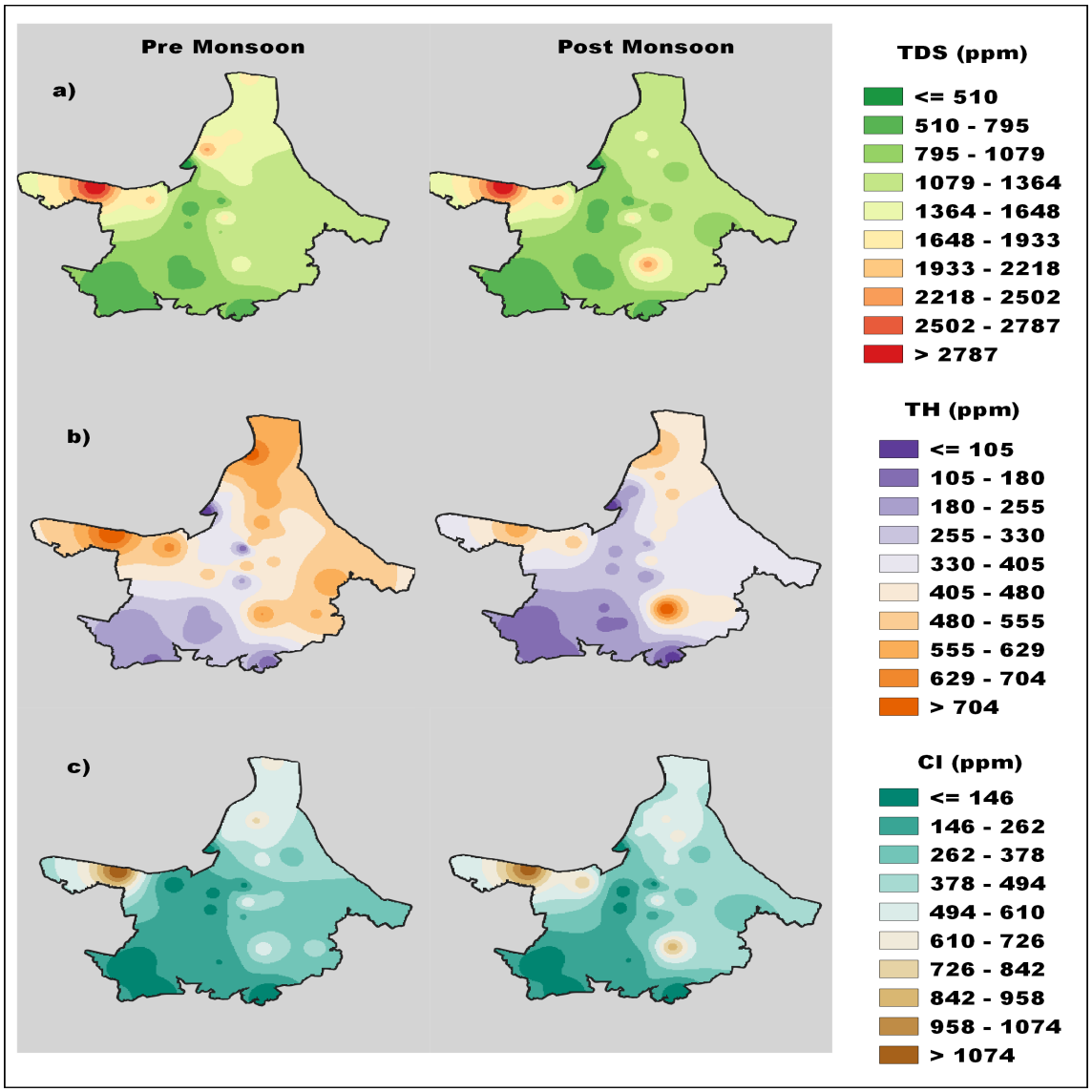


Figure 9.16. Spatial variation in hydrochemical properties of groundwater in pre monsoon and post monsoon period (2011); source: SWID

over the year but in post monsoon Cl concentration increase in southern eastern part. Throughout this observation it is noted that, chemical properties of groundwater certainly change with seasons, monsoon create a definite impact upon the concentration of individual parameter. Groundwater quality changes to a better position after monsoon. It has been identified that, overall groundwater scenario is alarming in western and south eastern part of Kolkata. Whereas, groundwater chemical properties remains highly variable according to seasons in northern part of Kolkata and groundwater quality is better in southern part of Kolkata and mostly it remains unchanged after the effect of rainfall in groundwater.

9.7.5 Hydro-chemical facies of groundwater

Hydrochemical facies represents the characteristics of chemical processes occurring between the minerals with lithologic conditions and the groundwater. Changes occurs with flow pattern of groundwater. Piper (1944) outlined graphical diagram to analysis dissolved constituents in water. Three trilinear plotting diagram defined chemical properties of water. It is widely used method to analysis the nature of groundwater. It is to be reminded that, it represents comparative concentration rather than absolute concentration. Major components with characteristics of anion and cations, are used in Piper diagram. Generally, Na^+ and K^+ are primary alkaline cations; Ca^+ and Mg^+ are alkaline earth cations. $S0_{4^-}$, Cl^- and NO_3^- represents as strong acid and CO_3^- and HCO_3^- represents as weak acid. In this section, chemical properties of groundwater data selected from ten different locations around Kolkata in two different year i.e 2010 and 2020 (Appendix, Table 24). Next, collected datasets have been presented through piper diagram to identify the hydrochemical facies of the study area with a gap of a decade.

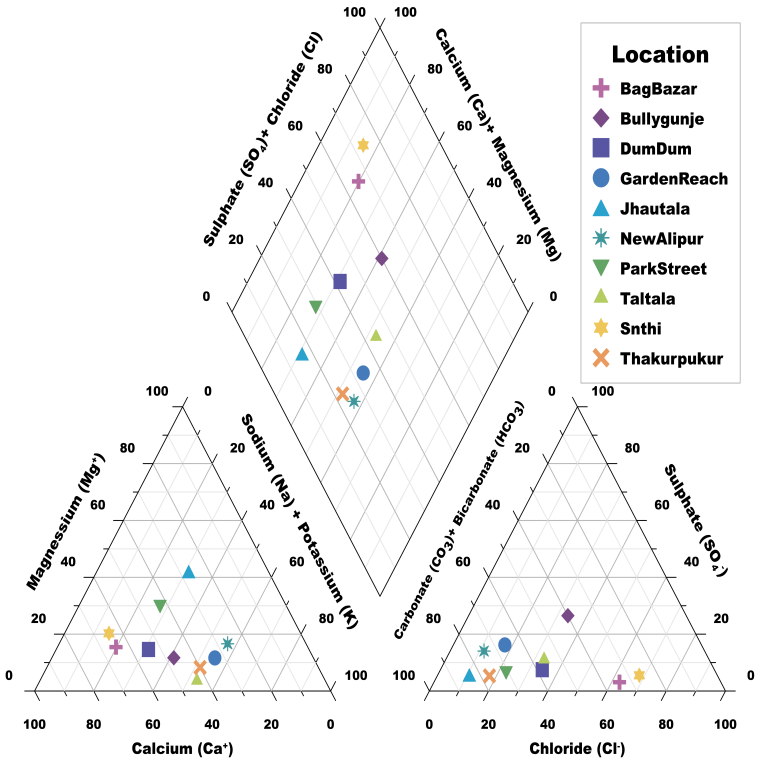


Figure 9.17. Piper trilinear diagram showing the hydrochemical characteristics and hydrochemical facies of the groundwater based on the hydrochemical data for 2010

Situation in 2010 It has been observed from the figure that, in 2010, Ca type groundwater was available at Bagbazar,and Sinthi; Na and K type groundwater was available at New Alipur, Garden Reach, Thakurpukur and Taltala. Cl type groundwater was available at Sinthi, Bagabazar and rest of the Kolkata was having CO_3 and HCO_3 type of chemical property. Overall, in Dum Dum, Park Street and Jhautala groundwater was Mg-HCO_3 type. At sinthi it was Ca-Cl type.

Rest of the Kolkata was having mixed type of hydrogeochemical properties. Groundwater of Bullygunge, Bagbazar, and Sinthi were with strong acid properties (Figure 9.17).

Situation in 2020 In next ten years, in 2020, Mg-HCO_3 type of groundwater observed in Bidhanngar and its surrounding area, where as Na-HCO_3 type of groundwater found in Thakurpukur, Jahutala and Kundghat area. Na-Cl type of groundwater found in Maniktala nd Rajabazar area. and rest of the area with mixed type of groundwater properties. Weak acidic quality found in Bidhannagar, Nagaerbazar, Bagabazar, Jahutala, Kundghat, Thakurpukur and Belghata area. where as strong acidic nature of groundwater found in Maniktala and Rajabazar area. Water properties of Nagarbazar and Bidhannagar was alkaline in nature and rest of the areas was having alkalie type of groundwater.Na and K type of cations were dominant in all over the Kolkata.Cl type of groundwater quality was dominant in Razabazar and rest of the areas were bicarbonate type (Figure 9.18).

Chemical properties of groundwater changed within a time of ten years. Mainly groundwater

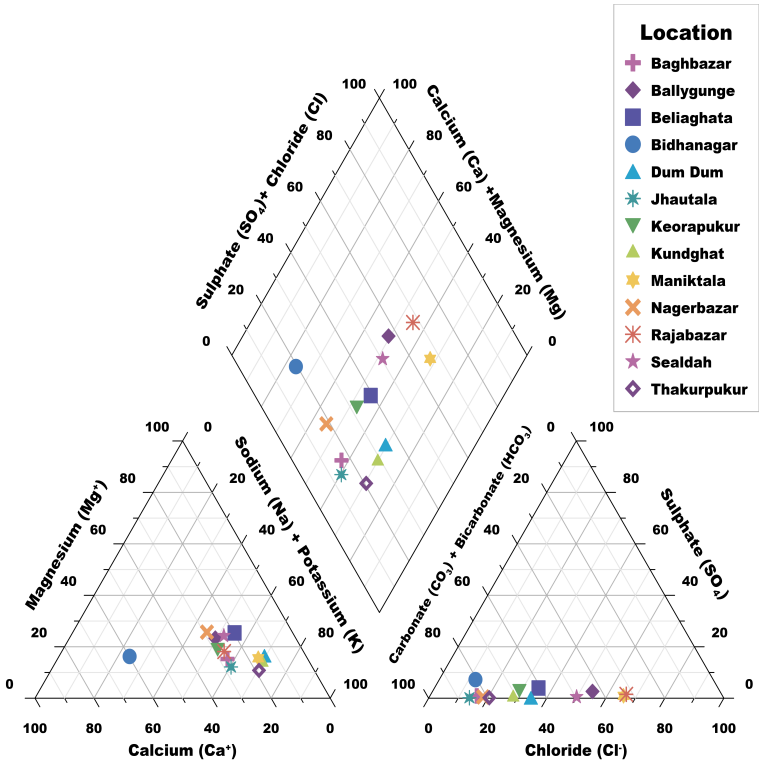


Figure 9.18. Piper trilinear diagram showing the hydrochemical characteristics and hydrochemical facies of the groundwater based on the hydrochemical data for 2020

type changed from Mg-HCO_3 type to Na-K-HCO_3 type. Dominance of sodium potassium and bicaronate increased in between ten years. Mainly groundwater properties changed in the southern part of Kolkata. Presence of Cl and Ca reduced with time. Groundwater properties majorly changed from strong acidic to weak acidic in nature and alkali proponents increased in between.

9.7.6 Water quality analysis

Groundwater chemistry is used as tool to overview water quality of an area. Various Hadro-chemical parameter interact with each other in groundwater and with the flow of groundwater, individual chemical parameter concentration differs within aquifer. Thus, water quality vary from place to place. Water quality certainly depends on available concentration of individual parameter, simultaneously combined effect of every individual parameter create a combined effect on overall quality of groundwater. WQI is common tool that is being used to analyse the water quality of an area. WQI generates comparative values based on used parameter for analysis and water quality of an area. It majorly describes the quality relative to other location. Much useful and valuable information about water quality gets lost during the WQI calculating process as the weight of each parameter is typically given by experts based on their practical experience, making it subjective.(Amiri, Rezaei, and Sohrabi, 2014). In this study, entropy weighted water quality index has been used for comparative understanding about the water quality of different locations in Kolkata.

For EWQI analysis, several hydro chemical parameters have been used. Water quality param-

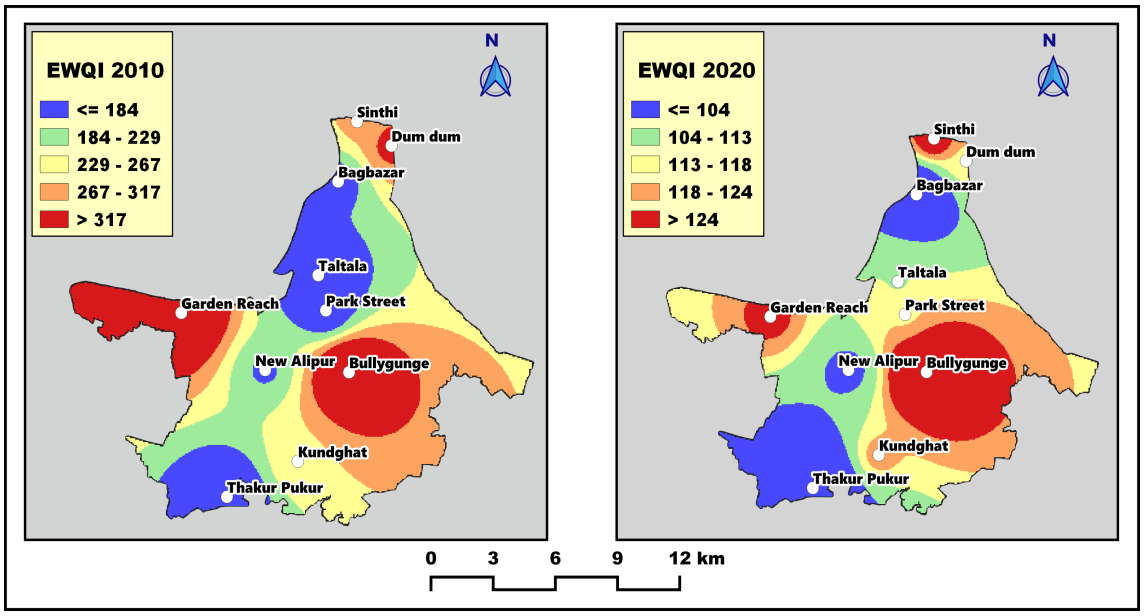


Figure 9.19. Entropy based water quality analysis for the year 2010 and 2020 showing water quality of major locations in Kolkata

eter prescribed by BIS 10500 (2012) and approved by CGWB, selected for further analysis (Appendix, Table 26). Based on available data for 2010 and 2020, total nine parameter have been selected for water quality analysis. Selected parameter are Ca, Mg, Na, Fe, Cl, F, SO_4, TDS and TH. From all these parameter, selection of Fe is quite uncommon, but it has been considered as one of the parameter as previously in this chapter, it has been observed that, high amount Fe is already present in groundwater of Kolkata and it is assumed that such high concentration of Fe certainly makes an impact on groundwater quality. Due to paucity of needful data, EWQI has been analysed based on selected ten major locations of Kolkata where Bagbazar, Dum Dum,

Sinthi, represents the northern part of Kolkata, Garden Reach and New Alipur represents the western portion of Kolkata, Park Street and Taltala represents central portion of Kolkata and Bullygunge, Kundghat and Thakurpukur represents the southern part of Kolkata. It is to be noted that, low value in EWQI reflects better water quality of a location compared with other locations and high values of EWQI represents the opposite. Further based on EWQI values for each year, ranking has given to each of the locations and based on the ranking spatial changes in water quality has been analysed and visualised using IDW method.

In the time of individual weightage calculation, difference has been observed between ten years. Weightage of Ca, Mg and Fe and TH reduced in ten years and weightage of Na, Cl, F, SO_4 and TDS increased in between 2010 and 2020. It is noteworthy to mention that, weightage of Fe reduced drastically with difference of ten years whereas, weightage of SO_4 increased two times than preceding year 2010.

In 2010, water quality of the central part was better than other regions of Kolkata northern part were after the central part. Water quality of central part of Kolkata was not appropriate at it was worse on the western part of Kolkata. Groundwater in southern and western part was not suitable for drinking, high amount of iron, chlorine and calcium chloride were the reason behind the degraded water in that part of Kolkata. In 2020, water quality in southern part got better even groundwater quality developed in western portion of Kolkata also but overall degradation has been observed in southern and central part of Kolkata compared to 2010.

Ranking wise it has been observed that, groundwater quality developed in Bagbazar and Dum Dum from the northern side but deteriorated in the extreme northern side of Kolkata specifically in Sinthi. Groundwater quality developed in Gardern Reach and New Alipur also but severely deteriorated in central part of Kolkata in ten years. Groundwater quality in Bullygunge and Kundghat also were not satisfactory rather it degraded within a decade but overall water quality of extreme southern portion specifically in Thkaurpukur remained in comparatively good quality compared with other major locations in Kolkata.

EWQI and IDW

Understanding of an area based on single water quality parameter can create biasses and unrealistic result. Thus, researchers have created a water quality index to represent overall quality of water as a function of numerical values. Several methods have been adopted for this calculation. Parameter also been varied in studies. In this chapter, Entropy weighted water quality index has been followed. Valuable and fruitful results have been found following this method (Amiri et al. 2014; Subba Rao et al. 2020; Ukah et al. 2020). In this method, an evaluation matrix must be created with collected number samples with each parameter. Where groundwater quality data will be for "m" samples along with "n" number of parameter (Su et al. 2018):

$$X = \begin{vmatrix} x_{11} & x_{12} & \dots & x_{1n} \\ x_{21} & x_{22} & \dots & x_{2n} \\ x_{m1} & x_{m2} & \dots & x_{mn} \end{vmatrix} \tag{9.6}$$

In the next step, standardization process must be followed to remove the influences of magnitude and dimensions with following equation:

$$y_{ij} = \frac{x_{ij} - (x_{ij})min}{(X_{ij})_{min} - (x_{ij})_{min}} \tag{9.7}$$

After the standardization process, now the standard grade matrix Y can be generated.

$$Y = \begin{vmatrix} y_{11} & y_{12} & \dots & y_{1n} \\ y_{21} & y_{22} & \dots & y_{2n} \\ y_{m1} & y_{m2} & \dots & y_{mn} \end{vmatrix} \tag{9.8}$$

Next, information entropy(e_j) is calculated following the equations(Su et al. 2018)

$$e_j = -\frac{1}{Inm} \sum_{i=1}^{m} P_{ij} ln P_{ij} \tag{9.9}$$

$$Where, P_{ij} = \frac{(1 + y_{ij})}{\sum_{i=1}^{m} (1 + y_{ij})} \tag{9.10}$$

Computation of entropy weight(w_j) and quality rating scale(q_i) can be done using following equations:

$$w_j = \frac{(1 - e_j)}{\sum_{i=1}^{m} (1 - e_j)} \tag{9.11}$$

$$q_j = \frac{C_j}{S_j} \times 100 \tag{9.12}$$

Where, C_j is the concentration of chemical parameters j (mg/l) and S_j is the permissible limits of Bureau of Indian standards (BIS: 2012) of parameter j (mg/l). Thus, the ultimate equation can be generated as:

$$EWQI = \sum_{j=1}^{m} w_j q_j \tag{9.13}$$

Spatial mapping process with Inverse Distance weighting Along with numerical values, for each parameter and collective water quality index parameter it is needful to visualise the groundwater quality scenario. For this process inverse distance weighting method (IDW) has been applied. IDW helps to find out nearby unknown values appropriately using known values of a certain location. As point data have been used in this process it is needful to identify unknown values for other points for the purpose of spatial mapping. IDW follows the equation:

$$\lambda_i = \frac{D_i^{-\alpha}}{\sum_{i=1}^{n} D_i^{-\alpha}} \tag{9.14}$$

Here, λ_i is the weight of an unknown location, D_i is the distance between point i and the unknown location, α is the power of ten of weight. In this process, higher weight will be generated against lesser power. In this study, IDW has been used to generated spatial maps using QGIS 3.16 software.

9.8 Conclusion

Groundwater resource analysis is dependent on a wide range of detailed ground-based data. For the case of this study area, it is not sufficient. Detailed historical data are needed for analysis of the actual scenario which is not updated in the authorised organisation even some of the datasets are contradictory to each other. Erroneous data in the datasets misled the analysis sometimes. In this study, minutely all the data have been curated and cross-checked and verified with alternative datasets.

Geologically, a thick clay layer at the top of the soil layer is preventing groundwater recharge assuming a porosity of 0.2. Already incidences of land subsidence have been observed in several parts of the city. Adjoining areas of K.M.C (about 52% of the area of KMA) are dependent on groundwater resources that ultimately create an impact on the groundwater of Kolkata also. Heavy pumping in the flat lowland of Kolkata declined the groundwater level abruptly. Before the observation period in this study, already excessive groundwater recessions were observed in the southwestern part of Kolkata. Gradually northern part of Kolkata is at an alarming position. Here, the groundwater level is positively correlated with the amount of precipitation. Spatial differences in groundwater level and quality are prominent in this study area. Landfill area creates a definite negative impact on the quality of groundwater. Percolation from surface water sources like canals also participates in exploiting the groundwater quality in Kolkata.

From the satellite data, it has been observed that terrestrial groundwater storage is depleting

because of groundwater depletion at an increasing rate. From the collected data, it has been observed that the groundwater level of Kolkata is in a much lower state than the adjoining districts having almost the same characteristics as the aquifer environment. With every decade groundwater level is depleting constantly but in three decades of observation period depleting nature of spatial variation is prominent. Analysing, yearly data for consecutive years of recent times, it has been observed that the range between the minimum and maximum value of groundwater level is increasing. The constant tendency of declining groundwater below the surface is distinguished from the observation.

The physio-chemical properties of groundwater in Kolkata are highly fluctuating in nature. An excessive amount of sodium and TDS in groundwater makes the water brackish in the major portion of Kolkata. Bicarbonate is the most observed substance in groundwater. The proportion of anionic components is more than the cationic components in the groundwater of Kolkata. High amount of pH level in groundwater results in scale deposits for groundwater and the presence of iron in an excessive amount directly impacts groundwater by creating a reddish colour. With the observation of ten years, it has been identified that groundwater type changed in between a decade. Majorly it was Mg-HCO_3 in 2010 and it turned into Na-K-HCO_3. The highly varying nature of available substances constantly changes the type of water with time. Gradually, changes in the acidic nature of water and alkaline properties transform the water type. Obviously, with the effect of hydrochemical properties, a change in water quality was also observed in Kolkata. Western and southeastern portions of Kolkata are comparatively lower in quality than the extreme northern and southern parts of Kolkata.

Overall groundwater quality of Kolkata is not recommendable for drinking. It can be used for other domestic purposes rather than drinking. The chemical properties of groundwater indicate the possibility of seawater intrusion in the aquifer beneath Kolkata. As prescribed by CGWB, Kolkata is under a double restricted zone and groundwater resources of Kolkata are in critical condition; groundwater abstraction is strictly prohibited here. Besides such strict laws and regulations, without intimating the official authorities groundwater being abstracted for years from the subsurface environment. Overall groundwater resources of Kolkata are at a vulnerable stage.

References

Ali, S. A., & Ahmad, A. (2020). Analysing water-borne diseases susceptibility in Kolkata Municipal Corporation using WQI and GIS based Kriging interpolation. *GeoJournal*, *85*(4), 1151–1174. Retrieved from https://doi.org/10.1007/s10708-019-10015-3 doi: 10.1007/s10708-019-10015-3

Banerji, S., & Mitra, D. (2019). Geographical information system-based groundwater quality index assessment of northern part of Kolkata, India for drinking purpose. *Geocarto International*, *34*(9), 943–958. Retrieved from http://doi.org/10.1080/10106049.2018.1451922 doi: 10.1080/10106049.2018.1451922

Bardhan, M. (2016). Depletion of Water Level and Environmental Threat in Urban Areas: A Case Study of Kolkata and Salt Lake City, West Bengal. In *Springer geography* (pp. 153–173). Springer. Retrieved from http://link.springer.com/10.1007/978-3-319-26443-1{_}11 doi: 10.1007/978-3-319-26443-1_11

Bhattacharya, A. K., & Kumar, D. (2012). Land subsidence in south calcutta. *IJRRAS*, *10*(2), 300–302.

Chakraborti, D., Das, B., Rahman, M. M., Nayak, B., Pal, A., Sengupta, M. K., ... Dutta, R. N. (2017). Arsenic in groundwater of the Kolkata Municipal Corporation (KMC), India: Critical review and modes of mitigation. *Chemosphere*, *180*, 437–447. Retrieved from http://dx.doi.org/10.1016/j.chemosphere.2017.04.051 doi: 10.1016/j.chemosphere.2017.04.051

Chatterjee, R., Fruneau, B., Rudant, J., Roy, P., Frison, P.-L., Lakhera, R., ... Saha, R. (2006, may). Subsidence of Kolkata (Calcutta) City, India during the 1990s as observed from space by Differential Synthetic Aperture Radar Interferometry (D-InSAR) technique. *Remote Sensing of Environment*, *102*(1-2), 176–185. Retrieved from https://linkinghub.elsevier.com/retrieve/pii/S0034425706000757 doi: 10.1016/j.rse.2006.02.006

Ghosh, S., Majumder, S., & Roychowdhury, T. (2019, dec). Assessment of the effect of urban pollution on surface water-groundwater system of Adi Ganga, a historical outlet of river Ganga. *Chemosphere*, *237*, 124507. Retrieved from https://linkinghub.elsevier.com/retrieve/pii/S004565351931731X doi: 10.1016/j.chemosphere.2019.124507

John, B., & Das, S. (2020a, oct). Identification of risk zone area of declining piezometric level in the urbanized regions around the City of Kolkata based on ground investigation and GIS techniques. *Groundwater for Sustainable Development*, *11*, 100354. doi: 10.1016/j.gsd.2020.100354

John, B., & Das, S. (2020b, oct). Identification of risk zone area of declining piezometric level in the urbanized regions around the City of Kolkata based on ground investigation and GIS techniques. *Groundwater for Sustainable Development*, *11*, 100354. Retrieved from https://linkinghub.elsevier.com/retrieve/pii/S2352801X19302322 doi: 10.1016/j.gsd.2020.100354

John, B., & Das, S. (2020c). Role of Electrical Conductivity on Salinity and Mineralization due to Groundwater Level Fluctuations in Kolkata City. *IOP Conference Series: Earth and Environmental Science*, *505*(1). doi: 10.1088/1755-1315/505/1/012021

Maity, P. B., Saha, T., Ghosh, P. B., & Chatterjee, D. (2002). The ground water quality status of waste disposal site in the eastern part of Kolkata - A case study. In *Sustainable environmental sanitation and water services: Proceedings of the 28th wedc conference.* Retrieved from https://www.researchgate.net/publication/331132351

Malakar, A., Islam, S., Ali, M. A., & Ray, S. (2016, oct). Rapid decadal evolution in the groundwater arsenic content of Kolkata, India and its correlation with the practices of her dwellers. *Environmental Monitoring and Assessment*, *188*(10), 584. Retrieved from http://link.springer.com/10.1007/s10661-016-5592-9 doi: 10.1007/s10661-016-5592-9

Mitra, D. (2019). Groundwater scenario in Kolkata metropolitan area. *Transactions of the Institute of Indian Geographers*, *41*(2), 217–225. Retrieved from https://iigeo.org/wp-content/uploads/2019/11/Transaction-41-2-5.pdf

Pal, A., Chowdhury, U. K., Mondal, D., Das, B., Nayak, B., Ghosh, A., ... Chakraborti, D. (2009). Arsenic burden from cooked rice in the populations of arsenic affected and nonaffected areas and Kolkata City in West-Bengal, India. *Environmental Science and Technology*, *43*(9), 3349–3355. doi: 10.1021/es803414j

Sahu, P., Michael, H. A., Voss, C. I., & Sikdar, P. K. (2013). Impacts on groundwater recharge areas of megacity pumping: Analysis of potential contamination of Kolkata, India, water supply. *Hydrological Sciences Journal*, *58*(6), 1340–1360. doi: 10.1080/02626667.2013.813946

Sahu, P., & Sikdar, P. K. (2011a, mar). Groundwater potential zoning of a peri-urban wetland of south Bengal Basin, India. In *Environmental monitoring and assessment* (Vol. 174, pp. 119–134). Environ Monit Assess. Retrieved from https://pubmed.ncbi.nlm.nih.gov/20437269/ doi: 10.1007/s10661-010-1443-2

Sahu, P., & Sikdar, P. K. (2011b). Threat of land subsidence in and around Kolkata City and East Kolkata Wetlands, West Bengal, India. *Journal of Earth System Science*, *120*(3), 435–446. doi: 10.1007/s12040-011-0077-2

Sikdar, P., Biswas, A., & Saha, A. (1996). A study on the possible land subsidence in Calcutta and Howrah cities due to groundwater overdraft. *Indian Journal of Geology*, *68*(3), 381–395.

Singh, R. K., Datta, M., Nema, A. K., & Pérez, I. V. (2013, jan). Evaluating Groundwater Contamination Hazard Rating of Municipal Solid Waste Landfills in India and Europe Using a New System. *Journal of Hazardous, Toxic, and Radioactive Waste*, *17*(1), 62–73. Retrieved from https://ascelibrary.org/doi/10.1061/{%}28ASCE{%}29HZ.2153-5515.0000145 doi: 10.1061/(ASCE)HZ.2153-5515.0000145

Suganthi, S., & Elango, L. (2020, dec). Estimation of groundwater abstraction induced land subsidence by SBAS technique. *Journal of Earth System Science*, *129*(1), 46. Retrieved from https://ui.adsabs.harvard.edu/abs/2020JESS..129...46S/abstracthttp://link.springer.com/10.1007/s12040-019-1298-z doi: 10.1007/s12040-019-1298-z

Chapter 10

Impact of Urbanisation on Groundwater Resources

10.1 Introduction

Urbanisation and groundwater resources are two different individual variables that are parallelly important factors for an urban area. Both these variables have individual characteristics on their own. Urbanisation defines the process of land transformation. At the same time, groundwater resources of an urban area describe the situation of freshwater beneath the surface. Urbanisation is an artificial process whereas, the situation of groundwater resources are mainly dependent on its natural properties but in an urban area, the groundwater resource scenario can be altered by anthropogenic activities also.

Ultimately, in this chapter, two different individuals from an urban area, urbanisation and groundwater resources have been aimed to correlate with each other to identify the actual effectiveness of urbanisation on groundwater resources. This detailed analysis has been processed further proposing that urbanisation is an independent variable and groundwater resource is the dependent variable.

It has been already discussed that changes in land use and land cover, impervious surface and the built-up area directly reflect the process of urbanisation. So, in this chapter, along with above mentioned components of urbanisation, other crucial factors have been analysed in detail for this study area and all these generated data have been directly correlated with groundwater resources. Primarily it has been observed that, among the groundwater resources, groundwater level changes reflect the impact of withdrawal and changes in groundwater chemical composition reflect the quality of groundwater. So, both properties of groundwater have been correlated with the process of urbanisation to identify the impact. The observation period is limited to the recent times of thirty years (1990-2020) to understand the contemporary situation regarding the impact of urbanisation on groundwater resources.

10.2 Objectives

Some objectives have been identified for the investigation which are specified to this study area. Those are listed below:

- To identify the impact of built-up area on groundwater resources for last thirty years and in near future.
- To identify the changes in groundwater level with changes in landuse and landcover.
- To assess correlation and regression between urban impervious surface and groundwater level.
- To estimate changes in groundwater recharge proportion after expansion of impervious surface.
- To identify changes in groundwater level with changes in population and household over the time.
- To observe groundwater quality specially in landfill area to identify impact of contaminants on groundwater resources.

10.3 Data collection and methodology

10.3.1 Built-up area

For this analysis, thirty years of average built-up area data have been collected for Kolkata. Processing behind this large amount of dataset have been mentioned in the chapter 08 (Section 8.3.2). Along with these dataset thirty years of average groundwater level data have been calculated for Kolkata. Both the yearly scenario for Kolkata have been visualised with time series analysis. Next, built-up area and groundwater level have been projected for 2030 to assume the condition in future. For this ARIMA model has been used. Effect of built-up-area on groundwater resources vary with different locations.Additionally, GWR model has been incorporated in this study to analyse spatial variation. Model has been performed two times to calculate the effect of built-up in groundwater level and groundwater quality individually.
Process of these above mentioned models have been clarified in details with needful equations below:

ARIMA model

The acronym ARIMA stands for Auto-Regressive Integrated Moving Average. Lags of the stationarised series in the forecasting equation are called "autoregressive" terms, lags of the forecast errors are called "moving average" terms, and a time series which needs to be differenced to be made stationary is said to be an "integrated" version of a stationary series.A non-seasonal ARIMA model is classified as an "ARIMA (p,d,q)" model, where:

- p is the number of autoregressive terms,
- d is the number of non-seasonal differences needed for stationarity

- q is the number of lagged forecast errors in the prediction equation.

The forecasting equation is constructed as follows. First, let y denote the d_{th} difference of Y, which means:

$$d = 0 : yt = Yt \tag{10.1}$$

$$d = 1 : yt = Yt - Yt - 1 \tag{10.2}$$

$$d = 2 : yt = (Yt - Yt - 1) - (Yt - 1 - Yt - 2) = Yt - 2Yt - 1 + Yt - 2 \tag{10.3}$$

The second difference of Y ($d = 2$) is not the difference from 2 periods ago. Rather, it is the first-difference-of-the-first difference, which is the discrete analog of a second derivative, i.e., the local acceleration of the series rather than its local trend. In terms of y, the general forecasting equation is:

$$\hat{y}t = +1yt - 1 + \ldots + pyt - p - 1et - 1 - \ldots - qet - q \tag{10.4}$$

Here the moving average parameters ('s) are defined so that their signs are negative in the equation, following the convention introduced by Box and Jenkins.

Geographically weighted regression

Geographically weighted regression is an advanced part of linear regression model. It is observed that, linear regression model can be expressed in simplified form as

$$y = \alpha + \beta x + \varepsilon \tag{10.5}$$

In this equation,y is dependent variable and x is independent variable are related together with this equation where a is intercepting value and b is the slope value between two variables. And e defines the error value. More than one independent value can also be added advancing the equation. The regression model finds the relation between dependent and independent value assuming it on global perspective. This model is purely based on the concept of spatial stationarity between variables in the study. It is to be noted that, global perspective on spatial analysis is not acceptable. Linear regression model does not show a better result in in case of spatial analysis because relationship of variables with dependent value changes with varying space. Relationship between variables in a fixed location, can be identified by spatial non stationarity and it is appropriate more for local analysis than global analysis (Fotheringham, 2002) If non stationarity is evident the global model, it will provide an average impression between the variables locally.Therefore,non stationary in a relationship has a great impact upon regression in descriptive and predictive studies. Geographically weighted regression mainly used for spatial data analysis. It is a model that can be applied to identify spatial variation.it can be simplified as,

$$y(\theta) = \alpha(\theta) + \beta(\theta) + \varepsilon \tag{10.6}$$

where, θ indicates that the parameters are to be estimated at a location for which the spatial coordinates are provided by vector θ. Now geographical locations are a part of the equation.

Weighting is an another important factor.it is not constant but function of location.
The weighting is associated with the Toblar's 1st law of geography. Prediction and estimation of parameters are obtained in a matrix form as,

$$\hat{\beta}(\theta) = (X^T W(\theta) X)^{-1} X^T W(\theta) y \tag{10.7}$$

Where, W(θ) is weighting matrix.The off diagonal elements of the matrix W(θ) are set to zero and its diagonal elements represent the geographical weighting associated with each site at which measurements are made for the specific location under consideration (Fotheringham, 2002). This weightage influence in a location. The weight is implemented with spatial kernel function.Bandwidth defines distance decay in weighting function. Often fixed kernel size with Gaussian function is used. Alternative approach are also there where variable bandwidth can be taken. Gaussian function returns a vector of weights using the Gaussian scheme:

$$w(g) = e^{-(d/h)^2} \tag{10.8}$$

where, d are the distances between the observations and h is the bandwidth In this paper Gaussian function has been applied as it returns a vector of weights using Gaussian scheme:

$$w(g) = e^{-(1/2)(d/h)^2} \tag{10.9}$$

Geographically weighted regression model generates the value of R^2, it varies locally. It is observed that, the model fits confidentially where R^2 value is high. The model can be validated using Local R^2 values, sigma value, RMSE, and AIC values.

10.3.2 Land use and land cover

Observation for landuse and landcover change over the decade and related groundwater level change on that time period persistently developed in geospatial software environment. LULC maps were already produced for understanding the process of urbanisation (Subsection 8.4.1). Further, Ward wise area has been calculated for each class using zonal area calculation technique. Groundwater level data also collected following the same process. Further geospatial analysis has been processed with certain queries using SQL to identify wards with significant changes.

10.3.3 Impervious surface

In this chapter, correlation has been established between different land types and groundwater levels based on significant statistical approaches. Understanding of the correlation has been created based on a long period of time, i.e.; three decades (1990-2020). First of all, every land type has been correlated with a scatterplot for both two ends of the observation period i.e., 1990 and 2020 from 141 wards of Kolkata. Pearson's correlation of coefficient has been calculated to understand the correlation between variables. For this process, ward-wise percentage of land

types and groundwater level data in meters below the surface level has been collected . Further changes between 1990 and 2020, have been calculated in percentage for both land types and groundwater levels (Appendix, Table 13 and Table 19). With this data, individual regression has been identified with linear regression model and the combined effect on groundwater level has been identified applying multiple linear regression model where validation of these equations calculated by the value of R^2 for each equation.
Procedure regarding the linear regression model and multiple linear regression model has been discussed below:

Linear regression model

Linear regression attempts to model the relationship between two variables by fitting a linear equation to observed data. One variable is considered to be an explanatory variable, and the other is considered to be a dependent variable. A scatterplot can be a helpful tool in determining the strength of the relationship between two variables. If there appears to be no association between the proposed explanatory and dependent variables (i.e., the scatterplot does not indicate any increasing or decreasing trends), then fitting a linear regression model to the data probably will not provide a useful model. A valuable numerical measure of association between two variables is the correlation coefficient, which is a value between -1 and +1 indicating the strength of the association of the observed data for the two variables. A linear regression line has an equation of the form is

$$Y = a + bX \tag{10.10}$$

where $X$is the explanatory variable and Y is the dependent variable. The slope of the line is b, and a is the intercept (the value of y when $x = 0$).

Least-squares Regression
The most common method for fitting a regression line is the method of least-squares. This method calculates the best-fitting line for the observed data by minimizing the sum of the squares of the vertical deviations from each data point to the line (if a point lies on the fitted line exactly, then its vertical deviation is 0). Because the deviations are first squared, then summed, there are no cancellations between positive and negative values.

Multiple linear regression model

The multiple linear regression equation is as follows:

$$\hat{Y} = b_0 + b_1X_1 + b_2X_2 + ... + b_pX_p \tag{10.11}$$

where equation image indicator is the predicted or expected value of the dependent variable, X_1 through X_p are p distinct independent or predictor variables, $b_o$is the value of $Y$when all of the independent variables (X_1 through X_p) are equal to zero, and $b_1$through bp are the estimated

regression coefficients. Each regression coefficient represents the change in Y relative to a one unit change in the respective independent variable. In the multiple regression situation, b_o, for example, is the change in Y relative to a one unit change in X_1, holding all other independent variables constant (i.e., when the remaining independent variables are held at the same value or are fixed). Again, statistical tests can be performed to assess whether each regression coefficient is significantly different from zero.

10.3.4 Population and household

Groundwater data were collected for the years 1991 and 2020 ward-wise. For this IDW interpolation method has been used. Census data from 1991 has been used to understand the population and household data ward wise and for 2020, data has been projected using the population projection method as census data is unavailable after 2011. As observed from previous census data, ward-wise growth pattern is diverse within the city. So, the compound growth rate method has been used in this study to calculate the ward-wise population. As it is assumed that number of households is directly relational with the population, further total household data has been calculated for the year 2020 following the same method. It is noteworthy to mention that projections always have a degree of uncertainty and it might be reflected in the analysis.

10.3.5 Landfill area

Kolkata is one the main metropolitan city with near about ten million population including a six million floating population. This city generates about 3500 MT of solid waste in a day. Kolkata municipal corporation uses Dhapa as a major dumping ground to treat the waste. Dhapa landfill area covers around 21.47 hector of land and about 3000 MT of waste dump here every day (Paul et al., 2014). The nature of solid waste composition is changing with time. Biodegradables are most common in solid waste and it is increasing with time along with wastes like paper and plastics (Chattopadhyay et al., 2009). Due to continuous urbanisation in Kolkata, solid waste also increasing. Analysing satellite images it has been observed that landfill area continuously increased rapidly in the last decade (Figure 10.1). Tangra and Topsia are the two adjoining areas of Dhapa situated within a 4 km distance. These two areas are majorly occupied with different kinds of small-scale industries like leather, plastic, paper etc. From the extensive literature review, it has been identified that landfill area in cities negatively affects the subsurface environment through leaching and seeping. In this chapter, the impact of landfill areas along with industrial zones on groundwater resources has been identified. Three observational locations have been selected Dhapa, Tangra and Topsia to understand the effect of urban characteristics specifically upon the groundwater in this area. Dhapa is selected as a Landfill area and as groundwater grossly flows from west to east in Kolkata, Topsia and Tangra have been selected along for their nature of industrial land. For this analysis, data were collected for three locations from the WBPCB, which publish yearly groundwater quality related data for these locations

from 2010 to 2020.

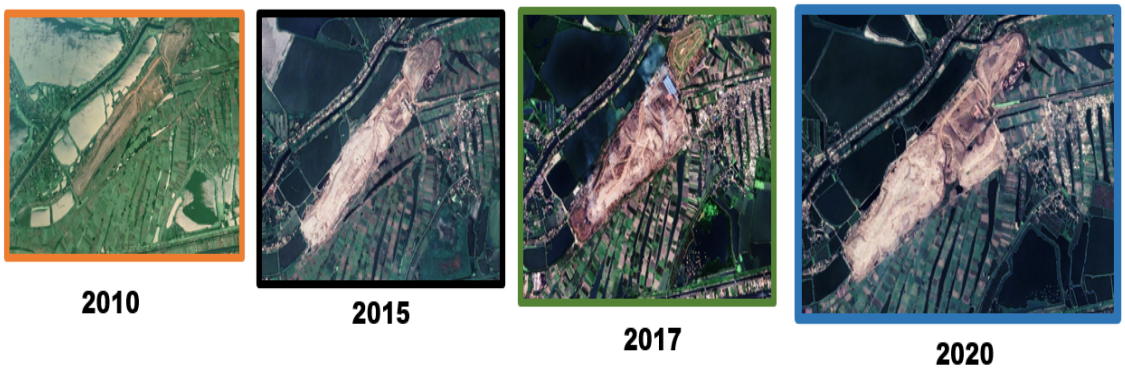


Figure 10.1. Satellite images of Dhapa dumping ground showing increasing area of the landfill area over time (Source: Google Earth Pro, 2022)

10.4 Impact analysis

10.4.1 Built-up area

Analysing thirty years of data, it has been observed that, the average built-up area is continuously expanding in Kolkata but the rate of expansion is different with time (Figure 10.2). Between 1990 to 2020, the average built-up area increased by about 1% every year. In 1990, only 40% area was covered with built-up area in the next thirty years, built-up increased by 26% in area. Contrarily, the groundwater level continuously declined from its previous level in between this mentioned time frame. In 1990, the average groundwater level of Kolkata was around 11 to 12 meters on an average below the surface in the next thirty years groundwater further declined from its level and in 2020, the average groundwater level of Kolkata was 16 meters below the ground surface. In the first five years of the observation period, the built-up area increased by about 3% whereas groundwater declined near about 1%. In the next five years, built-up area increased by 9.5% and in the mean time groundwater level declined 2.5 meters below the ground level. In 2005, built-up area increased by 16% in total and groundwater declined 2 meters below the surface. In 2010, further groundwater level declined almost at the same rate but built-up area further increased and in twenty years built-up expanded by 20% of its area. In the next five years, the built-up area increased by about 25% of area, and in the meantime groundwater level declined by 3.5 meters below the surface on average. Further in the next five years average growth of the built-up process slowed down and increased only 2% but groundwater level declined more than 1 meter in these last five years of the observational period. Overall, both of the processes were continuous between 1990 to 2020, built-up increased continuously whereas the groundwater level deteriorated. Correlating both of the observation using Pearson's method, the correlational factor found between these variables is 0.83, which signify a high positive correlation between both of the variables.

Based on the time series analysis dataset, autocorrelation has been identified between variables

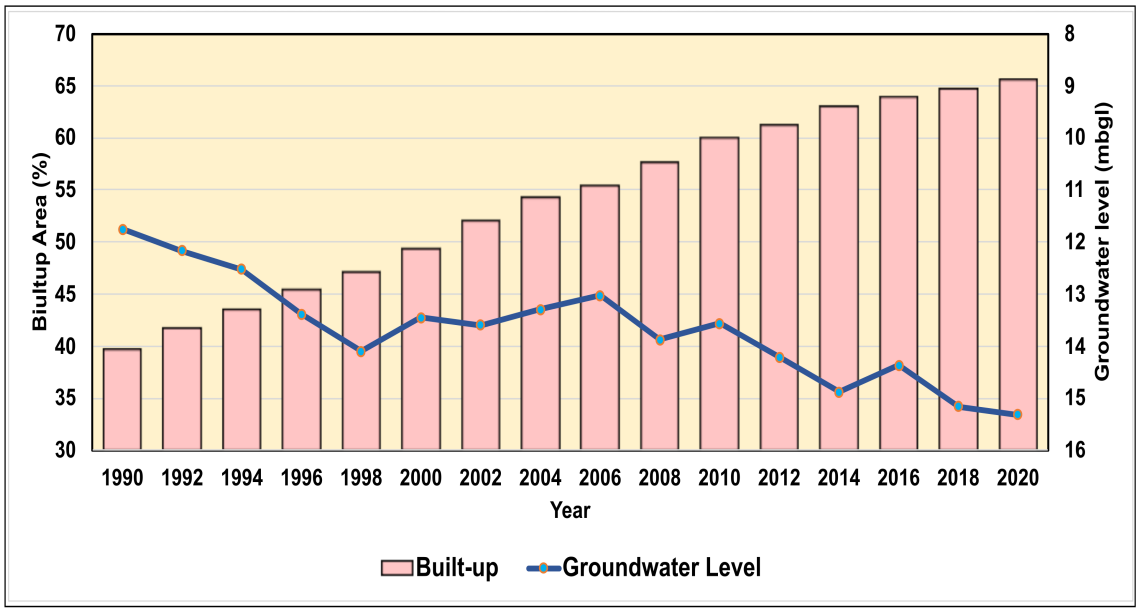


Figure 10.2. Time series analysis showing average percentage of built-up area and groundwater level from 1990 to 2020

applying ARIMA model (Figure 10.3). The future scenario till 2030 has been predicted using this model. It has been observed that further in upcoming years built-up area will increase in Kolkata. The model predicted that more than 70% of the total area of Kolkata will be covered with the built-up area. Further in 2030, the impact of urbanisation will be more prominent in three fourth part of Kolkata. Simultaneously, it has been projected that the declining trend of groundwater will persist in future also. In 2025, it is estimated that average groundwater level will be around 17 meters below the surface and in 2030, groundwater level will decline up to 18 meters on average. From figure 10.3, it can be identified that further increase in built-up will be a steady process, but high fluctuation in groundwater level possibility will be observed in near future. As the usage of groundwater is already prohibited in this study area and awareness about groundwater resources is rising among the residents of Kolkata, it is assumed that in the future declining situation, groundwater level will slow down either or it will be sluggish. Overall, it is assumed that, in near future, the negative impact of built-up on groundwater level will be distinguished clearly (Appendix, Table 27).

From the previous analysis it has been observed that, built-up area share positive correlation with groundwater resources that defines with increase of one unit of built-up area, groundwater level decline and groundwater quantity will degrade one unit further. Applying GWR method, additional effort has been given to identify spatial variation in regression analysis. Geographical approach has been prioritised here based on the importance of locational weightage.

Effect of built-up area differs from place to place in Kolkata that has been visualised ward wise with built-up coefficient value individually for groundwater level and quality (Figure 10.4). It has been observed that, built-up coefficients are positive in northern and eastern part of Kolkata and mostly negative in western part of Kolkata. Highly positive built-up coefficients have been observed in north eastern part of Kolkata specifically around Ward No. 33,57 and 58 whereas

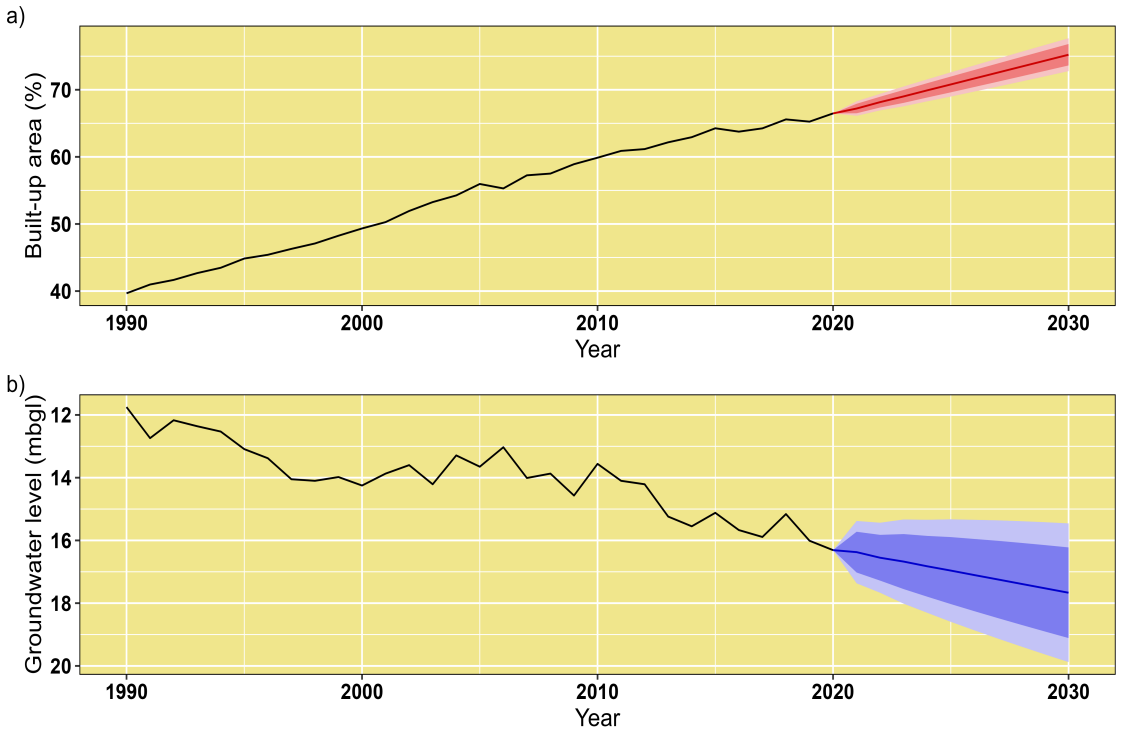


Figure 10.3. Time series analysis showing projection of a) average percentage of built-up area and b) groundwater level upto 2030

negative built-up coefficients have been observed mainly in south western part of Kolkata for groundwater level.

Effect of built-up area creates moderate effect in groundwater quality. It has been observed

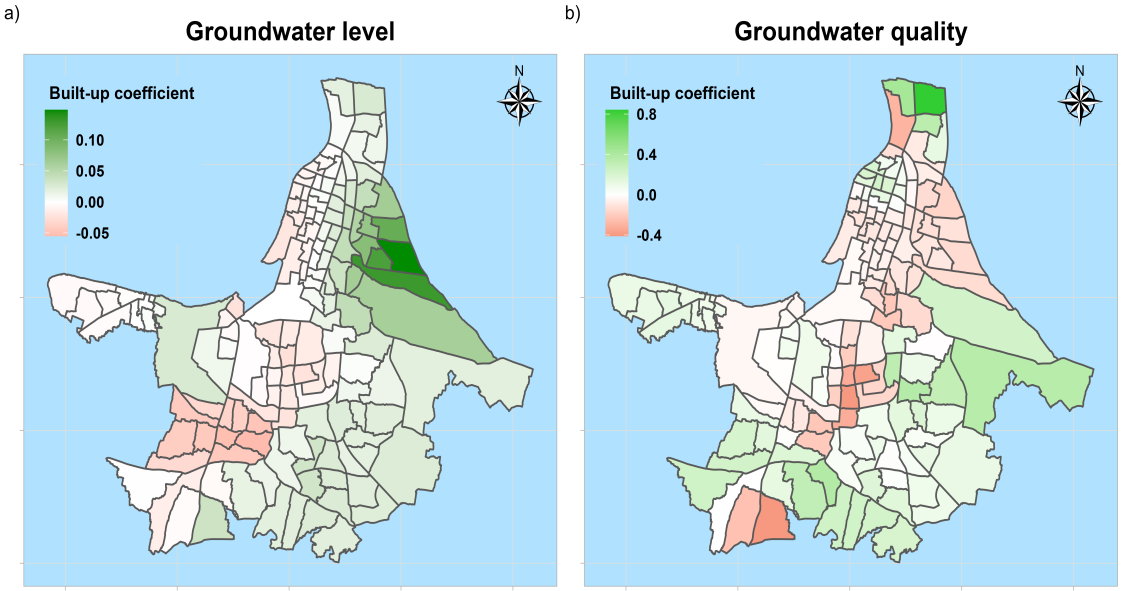


Figure 10.4. Effect of built-up area upon groundwater resources in 2020 using GWR model; a)groundwater level b) groundwater quality

that, in the central part of Kolkata and specifically Ward No. 84,85 and 87, built-up coefficients are negative and other remaining wards has positive effect on groundwater quality. Built-up area coefficients are highly positive in south eastern part of Kolkata. Few wards in extreme southern part of Kolkata, showing negative effects of built-up area on groundwater quality. This possibility minimises with low significance generated from the result.
Basically, built-up really impacts on groundwater level decline in eastern part of Kolkata. In this part of Kolkata, further built-up process will be vulnerable for groundwater level. Already possibility of further decline in groundwater level persists with additional built-up process. In some wards of Kolkata, effect of built-up on groundwater level is neutral; here groundwater level remains unaffected with change in built-up area. In south western part of Kolkata and in the central part, groundwater level holds possibility to be in better position with increase in built-up area but low significance value creates low confidence about this propagation. Groundwater quality also affected by built-up area and this impact is prominent in south eastern part of Kolkata. Extreme western part of Kolkata also affected by dense built-up area. Overall impact of built-up area is negative on groundwater resources and this impact certainly varies location wise.

10.4.2 Landuse and landcover

Situation between 1990 to 2000

It can be observed from the result that, in between 1990 to 2000, significant change has been observed in HDB in first ninety wards in Kolkata. Mainly LDB transformed into HDB in these years for the first 90 wards which are in northern and central part of Kolkata (Figure10.5). Significant changes observed in LDB in Wards from 91 to 141. Wetlands from wards between 101 to 111, also reduced significantly for abrupt increase in HDB and LDB. In this decade, groundwater level declined all over the study area but change rate was unequal in 141 wards. Abrupt changes with near to 30% downdrift in groundwater level observed in some wards from North and Central Kolkata. On an average, groundwater change level is about 15% to 20% in Wards between 1 to 91. After Ward No.91 a sharp change has been observed up to Ward No.109 where groundwater declination rate tends to be lower than other wards. From Ward No.110 to 141, groundwater level changed at an increasing rate further (Figure 10.5)
. Years between 1990 to 2000, two significant observations have been found for Kolkata. Firstly, From Ward No.1 to Ward No. 91, where mostly LDB transformed into HDB as proportion of water body and green space were minimum for those wards already. Groundwater level declined sharply on those wards nearly 2% in each year at an average. Whereas, after Ward No. 91, scenario has been changed abruptly. From Ward No. 91 to Ward No. 141, situated in the southern part of Kolkata where changes have been observed in every LULC class. Mostly, land has been transformed into LDB at a cost of reducing green spaces, water bodies and wetlands. In these wards groundwater declination was comparatively low. Secondly, In such wards where significant amount wetland and greenery were present but reduced for the sake of urbanisation in such time period, on such wards groundwater declination level was comparatively lower than all other wards.

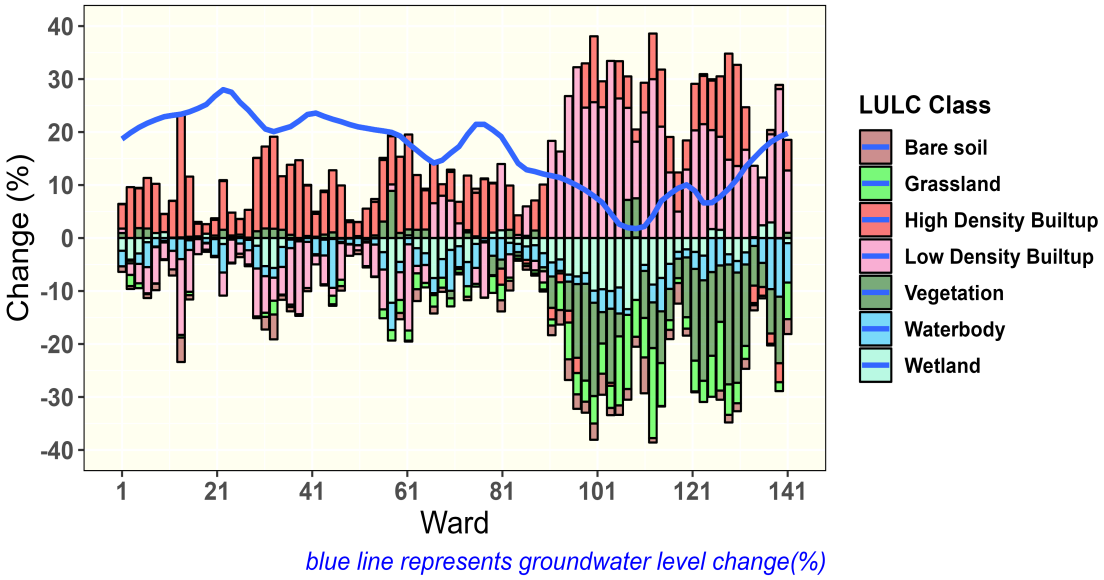


Figure 10.5. Changes in LULC classes and groundwater level; columns showing LULC changes in percentage and line showing groundwater level changes in percentage in between 1990-2000

Situation between 2000 to 2010

In years between 2000 and 2010, changes in LULC class was comparatively low from previous decade. LULC changes in wards almost ranged within 10% except few wards (Figure 10.6). Transformation of HDB into LDB has been observed in northern and central part of Kolkata. HDB increased significantly after Ward No. 75. In the south eastern part of Kolkata, wards between 101 to 121, vegetation cover transformed into HDB and LDB rapidly. After Ward No. 131 significantly vegetation cover has been increased in few wards. Groundwater level declined 12% on an average from its preceding level in between 2000 to 2010 and inequality in groundwater level change was persistent between wards. Groundwater level declination was comparatively higher in wards between 1 to 41 than other wards. A consistent downward change has been observed from Ward No. 1 to Ward No. 81. Decline of groundwater level change was for wards between 121 to 131 and it decreased after Ward No. 131 to 141. In between 2000 and 2010, urbanisation process was comparatively slower than previous decade. Specifically in northern and central part, where further increase in HDB was negligible, urbanisation was limited within increase of LDB. After Ward No. 91 process of urbanisation were high with increase of HDB at cost of vegetation cover. In this wards groundwater decline level was comparatively lower than previous decade but now it increased with further transformation of LULC class. Significantly it has been observed that, groundwater decline level was still active in such places vegetation cover increased prominently. All over it has been identified that, in that stipulated timespan, change rate of LULC was reduced comparatively and declination of groundwater level reduced also.

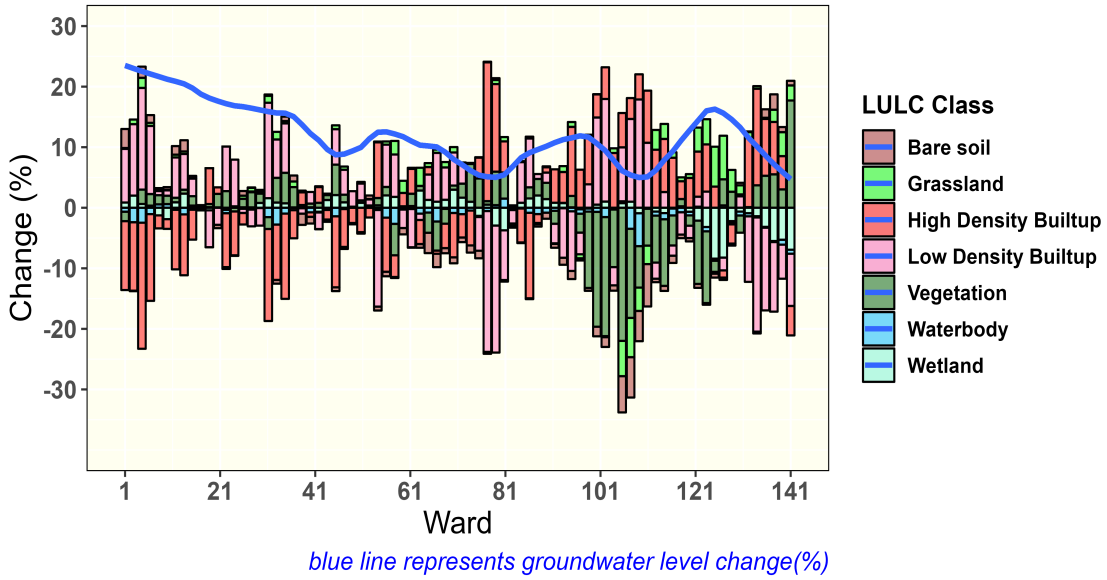


Figure 10.6. Changes in LULC classes and groundwater level; columns showing LULC changes in percentage and line showing groundwater level changes in percentage in between 2000-2010

Situation between 2010 to 2020

It has been observed that, vegetation and grassland cover increased in most of the wards in Kolkata and HDB transformed into LDB in between 2010 to 2020 (Figure 10.7). Change of LDB remained high in between Ward No. 91 to Ward No. 111. Overall, LULC change became slower than other decades. Unequal change between groundwater level became more or less equal within an average of 10% in a decade. Groundwater level fluctuation became consistent with time. From the above result it can be defined that, with comparatively lower changes in LULC class overall groundwater level declination got reduced. Significant changes only observed in south eastern part of Kolkata.

Scenario Analysis

For easy understanding about LULC change and related groundwater level change spatially, two scenarios have been created for wards under KMC. In ***Scenario 1***, wards with more than 10% landuse change has been identified for HDB and LDB where groundwater level also changed (declined) more than 10% from its previous level. In ***Scenario 2***, more than 20% groundwater level change (decline) has been identified with change in greater than 10% of land use. Scenario 1 represents comparatively a regular situation where landuse change has been increased about 1% in each year and groundwater level also declined 1% from its previous level at an average. Scenario 2 is comparatively an alarming situation where with 10% increase in landuse, groundwater level declined over 20% in a decade. Only HDB and LDB considered for this analysis as this two landuse classes directly represent the process of urbanisation. The whole process has been done separately for three decades (Figure 10.8). In between 1990 to 2000, scenario 1 is valid for HDB in wards from western and north-eastern part and for LDB in wards from south

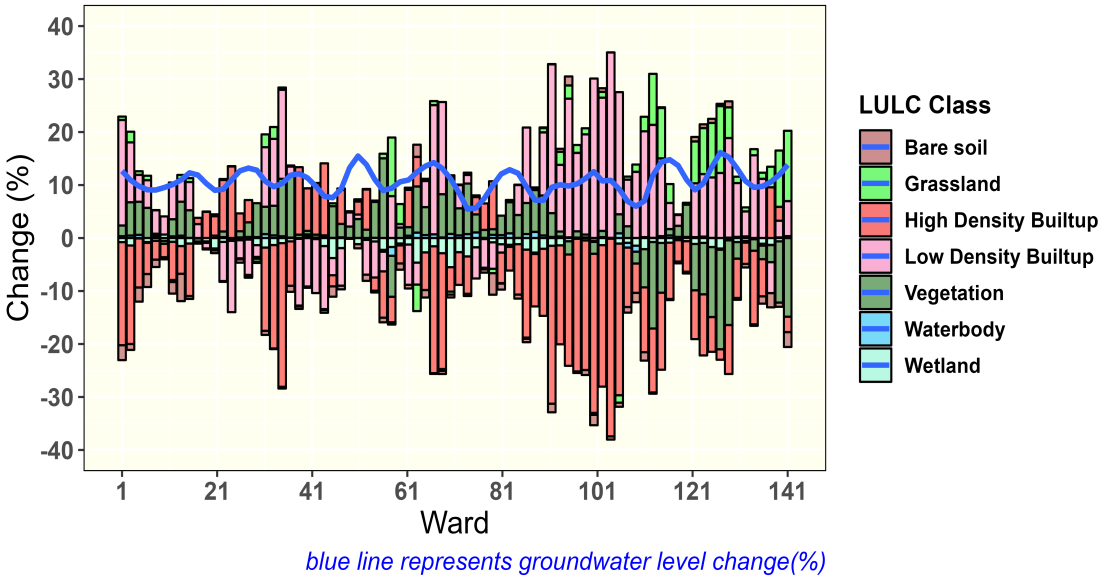


Figure 10.7. Changes in LULC classes and groundwater level; columns showing LULC changes in percentage and line showing groundwater level changes in percentage in between 2010-2020

western part of the study area. On that decade, Scenario 2 is valid for HDB in certain wards from north western portion only and for LDB, only few wards in western part.

In next decade (2000-2010), scenario 1 is applicable for HDB in few wards from southern part in fragmented way and for LDB in extreme northern and southern part of the study area. Scenario 2 is valid for only LDB in few wards from the extreme northern portion.

In the last decade (2010-2020), scenario 1 is valid for HDB in limited wards from western part but significantly valid for LDB in wards from the southern part of the study area and even some wards in extreme northern part also. Scenario 2 is valid for only LDB in few wards from central and south portion.

From the above observation it is revealed that, in the beginning of the observation period, groundwater declined rapidly in wards mostly covered by HDB and LDB but with change in time groundwater level declining rate decreased in a decade and also effect of urbanisation through HDB and LDB reduced with time. About 10% groundwater level is quite common than 20% groundwater level decline.

After understanding about the LULC change and groundwater level change individually for every decade a table has been produced comparing the situation of every decade. In this table it has been calculated that, with each unit positive change in every LULC class, groundwater level declined in how many wards (Table 10.1).

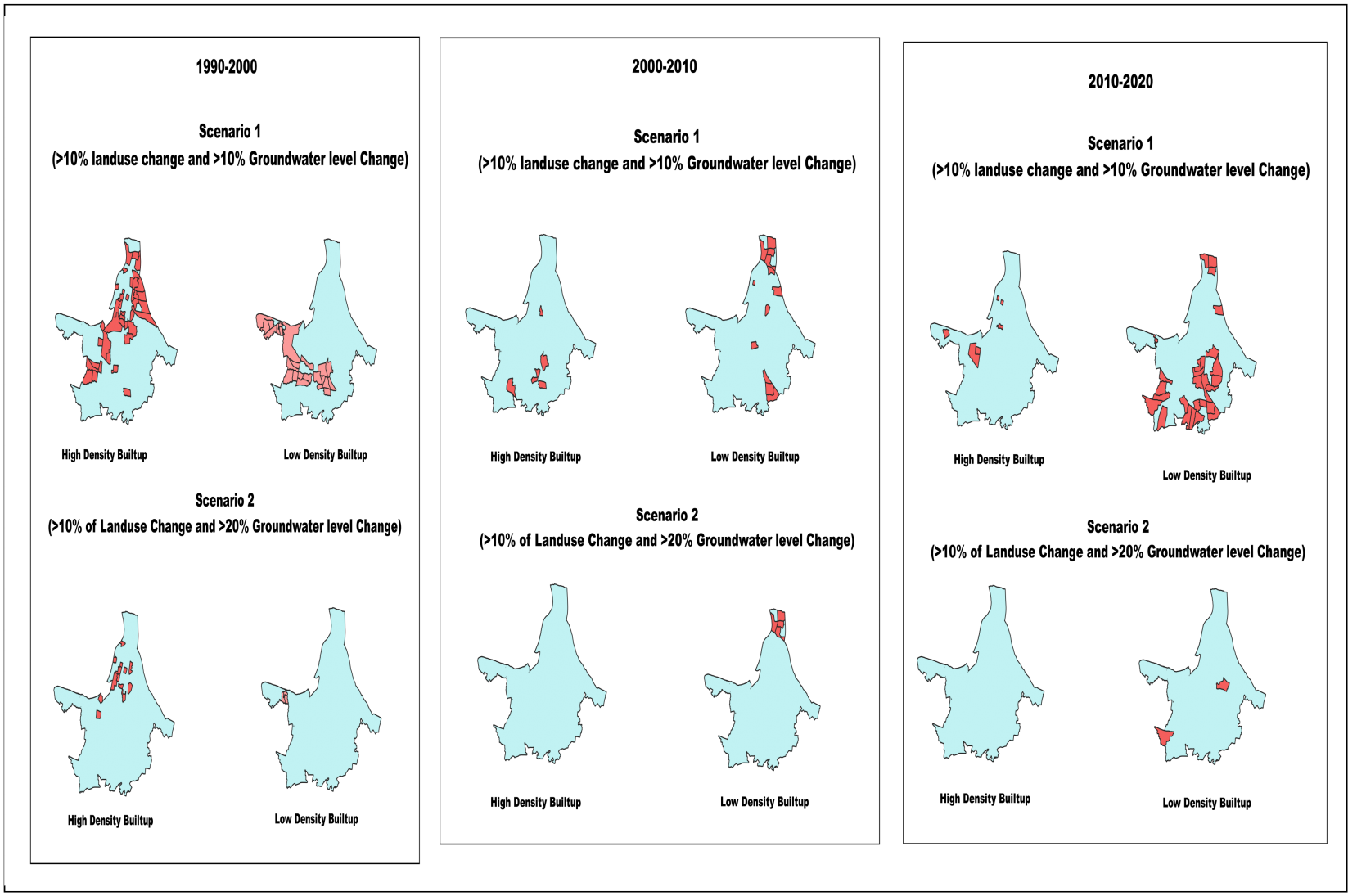


Figure 10.8. **Land use classes and groundwater level interaction in different decades with different scenario in wards of Kolkata**

Table 10.1. Effected wards in percentage showing groundwater level decline due to LULC type change

LULC Type	1990-2000	2000-2010	2010-2020
High Density Built-up	79.43	65.24	51.06
Low Density Built-up	51.04	67.37	73.04
Vegetation	38.29	57.44	64.53
Grassland	6.38	13.47	19.14
Waterbody	24.11	7.09	15.6
Wetland	14.18	33.12	6.38
Bare soil	24.11	30.49	24.82

It can be observed from the table that, in between 1990 to 2000 groundwater level declined in 80% wards with increase of HDB and groundwater level declined in 51% wards with increase of LDB. Groundwater level declined for increase in vegetation, grassland, waterbody, wetland and bare soil also but number of wards are comparatively much lower for these classes. For next decade percentage of wards reduced for HDB and waterbody classes but increased for rest of the classes. In between 2010 to 2020, with a change in HDB groundwater level declined in 51% wards. But for LDB it was 73% and for vegetation it is about 65%.
It is clear from the observation that, behind the groundwater level decline HDB and LDB plays more crucial role than other LULC classes. At the beginning of observational period, vegetation class was comparatively less effective behind decline level of groundwater but in last ten years of observation it can be seen that, vegetation also played a crucial role in decline of groundwater level and surprisingly it created more impact than HDB. Finding the reason behind it, it has been identified that, at the beginning of the observation period, groundwater level mainly declined due to increase in HDB and LDB, but continuous increasing proportion of HDB and LDB reduced the effect of green spaces to percolate water into subsurface environment. Ultimately, wards having certain amount of green space or water body that also got affected negatively and compelled to decline the groundwater level recently.

10.4.3 Impervious Surface

Situation in 1990

In this year, a strongly positive correlation has been identified between impervious surface and groundwater level (Figure 10.9). With every percentage of increase in impervious surface area, groundwater level going down generally. At the same time, soil and vegetation cover creating a negative correlation where with each positive percentage change, groundwater level comes nearer to the ground level. It has been observed that, certain wards with more than 80% of impervious surface, does not strongly correlate with groundwater level. For soil, only few wards

only follow any correlation, for vegetation cover it is better than the situation of soil but poorer than impervious surface with groundwater level condition.

From the result of correlation of coefficients, it can be identified that, impervious surface and

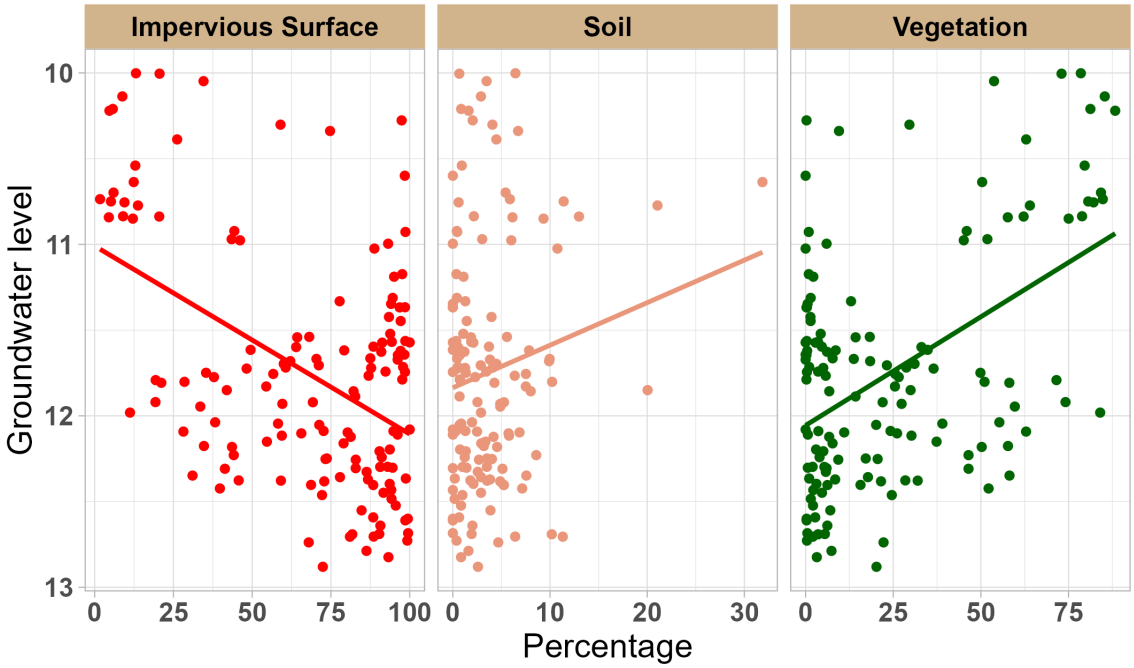


Figure 10.9. Scatter plot showing co-relation between different land surface and groundwater level in 1990

vegetation cover sharing a highly negative correlation with value of -0.97 and soil sharing a comparatively low negative relation with value of -0.40. Correlation of coefficient value is significantly positive between impervious surface and groundwater level with value of 0.47. Simultaneously vegetation cover and soil share a low negative correlation with value of -0.48 and -0.15 respectively with groundwater level.

Situation in 2020

Groundwater and impervious surface sharing a strong positive correlation and synchronously vegetation cover and bare soil sharing a low negative correlation with groundwater level (Figure 10.10). It is showing from the correlation of coefficient value that, in 2020, impervious surface and groundwater level maintaining a highly positive correlation with groundwater level with value of 0.51 and vegetation cover and bare soil maintaining a negative correlation with groundwater level with value of -0.51 and -0.13 respectively.

Observing both the scenario it can be understood that, wards with notable amount of impervious surface definitely crated an impact upon groundwater level decline whereas, area with trees, grassland and bare soil created comparatively low positive effect in groundwater level rise as most the wards in Kolkata where maximum portion of the land was covered by impervious surface. With timespan of thirty years in between, further correlation factor between impervious

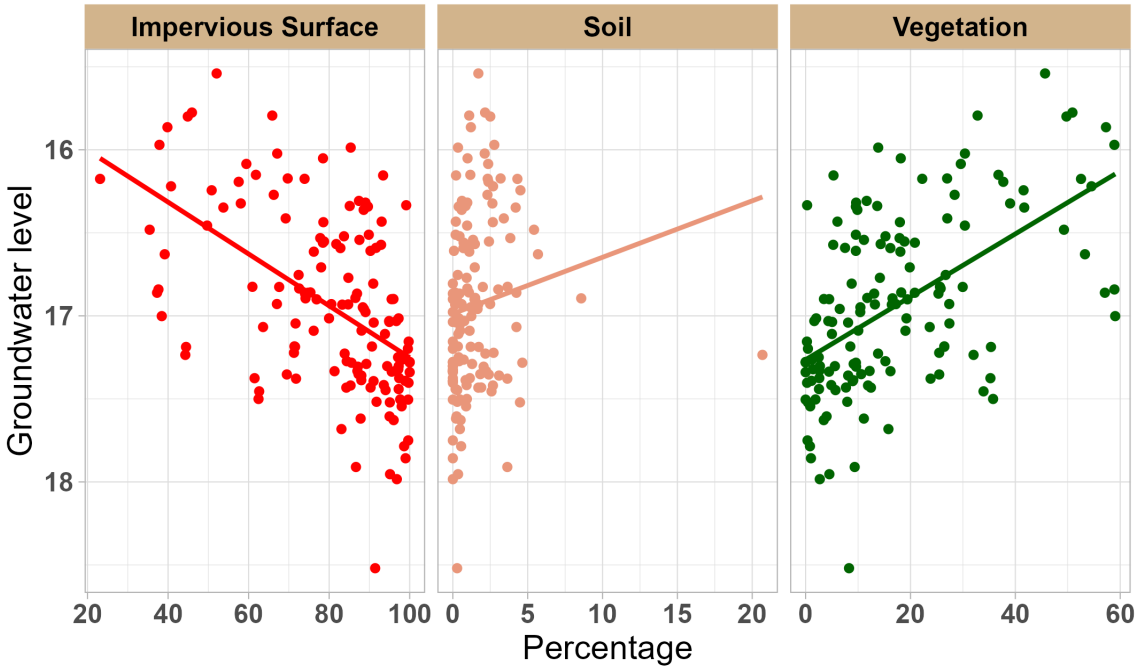


Figure 10.10. Scatterplot showing correlation between different land surface and groundwater level in 2020

surface and groundwater level impacted strongly upon Kolkata and consequentially, for vegetation cover it happened in exact opposite manner. Already proportion of soil was very minimum in Kolkata, so it proved its minor importance in correlational effect. Further details have been provided with coefficient values in the table for both the year 1990 and 2020 (Table 10.2).

Table 10.2. Correlation matrix between different land surface and groundwater level for 1990 and 2020

	Impervious surface (%)	**Vegetation cover (%)**	**Bare soil (%)**	**Groundwater level (mbgl)**
		2020		
Impervious surface (%)	1.00	-0.98	-0.53	0.52
Vegetation cover (%)	-0.98	1.00	0.42	-0.54
Bare soil (%)	-0.53	0.42	1.00	-0.14
Groundwater level (mbgl)	0.52	-0.54	-0.14	1.00
		1990		
Impervious surface (%)	1.00	-0.98	-0.40	0.47

Table 10.2. Correlation matrix between different land surface and groundwater level for 1990 and 2020

	Impervious surface (%)	**Vegetation cover (%)**	**Bare soil (%)**	**Groundwater level (mbgl)**
Vegetation cover (%)	-0.98	1.00	0.28	-0.48
Bare soil %)	-0.40	0.28	1.00	-0.15
Groundwater level (mbgl)	0.47	-0.48	-0.15	1.00

Change in land types and groundwater level over thirty years and its regression has been analysed with linear regression equation individually (Fig: 10.11). It has been identified from the linear regression that with each amount of change in impervious surface groundwater level changes positively (decline) with a coefficient value 0.15 and R^2 value 24 defines that co-relation justifies for 24% wards from over all 141 wards. Change in vegetation reflects a negative linear regression with groundwater level by coefficient value -0.17, that defines with each amount of positive change in vegetation, groundwater level negatively (rise) change and this equation is applicable for 26% wards from all over 141 wards with R^2 value 0.26. Relation between changes in soil cover and groundwater level is neutral or irrational with value of R^2 0.04.

Further, with the multiple linear regression equation, combined effects of different land type changes have been tried to co-relate with changes in groundwater level . It has been identified that, changes in impervious surface represented with a positive coefficient value and changes in vegetation cover and soil cover represented a negative coefficient value (Table 10.3). Among the coefficient values, vegetation cover representing highly negative value than other land types. It defines that among three land types in this study area, vegetation cover created a negative impact upon groundwater level change (decline). Actually it prevented from further decline in groundwater level when all the land types created combined impact upon groundwater level for a long time.

Table 10.3. Summary of linear and multiple linear regression model showing regression between different land surface and groundwater level

	Coefficient		**Land type**		**Intercept**	**R^2**	***p-value***
Linear Regression							
CGW =	0.15	*	CIMPV	+	42.86	0.24	<0.05
	-0.17		CVEGE		43.45	0.26	<0.05
	-0.42		CSOIL		43.83	0.04	<0.05
Multiple Linear Regression							
	0.06		CIMPV				<0.05
CGW =	-0.242	*	CVEGE	+	43.56	0.27	

Table 10.3. Summary of linear and multiple linear regression model showing regression between different land surface and groundwater level

Coefficient	Land type	Intercept	R^2	*p-value*
-0.09	CSOIL			

In thirty years, urbanisation process was continuous and rapid. At the same time, groundwater level declined significantly. Correlating both changes individually for different land types and groundwater, it is showing that, with every positive change in impervious surface, groundwater level changed positively. It signifies that, groundwater level declined with every positive change in impervious surface. It is also seen that, with every positive or negative change in vegetation cover, either it impacted groundwater level or it did not create any impact upon groundwater level though all over it created a negative correlation that defines, with every positive change in vegetation there a possibility creates for rise up in groundwater level. It has been also found that, groundwater level change and open soil area change creates almost neutral relationship but tend towards negativity, that defines increase in open soil are beneficial for groundwater level situation. Both vegetation cover and soil represent the permeable characteristics of land and that reflected in result.

10.4.4 Impact on groundwater recharge due to increase in impervious surface

Urbanisation creates definite impact upon groundwater recharge (Healy & Scanlon, 2010). Groundwater recharge is complex process as various factors are related to it. Weather recharge increase or decrease after urbanisation it is a matter of debate among researchers. It is presumed that in urban setting, leakage from urban sewers create additional water supply to subsurface apart from normal recharge. Simultaneously, researchers have unanimously admitted that, natural process of groundwater recharge gets obstructed by impervious surface which is the most common land type in urban setting and on a long run, proportion of recharge decrease gradually. As calculation of recharge is complex in nature specially in urban setting, most common water budget approach is used to estimate the groundwater recharge. A common conceptual framework has been incorporated here for better understanding (Figure 10.12) .

In this chapter water budget estimation method has been applied based on satellite data that was produced by TerraClimate[1]. Individual four years (1990,2000, 2010 and 2020) has been selected for this estimation. Basically, a conceptual method has been applied in this section to get an overview about the impact of impervious surface on groundwater recharge (Figure 10.13). It is to be noted that groundwater recharge estimation has been calculated excluding the estimation of recharge from any leakage from water supply or sewage system and this exclusion certainly reflected in the result.

In 1990, it has been observed that, when 43% of the land was covered with impervious surface

[1]Terra Climate (https://www.climatologylab.org/terraclimate.html) produce grided data collected from World-Clim (https://www.worldclim.org/data/index.html)

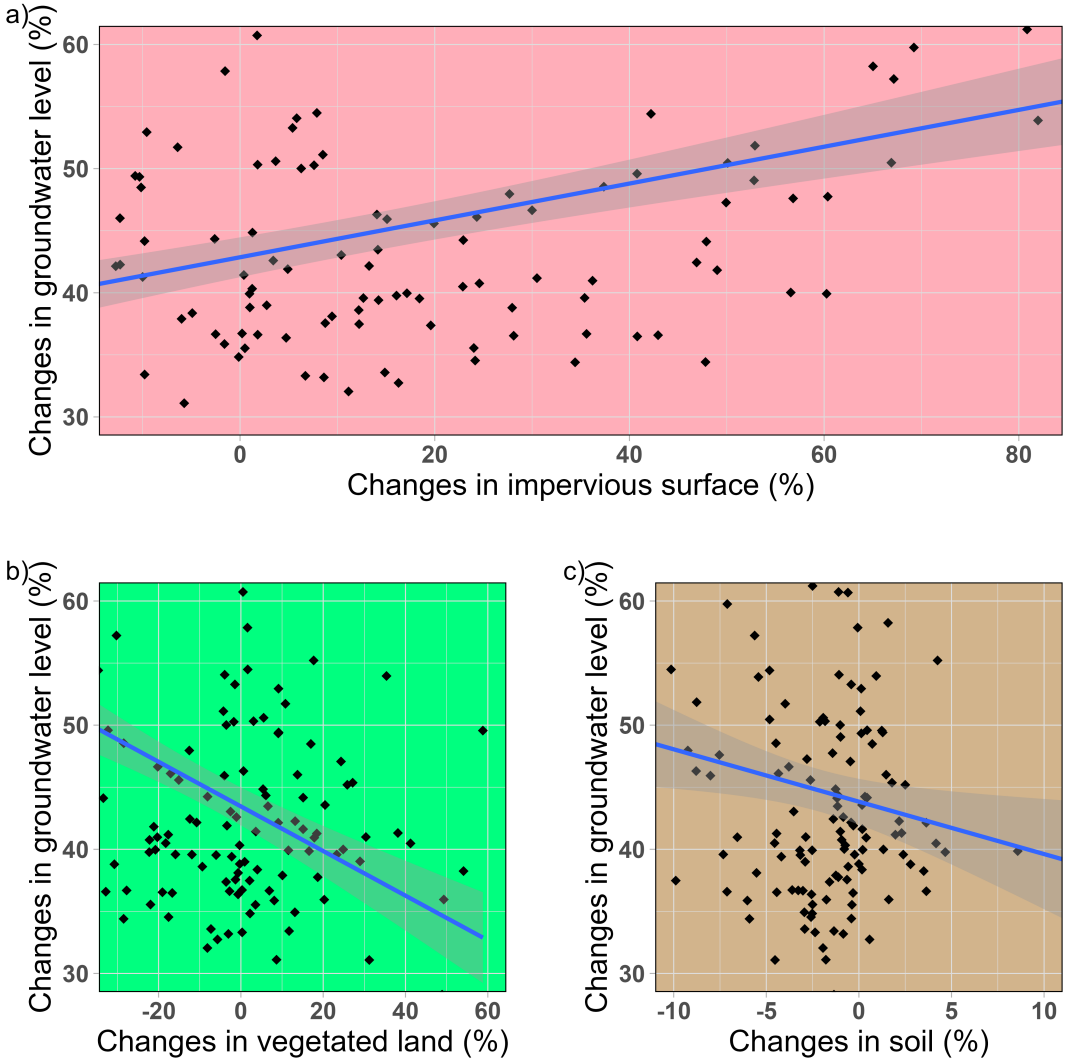


Figure 10.11. Scatterplot with trend line showing co-relation observed between different land surface changes and groundwater level changes in between 1990-2020

then about 38% recharge has been generated from the total rainfall in Kolkata, at that year, about 17% water infiltrated into subsurface environment as recharge. In 2000, runoff was 44% yearly and recharge was about 13% when 53% land was covered with impervious surface. In next ten year runoff generated about 48% from the total rainfall in that year and recharge was about 12% at that time and about 58% land was covered with impervious surface in Kolkata. After a decade, in 2020, about 63% land was covered with impervious surface and 53% runoff generated from the rainfall and about 9% water directly percolated into subsurface. From the above estimation, briefly it has been observed that, impervious surface continuously increased in Kolkata and with this process evapotranspiration reduced with lack of green space in he city. Due to increasing imperviousness in land, proportion of runoff from rainfall increased gradually. As a result groundwater recharge percentage reduced with time. Process of urbanisation directly impacted on groundwater recharge also, that ultimately affected groundwater resources.

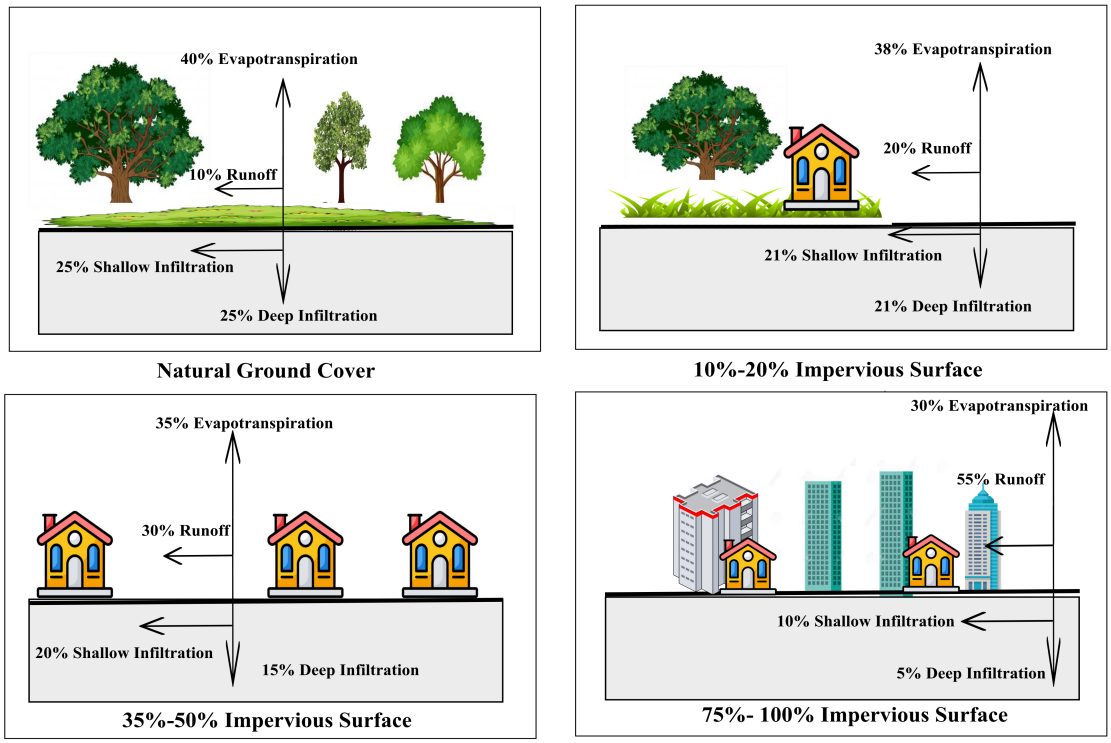


Figure 10.12. Conceptual framework showing changes in hydrological cycle with increasing impervious surface in an urban area (Source: Saraswat et al. 2016)

10.4.5 Population and household

Following compound growth rate of population projection, it has been observed that, in certain wards population is increasing and in certain wards population is decreasing, disparities are prominent in changing population. Within thirty years, population decreased mainly in wards from North Kolkata. Decreasing population pattern is prominent within 1 to 101, after Ward no 101, population increased. In the meantime, groundwater level change is positive in most of the wards except few wards from south western and north eastern part. Positive groundwater level change reflects decline in groundwater level and negative groundwater level change reflects rise in groundwater level. Groundwater level declined at an average 4 to 6 meters in northern wards where population also decreased. After Ward No. 81, increasing pattern of population along with declining trend of groundwater level was prominent till the Ward no 101. It is also observed that, from Ward no 101, population increased significantly and groundwater level declined on an average 2 to 4 meter in between the observed years.

Two types of situations have been identified for Kolkata. In between thirty years, groundwater level declined highly in northern part where population also decreased. Simultaneously in southern and western part of Kolkata where population increased but groundwater declined comparatively lower than northern part. Reason behind this observation lies in past history of urbanisation in Kolkata. Northern part of Kolkata was highly populated for years. Groundwater abstraction rate was higher than other places to meet demand of water and extreme saturation with dense population created deterioration in living condition with time in these wards. After

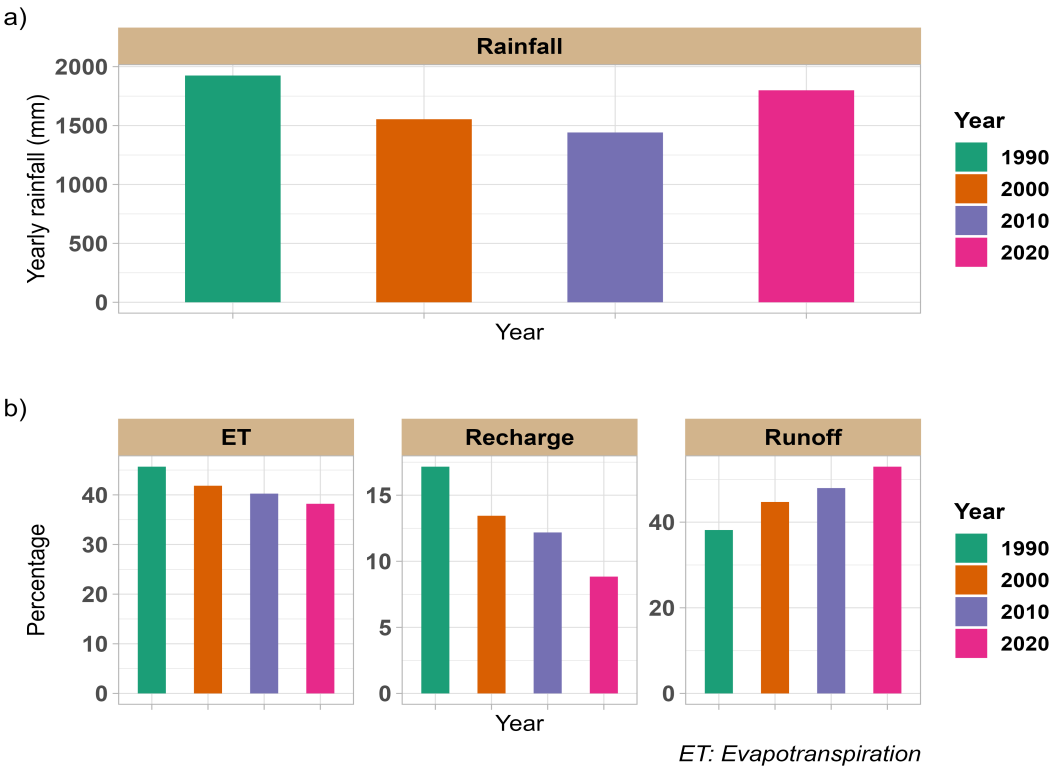


Figure 10.13. Proportion of evapotranspiration, recharge and runoff after yearly rainfall in different years

2000, population started to decline abruptly in these wards and this situation reflected in total population around 2020. Groundwater level change is comparatively a long term process, it takes years to create a significant impact. In Northern part of Kolkata, population declined recently but effect on groundwater due to high population and its havoc consumption reflected in groundwater level data much later. This situation is different in southern part of Kolkata where increase in total population mainly observed after 1990 and on that period of time groundwater level was in better position as southern part of Kolkata, prominent amount of wetlands were there over that area. With the beginning of this century, further development in these zone, attracted people from its adjoining states and other countries to live in, so further in next twenty years population increased significantly in these wards and it is assumed that consumption of water increased with time but as groundwater abstraction takes time to reflect this in its level data, so situation reflected accordingly. Condition of population reflects in umber of households also. In Kolkata number of households increased continuously. Now with nuclear family culture, households are increasing rapidly in Kolkata. Calculating Household population ratio, it has been observed that, it is decreasing with time. In 1990 it was 5 person on an average in each households of Kolkata. Now,after 30 years almost one person has been reduced from that ratio. With increase in household number water consuming capacity also increased from the past years and on a whole its creating more demand of water. As, a result groundwater usage is getting increased. Private consumption and illegal pumping is the most common method that people

have followed throughout the years.

10.4.6 Landfill area

It is observed that, with low level in pH value, metal substances tend to be more toxic when it is dissolved in groundwater. pH level is highly variable in and around of landfill site of Kolkata. In 2010, basic pH level was in between 7.2-7.4 but with time it highly fluctuated. Next year in 2011, it highly increased and suddenly it got reduced in next year. Fluctuation persisted throughout the decade. Abrupt change observed in 2018, where, pH level of Dhapa (7.85) and Tangra (7.96) increased highly but it highly decreased for Topsia (6.85) area. Recently it showing a decreasing trend in pH level.

Usually, higher amount of BOD in groundwater signifies amount of oxygen needed to feed species under water, ultimately higher amount of demand for oxygen reflects low quality in groundwater. Value above 2 mg/l confirms presence of polluting nature of groundwater. Available amount of BOD in three observation point are fluctuating in nature, but it abruptly fluctuated in 2017, where in Tangra it crossed BOD level more than 4 mg/l. Same situation was observed in 2015 for Topsia where it reached up to 3.5 mg/l. Recently it showing decreasing trend for the last two years.

Chemical oxygen demand (COD) is the amount of dissolved oxygen that must be present in water to oxidize chemical organic materials, like petroleum. COD is used to gauge the short-term impact waste water effluents will have on the oxygen levels of receiving waters. Available amount of COD is nominal throughout the decade with a range in between 5 to 15 mg/l.

Generally, it is already observed that high temperature in groundwater can help to dissolve more suspended materials that ultimately reflects in electrical conductivity value, higher value in temperature shows, decrease in groundwater quality also increase in temperature leads to decrease saturated oxygen and decline in pH level (Riedel, 2019).It has been observed that, temperature is fluctuating in nature over the years. Tendency of increase in temperature has been observed from 2010 to 2015 and in next two-year temperature decreased gradually. After 2016, increasing trend has been observed for Dhapa and Tangra but decreasing tendency in temperature has been consistent for Topsia after 2014.

Conductivity measures the ability of groundwater to conduct the electrical current. It increases with available dissolved salts in it. Concentration of salts here are comparatively higher than other parts of Kolkata. Conductivity stays above 1600 µs/cm in between ten years of observational period. Conductance in groundwater is comparatively low in Dhapa than Topsia and Tangra. In 2015, conductivity crossed 2300 µs/cm in Tangra and in 2018, conductivity reached up to 3000 µs/cm in Topsia. Within the observational period increasing tendency has been observed for the areas.

High turbidity in groundwater makes the groundwater cloudy or murky in nature. Sufficient amount of dissolved materials in groundwater scatter the light that makes the water murky and at the same time reflects the presence of dissolved materials in groundwater. According to Indian standard permissible level for turbidity has been set to 1 NTU but in the area around the land fill site, turbidity crossed the prescribed limit. In around 2010, turbidity in groundwater was

within 4 to 5 NTU but in 2017 and 2018, turbidity in groundwater has been doubled in Topsia and Tangra, comparatively turbidity in groundwater remained consistent in Dhapa throughout the observation periods and that amount is quite high than prescribed limit.

Chloride in groundwater is highly fluctuating in nature around the landfill site of Kolkata. Wide

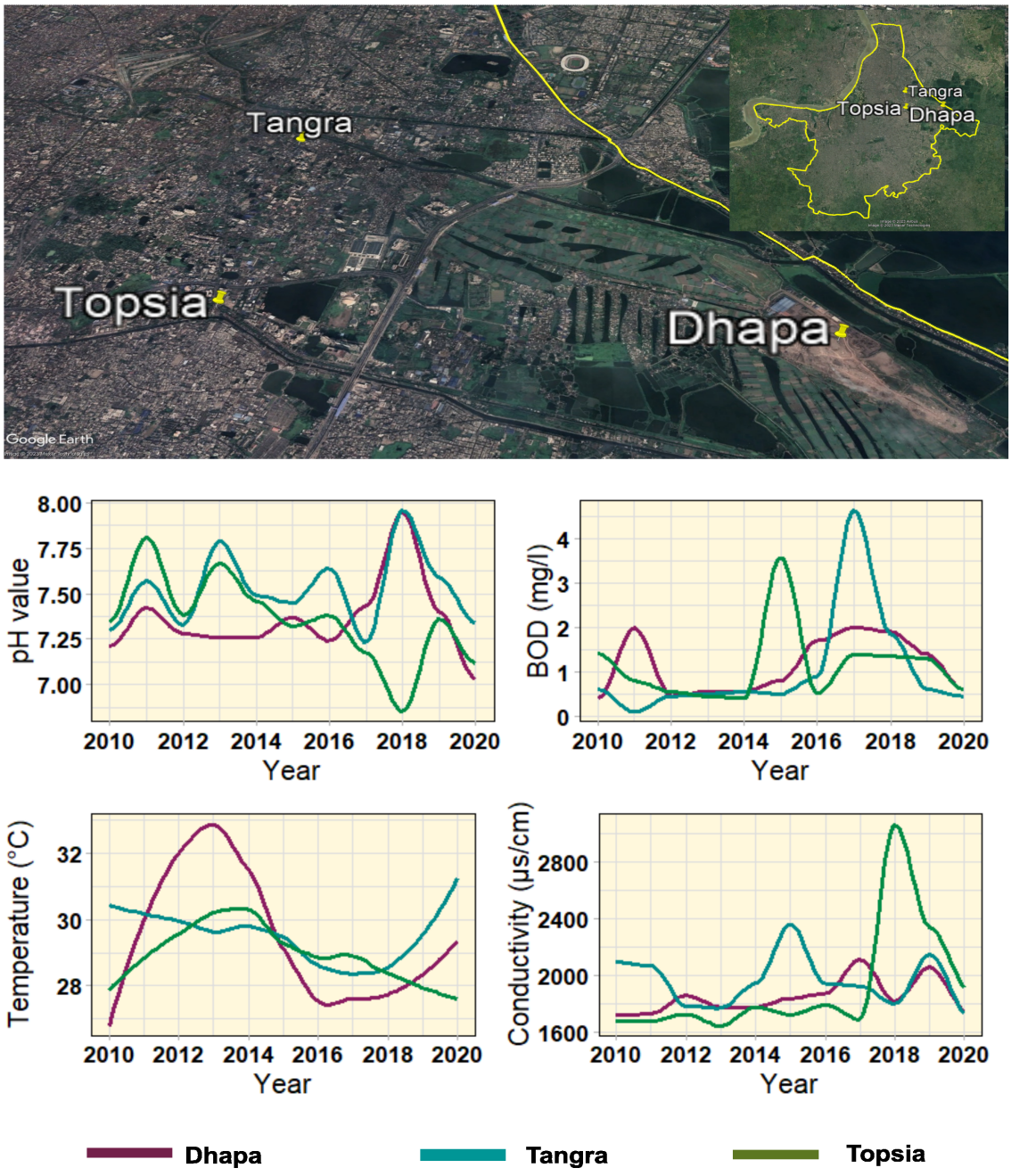


Figure 10.14. Location of landfill site Dhapa (up), Condition of physio chemical parameters of groundwater in Dhapa, Tangra and Topsia from 2010 to 2020

range of chloride concentration from 350 mg/l to 600 mg/l has been observed in around the landfill area of Kolkata. Chloride concentration is highly fluctuating in nature. Clear increasing

tendency has been observed in Topsia and Dhapa area. Concentration of chloride in these areas already crossed the permissible limit prescribed by Indian standard.
Lead and Mercury are the poisonous material. According to Indian standards lead more than 0.01 g/l and 0.001 gl/ of mercury should be treated as concerning toxic substance in drinking water. Concentration of lead and mercury data are not available for the landfill area for every year but in the beginning of observation period, presence of lead and mercury have been found in around landfill site and available amount at that period reflected high concentration of lead in groundwater which quite a few times more than prescribed limit and same situation observed for mercury also.
It has been observed that, groundwater in Dhapa, Tnagra and Topsia are quite polluted in nature. With every individual parameter, it has been observed that, organic and inorganic components both percolate from these locations through leaching process. Waste materials, sewage and other sanitation materials directly infiltrate into the subsurface environment consistently. On a long run, it pollutes the groundwater. Hazardous toxic materials generated from the waste of Kolkata also prominently present in this landfill area. Groundwater in this area is murky in nature with high amount of TDS value, that strictly prohibited for drinking purpose. According to the measurements of CPCB, these kind of water with concentration of such polluting materials is not even recommended for animals and fishes also.

10.5 Conclusion

This chapter examined the impact of urbanisation on groundwater resources with various factors that directly represent urbanisation process. Observing past years, it is clear that, Kolkata was already densely populated urban land where built-up area increased over the land continuously, in the mean time groundwater level also declined and correlation was quite high between these variables. In upcoming future this situation will continue. It is evident in Kolkata that spatial effect of urbanisation varies with location. Groundwater level fluctuation is much more dependent on effect of urbanisation in the eastern part of Kolkata than western part. Water quality of south eastern and south western part also gets affected by urbanisation compared to other area. In the past, urbanisation process was comparatively high at that time groundwater declined rapidly in high density built-up area. Further groundwater level declined in low density built-up area also. Groundwater level declined at low rate where there was dominance of vegetation cover and water bodies. Later with decrease in vegetation cover, groundwater level declined in all over Kolkata but groundwater declining rate reduced also. These changes made an impact on impervious surface. With time permeable surface decreased and impervious surface increased in Kolkata. Groundwater level change shares a positive correlation with impervious surface whereas it is negative with permeable surface. Groundwater level deteriorated with further increase in impervious surface. Decreasing vegetation cover further reduced the groundwater recharge scope. With combining effect of permeable surface and impervious surface, permeable surface reduction through urbanisation turned out to be the major reason behind groundwater depletion in Kolkata. Overall impact of impervious surface on groundwater is moderate. Urbanisation

process also reduced the possibility of groundwater recharge with time. Dense population density, a product of urbanisation is another reason that created impact upon groundwater resources. Anthropogenic activities related to urbanisation affected the subsurface environment deliberately. Lastly, landfill areas with continued process of dumping definitely impacted upon groundwater composition and degraded its quality.

References

Chattopadhyay, S., Dutta, A., & Ray, S. (2009, apr). Municipal solid waste management in Kolkata, India – A review. *Waste Management*, *29*(4), 1449–1458. Retrieved from https://linkinghub.elsevier.com/retrieve/pii/S0956053X08003371 doi: 10.1016/j.wasman.2008.08.030

Healy, R. W., & Scanlon, B. R. (2010). *Estimating Groundwater Recharge*. Cambridge University Press. Retrieved from https://www.cambridge.org/core/product/identifier/9780511780745/type/book doi: 10.1017/CBO9780511780745

Chapter 11

Major Findings, Conclusion and Recommendations

11.1 Major Findings

This study aims to define urbanisation and its impact on groundwater resources. In the beginning of this thesis, worldwide situation of urbanisation and groundwater resources have been discussed individually. Interaction between urban area and groundwater resources have been identified also. Appropriate methodologies have been identified from extensive literature review and finally a study area has been selected to observe the actual scenario. Kolkata has been selected for case study. This urban land has been investigated for thirty years of timespan (1990-2020). Kolkata is leading example of an urban area in a developing country where process of urbanisation is relevant and groundwater related problems are major concern. After detailed inspection about urbanisation and groundwater scenario of Kolkata, further individual changes between these factors have been correlated with appropriate methodologies to identify the impact of urbanisation on groundwater resources. Through this investigation several facts have been raised up about urban groundwater condition specifically for Kolkata. These facts are the main findings of these study and these observations have been mentioned below:

- Urbanisation is related with urban process. Generally, urbanisation relates with change of rural part of the land in to urban. Urbanisation is not limited with landuse use change. Various types of social, political and economic process are also related with it and the definition of urbanisation varies with countries. The focus of urbanisation specialises in between the boundaries of the city sometimes above it. Historical evidences of urbanisation were prominent in distant past also. Urbanisation was initiated after the industrial revolution in western part of the world later concept of urbanisation spread by the effect of colonisation throughout the world. In the developed countries, urbanisation process already saturated the urban land in major cities. With the beginning of this century, cities in the developing countries going through rapid phase of urbanisation. Urban population

is increasing continually.

- Groundwater resources represent about 30% of the total freshwater resources all over the world. It is one of the most reliable sources of drinking water specifically in major parts of the world where alternative source of freshwater is limited. Groundwater storage mainly observed in aquifers beneath the surface. Major groundwater basins are residing under the riverine landforms. Groundwater mainly abstracted to serve the demand from irrigation, domestic and industrial sector. Asia has the largest amount of groundwater storage beneath its surface and at the same time, Asia consumes most of the groundwater compared with other continents. Due to leading advantages, groundwater is abstracted vigorously without even thinking about further sustainability. As a result, groundwater table is declining in the major parts of the world. This situation is getting more critical in urban area. Mexico City is one of the relevant examples among the cities.
- Usage of groundwater resources are common in urban area as the large amount storage is available beneath the surface. It is easily extractable resource at the same time it is comparatively low polluting in nature also it is available throughout the year in same condition. In urban area groundwater is used as supply source to residential, commercial and industrial sectors to fill up the demand of fresh water but often after the use of water it gets contaminated with other substances related to urban activities. Thus, polluted water ultimately completes its hydrological cycle through further recharge. Overall groundwater serves as a crucial factor in urban area. It is used as water supply source; it also gets involved in sanitation process and pluvial drainage. As the city grows, groundwater extraction gets started to fill up the huge demand from a short span of area. In the beginning of urbanisation process, groundwater resources were counted as a beneficial resource but on a long term negative effect of groundwater abstraction proves to be a crucial factor in terms of sustainability. Groundwater abstraction in a non-responsible manner is the major concern for a densely populated urban area. Due to excessive abstraction ultimately groundwater level declines that further leads to serious issues like land subsidence and sea water intrusion.
  Urbanisation process further creates impervious surface throughout the administrative boundary and possibly beyond. Thus, limited scope of recharge further gets prevented. Leakage and seepage are the only options remains left for groundwater recharge that already generated from polluted sources after urban activities. Groundwater quality also gets affected by the process of urbanisation. Different polluting sources like industries landfill area, petrol pump, cars, residential houses contaminate the subsurface by sourcing polluting materials. Several cities throughout the world are solely or partly dependent on groundwater resources and impact of further urbanisation is creating an alarming situation for these cities. Issues like land subsidence, abrupt groundwater level decline, degraded water quality, presence of arsenic and other radioactive substances are common among them.
- It is comparatively new topic in research field because groundwater resource is invisible to

human eyes and previously awareness about the negative effects of groundwater resource was really limited. Further researchers have dedicatedly made an effort to understand about the problems related to groundwater and recommended efficient measures related to it. In the beginning, researchers broadly identified the causes related to urban groundwater resource deterioration. Mainly statistical methods and mathematical approaches have been applied. Researches were majorly dependent on primary survey-based data. Recently, location-based approach has been adopted to analyse this issue. Modern appliances are being used to collect data remotely. Satellite data and application of remote sensing technology revolutionised research possibilities. Further advanced statistical methods and advanced computational technology like machine learning, deep learning being applied in this theme. Interdisciplinary approach in this research field stretched the scope for more possibilities from other allied subjects.

- After the above observation, it was needful to understand the actual scenario of groundwater resources for an urban area taking a case study. In this study, Kolkata has been selected as a study area. Kolkata began its journey from the end of seventeenth century. From the beginning it was counted as an urban area. At a time, it was one of the most densely populated cities in the world and it was one of the first megacities in the world. In the time of British empire, the city was the capital of India. After independence it was the smallest district in the state West Bengal and still it is the capital of this state. It is administrated by Kolkata Municipal Corporation from the British era. For administrative purpose it has been divided into wards and boroughs. Due to pull factor of migration, urbanisation process was instantaneous in this city. After the initiation of globalisation another wave of urbanisation occurred in Kolkata.

- Physical setup describes the natural condition of Kolkata. Principally, physical set up of Kolkata has been identified with perspective of urbanisation. Kolkata is situated on the floodplain; extremely gentle slope has been formed with nearness to the sea level. River Hooghly is in the western side and vast wetlands are in the eastern part of the city. With gentle slope, several canals intersected the land of Kolkata. Kolkata is constructed upon deltaic plain by enormous amount of quaternary alluvium. Recent sedimentary deposits made the land mostly clayey in nature with certain amount of sand and silt. Soil of Kolkata is mainly high potential to runoff. This type of characteristics of the land generally obstructs direct recharge from the rainfall Further due to urbanisation water logging after hours of rainfall is a common problem in Kolkata Whereas, aquifer beneath the surface is semi confined to confined in nature. Generally, groundwater table is available at the depth of 100 meter to 150 meter and another table can be observed beneath this water table. In core urban part of Kolkata, land surface temperature is comparatively higher by 2°C to 3 °C than other adjoining districts thus available amount of soil moisture gets evaporated further. Rainfall of Kolkata is dependent on monsoon and it fluctuates over the years. Mainly rainfall persists between June to September and average yearly rainfall is about 150 cm to 160 cm. Winter persists minimum time here and rest of the year is considered as summer. In summer temperature rise up extremely even upto 45°C and

in winter minimum temperature stays with 10°C to 12°C. Recently difference between diurnal temperature is getting minimised. Night time minimum temperature is increasing in Kolkata.

- Depth of urbanisation properly reflects through the socio economic status of the city. Kolkata is densely urbanised than any other districts of West Bengal. Land of this city is majorly covered by urban built-up area. Population in Kolkata increased in multifold within a century. Recently total population of Kolkata decreased but overall Kolkata is densely populated and in certain wards population density crossed one lakh population within a sq. km area. Households increased also in the meantime. Apart from residential population, large number of floating populations are the major component of urbanisation. Minimizing difference in sex ratio is another sign of developed urbanisation in Kolkata. Effluent urban amenities are the major characteristics of urbanisation. Kolkata has every kind of urban facilities like any other world class city. From world class medical facilities to internationally acclaimed educational facilities, giant business conglomerates, cultural exuberance all are available here. Dense road network along with advanced intracity metro railway system reached excellence in transport and communication. Public water supply system is one the oldest facilities that was available in Kolkata. Architecture behind the water supply system was created by Britishers. Water is supplied by KMC in almost every part of the city. Previously groundwater was one of the main sources of supply water specially where alternative source was unavailable. Recently water is treated with five water works and it is supplied to the households. Public water supply system is reducing the proportion of groundwater from their water source. Still, it is being used privately in many parts of the city and water loss through supply system is another serious issue in Kolkata.

- Urbanisation process in Kolkata is not properly planned and urban area expanded haphazardly according to local need. Northern and central part of Kolkata was already saturated with urbanisation, further scope was remained in southern part of Kolkata. In 1990, Dominance of vegetation was prominent in central eastern part to south western part. Northern part was covered with HDB whereas, southern part of Kolkata was covered with LDB. Till 2000, eastern part of Kolkata was dominated by green space and waterbodies but wetland decreased drastically. In the next decade, LDB increased continuously in the southern part of Kolkata. Built-up area was encroaching other landuse and landcover. In 2020, HDB remained clustered only within central portion of Kolkata. Dominance of LDB observed throughout the study area. Significant amount of bare land was only available in Maidan area. Grassland was only limited to the south eastern part of Kolkata. In thirty years of observational period landuse with HDB was checked in Kolkata but LDB continuously increased. About 50% of the wetland transformed into another land type in every decade. Vegetation cover decreased gradually over the years. Grassland also decreased in the beginning but later it was checked and further grassland has increased in recent times. Near about 50% of bare land was utilised in further built-up process.
  Urbanisation level was 78% in 1990, that further increased over the decades. In 2020,

about 92% land was urbanised. Urban expansion rate in every year was high in between 1990 to 2000, further it slowed down in next decades. Urban expansion ratio also reflected the growth rate that was high in the end of the last century further it was checked. Saturation in already dense urban area left minimum scope for further urbanisation Specifically in northern and central part.

Built-up area increased continuously. At the beginning it was densely concentrated only in northern part of Kolkata later built-up area expanded towards southern part of Kolkata. But density of built-up is less than northern part. Average percentage of built-up area in wards of north was more than 50% on an average, whereas, in southern wards average built-up area was around 25%. It increased further. At the beginning, inequality was prominent in between the wards but later difference reduced. In 2020, all of the wards were having more than 50% of built-up area from the total land. Built-up area reached near to 100% in some wards. Built-up area highly increased in between Ward no. 101 to 141, that were added with KMC just before ninetees.

As built-up area increased over the time, impervious surface also increased as a consequence. from 1990 to 2020, impervious surface increased about 43%. In the beginning of the observation period about 45% of the total land was covered with impervious surface in next thirty years about 65% land was impervious in nature from the total land of Kolkata. Growth percentage of impervious surface was about 20% in between first ten years. In next twenty years growth percentage was 12% on every decade. Impervious surface increased at cost of damaging natural environment. With increase in impervious surface, about 41% of permeable surface was lost from total land of Kolkata.

- Kolkata is situated in the floodplain. Slope of the land is extremely gentle. Soil is composed of thick clay layer which is highly potent for runoff. Aquifer is semi confined to confined in nature. Groundwater flow is very sluggish due to its land properties but heavy pumping creates impact on flow. Groundwater inflow depends on adjoining districts. Scope of recharge is minimum in Kolkata due to dense urbanisation. Groundwater level is comparatively lower than other surrounding districts. Minimum observed groundwater level is increasing recently in Kolkata simultaneously maximum level is declining gradually. Groundwater level is deteriorating in every decade. A trough zone persist in Kolkata that changed its position in every decade. In nineties it is in the central part of Kolkata but recently it stretched between north to south longitudinally. Yearly groundwater level is fluctuating in nature but overall, it is declining. Previously groundwater declination level was high in the central part of Kolkata, later groundwater level declined progressively in southern part of Kolkata. Groundwater level usually rise up after monsoon season. Spatial variation within this urban area is noteworthy. Seasonal fluctuation of groundwater level is high in populated areas.

  Calcium, magnesium,sodium, chloride, bi-carbonate, sulphate and potassium are sufficiently available in chemical composition of groundwater. These components of water highly fluctuate yearly. Available amount of Calcium and Magnesium almost cross the permissible limit prescribed by Indian government. Sodium is also available in ground-

water with higher amount. Sulphate is also available in groundwater but that stays with permissible limit. Bicarbonate is the most available substance in groundwater of Kolkata. pH level varies with time but here generally it is alkaline in nature. Due to higher amount of TDS in groundwater, electrical conductivity is significantly high in Kolkata. As per this study correlation factor between these two parameters are 0.6. Due to availability of calcium and magnesium in groundwater, total hardness in groundwater also high in nature. Significantly, groundwater of Kolkata is reddish in colour due to presence of iron in higher amount. Turbidity of groundwater is also high that creates water cloudy. Alkaline nature of groundwater creates scaling in water system. Groundwater type of Kolkata majorly are Mg-HCO_3 and Na-K-HCO_3 in nature. After monsoon, overall groundwater quality deteriorates. Analysing entropy-based water quality index maintaining Indian standards, it has been assessed that, groundwater quality is poor in Kolkata due to iron, and sulphate in high amount. Groundwater quality is more degraded in western and south eastern part of Kolkata. Central Kolkata and South west Kolkata are better in terms of groundwater quality. Physiochemical components of groundwater spatially vary with time, often one individual component dominates over other components within a small scale area.

- Built-up area continuously increased over the thirty years of time period and groundwater level gradually declined. Significant opposing changing pattern has been recognised here. Further, it will increase and situation will deteriorate further in near future. Effect of built-up area on groundwater level is comparatively high mainly in eastern part of Kolkata and groundwater quality is affected mostly in eastern and south western part of Kolkata because of dense built-up area. Groundwater level declined majorly in high density built-up areas in the last decade of century. Further groundwater level declined because of Low-density built-up area also. Wards with major portion covered with vegetation or waterbodies were less affected but with time vegetation cover, wetland and waterbodies transformed to built-up area and ultimately groundwater level declined in every wards. In the first stage of the observational period, groundwater decline rate was comparatively higher in densely populated urban areas and inequality was prominent in wards but in later stage, groundwater level declined almost in every ward at moderate rate. Two scenarios have been identified where groundwater level declined abruptly in northern western part of Kolkata. Later groundwater declined specifically from south eastern part of Kolkata. With increase in built-up area, imperviousness increased in surface. Within thirty years, groundwater level declined majorly in those wards where impervious surface increased at faster rate. This situation is significantly opposite in case of permeable surface. Groundwater raised up where permeable surface is dominant in nature. Loss of permeable surface majorly affected groundwater resources whereas continuous increase in impervious surface ultimately reduced groundwater recharge. Increasing number of population positively correlates with decline in groundwater level. Even groundwater quality in and around landfill area is in degraded condition than other parts of the city. All the major characteristics of urbanisation showed indication of deterioration in groundwater resources.

Evaluation of groundwater environment using DPSIR framework

DPSIR framework is a widely accepted tool that asses the environmental issues. It supports the interdisciplinary approach to analyse the environment; holistically. EEA developed this model from earlier stress-response framework. D-P-S-I-R is composed of five basic indicators that usually interacts with each other and ultimately provides an overall observation in cyclic form about the whole scenario. In DPSIR, D demarcates the *drivers* which affects the environmental condition, P distinguish the related *pressures*, S analyse the condition or *states*, while I stands for identifying *impacts* related to this condition and R addresses the *responses* related to it. Jago-on et al. (2009) for the first time applied this method to assess the condition of groundwater environment in urban area. The study was based on the city Katmandu in Nepal.
Driving force find the root cause of change,and it generates pressure that directly or indirectly influence the groundwater resources, with time or with no time external influences can change the state of the condition or situation. This specific changes certainly make an impact on the subsurface environment condition.Ultimately, this impact stimulate or provoke to response differently to revise the condition.
Applying DPSIR method for Kolkata it has been identified that, population growth, urbanisation,

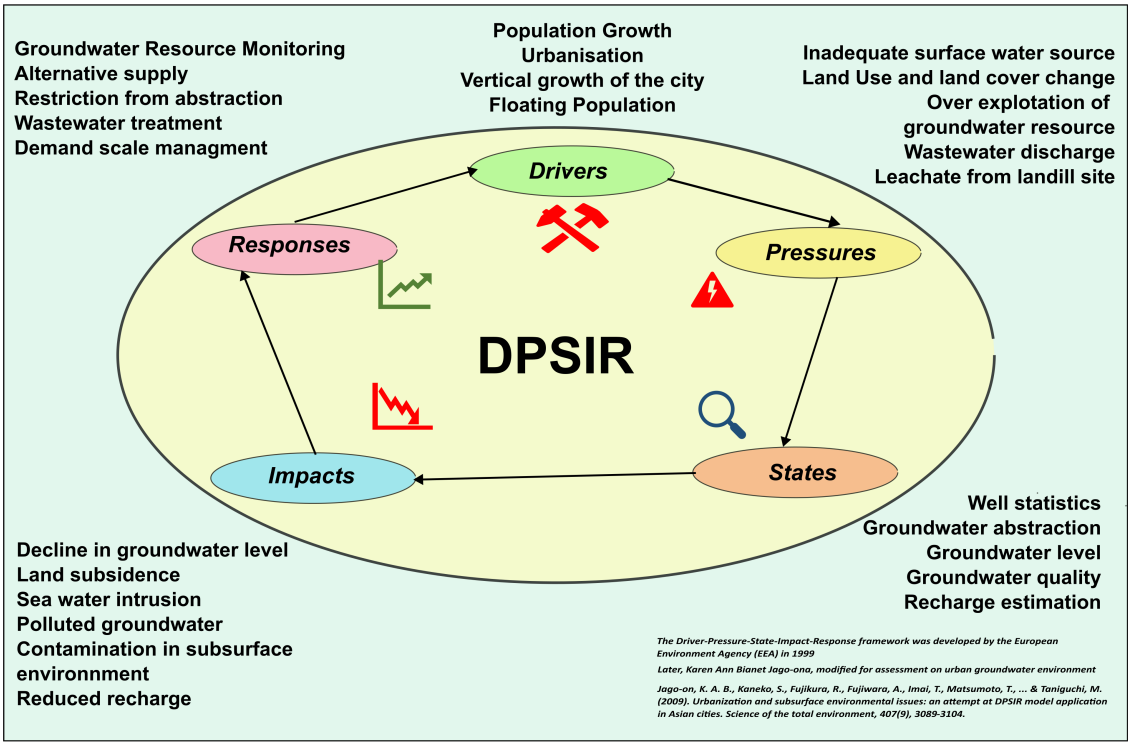


Figure 11.1. Assessment of groundwater environment for Kolkata with DPSIR framework

vertical growth of the city and mostly floating population works as the drivers behind the deteriorated groundwater resource condition in Kolkata. Inadequate surface water supply against the demand, rapid land use and land cover change, excessive amount of groundwater

withdrawal, waste water discharges and leaching from landfill sites are factors that created pressure on subsurface environment of Kolkata. Concerned situation has been analysed by monitoring water level data, condition of wells, analysing groundwater quality and estimating recharge amount. After investigation it is revealed that, impact on groundwater resources is easily recognised further analysing decline in groundwater level, land subsidence, sea water intrusion and contamination of pollutants. It is assumed that by groundwater resource monitoring, engaging alternative water supply, restricting from abstraction privately, treating the waste water and managing demand scale groundwater resources can revitalised in future.

11.2 Conclusion

The study investigates about the urbanisation and its impact on groundwater resources. It has been observed that, urbanisation is an unavoidable process, socio-economic development of an urban area majorly dependent on urbanisation. Cities in the developed countries are already saturated for further urbanisation but in developing countries urbanisation process is going on with a rapid pace. As an effect of urbanisation, natural resources are getting exploited excessively. Groundwater resources are among them which is being utilised in an uncontrolled manner in urban area. Urbanisation process accumulates more people in a smaller place that ultimately creates huge demand of water then groundwater is used to cater that demand. As a result, groundwater level declines from its normal level and unrestricted pressure of abstraction ultimately leads to liquefication of land and land subsidence. Urbanisation create changes in landuse pattern that ultimately reduce vegetation cover, and grassland even waterbodies from the land. With deduction of permeable surface, urbanisation creates more impermeable surface that generates more surface runoff; ultimately obstructs the groundwater recharge and indirectly soil loses it moisture retaining capacity without vegetated land. Subsurface environment is also used for drainage and sewage system in urban area, that ultimately creates condition of leakage and seepage from that water system. Eventually, water percolates from the water supply system to subsurface environment which are mostly polluted after urban usage. Contamination of hazardous material from landfill sites are common in urban area. Even roads, buildings, petrol pumps parks play a crucial role in percolation of polluted materials to subsurface environment. All these factors eventually, degrade the water quality. Water borne diseases affect people seriously those are dependent upon groundwater resources. In the long run, if the deterioration process persists on that urban area, then modification in aquifer environment and hydrological cycle is inevitable. As a result, land subsidence, sea water intrusion, and permanent damage in health condition is the most common outcome.

This case study geospatially analysed the effects of urbanisation on groundwater resources. Effects of urbanisation have been identified for Kolkata on groundwater resources from every possible aspect. Though data insufficiency and other related hindrances limited this study at a level. It has been recognised that Kolkata was a densely populated urban area for few hundred years. Densely built-up was clustered in northern part while southern part of Kolkata was not developed properly. Urbanisation process was evident on that part of Kolkata after

nineties. In next decades, rest of the Kolkata was almost urbanised and urbanisation level reached above 90%. Built-up area continuously increased in Kolkata and green space and water bodies reduced abruptly within few years. Wetlands almost vanished from the land of Kolkata. As a result, impervious surface increased in Kolkata. Population increased over the years and households increased respectively. With high population density it created high demand of water within a small area. As a result, groundwater abstraction process exceeded its replenishable capacity. Groundwater level continuously declined over the years. Soil in Kolkata supports more runoff than recharge and as the city is under confined aquifer water, chance of water infiltration is minimum. With further increase in impervious surface, hardly possibilities remain left for groundwater renewal. In this condition, continuous groundwater abstraction, ultimately reduce the groundwater quantity in Kolkata. Also, groundwater quality is not at satisfactory level. Leakage and seepage from drainage and sewage is usual in Kolkata that provides polluted materials to subsurface. Groundwater of Kolkata is hard in nature. pH level always remains above 7. Groundwater is murky and with concentration of iron it is mostly reddish in colour. Hydro physical components of groundwater create scaly deposits. It is not recommendable for drinking. The study revealed that, in between observation period, groundwater level declined with built-up area increase in Kolkata. Groundwater level declined on those wards of Kolkata at much faster rate where proportion of built-up area was maximum and groundwater declined at much slower rate where dominance of green space was prominent. Groundwater level deteriorated at much faster rate on that phrase of time when urban expansion ratio was comparatively high. Groundwater level declined positively with increase in impervious surface. Permeable surface rather prevented from groundwater level decline. With combined effect of impervious surface and permeable surface, it has been revealed that, vegetation cover reduction from the land of Kolkata proves to be more crucial than increasing impervious surface. Surface runoff increased over the land. Groundwater recharge potentiality obviously reduced with time. Effect of built-up area remains high in the eastern part of Kolkata about groundwater level and in the south eastern part about groundwater quality. Sufficient water supply from surface water source can possibly temporarily solve the groundwater abstraction issue. But in case of Kolkata, water supply is not up to the mark. Even supply system does not match up the national benchmark of per capita water supply and water facility is not provided to every corner of this city. At one time, public water supply was also dependent upon groundwater resources where treated water supply was not available. Recently it is not used for water supply its but that affected groundwater storage for a long time. Also, private groundwater abstraction from individual households is common in Kolkata and this practise is affecting the environment in a negative way. Whereas, groundwater quality in Kolkata is worse around Dhapa, the landfill site of Kolkata. It is continuously polluting the groundwater quality. Impact of urban sources are prominent behind degrading groundwater quality but geological structure of Kolkata prevents from direct percolation of polluting materials to some extent.

On a concluding note, it can be firmly stated that, definitely urbanisation process creates an impact upon groundwater resources and mostly it is negative. Magnitude of this process depends upon local environmental condition but overall human intervention speed up this process with much faster rate. Various important cities in the world already suffered the effect of it and it is

not different in case of Kolkata also. Cracks in building walls and titled buildings are commonly found in Kolkata espcially where groundwater depletion rate is in alarming stage. Drying up of wells and murky water in it clearly depicts about condition of the disturbed aquifer. It is realised that in near future the situation will further deteriorate.

11.3 Recommendations

From the study, overall impact of urbanisation on groundwater resources has been discussed. Also, situation of Kolkata has been investigated thoroughly. Urbanisation already engulfed most part of Kolkata and immediately it is not possible to pause urbanisation process. Considering this situation, some recommendation prescribed after extensive literature review and understanding this city from ground level. It is assumed that, in the end of this study this recommendation will be beneficial for Kolkata on a long run. Briefly, it is suggested that pattern of urbanisation process should be analysed more accurately. Every aspect of urbanisation should be considered in this process. Considering it already an urbanised area, further construction should be planned in effective way. Concept of sustainability should be prioritised.

- As Kolkata is already urbanised in an unplanned way, limited scope are left for this city but it suggested that further development should done be in controlled manner. First of all, unoccupied open land must be conserved and restricted from further built-up area further it should be transferred into vegetated land. Plantation should be prioritised. Grassland should be created immediately on open spaces.
- It is suggested that governmental rules about building laws should strictly amend in urban area. Space between buildings, height of the buildings, materials of the buildings should be strictly maintained at the time of further construction.
- Construction material for road and pavement should be environment friendly and those must have water percolating capability. Use of concrete (cement) should be strictly prohibited for road construction.
- Artificial recharge is the most effective way to check the groundwater level decline. High proportion of surface runoff is common after hours of rainfall in Kolkata. This large amount of rainwater creates situation of waterlogging all over the Kolkata. It is suggested that, by injecting high volume of surface runoff into subsurface environment, both of problems can be solved efficiently.
- It is suggested that groundwater level data should be monitored with TLC meter in every three months in year. Groundwater level data should be collected from every ward of KMC, if that is not possible at least borough wise data collection should be improvised. Groundwater data collection point should be selected based on mean coordinates of any ward or borough.
- For groundwater quality analysis, at least data should be collected on every season and four seasons should be covered. Every major physio chemical parameter should be analysed in

a well-equipped laboratory. Focus should be given on those parameters that counted as harmful particle for humankind.

- Groundwater flow pattern should be analysed on micro level and groundwater deficit zone should be demarcated.
- Kolkata has well enough source of surface water that should be identified and used after necessary treatment. Water from river Hooghly should be collected and with proper treatment it should be provided to every household of this city.
- Rainwater harvesting is highly recommended in urban area like Kolkata where sufficient amount of rainfall is available throughout the year. Rainwater reservation and its application should be practised at least in commercial centres and administrative buildings where need of water more than singular household. This practise should be forced on high class residential apartments. If possible, equipments should be available in subsidised rate for further application of it in individual households also.
- Apart from drinking water, other used water can be reused for another purpose. Awareness should be created among residents about efficient use of water and smart reuse of water in daily life.
- Water loss through water supply system is major issue in Kolkata.Near about 30% of treated water is misused on daily basis that should be controlled immediately. Water supply system runs on very old infrastructure that should be developed as early as possible.
- Use of IoT should be encouraged and water meter should be engaged in household to get idea about the water consumption of the residents on daily basis. Collecting the daily data, it will be easy to understand daily needs of the people location wise and thus water budget will be easily calculated.
- It is suggested after developing infrastructure and with use of IoT, water supply should prioritised according locational demand
- Waste disposal area should not be placed in open ground and regular cleaning up is needed for proper percolation. To reduce leaching of polluted water from landfill areas into the subsurface, it is suggested that, biological treatment and activated carbon treatment should be applied and other physical processes like, grading, plantation, use of caps and covers can be applied also.
- Policy-makers and city planners should evaluate the urban groundwater condition frequently with other resilient cities. Coordination between administrators and experts are necessary for this.

Kolkata is already under double restricted zone, individual groundwater abstraction is strictly prohibited here. Private consumption of groundwater abstraction still practised in almost every part of this city without informing local authority. It is a serious and most prior concern for this city. As groundwater is not visible to human eyes awareness for it also not clear to common

people. Above said measures can not be effective after spontaneous participation from every resident of Kolkata. Strict laws and other preventive measures are already available for this city but mass awareness among people is the ultimate option to save such precious resource like groundwater specially in urban area.

Appendices

Chapter 2

Table 1. Total Population in continents and world

1950	1970	1990	2000	2020	Location
2519470	3696588	5279519	6085572	7577889	World
224068	363534.7	635684.7	812465.6	1228276	Africa
1396254	2140425	3168616	3675799	4553791	Asia
547404.8	655862.3	721389.8	728462.6	714958.7	Europe
112994.8	192467.2	297125.8	349434.1	446297.1	S.America
171614.9	231931.4	283361	314967.6	374999.6	N.America

Table 2. Urban population in continents and world

1950	1970	1990	2000	2020	Location
731764.8	1328847	2270869	2844802	4177106	World
32844.01	84939.75	203227.5	294391.8	556191.2	Africa
234417.5	485159.2	1011412	1363035	2191963	Asia
276657.9	410657.7	508950.4	522107.8	537145.1	Europe
49451.5	115252.7	221420	277410.2	384473.8	S.America
109666.6	171166.8	213744.8	249242.2	317345.8	N.America

Table 3. Urbanisation rate

1950	1970	1990	2000	2020	Location
29.0444	35.94792	43.0128	46.74666	55.12229	World
14.65806	23.36496	31.96986	36.23437	45.28227	Africa
16.78903	22.66649	31.91967	37.08132	48.1349	Asia
50.5399	62.6134	70.55137	71.67256	75.12954	Europe
43.7644	59.88172	74.52063	79.38841	86.14751	S.America
63.90276	73.8006	75.43197	79.13263	84.62563	N.America

Table 4. Urban growth rate

1950-1955	1970-1975	1990-1995	2000-2005	2020-2025	Location
1.325609	0.605651	0.829326	1.035191	0.753341	World

Table 4. Urban growth rate

1950-1955	1970-1975	1990-1995	2000-2005	2020-2025	Location
2.651819	1.816919	1.179579	1.055948	1.080141	Africa
1.93302	1.056211	1.528759	1.847732	1.095757	Asia
1.045853	0.743345	0.16488	0.249432	0.320246	Europe
1.98671	1.242045	0.730162	0.369492	0.237384	S.America
0.96007	0.012747	0.489981	0.213439	0.244423	N.America

Table 5. Urban agglomeration all over the world at different years

Size	Type	1950	1980	2000	2020	2030
10 million or more	Number of Agglomerations	2	5	16	34	43
10 million or more	Percentage of Urban Population	3	5	9	13	15
10 million or more	Population	23613	86295	245386	556770	751934
5 to 10 million	Number of Agglomerations	5	19	30	51	66
5 to 10 million	Percentage of Urban Population	4	8	7	8	9
5 to 10 million	Population	32172	139606	213794	348132	447815
1 to 5 million	Number of Agglomerations	69	174	325	494	597
1 to 5 million	Percentage of Urban Population	17	19	22	22	23
1 to 5 million	Population	127484	335936	625857	976786	1182839
500 000 to 1 million	Number of Agglomerations	101	247	396	626	710
500 000 to 1 million	Percentage of Urban Population	9	10	9	10	10
500 000 to 1 million	Population	67471	170247	269041	431401	493629
300 000 to 500 000	Number of Agglomerations	129	297	524	729	827
300 000 to 500 000	Percentage of Urban Population	7	6	7	6	6
300 000 to 500 000	Population	49854	113703	199623	278900	319827
Fewer than 300 000	Percentage of Urban Population	60	52	46	41	38
Fewer than 300 000	Population	450309	908415	1314607	1787005	1971215

Table 6. Groundwater dependent cities

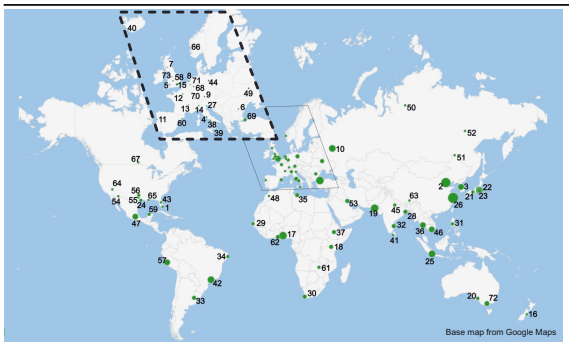
City Name	Country Name	City Name	Country Name	City Name	Country Name	City Name	Country Name
Juneau	United States	Bursa	Turkey	Tripoli	Libya	Hanoi	Vietnam
Riga	Latvia	Beijing	China	Benghazi	Libya	Merida	Mexico
Ufa	Russia	Indianapolis	United States	Tel Aviv-Yafo	Israel	Mexico City	Mexico
Vilnius	Lithuania	Tangshan	China	Amritsar	India	Toluca	Mexico
Minsk	Belarus	Cincinnati	United States	Lahore	Pakistan	Santo Domingo	Dominican Republic
Hamburg	Germany	Tianjin	China	Faisalabad	Pakistan	Dakar	Senegal
Berlin	Germany	Pyongyang	North Korea	Cairo	Egypt	Guatemala	Guatemala
Amsterdam	Netherlands	Lisbon	Portugal	Houston	United States	Tegucigalpa	Honduras
Irkutsk	Russia	Sacramento	United States	San Antonio	United States	Bangkok	Thailand
Lille	France	Smyrana	Turkey	Tampa	United States	San Salvador	El Salvador
Prague	Czech Republic	Shijiazhuang	China	Jaipur	India	Niamey	Niger
Paris	France	Taiyuan	China	Lucknow	India	Bamako	Mali
Munich	Germany	San Francisco	United States	Guiyang	China	Ouagadougou	Burkina Faso
Ulaanbaatar	Mongolia	San Jose	United States	Kanpur	India	Managua	Nicaragua
Seattle	United States	Jinan	China	Miami	United States	Ndjamena	Chad
Budapest	Hungary	Taejon	South Korea	Monterrey	Mexico	Kano	Nigeria
Harbin	China	Qingdao	China	Patna	India	San Jose	Costa Rica
Lyon	France	Tokyo	Japan	Hyderabad	Pakistan	Addis Ababa	Ethiopia
Milan	Italy	Memphis	United States	Kunming	China	Panama	Panama
Portland	United States	Kyoto	Japan	T'aichung	Taiwan	Georgetown	Guyana
Turin	Italy	Zhengzhou	China	Dhaka	Bangladesh	Paramaribo	Suriname
Minneapolis	United States	Xian	China	Ahmadabad	India	Abidjan	Cote d'Ivory
Belgrade	Serbia	Los Angeles	United States	Kaoshsiung	Taiwan	Douala	Cameroon
Changchun	China	Fukuoka	Japan	Calcutta	India	Mogadishu	Somalia
Urumqi	China	Phoenix	United States	Honolulu	United States	Belem	Brazil
Milwaukee	United States	Lima	Peru	Agra	India	Fortaleza	Brazil
Bishkek	Kyrgyzstan	Linyi	China	Allahabad	India	Natal	Brazil
Rome	Italy	Xuzhou	China	Dhanbad	India	Jakarta	Indonesia

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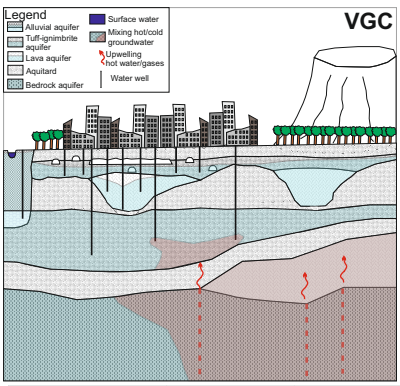
Review: Urban groundwater issues and resource management, and their roles in the resilience of cities.

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Groundwater city classification



Location of cities cited in the paper and reported in the following tables per typology.
Label numbers are listed in the paper's Appendix and symbol dimension is proportional to number of inhabitants.

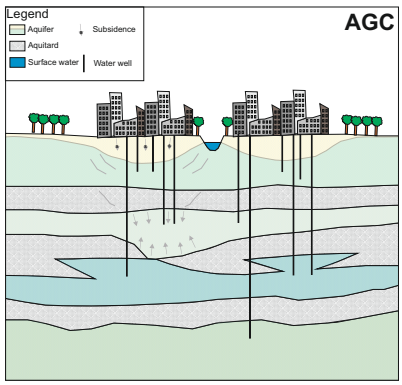


Volcanic groundwater cities

These cities are characterized by aquifers with a particular setting usually influenced by the volcanic depositional activity, with frequent abrupt changes in permeability. Moreover, thermalized and mineralized groundwater is frequent, even if the volcano is quiescent or no longer active; also the presence of natural background contaminants is possible in these contexts due to the volcanic nature of rocks.

VGC

Citation order an label	City	State	Continent	Reference
4	Rome	Italy	Europe	La Vigna et al. 2016
18	Nairobi	Kenya	Africa	Oiro et al. 2020
37	Addis Ababa	Ethiopia	Africa	Adelana et al. 2008
38	Naples	Italy	Europe	Corniello and Ducci 2019
39	Catania	Italy	Europe	Ferrara and Pappalardo 2008
40	Reykjavik	Iceland	Europe	Kononov 1979
47	Mexico City	Mexico	North America	Anton 1993
72	Melbourne	Australia	Oceania	Bell et al. 1967

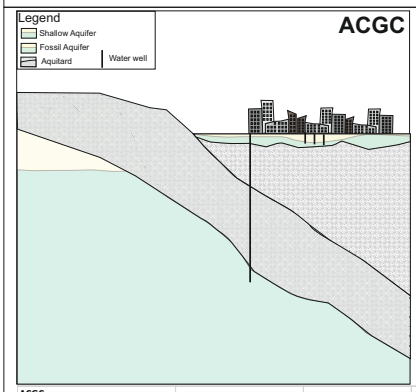


Alluvial groundwater cities

These cities developed on alluvial or generally sedimentary depositional basins or in basins characterized by glacial deposits, where their thickness allows groundwater circulation that is useful or interferes with the city. The frequent multilayer setting of the geological units influences the aquifers' geometry. Subsidence is a typical issue of AGCs, especially when aquifers are overexploited.

AGC

Citation order an label	City	State	Continent	Reference
2	Beijing	China	Asia	Chen et al. 2016
6	Bucharest	Romania	Europe	Boukhemacha et al. 2015
8	Amsterdam	The Netherlands	Europe	de Vries 2007
9	Munich	Germany	Europe	Menberg et al. 2013
13	Lyon	France	Europe	Attard et al. 2016a
14	Milan	Italy	Europe	Gorla et al. 2016
15	London	United Kingdom	Europe	Shanahan 2009
16	Christchurch	New Zealand	Oceania	NIWA 2004
17	Lagos	Nigeria	Africa	Adelana et al. 2008
28	Kolkata (Calcutta)	India	Asia	McArthur et al. 2018
44	Berlin	Germany	Europe	Menberg et al. 2013
45	Lucknow	India	Asia	Singh et al. 2013
46	Ho Chi Minh City	Vietnam	Asia	IGES 2007
47	Mexico City	Mexico	North America	Anton 1993
49	Kyiv	Ukraine	Europe	Shestopalov et al. 2000
63	Lhasa	China	Asia	Liu et al. 2018
67	Winnipeg	Canada	North America	Keller et al. 2009
68	Cologne	Germany	Europe	Zhu et al. 2010
70	Basel	Switzerland	Europe	Michel et al. 2017
71	Eindhoven	The Netherlands	Europe	Bonte et al. 2013
73	Manchester	United Kingdom	Europe	Arnhardt and Burke 2020

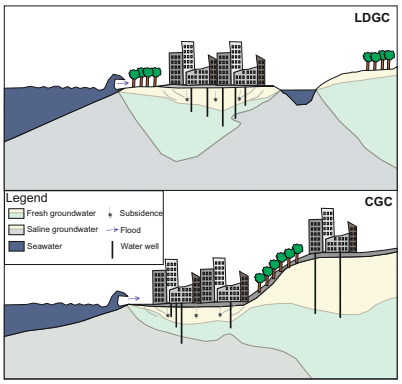


Arid climate groundwater cities

These cities have sometimes very shallow groundwater systems which are more sensitive to the few seasonal recharge events, or sometimes very deep "fossil" groundwater resources, which are sometimes huge but not renewable.

ACGC

Citation order an label	City	State	Continent	Reference
47	Mexico City	Mexico	North America	Anton 1993
53	Kuwait City	Kuwait	Asia	Al-Rashed and Sherif 2001
54	Tucson	USA	North America	Eastoe et al. 2004
55	Waco	USA	North America	Yelderman and Joe 2019
56	Dallas	USA	North America	Caldwell 1993
62	Accra	Ghana	Africa	Kortatsi et al. 2008
64	Las Vegas	USA	North America	Wyman et al. 1993

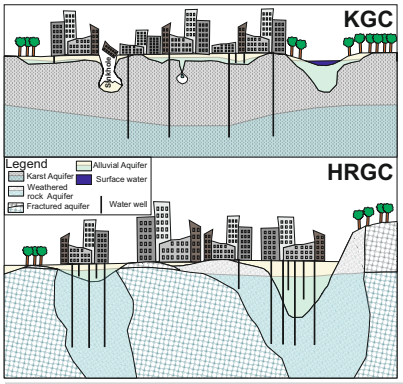


Coastal and Lagoon/Delta groundwater cities

These cities are in correspondence with the "zone of transition" where the seawater/freshwater interface is below the ground surface. When these cities are located on soft sedimentary soils, they can be subjected to severe subsidence as a result of overdraft and this can also contribute to an increase in local coast-related hazards.

CGC - LDGC

Citation order an label	City	State	Continent	Reference
1	Miami	USA	North America	Williams and Kuniansky 2016
4	Rome	Italy	Europe	La Vigna et al. 2016
5	Cardiff	United Kingdom	Europe	Heathcote et al. 2003
8	Amsterdam	The Netherlands	Europe	de Vries 2007
16	Christchurch	New Zealand	Oceania	NIWA 2004
17	Lagos	Nigeria	Africa	Adelana et al. 2008
19	Karachi	Pakistan	Asia	Khan et al. 2020
20	Adelaide	Australia	Oceania	Gerges 2006
21	Kobe	Japan	Asia	Shrestha et al. 2016
22	Tokyo	Japan	Asia	Shrestha et al. 2016
23	Yokohama	Japan	Asia	Shrestha et al. 2016
24	Huston	USA	North America	Braun and Ramage 2020
25	Jakarta	Indonesia	Asia	Lubis 2018
26	Shangai	China	Asia	Zhang et al. 2019
27	Venice	Italy	Europe	Da Lio et al. 2013
28	Kolkata (Calcutta)	India	Asia	McArthur et al. 2018
29	Dakar	Senegal	Africa	Adelana et al. 2008
30	Cape Town	South Africa	Africa	Adelana et al. 2008
31	Manila	Philippines	Asia	David et al. 2001
32	Chennai	India	Asia	Senthilkumar 2017
33	Buenos Aires	Argentina	South America	Anton 1993
34	Recife	Brazil	South America	Anton 1993
35	Tripoli	Libya	Africa	Alfarrah and Walraevens 2018
36	Bangkok	Thailand	Asia	IGES 2007
41	Colombo	Sri Lanka	Asia	Herath and Ratnayake 2007
57	Lima	Perù	South America	Anton 1993
60	Barcelona	Spain	Europe	Filbà et al. 2016
62	Accra	Ghana	Africa	Kortatsi et al. 2008
65	New Orleans	USA	North America	Prakken 2009
66	Bergen	Norway	Europe	Seither et al. 2016
72	Melbourne	Australia	Oceania	Bell et al. 1967

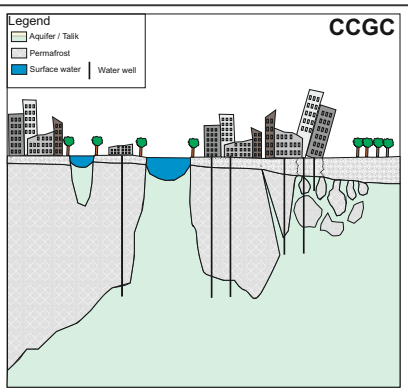


Hard-rock and karst groundwater cities

These cities are characterized by the presence of massive rocks and thus they are mainly characterized by fissured aquifers or, in the case of carbonate rocks also by karst aquifers. Groundwater circulation is also possible in more degraded sectors of rock mass. In karst contexts, the groundwater also has an important role in triggering sinkhole formation.

KGC-HRGC

Citation order an label	City	State	Continent	Reference
1	Miami	USA	North America	Williams and Kuniansky 2016
3	Seul	South Korea	Asia	Shrestha et al. 2016
7	Glasgow	United Kingdom	Europe	Dochartaigh et al. 2019
10	Moscow	Russia	Asia	Osipov 2015
11	Porto	Portugal	Europe	Afonso et al. 2007a
12	Paris	France	Europe	Thierry et al. 2009
15	London	United Kingdom	Europe	Shanahan 2009
18	Nairobi	Kenya	Africa	Oiro et al. 2020
19	Karachi	Pakistan	Asia	Khan et al. 2020
32	Chennai	India	Asia	Senthilkumar 2017
41	Colombo	Sri Lanka	Asia	Herath and Ratnayake 2007
42	Sao Paolo	Brazil	South America	Anton 1993
43	Orlando	USA	North America	Wilson and Beck 1992
48	Beni Mellal City	Morocco	Africa	El Baghdadi et al. 2019
57	Lima	Perù	South America	Anton 1993
58	Birmingham	United Kingdom	Europe	Bottrell et al. 2008
59	Merida	Mexico	North America	Anton 1993
61	Lusaka	Zambia	Africa	Adelana et al. 2008
66	Bergen	Norway	Europe	Seither et al. 2016
69	Istanbul	Turkey	Europe	Ozgul 2011



Cold climate groundwater cities

These cities sometimes have to deal with permafrost and its related issues. Permafrost usually constitutes a real barrier to natural aquifer recharge; moreover the urban infrastructure and buildings themselves (together with climate change) induce a heat island effect on it that contributes to the ground thawing and generating ground instability.

CCGC

Citation order an label	City	State	Continent	Reference
50	Norilsk	Russia	Asia	Shiklomanov et al. 2017
51	Mohe County	China	Asia	Yu et al. 2014
52	Yakutsk	Russia	Asia	Pavlova et al. 2020
63	Lhasa	China	Asia	Liu et al. 2018

Chapter 7

Table 7. Wardwise census data from district statistical handbook of Kolkata for the census year 1991, 2001 and 2011

WARD	AREA	HH 1991	POP 1991	HH 2001	POP 2001	HH 2011	POP 2011
1	1.37	10571	52499	10038	49018	11394	53125
2	1.72	9198	49892	10486	47327	11305	48190
3	1.35	9844	54147	10799	53299	11617	53855
4	0.95	8630	41505	8642	40121	8558	34476
5	1.36	5149	27581	5322	26117	5815	23707
6	1.74	8181	40273	8750	48096	8855	42346
7	0.42	3888	19809	4479	20226	4240	19180
8	0.36	4279	23306	4366	21071	4285	18760
9	0.3	4416	23687	4265	20374	3834	16420
10	0.44	5660	29679	5872	33807	5139	27700
11	0.33	5327	29105	5260	26190	4715	22152
12	0.53	5437	28952	5701	28912	4864	21493
13	0.79	5543	26912	6684	31118	7292	33066
14	1.01	10834	53855	10986	49698	12387	53343
15	0.53	5442	32296	5803	26709	5397	23922
16	0.31	4203	23172	4263	26665	4230	20904
17	0.36	5394	29424	5062	24016	4895	21023
18	0.24	5563	24556	5594	25508	5525	22267
19	0.24	4960	25509	5488	24479	4593	21158
20	0.3	4119	23836	4271	20481	4310	21576
21	0.34	4847	24980	4413	24629	4304	21187
22	0.35	3303	19864	3218	20569	2884	15730
23	0.16	4232	26530	3797	21775	3338	18256
24	0.2	3523	19713	3558	19520	3842	19824
25	0.41	7448	43149	7654	39160	5838	27484
26	0.35	6473	34145	6023	31400	5659	25371
27	0.43	4188	23543	4831	23089	4352	19350
28	0.43	7030	44507	7286	41775	7223	38110
29	0.56	7716	47598	7446	46887	9047	53782
30	0.58	5823	30422	5932	28278	6747	30050
31	1.39	7379	35992	7606	36456	8800	39025
32	1.67	8717	41477	9996	46081	10708	45636

Table 7 continued from previous page

WARD	AREA	HH 1991	POP 1991	HH 2001	POP 2001	HH 2011	POP 2011
33	1.83	8026	42108	9428	44230	11095	45919
34	0.79	7333	34948	6266	27808	7611	29773
35	0.83	7385	35633	6746	31320	8524	35024
36	0.99	6505	28734	3871	22851	4574	27238
37	0.31	4600	24187	4275	24004	4688	24020
38	0.49	6115	35202	5449	28083	6500	28791
39	0.2	3502	25558	4158	28255	3716	21296
40	0.37	5698	28403	4948	24384	4733	20549
41	0.21	4175	29174	3814	25486	3425	19946
42	0.32	4816	28862	4169	26077	3749	21746
43	0.24	3827	24446	4083	29647	2878	17677
44	0.52	5255	33773	5061	33652	5043	29600
45	1.54	2996	16025	2843	15360	1704	8394
46	1.31	3679	20986	3849	22959	2316	12823
47	0.4	4293	23653	3783	21218	3271	14684
48	0.25	5767	25472	5159	21856	4671	20437
49	0.26	4264	19945	3601	20671	3965	19416
50	0.38	4861	23367	3861	18365	3791	17251
51	0.3	3933	19519	3666	16272	3273	13556
52	0.24	3920	22493	4185	24672	3304	16869
53	0.35	5232	29077	5509	28910	5405	25598
54	0.38	6132	39077	6612	40299	6666	36235
55	0.98	6208	31235	6946	35955	6745	32254
56	0.68	8212	43948	7901	43304	8941	43622
57	2.74	10124	48951	9236	45206	11051	49856
58	10.81	15702	78565	16257	86487	20093	88465
59	1.94	12524	63623	12687	66690	15157	70261
60	0.58	6560	41040	7256	42585	6755	35732
61	0.64	6515	35211	5857	34128	5447	29704
62	0.39	6252	36282	7484	46640	6400	34832
63	3.8	6456	32554	6307	32123	4674	24387
64	0.85	5914	31041	4627	26891	6342	31280
65	1.33	12096	70846	13292	80098	14092	72427
66	1.91	11308	62621	13420	70179	20797	98024
67	1.84	10302	49679	11662	54380	13631	56284
68	0.93	5955	26457	5702	24181	4812	20724
69	2.02	9700	48938	8696	43358	9615	44111
70	0.83	6154	30893	6575	31774	3879	18618
71	1.04	6915	35656	7271	33199	6266	29922
72	0.58	5333	27094	5159	24487	4306	19167
73	0.54	5048	24876	5456	24416	5260	23512
74	3.35	7247	35518	7123	37119	9189	42176
75	0.56	5170	22996	4806	24392	5978	26925
76	0.44	6185	28962	5106	24248	5052	21946

Table 7 continued from previous page

WARD	AREA	HH 1991	POP 1991	HH 2001	POP 2001	HH 2011	POP 2011
77	0.5	8111	45987	7802	44071	8829	45984
78	0.68	11226	58444	10668	58930	10637	54090
79	2.93	8982	42775	8676	42229	9235	44303
80	9.08	6962	36305	7837	38587	7124	31094
81	1.27	10028	49285	9897	47258	10211	41501
82	0.93	9322	43790	9469	43347	9994	38838
83	0.48	6134	31739	4952	24381	5176	22163
84	0.47	4694	23710	4769	23400	4420	19230
85	0.72	6970	32477	6762	31231	6402	29566
86	0.89	5498	25689	5727	25148	4921	19195
87	0.75	3846	18534	3121	13324	3227	12675
88	0.49	6119	28378	6002	27050	6109	23672
89	0.7	5925	29754	5836	26781	5819	22304
90	1.15	4870	21248	5264	22145	4761	18857
91	1.08	6906	34439	8389	36453	9995	38450
92	1.58	7890	38127	8645	35916	10177	36450
93	1.87	11727	54493	12386	56029	11871	44364
94	1.67	4787	22702	6295	29570	7121	27469
95	1.01	6229	28778	7123	28500	7651	26737
96	1.13	6215	29443	7207	28990	8893	31033
97	1.94	7456	35944	8771	37404	10222	37199
98	1.16	6143	29520	7297	30514	8904	31708
99	0.91	3840	19580	4448	19855	7222	26739
100	1.41	5892	27850	7359	29665	7269	25507
101	1.68	6563	30896	8946	37634	10934	40208
102	0.99	4346	21240	4854	20646	5867	21503
103	0.96	4708	21417	6324	25528	7105	25428
104	1.19	5433	25527	7374	29459	9224	33185
105	0.67	3903	18994	4881	20980	5639	21267
106	1.91	4613	22729	7124	30500	10558	40618
107	2.7	5880	27616	9335	39730	13518	54260
108	11.95	3717	18326	9334	38338	15854	64777
109	7.1	4693	23271	8756	37610	16238	64567
110	1.75	4523	20776	5798	22765	7628	27470
111	2.43	4765	23003	7556	32149	10156	38647
112	1.61	4513	21547	5907	25497	8373	32404
113	1.65	4714	22674	7316	30933	8508	33475
114	2.31	5053	24875	7018	31416	10958	41913
115	1.47	5584	27108	7074	30616	8461	31919
116	1.22	5257	26274	6461	28473	6897	28338
117	0.73	4980	24426	5081	25276	5226	21824
118	0.85	5056	23935	5938	25922	5433	21810
119	0.63	3970	18863	4074	19410	4081	16491
120	0.7	4460	21162	5155	21900	5249	19710

Table 7 continued from previous page

WARD	AREA	HH 1991	POP 1991	HH 2001	POP 2001	HH 2011	POP 2011
121	1.48	5951	27829	6156	29970	7712	29921
122	3.16	5576	27561	7996	34957	9977	39198
123	1.9	4739	22732	7215	30569	9425	35386
124	2.55	5911	26556	7560	34295	10128	39179
125	2.88	6285	30016	9984	42245	11297	44850
126	2.96	4835	23301	6465	27234	8247	31631
127	3.43	5716	27672	8706	36584	11221	43782
128	1.84	5385	25412	7520	31864	8405	32179
129	2.11	6610	31857	9087	38967	10206	39654
130	1.04	5077	23314	5980	26630	6150	23227
131	1.41	5753	25522	7301	30136	8284	30911
132	0.92	5458	24028	6771	28089	6722	26274
133	0.51	4588	22975	4360	23881	5306	25588
134	0.38	5766	31462	5869	36687	6281	35780
135	0.34	4710	28822	5019	31743	5911	33258
136	0.53	3726	19837	4029	21810	4485	21482
137	0.63	4024	18592	2974	20036	3373	19385
138	0.81	4170	26051	4340	34724	4629	28858
139	1.62	4605	33114	6210	45006	6937	42014
140	1.55	2685	21224	3935	29636	5004	30504
141	2.61	3753	24106	5048	31183	7755	41152

Table 8. Water supply from KMC; Source KMC, 2018

Location	District	Capacity	Total Capacity	Supply
TALLAH	North and Central	44	132	122.7
MD. ALI PARK	North and Central	4	12	11.2
RSM SQ	North and Central	6	18	16.7
AUCKLAND SQ.	North and Central	6.5	19.5	18.1
BAGMARI	North and Central	6	18	16.7
NEW PARK	North and Central	3	9	8.4
PARK CIRCUS	North and Central	4	12	11.2
KASBA	North and Central	3.5	10.5	9.8
CONVENT PARK	North and Central	3	9	8.4
CHAULPATTY	North and Central	2	6	5.6
GARDEN REACH	South and Suburban	18	54	52.5
BEHALA CHOURASTA	South and Suburban	4.5	13.5	13.1
KALIGHAT	South and Suburban	4	12	11.7
GARFA	South and Suburban	3	9	8.8
BANSDRONI	South and Suburban	2	6	5.8
BANSDRONI UGR	South and Suburban	1.2	3.6	3.5
RANIKUTHI UGR	South and Suburban	3.5	10.5	10.2
RANKIKUTHI ESR	South and Suburban	1	3	2.9

Table 8 continued from previous page

Location	District	Capacity	Total Capacity	Supply
SIRITI	South and Suburban	2	6	5.8
DASPARA	South and Suburban	3	9	8.8
SENPALLY	South and Suburban	2	6	5.8
PARFULLA PARK	South and Suburban	3	9	8.8
LAYELKA	South and Suburban	1.8	5.4	5.3
PARNASREE	South and Suburban	2	6	5.8
HARISH PARK	South and Suburban	0.5	1.5	1.5
GARDEN REACH (JUSCO)	South and Suburban	2.5	7.5	7.3
GARDEN REACH(L&T)	South and Suburban	8.5	25.5	24.8
COCOLA BAGAN	South and Suburban	0.14	0.42	0.4
NAGENDRA UDYAN	South and Suburban	0.14	0.42	0.4
PARNASHREE QUARTER	South and Suburban	0.2	0.6	0.6
AIRPORT ROAD	South and Suburban	0.2	0.6	0.6
CHETLA	South and Suburban	2	6	5.8
C.N.ROY ROAD	South and Suburban	0.2	0.6	0.6
BANGUR PARK	South and Suburban	0.4	1.2	1.2
SACHIN SENGUPTA PARK	South and Suburban	0.131	0.393	0.4
AGRASI MATH	South and Suburban	0.211	0.633	0.6
RAJANI MUKHERJEE ROAD	South and Suburban	0.131	0.393	0.4
DESHAPRIYA PARK	South and Suburban	0.26	0.78	0.8
GJ KHAN	Eastern	2	4	3.2
ANANDAPUR	Eastern	0.5	1	0.8
MUKUNDAPUR	Eastern	0.5	1	0.8
PATULI	Eastern	0.5	1	0.8
TELIPARA	Eastern	1	2	1.6
ANANDAPUR EXTENSION	Eastern	2	4	3.2
PATULI EXTENSION	Eastern	1.7	3.4	2.7
HATGACHIA	Eastern	0.49	0.98	0.8
PANCHANNAGRAM	Eastern	0.2	0.4	0.3
PANCHASAYAR	Eastern	0.11	0.22	0.2
KAYASHTHYAPARA	Eastern	0.405	0.81	0.6
ACHENA PARAK	Eastern	0.2	0.4	0.3
NARKEL BAGAN	Eastern	0.13	0.26	0.2
KHEJURTALA	Eastern	0.13	0.26	0.2
SANTIPALLY	Eastern	0.13	0.26	0.2
HATISUR	Eastern	0.13	0.26	0.2
ANANPAPUR HW	Eastern	0.34	0.68	0.5
ANANDAPUR HW2	Eastern	0.34	0.68	0.5
LALGATE	Eastern	0.33	0.66	0.5
MUKUNDAPUR HW	Eastern	0.6	1.2	1.0
MUKUNDAPUR HW	Eastern	0.49	0.98	0.8
PHOOL BAGAN	Eastern	0.31	0.62	0.5
PATULI HW	Eastern	0.88	1.76	1.4

Table 8 continued from previous page

Location	District	Capacity	Total Capacity	Supply
JORABAGAN	Business (N&S)	3.5	7	4.4
WATGUNGE	Khidderpore	2.5	5	3.0

Chapter 8

Table 9. Details about satellite data used in this study (Source: Landsat USGS Earth explorer)

Spacecraft	**Sensor Id**	**Spatial Resolution**	**Acquired Date**	**Data Type**	**WRS Path**	**WRS Row**	**Cloud Cover**
LANDSAT 5	TM	30m*30m	30-01-1990	L1TP	138	44	0
		30m*30m	26-01-2000	L1TP	138	44	0
		30m*30m	21-01-2010	L1TP	138	44	0.01
LANDSAT 8	OLI TIRS	30m*30m	02-12-2020	L1TP	138	44	0.01

Table 10. Accuracy Asssesment of LULC data

Year	User's Accuracy (%)						
	HDB	LDB	Vegetation	Grass land	Water Bodies	Wetland	Bare land
1990	93.88	92.31	90	90.32	82.35	91.67	85
2000	94.23	92.86	88.57	91.67	86.67	95.65	90
2010	94.55	93.33	94.29	94.12	94.74	95	88.24
2020	96.49	95.74	96.97	92.86	95.24	94.74	85.71
Year	Producer's Accuracy(%)						
	HDB	LDB	Vegetation	Grass land	Water Bodies	Wetland	Bare land
1990	95.83	92.31	97.3	82.35	82.35	91.67	85
2000	96.08	95.12	96.88	89.19	86.67	91.68	85.71
2010	96.3	95.45	97.06	91.43	90	95	83.33
2020	96.49	97.83	96.97	92.86	90.91	94.74	92.31

Table 11. Details about urbanisation indices from 1990 to 2020

Year	**UL**	**UI**	**UX**	**UXr**
1990	144.8721	77.67987	0	0
2000	162.6939	87.23585	1.78218	12.30175
2010	167.9724	90.06616	0.52785	3.244436
2020	171.7137	92.07223	0.37413	2.22733

Table 12. Area wise description of LULC changes in every ten years from 1990 to 2020

	HighDensity Builtup	**LowDensity Builtup**	**Vegetation**	**Grassland**	**Waterbody**	**Wetland**	**Bareland**	***1990***
HighDensity Builtup	45.0477	9.8199	3.0996	0.0657	0.1665	0.7578	0.2979	59.2551
LowDensity Builtup	9.8235	13.0725	0.6327	0.1287	0.0495	0.1332	0.9252	24.7653
Vegetation	9.2988	7.5528	24.3234	1.0845	0.6705	1.4148	0.5607	44.9064
Grassland	0.6435	4.5135	4.0392	4.4955	0.1116	0.2673	1.8756	15.9462
River	0	0.0027	0	0.0072	0.0108	0.0477	9.00E-04	0.0819
Waterbody	2.7495	0.4212	3.33	0.1359	6.8706	2.1096	0.1404	15.7662
Wetland	3.3759	2.79	5.4036	0.711	1.9791	1.7559	0.297	16.3143
Bareland	0.6993	3.582	0.5004	1.3599	0.0729	0.0594	3.2832	9.5571
2000	71.6382	41.7546	41.3289	7.9884	9.9315	6.5457	7.3809	186.5925

	HighDensity Builtup	**LowDensity Builtup**	**Vegetation**	**Grassland**	**Waterbody**	**Wetland**	**Bareland**	***2000***
HighDensity Builtup	48.8952	13.9671	6.5988	0.2646	0.1116	1.3914	0.4095	71.6382
LowDensity Builtup	16.4277	19.3968	3.4317	1.0323	0.081	0.1827	1.1907	41.7546
Vegetation	5.9022	7.1118	22.5135	3.5982	0.5913	1.0494	0.558	41.3289
Grassland	0.2322	2.0079	1.1907	3.5532	0.0063	0.0459	0.9522	7.9884
River	0	0.0036	9.00E-04	0.0018	9.00E-04	0.009	0	0.0243
Waterbody	0.3456	0.306	1.9782	0.198	5.8293	1.0413	0.045	9.9315
Wetland	1.2834	0.7452	1.8225	0.3708	0.9513	1.2087	0.1269	6.5457
Bareland	0.5139	2.8836	0.4401	0.9567	0.0333	0.0369	2.5164	7.3809
2010	73.6002	46.422	37.9764	9.9756	7.605	4.9653	5.7987	186.5925

	HighDensity Builtup	**LowDensity Builtup**	**Vegetation**	**Grassland**	**Waterbody**	**Wetland**	**Bareland**	***2010***
HighDensity Builtup	41.5341	22.7988	7.7463	0.7299	0.1854	0.2565	0.3474	73.6002
LowDensity Builtup	10.8288	28.6542	4.3569	1.5111	0.1962	0.1836	0.6912	46.422
Vegetation	2.6559	6.8364	18.1278	8.3745	0.8172	0.5409	0.6237	37.9764
Grassland	0.1386	2.0475	1.7883	4.4775	0.0585	0.0747	1.3905	9.9756
River	0	0.0081	0.0738	0.0567	0.054	0.0495	0.0036	0.2493
Waterbody	0.1233	0.1674	0.6102	0.6876	5.1633	0.8109	0.0405	7.605
Wetland	1.1331	0.5868	1.197	0.5994	0.567	0.8208	0.0405	4.9653
Bareland	0.5958	2.4156	0.3015	0.6894	0.027	0.0189	1.7505	5.7987
2020	57.0096	63.5148	34.2018	17.1261	7.0686	2.7558	4.8879	186.5925

Table 13. Wardwise percentage of Impervious surface in different years from 1990 -2020

Ward No.	1990	2000	2010	2020
1	84.49	89.22	86.16	85.87
2	73.05	81.77	85.02	83.74
3	69.04	78.54	77.21	62.44
4	88.53	91.47	88.74	89.05
5	73.86	76.66	71.35	63.48
6	81.82	87.16	83.89	82.17
7	88.36	91.92	90.26	89.31
8	93.63	96.12	94.46	95.57
9	92.26	92.59	92.26	94.28
10	99.09	99.77	98.86	99.32
11	99.08	99.69	99.08	99.08
12	89.35	93.54	89.73	87.07
13	84.35	93	86.13	90.2
14	84.08	91.54	90.85	85.77
15	94.75	98.31	95.31	88.74
16	99.68	99.68	97.73	99.35
17	99.45	99.72	99.72	99.72
18	99.58	99.58	100	100
19	94.24	95.47	94.65	95.88
20	94.93	96.62	94.26	97.64
21	91.5	93.84	92.96	94.43
22	84.68	92.77	89.02	87.57
23	97.56	100	100	98.78
24	99	99.5	100	100
25	99.02	99.51	99.02	99.75
26	98.02	99.15	96.03	95.47
27	96.71	98.12	95.53	94.35
28	96.71	99.29	97.88	96
29	90.96	96.99	93.26	90.78
30	91.9	94.31	92.59	85.17
31	72.64	80.65	83.9	79.86
32	63.12	76.94	74.71	68.05
33	57.6	72.05	69.75	60.18
34	89.35	95.18	90.49	86.82
35	88.81	92.42	86.64	72.68
36	90.09	94.34	87.56	73
37	97.77	98.09	95.54	92.36
38	98.17	98.98	98.98	98.17
39	90.05	91.54	95.52	96.02
40	97.55	97.83	99.46	97.55
41	94.29	94.76	92.86	91.43
42	95.03	98.76	99.07	99.69
43	98.73	100	99.58	100

Table 13 continued from previous page

Ward No.	1990	2000	2010	2020
44	94.83	96.74	94.44	96.74
45	65.67	77.68	71.9	70.08
46	71.56	82.8	75.76	71.79
47	98.03	99.02	98.03	98.53
48	98.39	98.79	100	99.6
49	98.84	98.84	98.84	99.22
50	96.88	98.44	98.18	98.44
51	96.72	98.36	96.72	92.46
52	99.17	99.59	98.76	99.59
53	98.55	99.42	98.84	98.27
54	98.41	98.41	98.67	98.41
55	93.05	93.77	92.13	72.52
56	92.48	92.92	91	80.83
57	38.62	51.52	52.47	50.97
58	21.21	26.5	32.25	35.85
59	61.52	76.95	75.82	72.74
60	88.49	92.78	89.69	85.57
61	83.98	87.09	84.91	85.07
62	97.94	98.2	97.68	97.68
63	43.5	57.55	48.79	45.05
64	84.15	88.97	89.79	86.03
65	82.07	85.22	91.45	88.45
66	69.62	79.83	89.31	89.94
67	62.42	84.97	90.47	89.98
68	92.35	94.83	96.55	95.04
69	60.36	73.19	74.28	62.74
70	81.39	92.32	89.08	89.2
71	72.12	82.31	79.33	72.02
72	95.5	98.27	98.44	97.4
73	91.88	95.39	93.17	91.51
74	41.24	60.7	51.12	37.65
75	78.51	83.13	78.51	76.91
76	95.41	96.79	98.17	97.48
77	95.96	97.98	97.58	97.37
78	93.11	93.7	90.76	89.59
79	60.88	73.7	70.53	76.57
80	55.53	65.93	60.13	61.73
81	88.46	93.96	93.33	86.58
82	89.63	93.84	93.74	81.75
83	95.43	97.51	98.34	95.43
84	94.84	98.71	98.28	97.85
85	93.01	96.08	94.83	91.75
86	86.97	92.66	90.36	86.97
87	69.39	74.6	70.19	63.64

Table 13 continued from previous page

Ward No.	1990	2000	2010	2020
88	95.09	96.52	96.32	89.98
89	79.67	88.08	85.91	73.58
90	46.42	53.14	48.17	44.24
91	72.38	90.08	93.23	92.96
92	67.24	84.83	88.95	87.81
93	75.44	84.7	82.08	77.96
94	32	44.08	43.96	40.01
95	44.3	81.67	78.39	79.39
96	55.81	88.64	92.99	93.97
97	40.1	58.6	62.95	54.26
98	43.98	82.36	90.53	86.49
99	26.45	64.43	88.58	94.51
100	32.22	74.18	87.34	90.54
101	19.08	59.51	87.84	90.16
102	33.77	59.63	84.28	79.61
103	46.6	82.62	91.62	91.2
104	43.48	79.81	91.59	91.51
105	45.66	74.4	91.47	93.11
106	10.72	42.47	86.45	84.15
107	13.29	52.87	84.3	79.75
108	4.08	11.24	18.68	23.13
109	1.32	16.82	43.44	51.57
110	12.05	35.41	65.85	67.45
111	4.24	32.14	47.71	58.3
112	11.25	55.87	60.22	70.73
113	7.2	51.82	62.65	68.77
114	4.89	29.81	34.66	39.46
115	25.53	64.22	82.76	79.9
116	61.13	76.6	79.95	71.28
117	77.19	85.79	85.25	78.01
118	76.3	89.86	87.74	93.16
119	75.68	88.55	91.1	79.33
120	75.11	90.65	92.95	91.22
121	33.85	69.87	76.57	75.42
122	3.55	28.79	41.08	45.23
123	19.82	55.09	66.21	67
124	11.98	39	53.26	52.16
125	8.74	35.5	36.92	46.29
126	8.65	33.48	31.15	38.95
127	5.34	33.05	29.31	40.58
128	17.79	58	54.95	63.33
129	9.99	46.57	44.44	59.35
130	58.48	90.17	88.82	89.5
131	38.53	75.78	83.57	85.98

Table 13 continued from previous page

Ward No.	1990	2000	2010	2020
132	61.61	85.5	82.12	83.64
133	65.23	88.61	87.82	89
134	95.81	97.38	96.6	95.81
135	94.93	97.31	94.63	96.12
136	51.51	70.94	69.81	77.74
137	81.44	83.68	74.24	76
138	49.38	72.52	72.77	75.37
139	34.84	65.04	65.78	69
140	18.16	42.53	34.32	37.43
141	28.56	46.45	32.23	36.8

Table 14. Wardwise percentage of builtup area in different years from 1990-2020

Ward No.	1990	1996	2002	2008	2014	2020
1	20.75	29.56	28.41	38.31	42.57	53.38
2	12.64	21.89	29.04	35.78	40.00	55.44
3	17.01	25.72	22.51	26.99	26.82	34.37
4	21.28	33.99	34.35	42.77	43.37	54.71
5	13.26	25.75	15.27	32.07	25.12	25.73
6	30.66	45.14	39.91	45.40	44.96	51.78
7	25.53	49.50	38.03	46.16	45.03	55.28
8	48.12	75.59	60.03	69.81	68.92	75.20
9	57.51	83.69	78.24	82.30	81.52	83.57
10	44.13	73.59	56.58	73.23	72.94	79.35
11	28.97	69.45	49.89	67.00	68.92	71.71
12	17.13	44.05	28.90	37.93	40.98	48.01
13	39.98	56.80	63.70	65.34	59.69	63.38
14	42.15	53.22	54.85	55.71	50.57	54.99
15	21.39	40.65	34.68	37.10	36.65	46.76
16	40.95	71.74	56.43	65.22	71.95	78.50
17	61.12	89.53	78.35	85.02	88.16	89.96
18	54.63	88.30	72.41	75.75	76.64	83.92
19	60.42	81.57	80.67	81.31	79.42	82.67
20	51.15	77.70	73.54	75.22	77.36	80.93
21	33.40	62.80	63.34	63.42	71.05	72.75
22	27.46	54.73	48.27	50.90	60.77	61.91
23	68.40	94.19	84.65	88.72	94.70	95.98
24	58.52	90.63	85.20	88.67	89.86	89.68
25	52.19	83.30	71.64	79.26	82.49	84.86
26	58.91	80.23	67.08	75.52	75.39	81.51
27	37.46	68.12	58.76	64.42	64.40	70.26
28	42.93	61.35	53.70	56.84	61.55	66.84
29	44.79	55.35	53.85	54.95	57.81	64.09
30	30.40	42.15	36.36	40.39	37.14	44.59

Table 14 continued from previous page

Ward No.	1990	1996	2002	2008	2014	2020
31	11.54	18.63	23.59	23.17	27.34	32.75
32	7.08	12.14	11.41	12.40	13.15	20.15
33	8.44	11.64	16.37	17.06	17.84	25.93
34	11.01	19.49	25.99	29.19	29.55	38.99
35	20.60	32.98	32.52	34.18	34.47	38.34
36	26.25	33.80	32.88	33.61	38.03	35.25
37	52.87	67.25	57.91	64.18	62.48	67.96
38	59.77	79.66	74.15	75.12	72.58	74.75
39	71.90	88.59	70.76	86.36	86.82	87.50
40	57.99	82.39	68.08	72.98	73.25	81.54
41	45.36	77.93	62.87	70.67	70.93	72.99
42	57.47	85.93	71.82	80.32	85.96	89.45
43	62.34	93.94	76.75	81.95	89.75	91.58
44	44.56	66.34	43.75	48.10	49.93	57.06
45	12.79	32.27	24.12	23.71	27.28	32.47
46	24.01	40.52	32.39	32.16	39.25	40.41
47	45.86	75.83	51.88	50.21	60.72	66.81
48	73.16	89.10	80.90	83.69	84.84	89.66
49	35.41	77.25	59.23	68.97	73.12	81.48
50	34.73	68.39	59.68	60.72	66.74	71.08
51	55.70	70.30	60.23	62.82	61.89	67.51
52	49.26	75.37	58.30	60.67	65.10	72.89
53	63.11	81.61	73.12	75.05	75.16	75.64
54	72.55	82.60	76.96	79.38	74.21	74.60
55	28.48	42.55	36.77	37.11	37.44	39.42
56	36.28	53.27	50.05	50.73	51.66	53.11
57	10.14	13.15	12.16	14.98	17.13	19.48
58	6.15	11.12	9.99	12.29	15.30	17.57
59	15.03	20.93	28.25	30.85	31.77	35.81
60	53.56	55.50	55.88	59.89	54.46	58.01
61	38.55	55.51	37.81	46.51	48.62	53.69
62	63.53	81.75	74.75	76.71	78.49	80.12
63	18.47	15.69	20.93	27.14	15.98	21.89
64	25.77	41.35	31.95	33.33	38.27	41.06
65	39.91	50.43	44.56	42.19	40.99	43.74
66	30.58	39.38	43.51	48.79	54.92	62.38
67	8.29	17.14	25.85	26.03	26.95	41.25
68	16.46	34.56	39.38	38.46	38.97	46.99
69	11.45	17.54	16.05	15.03	12.92	15.11
70	17.52	33.74	29.73	27.45	29.48	34.31
71	20.17	32.33	30.22	30.20	29.19	33.66
72	29.97	51.12	38.16	40.10	39.15	47.70
73	33.98	49.19	46.24	46.00	47.91	57.27
74	8.18	8.12	9.55	8.07	6.68	8.63

Table 14 continued from previous page

Ward No.	1990	1996	2002	2008	2014	2020
75	33.61	33.25	33.67	32.06	30.86	34.00
76	47.00	69.07	62.79	65.28	57.64	68.94
77	60.20	72.94	71.55	59.31	65.15	76.00
78	69.26	69.25	68.56	63.07	66.19	66.60
79	25.31	30.46	31.92	33.04	36.64	47.02
80	19.89	19.68	26.25	24.34	29.37	37.00
81	19.62	28.31	33.15	37.54	27.22	35.58
82	27.51	35.43	38.14	37.69	38.27	43.38
83	26.51	47.85	40.45	50.22	52.86	61.98
84	23.83	46.07	37.48	53.20	51.54	61.91
85	21.55	47.03	40.94	51.25	41.46	49.27
86	12.86	26.64	32.33	26.93	22.40	34.36
87	11.84	21.13	26.24	26.81	24.50	29.02
88	25.39	46.74	37.85	46.96	41.18	49.90
89	18.78	32.85	33.61	39.66	31.90	39.21
90	8.97	17.60	18.89	20.93	19.79	24.05
91	10.46	21.75	39.11	43.37	45.07	55.57
92	12.32	27.70	40.92	47.11	45.28	55.69
93	19.00	31.48	35.99	40.69	32.65	43.26
94	7.77	13.42	16.96	16.61	15.25	20.58
95	6.65	7.12	28.53	30.86	38.08	52.56
96	5.15	9.90	23.94	37.27	43.26	61.78
97	10.36	14.38	24.74	28.91	27.28	37.08
98	3.31	7.40	27.54	33.76	40.06	55.23
99	2.36	2.24	6.17	14.97	24.09	50.28
100	2.74	6.29	10.94	20.07	24.32	47.63
101	12.53	8.06	14.24	18.57	24.83	43.11
102	2.05	1.72	6.27	15.96	17.64	30.86
103	3.44	11.29	26.05	30.96	35.47	53.42
104	1.85	10.24	20.64	32.61	35.61	58.34
105	0.50	3.82	10.90	18.69	24.91	42.47
106	5.86	2.42	5.44	9.22	10.43	26.13
107	13.23	6.73	12.97	14.59	17.95	26.63
108	3.81	3.66	4.53	5.08	7.72	7.83
109	2.27	1.73	4.47	6.79	5.33	11.55
110	22.31	13.34	19.04	21.11	17.43	28.48
111	4.86	2.26	6.87	9.22	9.55	25.77
112	4.40	4.45	7.82	15.27	16.07	36.14
113	0.45	0.80	6.67	12.12	9.57	31.37
114	0.39	0.79	2.18	3.39	4.05	14.79
115	3.27	3.28	7.85	17.35	16.79	43.29
116	10.01	16.08	23.16	36.49	27.81	42.64
117	21.81	37.28	38.30	48.52	39.95	50.96
118	15.23	17.76	37.97	44.87	40.95	58.95

Table 14 continued from previous page

Ward No.	1990	1996	2002	2008	2014	2020
119	6.06	13.96	30.60	31.99	32.56	49.53
120	6.44	14.81	32.39	39.64	46.51	65.14
121	2.31	7.26	13.36	23.83	22.14	44.76
122	1.20	1.02	1.68	5.49	4.22	17.03
123	0.22	1.13	6.54	9.01	15.52	36.14
124	0.37	0.82	1.70	2.10	5.22	23.52
125	0.15	0.49	1.50	2.37	4.44	18.94
126	0.47	1.46	4.08	3.42	5.79	15.37
127	3.62	2.74	5.23	4.46	5.12	16.52
128	1.42	2.50	7.38	8.56	11.00	28.68
129	1.26	1.33	4.84	3.82	9.68	29.77
130	3.44	9.58	36.53	35.97	47.25	65.79
131	2.54	5.27	17.86	17.66	24.49	46.24
132	9.65	15.90	35.95	40.84	40.66	58.82
133	22.82	27.01	45.83	40.44	51.03	63.43
134	61.22	65.12	68.55	67.09	66.95	69.81
135	73.29	72.58	79.63	77.41	83.72	85.59
136	14.06	12.89	27.30	24.19	31.62	39.20
137	58.11	52.87	54.57	47.65	55.48	50.32
138	13.53	16.99	26.54	22.63	38.70	51.47
139	6.93	11.50	18.33	18.25	29.93	44.16
140	2.18	4.47	6.89	6.56	11.10	20.05
141	11.77	12.08	13.62	16.47	17.69	24.30

Chapter 9

Table 15. Groundwater abstraction Rate; adopted from (Sahu et al. 2013)(Sikdar 2000)

Year	Abstraction Rate (m3/day)
1956	55×103
1989	182×103
1999	292×103
2010	310×103
2025	385×103

Table 16. Long term groundwater level decline in differnt locations ;adopted from (Sikdar et al. 1996)

Location	Period	Average piezometric head drop (m)
Tilajala	1956-1993	8.3
Kasba	1958-1994	6.8
Beleghata	1956-1993	7.3
Mankitala	1956-1993	6.3
Tangra	1956-1993	7.3
Bagbazar	1958-1993	4.6
Jadvpur-Baghajatin	1957-1993	6.1
Gariya	1957-1993	6.1

Table 17. District wise groundwater level at different depth with minimum and maximum level observed for 2010 and 2020

Year	Season	District	No. Messured	Min	Max	0 to 2	2 to 5	5 to 10	10 to 20	>20
2010	Pre Monsoon	Howrah	16	0.75	13.41	4	3	3	6	0
2010	Pre Monsoon	Hugli	36	0.32	20.57	2	7	4	21	2
2010	Pre Monsoon	South 24 Parganas	34	0.07	9.51	4	5	25	0	0
2010	Pre Monsoon	North 24 Parganas	50	1.54	14.15	1	10	34	5	0
2010	Pre Monsoon	Kolkata	16	12.66	17.15	0	0	0	16	0
2010	PostMonsoon	Howrah	16	0.29	10.5	6	1	8	1	0
2010	PostMonsoon	Hugli	37	0.39	21.58	5	6	11	14	1
2010	PostMonsoon	South 24 Parganas	50	0.07	11.93	7	20	22	1	0
2010	PostMonsoon	North 24 Parganas	53	0	12.1	14	33	5	1	0
2010	PostMonsoon	Kolkata	16	13.58	16.5	0	0	0	16	0
2020	Pre Monsoon	Howrah	27	0.2	16.06	18	1	2	6	0
2020	Pre Monsoon	Hugli	70	0.3	19.97	20	6	5	39	0
2020	Pre Monsoon	South 24 Parganas	75	0.05	16.65	8	7	31	29	0
2020	Pre Monsoon	North 24 Parganas	113	0.38	14.4	13	55	34	11	0
2020	Pre Monsoon	Kolkata	23	0.55	20.75	3	0	0	18	2
2020	Post Monsoon	Howrah	27	0.47	18.25	17	1	1	8	0
2020	Post Monsoon	Hugli	78	0.31	15.95	18	3	20	37	0
2020	Post Monsoon	South 24 Parganas	73	0.04	15.57	8	10	33	22	0
2020	Post Monsoon	North 24 Parganas	113	0.42	13.7	18	65	23	7	0
2020	Post Monsoon	Kolkata	28	1.32	19.55	2	2	0	24	0

Table 18. Groundwater level of Kolkata at different depth in different season for 2010 to 2020; Source: CGWB, West Bengal Yearbook (2010-2020)

Time	Year	Monsoon	No. Messured	Min	Max	0 to 2	2 to 5	5 to 10	10 to 20	>20
Apr-10	2010	Pre	16	12.66	17.15	0	0	0	16	0
Oct-10	2010	Post	16	13.58	16.5	0	0	0	16	0
Apr-11	2011	Pre	18	10.68	17.83	0	0	0	18	0
Oct-11	2011	Post	16	8.25	18.25	0	0	1	15	0
Apr-12	2012	Pre	18	7.6	18.8	0	0	1	17	0
Oct-12	2012	Post	19	14.34	19.46	0	0	0	19	0
Apr-13	2013	Pre	19	10.92	19.83	0	0	0	19	0
Oct-13	2013	Post	20	8.08	17.48	0	0	1	19	0
Apr-14	2014	Pre	18	7.31	20.05	0	0	2	15	1
Nov-14	2014	Post	19	6.43	19.07	0	0	3	16	0
Apr-15	2015	Pre	33	0.63	20.15	3	1	4	23	2
Nov-15	2015	Post	34	1.22	19.55	1	1	2	30	0
Apr-16	2016	Pre	33	1.28	20.48	2	1	0	27	3
Nov-16	2016	Post	33	1.15	19.5	1	0	2	30	0
Apr-17	2017	Pre	33	1.28	20.48	2	1	0	27	3
Nov-17	2017	Post	33	0.52	19.21	3	0	0	30	0
Apr-18	2018	Pre	33	1.59	20.67	2	1	3	25	2
Nov-18	2018	Post	32	1.37	20.08	2	1	0	28	1
Apr-19	2019	Pre	33	1.59	20.67	2	1	1	27	2
Nov-19	2019	Post	32	1.37	20.08	2	1	0	28	1
Jun-20	2020	Pre	23	0.55	20.75	3	0	0	18	2
Nov-20	2020	Post	28	1.32	19.55	2	2	0	24	0

Table 19. Groundwater level depth (mbgl) in different locations

Location	1990	2000	2010
Sinthi	11	12.5	18.1
Chitpur	13	12.1	19
Bagbazar	11	12.5	19.2
Hedua	10	12	17
APC Road	12	11	18
Babughat	11.5	13.5	9.8
Entally	11.5	13.1	17.2
Hastings	11.2	13.2	15.69
Park Circus	11.5	13.2	17.3
Khidirpur	11	13.5	14.5
Beckbagan	12.2	13.6	19
Garden Reach	11.5	13.2	14.5
Bullygunge	13.5	12.8	18
Alipur	12.9	12.2	16
Deshapriya Park	12.5	13	15.9
Kalighat	12.6	13.5	14.3
Hazra	12.3	13	15.3
Picnic garden	11.1	13	9.4
Bantala	12.9	9	17
Keyatala	12.5	14.2	17.2
kasba	11.5	11	11.5
Sahapur	12.5	13.8	15.2
Tollygunge	12.5	16	16
Jadavpur	12.1	12	16.2
Bijaygarh	12.2	12.6	17.1
Kalikapur	11.9	10.8	10
Haltu	11.8	11.9	13.2
Mukundapur	11.5	11.7	10.5
Behala	12	13.6	17.2
Sarsuna	11.6	10.3	15.3
Haridebpur	12.4	12.3	14
Kudghat	12.6	12.6	14.2
Garia	11.5	9.9	11.1
Panchsayar	11.6	10.6	12.5
Thakurpukur	11.3	11	13.5
Kamdahari	11.6	10	8

Table 20. Groundwater level (mbgl) in different locations for different month of the year (2020-2021); Source: CGWB, West Bengal Yearbook 2020-2021

Location	RL	June	August	November	January
Salt Lake	3.25	15.54	18.6	15.93	16.99
Kundghat	4.43	14.24	15.85	15.06	15.63

Table 20 continued from previous page

Location	RL	June	August	November	January
Command Hospital Pz	4.73	15.61	18.88	14.81	19.46
Dum Dum	4.02	20.75	18.35	18.35	19.8
Taltala	5.57	19.35	18.89	19.3	18.4
Rajabazar	3.88	19.49	18.67	18.2	19.42
Baghbazar	5.53	20.59	19.25	19.55	19.6
Sinthi	4.46	19.12	19.65	17.95	18.75
Jhautala	4.55	16.32	16.44	16.38	13.5
Jadavpur	5	17.9	17.66	17.06	17.87
Rajbhavan	6	18.82	17.25	18.15	18.92
Ballygunge	3	15.08	16.47	3.64	15.9
Thakurpukur	4	14.26	14.9	16.55	14.65
Maniktala	6.5	19.51	18.65	15.49	18.11
Sealdah	7	17.8	16.9	16.01	17.65

Table 21. Seasonal chnages between groundwater level observed between 1996 to 2016, Source: CGWB,West Bengal Yearbook 2016

	Pre Monsoon		Post Monsoon	
Location	Rise	Fall	Rise	Fall
Bullygunge	4.753			-0.212
Baishnabghata Patuli		-0.41		-0.39
Kundghat	0.681		0.764	
Beleghata	6.252			-0.105
Beliaghata		-0.203		-0.833
Bidhanagar	0.069			-0.213
Park Street		-0.23		-0.652
New Alipur		-0.41		-0.465
Keorapukur		-0.047		-0.499
Maniktala		-0.518	0.14	
Garden Reach		-0.525		-0.699
Paikpara	4.66			-0.362
Parama Island		-1.927	0.054	
Dum Dum		-0.457		-0.826
Ramgarh		-0.753		-0.301
Tiljala		-0.452		-0.687
Sealdah		-3.241	1.642	
Shyambazar		-1.691	0.052	
Baghbazar		-0.742		-0.443
Taltala		-0.047		-0.579
Thakurpukur		-2.419		-0.029
Wesseley Market		-2.135		-0.373
Jhautala		-0.52		-0.225

Table 21. Seasonal chnages between groundwater level observed between 1996 to 2016, Source: CGWB,West Bengal Yearbook 2016

	Pre Monsoon	Post Monsoon
Sinthi	-0.339	-1.073

Table 22. Groundwater level depth in premonsoon and postmonsoon for 2005, 2008, 2011 and 2013, Source: SWID, 2020

Location	Pre 2005	Pos2005	Pre2008	Pos2008	Pre2011	Pos2011	Pre2013	Pos2013
Beniatola	16.27	15.29	17.816	16.28	19.5	18.6	19.5	17.7
Sinthee	14.63	12.72	16.2	14.59	19.052	17.45	20.15	17.55
Razabazar Science College	14.63	13	16.3	14.51	12.89	17.5	19.4	16.6
Hedua	15.29	12.08	15.66	13.87	17.85	16.65	18	16.85
Baghbazar	17.63	14.1	13.32	12.3	19.78	19.28	19.78	17.88
South Canal	14.58	13.1	15.89	14.4	16.13	14.86	16.2	14.8
Babughat	16.75	13.7	15.78	14.27	18.75	15.65	18.55	16.85
Bhawanipur	15.8	13.74	15.78	13.97	17.7	17.2	18.5	16.1
Tiljala	17.25	14.58	16.28	15.81	16.9	15.91	16.9	16
Kalighat	17.58	14.88	16.25	15.72	11.3	10.6	18.7	16
Hestings	18.57	15.67	14.92	13.5	16.35	16.65	15.75	15.55
Anandapur	14.48	11.69	13.28	12.57	12.5	12.3	13.7	11.4
Kasba	16.56	12.85	15.69	14.7	16.7	15.6	17.9	16
Vivekananda Park	16.47	13.77	14.47	11.52	19.6	16.1	18.3	15
Hazra Law College	17.81	14.2	15.2	14.28	16.3	16.3	18.3	16
Garia	12.58	11.05	11.34	11.25	14.55	13.65	16.55	14.05
Purbolok	12.57	10.85	13.28	12.84	14.4	13.95	15.28	14.58
Kundhat	16.21	13.1	13.58	12.57	16.8	14.9	17.2	15.1
Behala	15.5	10.9	11.8	13.6	17.3	15	17.3	14.4
Sarsuna	13.81	10.86	11.8	10.52	13.8	12.8	13.1	12.5
Siriti	18.44	18.44	16.25	15.69	17.55	14.95	16.15	15.55
Garia1	9.32	14.84	10.4	9.27	13.05	9.55	14.15	11.75
Lady Brabourne College	16.31	14.1	14.3	12.98	15.6	14.36	16.28	15.36
Haridebpur	13.15	11.1	14.69	13.28	15.6	14.2	16.4	14.3

Table 22 continued from previous page

Location	Pre2005	Pos2005	Pre2008	Pos2008	Pre2011	Pos2011	Pre2013	Pos2013
Thakurpukur	11.75	10.8	10.6	9.49	12.5	12.6	13.2	11.9
Behala	13.52	11.12	13.56	12.4	14.28	13.58	15.01	14.24
Taratala	12.71	10.85	11.93	9.68	14.4	13.7	13.9	12.7
Khidirpore	16.92	14.6	14.48	13.2	16.2	15	17.5	15.4
Chitpur	16.15	13.18	17.25	15.29	18.45	16.95	19.25	16.95
Bijoygarh	17.174	13.33	14.34	12.94	17.1	16.2	17.9	15.8
Panchyasayar	11.67	9.34	11.1	10.28	13.1	11.9	13.8	11.4
Mukundapur	11.65	10.15	12.89	11.97	14	12.5	14.9	11.8
Picnic Graden	14.52	10.48	13.1	12.87	16.9	14.4	16.9	14.8
Bondel Road	16.41	14.15	14.84	13.87	18.2	14.7	18.5	16.6
Vivekananda Road	16.5	14	15.3	13.95	18.05	16.3	18.2	16.7
Bangladesh High Commission	16.75	14.1	17.25	15.85	18.75	16.95	18.65	16.95
Deshopriyo Park	16.62	13.15	14.47	13.44	16.7	15.7	15.9	16.6
Anandapalit Road	16.42	13.45	16.3	13.1	19.3	17.1	19.2	17.1
Loreto College	16.38	13.25	16.25	15.97	18.6	17	18.8	16.9

Table 23. Groundwater quality data from 2010 to 2020 ; Source: CGWB, West Bengal Yearbook (2010-2020)

2010											
Location	EC	pH	Ca	Mg	Na	K	Fe	HCO_3	CO_3	Cl	F
BagBazar	1743	7.7	60	117	146	3.6	0.17	268	do	490	0.71
Bullygunje	1900	7.5	88	66	228	4.6	5.3	317	Nil	266	0.41
DumDum	1370	7.9	32	69	142	5.1	3.3	433	do	256	0.52
GardenReach	834	7.3	12	28	129	3.3	6.2	305	do	80	0.77
Jhautala	827	8	12	67	46	3.5	1.23	336	do	43	0.89
NewAlipur	913	7.9	16	47	158	3.3	1.53	488	do	75	1.05
ParkStreet	956	8.1	20	94	81	5.8	0.43	421	do	135	0.83
Taltala	850	7.4	12	11	155	5.4	0.51	220	do	131	0.92
2011											
Location	EC	pH	Ca	Mg	Na	K	Fe	HCO_3	CO_3	Cl	Fe
BagBazar	1700	7.3	42	68	216	1.3	-bdl-	177	nil	483	
Bullygunje Maidan	1070	7.2	89	104	248	1.6	0.36	122	nil	308	0.43
DumDum	1350	7.7	14	49	194	1.2	-bdl-	256	nil	312	
Jhautala	785	7.6	24	19	117	0.9	1.5	214	nil	117	
Kundghat	1070	6.9	34	63	109	1.1	-bdl-	171	nil	220	0.2
NewAlipur	822	7.5	22	57	102	0.9	1.4	244	nil	71	0.07
ParkStreet	1070	6.8	28	61	105	1.4	0.13	232	nil	185	0.14
Sinthi	2170	6.8	64	177	92	1.5	1.2	116	nil	564	
Taltala	2100	7.1	30	164	139	1.2	0.82	183	nil	657	
2012											
Location	EC	EC	pH	Ca	Mg	Na	K	Fe	HCO_3	Cl	F
Bagbazar	1380	1380	7.7	56	53	149	0.3	0.81	92	391	-BDL-
DumDum	1840	1840	7.9	46	57	318	0.1	0.47	92	572	-BDL-
Garden Reach	876	876	7.2	18	28	114	-BDL-	0.23	153	178	-BDL-
Jhautala	699	699	7.7	18	17	103	0.3	0.4	134	156	-BDL-
New Alipur	647	647	7.6	10	30	79	0.2	0.63	153	124	-BDL-
Park Street	1000	1000	8	22	56	90	-BDL-	3	110	203	0.13

Table 23 continued from previous page

Sinthi	2070	2070	7.5	72	73	250	0.2	3.8	79	640	-BDL-
Taltola	1440	1440	7.9	16	49	220	0.3	0.64	53	352	0.39
Tiljala	1460	1460	8.1	64	55	140	0.8	1.95	79	441	-BDL-

2013

Location	pH	EC	Ca	Mg	Na	K	Fe	HCO_3	Cl	F	TH
Ballygunge	8.2	987	36	27	155	4	0.93	342	156	0.7	200
Bantala (Natunhat)	8.2	2848	140	95	361	1	2.74	220	851	0.9	740
Bidhanagar	8.3	1005	68	44	89	9	0.24	244	206	0.8	350
Garden Reach	8.3	677	28	29	83	3	-Leaked-	366	35	0.9	190
Jhautala	8.3	750	40	22	102	3	0.51	336	71	0.7	190
Maniktala	8.3	1660	88	56	186	5	1.65	281	397	0.6	450
Nagerbazar	8.3	785	56	32	93	3	15.45	342	43	0.8	270
Park Street	8.2	960	52	61	91	5	0.14	488	106	0.8	380
Ramgarh	8.3	1268	48	29	200	1	0.44	403	213	0.9	240
Salt Lake Pz	8.2	1400	80	66	149	5	0.67	403	277	0.5	470
Shyambazar	8.3	1560	44	46	227	4	0.36	317	319	1	300
Sinthi (Belgachia)	8.3	1965	124	54	216	5	3.23	281	532	0.6	530
Taltala	8.3	1535	48	41	226	4	0.79	366	333	0.7	290
Thakurpukur	8.1	930	48	22	156	3	0.33	464	106	0.8	210
Tiljala	8.2	1466	84	73	134	6	0.72	281	348	0.7	510

2014

Location	EC	PH	H CO_3	Cl	TH	Ca	Mg	F	SO_4	PO_4	SO_2
Bagbazar	1350		238	210	275	68	26	0.04	206	27	0.05
Ballygunge Maidan	1470		317	267	200	50	18	0.55	99	23	0.09
Beliaghata	1550		323	220	620	164	51	0.8	135	25	bdl
Bidhannagar	1380		500	217	285	60	33	0.53	bdl	15	bdl
Dum Dum	1970		293	391	265	58	29	0.12	178	27	0.02
Garden Reach	954		299	640	140	30	16	bdl	85	24	0.12

Table 23 continued from previous page

Hoglapara	1060		250	135	310	70	33	bdl	90	18	0.004
Jhautala	1630		592	163	250	58	26	0.05	110	20	0.11
Keorapukur	2860		647	511	600	156	51	0.42	146	26	0.16
Kundghat	1690		281	320	275	68	26	bdl	117	21	0.1
Maniktala	2280		214	479	365	86	36	0.52	246	16	0.41
New Alipur	872		336	82	170	40	17	0.6	43	21	0.09
Park Street	1100		390	117	285	62	32	0.52	92	30	0.08
Ramgarh	1540		336	195	175	42	17	0.4	190	13	bdl
Shyambazar	2920		268	664	410	106	35	0.54	294	22	bdl
Sinthi (Belgachia)	2780		207	651	465	124	38	bdl	288	16	0.2
Taltala	2130		287	402	225	46	27	0.57	194	25	0.03
Thakurpukur	1160		342	163	120	36	7.3	0.01	67	16	bdl
Tiljala	1980		165	444	410	122	26	0.5	145	20	0.03
2015											
Locations	pH	EC	TH	Ca	Mg	Na	K	CO_3	HCO_3	Cl	SO_4
Baghbazar	7.8	970	216	50	22	115	19	BDL	189	220	34
Baishnabghata Patuli	7.5	1200	277	68	26	150	2.1	BDL	250	256	46
Ballygunge Maidan	7.7	1240	224	50	24	161	5	BDL	275	288	15
Beleghata	7.9	1580	306	78	27	214	12	BDL	433	291	45
Beliaghata	7.8	993	199	50	18	127	1.8	BDL	195	231	24
Bidhanagar	7.4	1230	299	70	30	140	1.6	BDL	214	284	49
Dum Dum	7.9	1480	305	76	28	184	2.3	BDL	293	337	23
Durgapur	7.7	1590	212	50	21	230	4.7	BDL	378	316	105
Garden Reach	7.8	619	124	28	13	92	1.2	BDL	79	67	17
Hoglapara	7.9	1010	199	50	18	138	5.9	BDL	281	195	52
Jhautala	8.2	730	124	30	12	117	3.4	BDL	189	149	41
Keorapukur	8.2	2300	400	122	23	322	9.2	BDL	653	426	155
Kundghat	7.8	1340	351	96	27	138	8.1	BDL	342	245	110
Maniktala	7.8	1550	259	64	24	232	15	BDL	458	288	83

Table 23 continued from previous page

Nagerbazar	7.7	1520	222	46	26	242	10	BDL	390	327	59
New Alipur	8.1	870	216	50	22	92	6.5	BDL	153	202	23
Paikpara	8	1000	224	50	24	129	10	BDL	281	195	102
Parama Island	7.6	2020	402	90	43	276	13	BDL	580	391	123
Park Street	8	1390	337	100	21	161	9	BDL	372	291	75
Ramgarh	8.1	1130	185	54	12	163	12	BDL	299	230	69
Salt Lake	7.6	2870	510	138	40	361	7.6	BDL	512	586	210
Sealdah	8	1610	316	62	39	299	3.3	BDL	458	319	68
Shyambazar	7.9	1470	247	74	15	209	18	BDL	384	291	115
Sinthi (Belgachia)	7.7	1980	456	110	44	232	0.8	BDL	360	288	125
Taltala	8.1	1540	275	82	17	207	1.2	BDL	397	280	85
Thakurpukur	8.1	934	176	44	16	133	15	BDL	262	178	13
Tiljala	7.9	1520	350	94	28	189	12	BDL	311	302	196
Wesseley Market	8	1200	248	68	19	161	3.5	BDL	311	249	45

2016

Location	pH	EC	TH	Ca	Mg	Na	K	CO_3	HCO_3	Cl	NO_3
Baghbazar	8.25	898	225	44	27.95	132.65	5.15	0	183	230.43	13
Baishnabghata Patuli	8.07	1234	205	26	34.02	197.15	5.8	0	323.3	262.33	12
Ballygunge	8.51	1104	260	20	51.03	169.25	6.95	9	250.1	276.51	13
Bantala Natunhat	8.13	1172	370	60	53.46	159.65	6.6	0	201.3	386.41	8
Beliaghata	8.59	1361	255	20	49.82	223.7	21.8	36	488	233.97	21
Bidhanagar	8.23	950	130	22	18.23	136.3	18.1	0	134.2	216.25	17
Dum Dum	8.26	1393	205	6	46.17	205.65	7.95	0	305	294.24	22
Durgapur	8	865	115	8	98.42	29.16	7.75	0	79.3	290.69	27
Hoglapara	8.26	958	290	18	59.54	99.55	12.7	0	396.5	141.8	26
Jhautala	8.29	1223	145	32	15.8	206.75	5.75	0	451.4	180.8	16
Keorapukur	8.22	2217	350	20	72.9	387.6	7.35	0	597.8	503.39	14
Kundghat	8.16	1108	155	14	29.16	198.2	5.9	0	317.2	198.52	31
Maniktala	8.23	1603	355	32	66.83	212.7	6.55	0	231.8	439.58	0

Table 23 continued from previous page

Nagerbazar	8.04	1571	360	30	69.26	197.3	5.8	0	280.6	375.77	9
Paikpara	8.12	2188	565	62	99.63	242.45	8.15	0	317.2	638.1	0
RajaBazar	8.03	1978	595	102	82.62	279.15	8.1	0	237.9	687.73	36
Ramgarh	8.3	1289	175	42	17.01	242.95	5.65	12	372.1	290.69	7
Sealdah	7.98	1108	510	36	102.06	42.89	7.2	0	140.3	343.87	32
Shyambazar	8.39	1764	185	8	40.1	361.2	5	21	506.3	333.23	11
Sinthi (Belgachia)	8	1789	425	64	64.4	275	7.25	0	176.9	609.74	38
Taltala	8.24	1487	235	22	43.74	273.3	9.9	0	378.2	368.68	18
Thakurpukur	8.4	677	115	16	18.23	94.61	11.87	18	256.2	67.36	8
Tiljala	8.38	1302	355	40	61.97	145.95	8.7	6	97.6	375.77	27
Wesseley Market	8.25	1242	410	44	72.9	113.15	6.6	0	305	287.15	15
					2017						
Location	pH	EC	TH	Ca	Mg	Na	K	CO_3	HCO_3	TA	Cl
Baghbazar	7.81	878	210	44	24	115	15.1	0	195	160	220
Beliaghata	7.68	1002	160	28	22	164	13.8	0	329	270	145
Bidhanagar	9.11	696	140	26	18	83	10.1	21	122	135	124
Dum Dum	7.78	1394	200	10	43	198	11.53	0	317	260	284
Durgapur	8.12	1664	515	40	101	127	7.75	0	561	460	255
Jhautala	7.95	737	110	22	13	113	7.2	0	159	130	138
Keorapukur	8.29	2243	360	46	60	369	12.35	0	622	510	457
Kundghat	7.87	1096	150	18	26	196	9.6	0	305	250	209
Maniktala	8.18	1735	380	42	67	214	4.15	0	293	240	418
Nagerbazar	8.06	1702	405	34	78	203	8.8	0	360	295	362
Ramgarh	8.38	1431	210	36	29	222	9.65	12	372	325	284
Sealdah	8	1854	610	60	112	149	6.2	0	512	420	358
Sinthi (Belgachia)	7.52	2074	400	66	57	288	13.25	0	238	195	571
Taltala	7.75	1530	245	24	45	264	8.2	0	397	325	340
Thakurpukur	7.88	878	190	22	33	109	10.72	0	311	255	121
Tiljala	7.43	1330	340	42	57	137	15.7	0	207	170	305

Table 23 continued from previous page

2018											
Location	pH	EC	TDS	CO_3	HCO_3	TA $CaCO_3$	Cl	SO_4	NO_2	F	Ca
Baghbazar	7.46	856	547.8	0	256.2	210	156.4	18	7.1	0.7	30
Ballygunge	7.3	1613	1032.3	0	305	250	366.2	1.3	0	0.6	168
Bantala Natunhat	7.39	1533	981.1	0	274.5	225	337.7	15	25	0.3	136
Beliaghata	7.28	1411	903	0	536.8	440	195.5	0	0	0.8	60
Bidhanagar	7.52	818	523.5	0	329.4	270	88.9	29	23	0.6	26
Dum Dum	7.38	1466	938.2	0	457.5	375	245.3	5	24	0.1	30
Gardenreach	7.48	748	478.7	0	158.6	130	67.5	162	41	0.5	30
Hoglapara	7.41	1307	836.5	0	542.9	445	184.9	6.7	5.3	0.6	28
Jhautala	7.53	884	565.8	0	451.4	370	60.4	0	0	0.1	40
Keorapukur	7.39	1864	1193	0	500.2	410	341.3	53	15	0.8	14
Kundghat	7.41	1220	780.8	0	445.3	365	163.5	5.4	24	0.3	96
RajaBazar	7.16	2174	1391.4	0	366	300	444.4	117	43	0.2	84
Ramgarh	7.54	1542	986.9	0	347.7	285	309.3	95	26	1	20
Taltala	7.26	1714	1097	0	384.3	315	355.5	2.9	1.8	0.6	50
Thakurpukur	7.57	1005	643.2	0	317.2	260	138.6	153	32	0.9	16

2019											
Location	pH	EC (µs/cm) 25 C	Total Hardness as CaCO3	Ca	Mg	Na	K	CO_3	HCO_3	Total Alkalinity as $CaCO_3$	Cl
Bagbazar	6.97	823	280	14	59	86	2	BDL	336	275	131
Ballygunge	6.78	1982	595	20	132	92	4	BDL	488	400	393
Bantala-Nutanhat	6.8	1739	480	40	92	112	3	BDL	464	380	355
Beliaghata	6.81	1582	530	26	113	70	14	BDL	714	585	167
Bidhannagar	6.55	1111	375	34	70	78	5	BDL	415	340	142
Dum Dum	6.6	1888	395	6	92	206	3	BDL	720	590	248
Jhautala	7.2	890	285	22	56	109	2	BDL	445	365	82
Keorapukur	6.84	1786	440	38	84	147	1	BDL	537	440	284

Table 23 continued from previous page

Kundghat	6.95	1408	355	12	79	144	2	BDL	616	505	184
Maniktala	6.65	1978	525	20	115	90	3	BDL	427	350	142
Rajabazar	6.63	2569	620	30	132	261	4	BDL	488	400	757
Sealdah	6.74	2122	575	30	121	151	4	BDL	604	495	432
Taltala	6.76	1921	430	34	84	151	3	BDL	488	400	355
Thakurpukur	7.12	964	240	28	41	118	2	BDL	470	385	117
2020											
Location	pH	EC	TH	Ca	Mg	Na	K	CO_3	NO_3	TA	Cl
Baghbazar	8.09	612	165	34	19	69	3	Traces	299	245	57
Ballygunge	7.74	1854	555	92	79	160	7	Traces	342	280	429
Beliaghata	8.03	969	295	38	49	87	19	Traces	293	240	170
Bidhanagar	8.06	592	255	70	19	20	8	Traces	256	210	39
Dum Dum	7.86	1368	295	40	47	188	10	Traces	476	390	252
Jhautala	8.14	905	225	52	23	110	4	Traces	445	365	71
Keorapukur	8.1	1312	395	76	50	120	19	Traces	451	370	195
Kundghat	7.56	1336	265	44	38	174	18	Traces	470	385	188
Maniktala	7.98	1408	290	46	43	180	8	Traces	183	150	358
Nagerbazar	7.83	790	270	44	39	64	5	Traces	348	285	78
Rajabazar	7.61	2537	665	126	85	249	9	Traces	323	265	663
Sealdah	7.77	1744	480	72	73	150	6	Traces	384	315	386
Thakurpukur	8.21	925	185	38	22	139	4	Traces	427	350	110

Table 24. Groundwater type identification using groundwater quality parameters of different locations

2010						
Ca	Na+K	Mg	Cl	SO_4	HCO_3+CO_3	ID
49	149.6	117	490	24	268	BagBazar
66	232.6	66	266	210	317	Bullygunje
56	147.1	69	256	55.9	433	DumDum
80	132.3	28	80	74.5	305	GardenReach
43	49.5	67	43	22.5	336	Jhautala
75	161.3	47	75	91.8	488	NewAlipur
135	86.8	94	135	38	421	ParkStreet
131	160.4	11	131	44	220	Taltala
56	130.5	177	564	46	218	Snthi
106	137.25	22	106	32	464	Thakurpukur
2020						
Ca	Na+K	Mg	Cl	SO_4	HCO_3+CO_3	ID
34	72	19	57	3	299	Baghbazar
92	167	79	429	21	342	Ballygunge
38	106	49	170	19	293	Beliaghata
70	28	19	39	23	256	Bidhanagar
40	198	47	252	1	476	Dum Dum
52	114	23	71	1	445	Jhautala
76	139	50	195	19	451	Keorapukur
44	192	38	188	2	470	Kundghat
46	188	43	358	5	183	Maniktala
44	69	39	78	2	348	Nagerbazar
126	258	85	663	15	323	Rajabazar
72	156	73	386	4	384	Sealdah
38	143	22	110	1	427	Thakurpukur

Table 25. Groundwater quality parameters in premonsoon and postmonsoon in different locations in 2011; Source: SWID, 2020

Pre Monsoon							
Location	pH	EC	HCO_3	Cl	TH	Fe	TDS
Beniatola	7.8	2400	200	520	600	3	1536
Bagbazar	8	230	280	520	790	1.2	1472
Chitpur	7.7	3600	570	560	410	2	2304
Sinthi	8	2700	350	640	600	0.5	1728
Hedua	7.8	2800	280	750	600	0.2	1792
Razabazar	7.8	2600	300	570	640	1.2	1664
Ananda Palit	7.8	2500	270	560	630	1.2	1660
Park Circus	7.9	200	310	370	570	0.5	1280
Beckbagan	8	1050	370	100	130	0.8	672
Chingrighata	7.8	1820	380	320	460	1.2	1165

Table 25 continued from previous page

Pre Monsoon							
Picnic Garden	7.9	1990	330	390	510	0.8	1274
Anandapur	7.8	1940	370	360	640	0.8	1242
Keyatala	7.9	1730	410	250	250	1.2	1107
Hazra	7.8	2800	200	600	560	1.2	1792
HarishMukherjee	8	930	540	100	350	0.3	595
Kalighat	7.8	1230	410	110	540	0.2	787
Babughat	8.1	380	200	80	40	1.2	243
Khidirpore	7.8	3200	370	80	670	0.5	2048
Gardenreach	7.5	4900	500	1190	800	2	3136
Behala	7.7	1090	60	100	200	0.8	698
Sarsuna	8	1070	180	100	210	0.8	685
Thakurpukur	7.7	970	370	80	170	0.8	621
Kundghat	7.8	1160	290	140	260	1.2	742
Haridevpur	7.9	1210	330	170	210	1.2	774
Siriti	7.9	1130	250	160	230	3	723
Garia	7.3	950	450	30	160	0.5	608
Mukundapur	7.6	2000	390	390	580	0.5	1280
Sulekha	7.5	2400	330	560	650	3	1536
Post Monsoon							
Location	pH	EC	HCO_3	Cl	TH	Fe	TDS
Beniatola	7.77	2000	410	490	520	2.5	1280
Bagbazar	7.79	1900	350	480	590	1.5	1261
Chitpur	7.73	2700	2380	510	220	5	1278
Sinthi	7.99	2100	750	570	470	0.4	1344
Hedua	7.85	2200	600	630	490	0.1	1408
Razabazar	7.85	2200	480	680	510	0.1	1408
Ananda Palit	7.86	2100	530	540	450	0.4	1344
Park Circus	7.8	1900	510	510	480	0.5	1216
Beckbagan	8.06	860	1030	100	220	0.31	550
Chingrighata	7.75	1500	600	310	350	0.1	960
Picnic Garden	7.87	1590	640	360	340	0.4	1018
Anandapur	7.847	1560	600	340	400	0.1	998
Keyatala	8.08	1320	840	220	200	0.1	845
Hazra	7.67	2700	230	620	460	3.5	1728
HarishMukherjee	7.9	810	240	70	230	1	518
Kalighat	7.8	1040	310	90	240	0.9	666
Babughat	8.32	350	160	20	30	0.3	224
Khidirpore	7.67	3200	220	810	520	4	2048
Gardenreach	7.9	4800	330	1150	600	4	3072
Behala	7.27	990	290	90	140	3	634
Sarsuna	8.76	880	380	100	110	0.6	563
Thakurpukur	8.19	940	330	70	120	1.5	602
Kundghat	8.22	1010	260	140	160	0.33	646
Haridevpur	8.21	1220	310	160	160	0.2	781

Table 25 continued from previous page

	Pre Monsoon						
Siriti	8.07	1080	200	190	170	0.5	691
Garia	8.23	880	360	40	80	0.1	563
Mukundapur	7.72	1800	200	420	430	1.2	1152
Sulekha	7.63	3600	170	890	780	0.8	2304

Table 26. Deatils about Entropy weighted water quality index

2010											
Location	**Ca**	**Mg**	**Na**	**Fe**	**Cl**	**F**	**SO_4**	**TDS**	**TH**	**EWQI**	**Ranking**
Bagbazar	60	117	146	0.17	490	0.71	24	959	630	148.97	4
Bullygunje	88	66	228	5.3	266	0.41	25	1045	540	525.41	9
DumDum	32	69	142	3.3	256	0.52	5.9	754	365	343.64	8
GardenReach	12	28	129	6.2	80	0.77	4.5	459	145	531.56	10
NewAlipur	16	47	158	1.53	75	1.05	1.8	502	235	173.45	5
ParkStreet	20	94	81	0.43	135	0.83	38	526	435	122.10	3
Taltala	12	11	155	0.51	131	0.92	44	468	75	71.63	1
Sinthi	64	177	92	1.2	564	0.74	25	1194	890	277.77	7
Thakurpukur	48	22	156	0.33	106	0.8	54	601	210	74.76	2
Kundghat	32	29	367	2.5	157	0.28	74	651	249	259.82	6
Weitage	***10.8421***	***14.032***	***5.11604***	***24.0069***	***12.6631***	***3.01417***	***16.6233***	***3.15555***	***10.5468***		
2020											
Location	**Ca**	**Mg**	**Na**	**Fe**	**Cl**	**F**	**SO_4**	**TDS**	**TH**	**EWQI**	**Ranking**
Bagbazar	34	19	69	2.01	57	0.4	31	368	165	70.96	2
Bullygunje	92	79	160	3.32	429	0.37	21	1001	555	159.60	10
DumDum	40	47	188	2.8	252	0.48	19	831	295	117.63	5
GardenReach	30	30.4	98	3.41	67.5	0.5	165	478.7	200	127.21	8
NewAlipur	28	56	182	2.1	82	1.26	1.8	682	256	98.75	3
ParkStreet	59	85.21	121.56	2.14	287.5	0.35	9.86	912	410	117.77	6
Taltala	22	66.29	302.56	2.26	302.56	0.68	44	468	75	112.90	4
Sinthi	72	64.4	275	2.1	309.74	0.21	52	1156	460	132.35	9
Thakurpukur	38	22	139	0.4	110	0.28	35	576	185	50.95	1
Kundghat	44	38	470	2.64	188	0.36	17	750	265	120.96	7
Weitage	***6.96319***	***7.30472***	***10.5957***	***5.52125***	***12.9218***	***10.0944***	***33.6203***	***4.15675***	***8.82184***		

Chapter 10

Table 27. Prediction of built-up area and groundwater level using ARIMA model for 2021 to 2030

Percentage of built-up area						
Year	**Point Forecast**	**Lo 80**	**Hi 80**	**Lo 95**	**Hi 95**	**RMSE**
2021	67.20	66.50	67.91	66.12	68.28	0.52
2022	68.16	67.36	68.96	66.93	69.39	
2023	69.01	68.05	69.97	67.54	70.48	
2024	69.91	68.85	70.98	68.28	71.55	
2025	70.79	69.62	71.97	69.00	72.59	
2026	71.68	70.41	72.95	69.74	73.62	
2027	72.57	71.21	73.92	70.49	74.64	
2028	73.45	72.01	74.89	71.25	75.66	
2029	74.34	72.82	75.86	72.01	76.66	
2030	75.22	73.63	76.82	72.78	77.66	
Groundwater level (mbgl)						
Year	**Point Forecast**	**Lo 80**	**Hi 80**	**Lo 95**	**Hi 95**	**RMSE**
2021	16.37	15.72	17.02	15.38	17.37	0.48
2022	16.55	15.82	17.28	15.44	17.67	
2023	16.67	15.80	17.55	15.33	18.02	
2024	16.82	15.86	17.79	15.34	18.31	
2025	16.96	15.89	18.03	15.33	18.59	
2026	17.10	15.95	18.26	15.34	18.86	
2027	17.24	16.01	18.48	15.36	19.13	
2028	17.39	16.08	18.69	15.39	19.38	
2029	17.53	16.15	18.90	15.42	19.63	
2030	17.67	16.22	19.11	15.46	19.88	