Prospects of Rainwater Harvesting in the Kolkata Municipal Corporation (KMC) Area, West Bengal

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Certificate from the Supervisor

This is to certify that the thesis entitled **“Prospects of Rainwater Harvesting in the Kolkata Municipal Corporation (KMC) Area, West Bengal”** submitted by Md Juber Alam who got his name registered on 30.09.2020 for the award of Ph.D (Science) degree of Jadavpur University, is an original piece of work and absolutely based upon his own contribution under my supervision and that neither this thesis nor any part of it has been submitted for either any degree/diploma or any other academic award anywhere before.

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Dedicated to my parents

Mr. Saidur Rahaman

and

Mrs. Jahanara

Index No. 17/20/Geo./26

Prospects of Rainwater Harvesting in the Kolkata Municipal Corporation (KMC) Area, West Bengal

Mr. Md Juber Alam

Abstract

The study investigates the potential, design, and governance of Rooftop Rainwater Harvesting (RRWH) within the urban boundaries of the Kolkata Municipal Corporation (KMC), an area facing seasonal water scarcity, rising urbanization, and diminishing groundwater resources. The research is organized into five primary objectives that collectively offer a comprehensive understanding of RRWH as a sustainable urban water management approach:

Analysis of Rainfall trend, variability, and forecasting: This research assesses 120 years of rainfall data to analyze temporal trends and interannual variability in rainfall. The research employs statistical methods, including the Mann-Kendall test, Sen's slope estimator, and forecasting models (ARIMA and Polynomial regression), to create a foundational understanding of the rainfall trend and patterns of the study area. These findings are essential for establishing assured rainfall thresholds that facilitate dependable RRWH system design. **Analysis of Land Use and Land Cover Changes:** The research evaluates 30 years of land use and land cover alterations (1990-2021) employing GIS and satellite images to comprehend the rise in impervious surfaces and their effect on stormwater runoff and groundwater recharge. The results highlight the necessity for decentralized water management strategies such as RRWH due to increasing urban expansion. **Assessment of Rainwater Harvesting (RWH) Potential:** The study used Google Earth Pro and field measurements to quantify the rooftop area of selected educational institutions, hence estimating possible rainwater harvesting volumes. This study determines the extent to which institutional water demand, especially for non-potable applications, can be mitigated through harvested rainwater, thus decreasing dependence on municipal and groundwater resources. **Dimensioning the Rooftop Rainwater Harvesting Structure:** This study aims to establish a scientifically rigorous methodology for calculating ideal tank sizes based on a design criterion of 60% assured rainfall. Weekly and monthly rainfall patterns have been examined to recommend tank capacity that optimizes cost, efficiency, and climatic dependability, with particular emphasis on monsoon intensity and dry-season water requirements. **Assessment of various policies and public perception regarding RRWH:** This study conducts a critical evaluation of national and local water policies, including ‘Jal Dharo-Jal Bharo’ and KMC’s building regulations in relation to Sustainable Development Goals (SDGs). Perception research complements this by capturing the community and institutional views toward RRWH, highlighting deficiencies in awareness, technical competence, and policy enforcement. This facilitates the development of specific recommendations to improve adoption, governance, and system maintenance.

This study offers a comprehensive, interdisciplinary framework for the integration of rainwater harvesting within the study area by combining hydrological data, geographical analysis, infrastructure design, and socio-political assessment. The study promotes RRWH not merely as a supplementary water source but as a climate-resilient urban infrastructure vital for sustainable urban development in monsoon-dependent areas.

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LIST OF FIGURES

LIST OF TABLES

APPENDIX

Table 1: Calculation of weekly assured rainfall (50%, 60% and 70%) and mean rainfall over 120 years of weekly rainfall

Table 2: Calculation of monthly assured rainfall (50%, 60% and 70%) and mean rainfall over 120 years of monthly rainfall

Questionnaire for People's Perception about problems and prospects to implement the Roof-top Rainwater Harvesting Structure

Questionnaire on Existing Roof-top Rainwater Harvesting System in Large hotels and shopping mall

Questionnaire on Existing Water Treatment Plant of KMC

ABBREVIATIONS

ACF	Autocorrelation Function
AIC	Akaike Information Criteria
AMRUT	Atal Mission for Rejuvenation & Urban Transformation
ANN	Artificial Neural Network
AR	Assured rainfall
ARIMA	Autoregressive Integrated Moving Average
CGWB	Central Ground Water Board
CPCB	Central Pollution Control Board
CPWD	Central Public Works Department
CV	Coefficient of Variation
DRHS	Domestic Rainwater Harvesting Systems
DRWH	Domestic Rooftop Water Harvesting
DT	Decision Tree
DW	Durbin-Watson
ENSO	El Niño-Southern Oscillation
GCM	Global Circulation Model
GEE	Google Earth Engine
GEO	Global Environment Outlook
GIS	Geographic Information Systems
GRWTP	Garden Reach Water Treatment Plant
GRWW	Garden Reach Water Works
IISWBM	Indian Institute of Social Welfare and Business Management
IMD	Indian Meteorological Department
INWQS	Interim National Water Quality Standards
IWRM	Integrated Water Resources Management
JJM	Jal Jeevan Mission

JSA	Jal Shakti Abhiyan
KDE	Kernel Density Estimation
KMC	Kolkata Municipal Corporation
MGD	Million Gallons per Day
MGNREGA	Mahatma Gandhi National Rural Employment Guarantee Act
MLC	Maximum Likelihood Classifier
NAPCC	National Action Plan on Climate Change
NWP	National Water Policy
PACF	Partial Autocorrelation Function
RWH	Rainwater Harvesting
RMSE	Root Mean Square Error
RRWH	Rooftop Rainwater Harvesting
RWHP	Rainwater Harvesting Potential
RWHS	Rainwater Harvesting Structures
SARIMA	Seasonal Auto-Regressive Integrated Moving Average
SBSS	Simulation-Based Spatial System
SCS	Soil Conservation Service
SD	Standard deviation
SDG	Sustainable Development Goal
SMW	Standard Meteorological Weeks
SUDS	Sustainable Urban Drainage Systems
SWMM	Storm Water Management Model
TWAD	Tamil Nadu Water Supply and Drainage Board
UNEP	United Nations Environment Programme
WRIS	Water Resource Information System
WTP	Water Treatment Plant

CONTENTS

CHAPTER 1

PRELUDE TO THE STUDY

1.1. Introduction

The significance of water is evident to all. We cannot conceive of the existence of life in the form of vegetation and fauna without water. Currently, space scientists are actively investigating the presence of water on other planets. In the absence of water, the idea of life on other planets is completely incomprehensible to us. By the year 2050, over 2 billion individuals are projected to experience high water stress, as indicated by the United Nations Environment Programme (UNEP), which cautions that water may become a constraining factor for growth in several global locations. Approximately one-third of the global population resides in nations experiencing moderate to high water stress, characterized by water consumption exceeding 10% of the renewable freshwater supply, according to the Global Environment Outlook (GEO) (UNEP, 2000). The analysis indicates that pollution, water resource scarcity, and climate change will be the principal rising challenges in the coming century.

The truth of the water issue is undeniable. Water scarcity is a growing concern in metropolitan areas worldwide, including Indian cities. Despite India's higher average annual rainfall of 1,170 mm compared to the global average of 800 mm, it lacks enough water resources (CWC, 2019; UNESCO, 2020). The forecasts of India becoming a water-stressed nation by 2025 can be refuted only if we effectively capture a substantial portion of the surface runoff (NITI Aayog, 2018). Indian cities are especially susceptible, as population increase and infrastructural development have exerted considerable pressure on finite water supplies (Singh et al., 2020). In Kolkata, despite an average annual rainfall of around 1,582 mm (IMD, 2020), a substantial fraction of this natural resource remains unexploited due to insufficient rainwater management practices. In this setting, rainwater harvesting becomes crucial. Rainwater harvesting (RWH), the collection and storage of rainwater for reuse, is a sustainable process to enhance urban water supply and diminish reliance on groundwater and surface water sources. Rainwater harvesting (RWH), acknowledged worldwide as a climate-resilient water management strategy (UN-Habitat, 2017), has gained fresh significance in Indian cities facing prevalent demand-supply disparities and groundwater depletion (CGWB, 2021). In Kolkata, where numerous regions face seasonal waterlogging while others contend with water scarcity, the establishment of efficient rainwater harvesting systems might significantly improve water security, mitigate urban flooding, and replenish diminishing aquifers.

In recent years, the Kolkata Municipal Corporation (KMC) has implemented several legislative efforts to promote rainwater harvesting through building regulations and awareness initiatives. However, the practical implementation is constrained by technical, economic, and social obstacles (Chakraborty & Dey, 2019). A comprehensive evaluation of the opportunities and obstacles associated with rainwater harvesting necessitates a multidisciplinary examination that includes environmental sustainability, infrastructural feasibility, policy efficacy, and community engagement. This study seeks to assess the rooftop rainwater harvesting potential in Kolkata by analysing rainfall trends, patterns, the existing water supply scenario, the feasibility of rooftop rainwater harvesting, and opportunities for implementation.

1.2. Conceptual Framework

1.2.1. Rainwater Harvesting

Rainwater harvesting (RWH) is a hydrological and environmentally sound engineering technique that entails the systematic collection, conveyance, filtration, and storage of precipitation runoff, mainly from rooftops and other impermeable surfaces, for beneficial utilisation or aquifer replenishment. The process is based on the principle of intercepting rainwater within the hydrological cycle, which reduces surface runoff, mitigates soil erosion, decreases peak stormwater flows, and improves local water availability (Boers & Ben-Asher, 1982). Contemporary rainwater harvesting systems incorporate civil and environmental engineering methodologies, including catchment surface analysis, storage tank dimensioning, water quality evaluation, and hydraulic modelling, to guarantee effectiveness and long-term viability (Campisano et al., 2017). Examining the system as a whole, rainwater harvesting plays a crucial role in decentralised water management, enhances groundwater recharge via percolation structures, and bolsters urban climate resilience by alleviating the effects of stormwater overflow and aquifer overexploitation. This approach is gaining acknowledgement as a solution rooted in nature within the frameworks of Integrated Water Resources Management (IWRM) and Sustainable Urban Drainage Systems (SUDS), especially in areas facing erratic precipitation patterns and urban water stress. In India, the Central Ground Water Board (CGWB) and different state urban development authorities have established technical recommendations for Rainwater Harvesting (RWH). At the same time, cities such as Kolkata have enacted municipal regulations requiring their implementation in new projects that surpass a designated roof area (CGWB, 2013).

Rooftop rainwater harvesting (RRWH) is a specialized form of rainwater harvesting (RWH) that encompasses the collection of rainfall from building rooftops and channelling it through pipes and filters into storage facilities or recharge pits. This efficient approach, tailored for urban environments, leverages existing infrastructure to capture rainfall, rendering it both economical and spatially efficient. In urban areas such as Kolkata, characterised by increasing water demand and diminishing groundwater levels, rooftop systems provide a decentralised approach to enhance water delivery and mitigate stormwater runoff. This approach conserves potable water while facilitating groundwater recharge and flood mitigation when implemented with appropriate design and maintenance methods (UNEP, 2009; CGWB, 2013).

1.2.2. Advantages of Rainwater Harvesting (RWH):

Rainwater harvesting (RWH) provides numerous environmental, economic, and social advantages, rendering it an essential element of sustainable urban water management. A major advantage is its capacity to diminish reliance on traditional water delivery systems, especially in water-scarce places like Kolkata, where increasing demand and overexploited groundwater supplies have resulted in intermittent shortages. Rainwater harvesting (RWH) captures and stores rainfall locally, offering an alternative supply for non-potable applications such as toilet flushing, gardening, and cleaning, therefore preserving treated municipal water for vital purposes (Campisano et al., 2017). Moreover, RWH facilitates groundwater recharge, aiding in the restoration of aquifers frequently depleted by over-extraction. This is particularly advantageous in Kolkata, where the unregulated utilisation of borewells has resulted in a significant decrease in groundwater levels.

Additionally, RWH is essential for stormwater management as it diminishes surface runoff and alleviates urban flooding, a common issue in Kolkata's low-lying regions during the monsoon season (Agarwal & Narain, 1997). It reduces soil erosion and the pollution of freshwater bodies by averting contaminated runoff. The initial investment in rainwater harvesting systems is frequently counterbalanced by long-term savings on water expenses and less dependence on external water sources. Rainwater harvesting fosters community involvement and understanding regarding water conservation, hence promoting a culture of environmental responsibility. When incorporated into urban strategy and regulatory frameworks, rainwater harvesting promotes water security and helps to promote climate adaptability and sustainable urban development (UNEP, 2009).

1.2.3. Drawbacks of Rainwater Harvesting (RWH):

While rainwater harvesting (RWH) has many advantages, it also comes with drawbacks that need to be considered, especially in crowded urban areas like Kolkata. A primary constraint is the variability and unpredictability of precipitation, which can significantly affect the reliability and consistency of harvested water, particularly during extended dry periods or amid shifting climatic trends (Boers & Ben-Asher, 1982). The initial cost of implementing a well-structured rainwater harvesting system, comprising catchment preparation, storage tanks, filter units, and distribution infrastructure, can present a financial hurdle for low-income houses and small institutions. Spatial limitations in urban environments restrict the feasibility of establishing extensive storage systems, especially in older or informally constructed districts with limited capacity for retrofitting (Campisano et al., 2017).

From a technical perspective, insufficient maintenance of the system, such as failing to clean catchment areas or filters, can lead to a deterioration in water quality, making the captured rainwater unsuitable for consumption or even non-potable applications. Moreover, inadequate design or excessive reliance on poorly constructed systems can result in water stagnation, mosquito proliferation, and contamination of stored water, posing health hazards. Challenges related to institutions and policies persist, including weak enforcement of construction laws, a lack of incentives, and inadequate public awareness or technical proficiency among end users (Ward, Memon, & Butler, 2012). These issues emphasize the need for contextually aware planning, public education, and government support to ensure that rainwater harvesting systems are safe, effective, and sustainable in the long term.

1.2.4. Why should we encourage rainwater harvesting?

Water is an essential resource for all life on Earth. It constitutes a significant element of the hydrosphere, covering nearly two-thirds of the Earth's surface. Water is vital to the ecosystem as it regulates temperature, contributes to the water cycle, and facilitates the dissolution and transportation of minerals and nutrients. Earth's water is renewable; however, it is not consistently accessible in sufficient amounts or of suitable quality for human needs. Numerous factors, including climate change, population growth, and economic development, can impact the availability of water supplies. A feasible solution to these issues is rainwater harvesting (RWH). The increasing economic prosperity of the global population has created a substantial demand for water, resulting in considerable pressure on its availability. The agricultural sector is the primary consumer of water, while the expansion of the industrial sector and the rapidly changing lifestyles of individuals are also contributing to rising water demands. Urban centres and industrial areas are disrupting the natural flow of rainwater in valleys and rivers. Many surface water bodies in plains and semi-plain regions have been polluted by human activities, leading to heightened demand for water and a continuous high rate of groundwater extraction. As a result, the water table has declined rapidly. In such critical situations, the rainwater harvesting method should be implemented. This can complement water requirements and help alleviate the issue of water scarcity on a micro scale. Therefore, Rainwater harvesting (RWH) should be promoted as a rational and sustainable solution to increasing water scarcity, urbanization, and environmental degradation. It reduces reliance on overexploited groundwater resources, facilitates aquifer recharge, and alleviates urban flooding through effective stormwater runoff management. Furthermore, collected rainwater can serve as an additional source for non-potable uses, thus conserving treated water for essential needs. Agarwal and Narain (1997) assert that traditional rainwater collection technologies have historically supported water self-sufficiency in India, demonstrating both ecological and economic benefits. Promoting its integration into modern infrastructure can significantly enhance long-term water sustainability.

1.3. Area under study:

The study area (KMC) encompasses a total area of 205 square kilometres, as the Kolkata Municipal Corporation reported in 2014. The latitudinal extent of the area ranges from 22°27’28” North to 22°38’20” North, while the longitudinal extent spans from 88°15’50” East to 88°28’45” East. (Alam & Majumder, 2022). The study focused on 141 wards out of the total 144 wards of the KMC due to the lack of available data on the recently established three wards numbered 142 to 144. The whole area under study is 187 km^2, which has been attained using ArcMap 10.2 by vectorizing the Kolkata Municipal Corporation (KMC) map in UTM projection and WGS84 datum. The geographical boundaries of the research site are demarcated by the North 24 Parganas district to the north and north-east, the South 24 Parganas district to the south, and the Hugli River to the west.

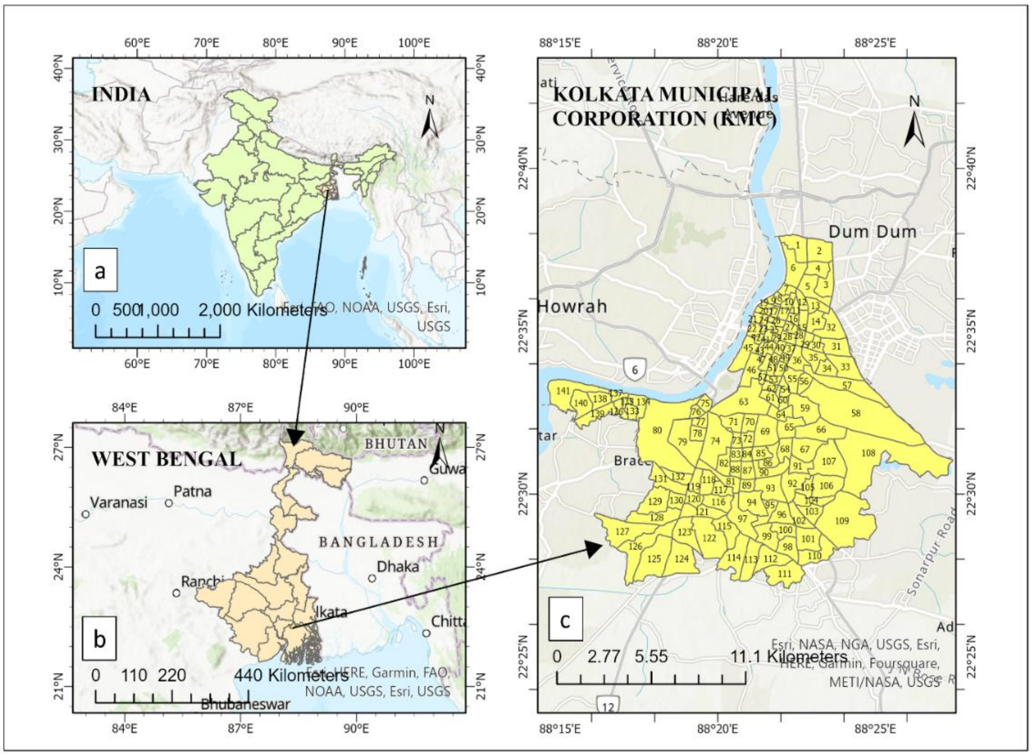

Figure 1.1. Location map of the study area: (a) India, highlighting West Bengal; (b) West Bengal, showing the Kolkata Municipal Corporation; and (c) Kolkata Municipal Corporation.

1.3.1 Selection of the area under study: Kolkata has been selected as the focus of investigation because of the various challenges it encounters concerning water. The challenges encountered in the study area are as follows-

- Groundwater levels are consistently decreasing.
- The water supply is insufficient, and the availability of groundwater is also limited during the lean months.
- Frequent flooding (pluvial) occurs on the streets during rainfall or the rainy season.
- The penetration of rainwater into the subsoil has significantly reduced as a result of swift urban development, leading to a decline in groundwater recharge.
- There is a concerning trend of illegal filling of water bodies in Kolkata and surrounding regions for the purpose of constructing buildings and other establishments. If these activities persist, the city is likely to encounter significant water scarcity issues. Many areas in South Kolkata are currently facing a significant water crisis due to over-reliance on groundwater and insufficient water supply from the KMC.

1.4. Geographical Facets of the Study Area:

1.4.1. Geology:

Kolkata lies at the base of the pericratonic tertiary basin known as the Bengal basin or the Ganga basin. The Bengal basin is made up of three structural units: the deep basinal portion in the east and southeast, the middle hinge or self/slope break, and the self or platform in the west. Kolkata lies roughly 25 kilometres from the summit of the high zone's western section. The subsurface lithology comprises Quaternary-age deposits. The geological configuration governs the presence of groundwater in the KMC area. The clay and silty-clay that make up an aquiclude have an average thickness of 25–40 meters, and take place at the sedimentary sequence's summit (Chakraborty, 2019). The aquiclude is situated above silt, fine to coarse sand, and frequently combined with gravel. The sand deposits are interconnected and function as a singular unconfined aquifer system, reaching considerable distances from the periphery of Greater Kolkata, including its suburbs, collectively referred to as the Kolkata Metropolitan Area (KMA), which radiates outward from the KMC (Chakraborty, 2019).

1.4.2. Geomorphology and Soil Types:

Kolkata is situated in the lower deltaic plain of the Ganga-Bhagirathi River system. As a southerly extension of the Bengal Basin, the lower deltaic plain of West Bengal results from delta formation (Bagchi, 1944). This area is characterized by typical deltaic flatland, with surface elevations ranging from 3.5 to 6 meters above mean sea level. Numerous low-lying depressions, including marshes, shallow lakes, and jhils, can be found within the city, most of which indicate river scars from the former pathways of the Bhagirathi River.

The primary gradient of the terrain is towards the south. The significant geomorphological units in the area include younger levees, deltaic plains, interdistributary marshes, paleochannels, and older levees flanking both banks of the old Adi Ganga, as well as younger levees next to the Hugli River (Figure 1.2). The region is comprised of younger alluvial soil, predominantly consisting of silty and clayey loams (Bagchi, 1944)

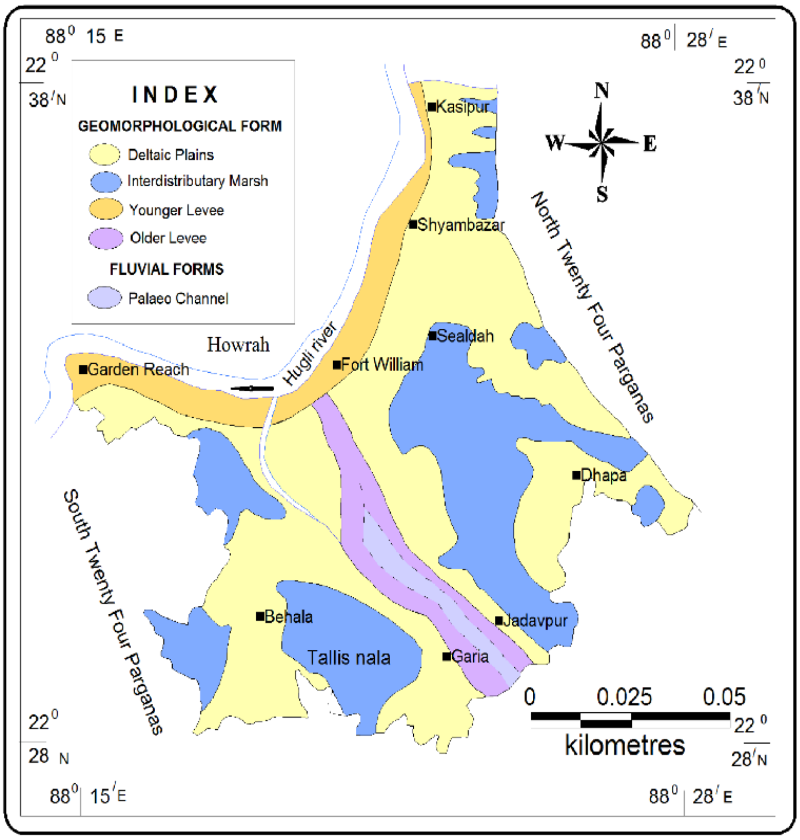

Figure 1.2: Geomorphologic division in Kolkata Municipal Corporation.

Source: CGWB report 1991; Kolkata (KMC) district profile

1.4.3. Climate:

The climate in Kolkata is sub-tropical, characterised predominantly by the summer season. It has four distinct seasons, which are as follows:

i) The Hot Season
ii) The Monsoon Season
iii) The Retreating Monsoon Season
iv) The Cold Weather Season

Kolkata has a scorching season that begins in early March and lasts until the onset of the monsoon in early June. During this season, average temperatures hover around 35°C, with May being the peak month, often nearing 40°C. Relative humidity varies between 65% and 80%. The southwest monsoon, which normally arrives in early June, brings substantial rainfall, particularly from June to September, raising the city's annual average precipitation to about 1500 mm. The monsoon slightly lowers the temperature, which typically ranges between 29°C and 30°C. The monsoon begins to retreat in early October, followed by a transitional period until mid-November, marked by a significant decrease in rainfall. The winter season starts in mid-November and continues until February, extending into early March. The winter lasts for about two and a half months, with temperatures sometimes dropping to around 12°C in December and January (India Meteorological Department, 2020).

1.4.4. Drainage:

The region that is now Kolkata was mostly uninhabited before Job Charnock's arrival, and it was distinguished by a system of waterways that connected two river channels. To the west, the village adjoined the Hugli River, also referred to as the Ganga. At the same time, a little eastern canal, once utilised by smaller vessels, constituted a segment of the natural drainage system. The Hugli River presently delineates the city's northwestern limit, while multiple notable waterways or khals intersect the metropolitan terrain. These encompass the Bagjola Khal in the north, Beleghata and Circular Khals in the middle regions, and the Adi Ganga (a paleo-channel) and Tolly Nala in the southern sections. All of these have a general flow direction from the north-northwest to the south-southeast. These khals and nalas collectively encompass a significant area of the city and historically functioned as essential channels for natural drainage and transportation. Currently, they are significantly silted, requiring extensive desiltation initiatives to reinstate their function in surface water management and facilitate the prospects for inland water transport (Chattopadhyay, 2001).

1.4.5. Ground Water:

In the Kolkata Municipal Corporation (KMC) area, groundwater is mainly restricted to semi-confined conditions, exhibiting a distinct hydrochemical profile. Generally, fresh groundwater is found above brackish groundwater throughout most of the region. However, exceptions occur in certain areas, specifically along the Hugli River from Fort William in the central region to Kalighat in the south, and around Kashipur to the west of Dumdum in the north, where the stratification is reversed, with brackish water overlaying fresh water (KMC, 2004). A shallow aquifer lens is located 12 meters below ground level in levee deposits along the Hugli River, where groundwater exists under unconfined water table conditions. Similar unconfined aquifers, situated at depths of 17 meters, are also found in marshy and low-lying regions such as Ballygunge, Tollygunge, Tiljala, Dhakuria, Kasba, Santoshpur, Garia, Behala, Barisha, and Thakurpukur (KMC, 2004).

1.4.6. Vegetation and Green Cover:

Urban vegetation is essential for preserving ecological equilibrium and reducing environmental contaminants in urban habitats. The Kolkata Municipal Corporation (KMC) has initiated the development of eco-friendly parks and green areas in Kolkata to improve urban liveability. Nonetheless, swift urbanisation and population expansion have resulted in a considerable decline in urban vegetation. Research conducted by Biswas et al. (2025) indicated a 27% reduction in urban green spaces from 1990 to 2022, predominantly attributed to the transformation of green areas into developed regions. The depletion of vegetation undermines ecological sustainability, intensifies urban heat island effects, and diminishes carbon sequestration capabilities (Banerjee et al., 2015). The reduction of green cover presents significant consequences for the city's environmental well-being. It highlights the necessity for cohesive urban design that emphasises the conservation and enhancement of green spaces.

1.5. Literature Review:

A literature review on the selected topic is an essential component of any methodical research endeavour. An examination of prior research pertinent to the current subject facilitates initial direction, foundational knowledge, and the identification of research gaps within the field. This chapter aims to review prior studies pertinent to the current research issue. The reviews of studies conducted in India and abroad are organized into the following five sections:

1.5.1. Rainfall trend and its variability

1.5.2. Land Use and Land Cover (LULC) Change

1.5.3. Implementation and Impact of Rainwater Harvesting

1.5.4. Rainwater harvesting structures and methods

1.5.5. Government Policies related to rainwater harvesting

1.5.1. Rainfall trend and its variability:

Malik et al. (2020) employed robust Global Circulation Models (GCMs) to examine the features and trends of yearly maximum precipitation events throughout the KMA. Their studies revealed that the region's rainfall patterns are influenced by intrinsic natural variability and long-term oscillatory behaviour, rather than displaying linear trends of rise or decline. This concept is crucial in the design of rainwater harvesting systems, as excessive dependence on short-term or recent rainfall data may result in systems that are either under or over-engineered.

This study establishes a scientific foundation for incorporating climatic variability into urban water infrastructure planning by recognising the cyclical nature of extreme rainfall occurrences. In places such as Kolkata, where drainage and water supply systems frequently experience strain during monsoonal peaks, the integration of predictive modelling might improve the reliability of rainwater harvesting systems.

Banerjee et al. (2020) examined how rainfall changes over time and space in the Bhilangana River Basin in the Uttarakhand Himalaya. They focused on annual, periodic, and monthly rainfall patterns based on data from monitoring stations and two grid locations. Their study gave us important information about how the number and intensity of rainy days change over time and space in a mountainous watershed. Their study was based on a high-altitude area that was not urban, but the methods and results show how important it is to look at rainfall in specific areas when planning for water consumption. The design of rainwater collecting systems, especially in metropolitan areas such as Kolkata, underscores the necessity of assessing both annual totals and the frequency and distribution of precipitation events. These factors influence the dimensions of storage tanks, the efficacy of catchment systems, and the robustness of urban infrastructure in response to catastrophic events.

Kundu and Tarun (2019) examined annual and seasonal rainfall patterns from 1901 to 2002, utilising the non-parametric Mann-Kendall test to identify significant trends in the rainfall time series. They employed the Theil-Sen slope estimator to quantify the amplitude of these trends, providing a robust statistical analysis of the direction and intensity of change. Their findings indicated regional disparities in rainfall patterns across seasons, underscoring the uneven effects of climate change on water resources. This detailed research is especially pertinent for cities like Kolkata, where rainwater harvesting systems must be tailored to both average annual rainfall and seasonal variations and trends. Integrating trend analysis into the planning process enhances forecasting, system resilience, and storage design efficiency, hence maintaining infrastructure effectiveness under changing environmental conditions. The methodology of Kundu and Tarun provides a valuable framework for assessing the long-term reliability of rainfall data essential for urban water resource planning.

Ghosh (2018) examined regional and temporal rainfall variability in Gangetic West Bengal utilising a comprehensive dataset covering 102 years (1901–2002) from 12 meteorological stations. The study analysed rainfall patterns on weekly, seasonal, and annual stages, offering a thorough understanding of temporal rainfall behaviour. A considerable increase of 33.87%

in post-monsoon precipitation was observed, whereas the average yearly rainfall had a small rise of 2.61%. The data suggest that whereas annual totals remained fairly constant, seasonal variations—especially the increase in post-monsoon precipitation—may affect water availability patterns and urban flood hazards.

Das et al. (2018) utilised monthly precipitation data from the Indian Meteorological Department (IMD) spanning 1901–2000 to examine district-specific yearly rainfall variability in West Bengal. Their research demonstrated a continuous rainfall surplus of 1.5–2% over the state, indicating moderate yet steady long-term rainfall circumstances. This surplus, although ostensibly minor, carries substantial ramifications for urban water management, especially in densely populated regions such as the Kolkata Metropolitan Region. In the realm of RWH system design, the findings of this study are crucial for assessing the feasibility of sustainable water collection and storage. Even slight surpluses in annual precipitation, when effectively allocated, can significantly bolster the water supply resilience of a metropolis confronting seasonal deficits and rising demand.

Kosanic et al. (2014) performed a comprehensive investigation of climatic variability utilising both modern and historical climate datasets. Their research highlighted that local climatic changes frequently diverge markedly from national or world averages, underscoring the constraints of generalised estimates for regional infrastructure design. Local variations are essential when designing systems such as RWH, which must function successfully within the specific hydrometeorological environment of a place. In a rapidly urbanising and climate-sensitive metropolis such as Kolkata, dependence exclusively on national monsoon forecasts may result in inadequate system designs. The findings of this study underscore the importance of integrating localised climatic data into planning frameworks to ensure that harvesting systems are suitably scaled and matched with seasonal variations. This method not only augments system performance but also bolsters resilience against future climate uncertainties.

Yadav et al. (2014) utilised the Mann-Kendall test and Sen's slope estimator to analyse rainfall and temperature trends in thirteen districts of Uttarakhand. Their investigation indicated erratic climatic patterns, with certain months demonstrating rising trends in precipitation and temperature, while others displayed declining trends across all districts. This unpredictability highlights the intricate and unpredictable characteristics of regional climate patterns, underscoring the necessity for comprehensive, site-specific climate evaluations in water resource management. Despite being done in the hilly regions of Uttarakhand, the technique and conclusions are pertinent to urban areas such as Kolkata, where microclimatic conditions and seasonal fluctuations can substantially influence the efficacy of rainwater harvesting systems.

Huang, Y. F. et al. (2014) employed Holt's exponential smoothing technique to examine monthly and periodic rainfall patterns in the Langat River Basin, Malaysia, from 1970 to 2012. Their investigation revealed increasing rainfall trends in March, July, and November, and decreasing trends in May and September. These findings demonstrate the significance of temporal rainfall variability in water resource management. The study, while concentrating on a distinct geographic area, highlights the significance of time-series forecasting methods in comprehending intra-annual rainfall patterns. This approach is similarly relevant to metropolitan environments such as Kolkata. This modelling can improve the precision of rainwater harvesting system design by synchronising storage and distribution capabilities with anticipated seasonal rainfall patterns.

Jain and Kumar (2012) examined temporal variations in rainfall throughout India, utilising the non-parametric Mann-Kendall test to identify trends in rainfall data. Their research quantitatively assessed the extent of these patterns using Sen's slope estimator, yielding a comprehensive analysis of temporal rainfall variability. This methodology facilitated the discovery of both ascending and descending rainfall patterns without presuming any particular data distribution, rendering it especially advantageous for hydrological research. Their findings provide significant insights into the comprehension of evolving rainfall patterns, which is essential for water resource management and planning in areas impacted by climate variability.

Mondal et al. (2012) examined temporal variations in rainfall in northeastern Cuttack, Orissa, employing statistical analyses to identify trends. Their findings revealed an increase in rainfall during certain months, followed by a decrease in others. Nevertheless, the total alterations in precipitation for the region were determined to be statistically negligible. This intricate pattern underscores the intricacy of regional rainfall variability, highlighting the necessity for comprehensive temporal analysis in climate effect evaluations.

Afzal et al. (2011) investigated precipitation trends and variability in Scotland by combining the Cumulative Sum (CUSUM) method with the chronological Mann-Kendall test. This integrated method improved the identification of nuanced alterations and trends in precipitation patterns across time, offering a thorough evaluation of rainfall variability. Their research enhances comprehension of regional climate dynamics and facilitates enhanced management of water resources amid evolving climatic conditions.

Brunet and Jones (2011) emphasised the essential significance of long-term climate records for precisely comprehending climatic variability. They contended that prolonged time series data are crucial for capturing natural variations and identifying significant trends in climate patterns. This viewpoint emphasises the importance of preserving and employing extensive climatic databases to facilitate thorough climate change evaluations and associated hydrological research.

Kumar et al. (2010) addressed the growing emphasis on acknowledging historical and tropical climate change via the enhancement and diversification of comprehensive databases and sophisticated data analysis methodologies globally. Their research underscores that enhancing data quality and analytical techniques improves comprehension of climate variability, especially in tropical regions characterised by complex and highly variable climatic dynamics.

Basistha et al. (2009) employed the Mann-Kendall test to examine historical rainfall fluctuations in the Indian Himalayas for trend detection. Their research indicated a rising trend in rainfall from 1902 to 1964, followed by a decrease from 1965 to 1980, underscoring significant temporal variations in regional precipitation patterns. These findings enhance the comprehension of climate variability in the Himalayan region, which is essential for efficient water resource management.

Kripalani et al. (2007) analysed the variability of summer monsoon precipitation in India and forecasted an increasing trend with a multi-model ensemble approach. Their analysis indicated a potential extension of the monsoon season, which has considerable ramifications for agriculture, water resources, and climate adaptation methods. This work highlights the significance of sophisticated climate modelling techniques to enhance predictions of future monsoon patterns in the context of evolving climatic circumstances.

Kripalani et al. (2002) performed an extensive analysis of the variability in Indian summer monsoon precipitation, investigating interannual and decadal variations through a long-term dataset covering 131 years (1871–2001). Their research employed rainfall data from the Indian subcontinent to discern trends and anomalies in monsoon behaviour, considerably enhancing the comprehension of the temporal fluctuations in the monsoon system. The researchers observed significant disparities in rainfall patterns throughout several regions of India, noting that these irregularities were frequently linked to extensive atmospheric-oceanic events like the

El Niño-Southern Oscillation (ENSO). The research highlighted the significance of identifying long-term cycles and variations in monsoon patterns, which are essential for enhancing seasonal forecasting and developing water resource management plans. The results highlight the intricacy of the Indian monsoon system and the need to integrate long-term climate data into monsoon modelling and forecasting systems.

Srivastava et al. (1998) identified a specific trend of diminished regional precipitation, underscoring that global climate change is modifying long-term rainfall patterns. They observed that these alterations elevate the danger of extreme droughts and floods, hence jeopardising dependable water supply systems. Their research highlights the essential requirement to comprehend changing precipitation patterns for sustainable water resource management.

The formulation of precise future climate scenarios relies on the thorough examination of essential climatic variables, including precipitation and temperature, across many spatial and temporal dimensions. Research conducted by Addisu et al. (2015) and Neil and Notodiputro (2016) underscores the need to examine precipitation trends to understand regional and local discrepancies in rainfall patterns, which directly influence water availability and agricultural output. Meshram et al. (2018) highlight the importance of temperature trend analysis in evaluating the extensive effects of climate change on ecosystems and human health. The integration of these assessments across several climatic variables establishes a solid foundation for climate modelling, thereby enhancing the reliability of projections that inform mitigation and adaptation efforts.

Recent studies indicate a rise in the occurrence of intense rainfall events in several regions of Asia, while there is a general decrease in the number of rainy days and the yearly average precipitation (Shrestha et al., 2000; Mirza, 2002; Lal, 2003; Dash et al., 2007). This paradoxical trend suggests that although total rainfall may be diminishing or stabilizing, precipitation is increasingly strong and concentrated, thereby elevating the risks of flooding and complicating water management. Understanding these fluctuating precipitation patterns is essential for formulating effective climate adaptation and disaster risk mitigation measures in the region.

1.5.2. Land Use and Land Cover (LULC) Change

Yang and Liu (2005) examined changes in land use and land cover (LULC) within the Pensacola estuary, Gulf of Mexico, using satellite images from 1989, 1996, and 2002. The research established a land-cover classification system for coastal areas, achieving an overall accuracy of over 90%. It demonstrated substantial growth in low-density urban regions in the lower drainage basin and an increase in mixed forest cover in the upper watershed through post-classification comparison and GIS overlay analysis. Meanwhile, evergreen forests and wetlands experienced significant reductions. These findings illustrate how urbanization and land transformation can alter watershed characteristics, highlighting the need to incorporate land use and land cover dynamics into urban water management practices, including the design of rainwater harvesting systems.

Kangabam et al. (2019) utilized multi-temporal satellite data and the maximum likelihood classification algorithm to assess land use and land cover (LULC) changes in the Loktak Lake area. Their study identified five land use and land cover categories, showing a significant increase in open water bodies, agricultural areas, and towns, along with a marked decrease in Phumdis floating biomass characterized by dense and sparse vegetation. These changes have adversely affected the lake's natural balance, resulting in declining water quality and threatening both aquatic ecosystems and the communities that depend on them. The research emphasizes the considerable effects of land use change on water systems, underscoring the need to incorporate land use and land cover dynamics into sustainable water management strategies, including rainwater harvesting, in environmentally sensitive and urbanizing regions.

Thakkar et al. (2017) examined land use and land cover (LULC) patterns in the Arjuni watershed of Gujarat with IRS LISS-III satellite images from 2001 and 2011. The study employed the Maximum Likelihood Classifier (MLC). It enhanced the outcomes with supplementary data, categorising land into eight Land Use/Land Cover (LULC) groups and increasing classification accuracy by 15% in 2001 and 15.5% in 2011 with post-classification modifications. Throughout the decade, there were gains in agricultural land, forested regions, and water bodies, whilst scrub forests and river sand areas experienced a decline. These findings demonstrate how landscape alterations affect watershed attributes, emphasising the necessity of incorporating land use and land cover monitoring into water resource planning. In metropolitan areas such as Kolkata, where land-use patterns influence surface runoff and water availability, such studies provide essential insights for the design of sustainable rainwater harvesting systems.

Shah et al. (2017) examined land use and land cover (LULC) alterations in the Aglar watershed in Uttarakhand, India, from 1993 to 2015 with LANDSAT ETM+, LANDSAT Thematic Mapper, and SRTM DEM imagery. The LULC data were categorised into six classifications, indicating a significant rise in barren land and a decrease in agricultural regions. The research ascribed these alterations to both human-induced stresses and natural elements, which together led to the deterioration of the watershed. The research integrated satellite views with ground-based data to elucidate LULC alterations and their implications for watershed management. These methodologies are especially relevant in metropolitan environments such as Kolkata, where land use dynamics profoundly affect runoff patterns, water availability, and the efficiency of rainwater harvesting systems.

Reddy et al. (2017) assessed land use and land cover (LULC) changes in the Kanchinegalur sub-watershed of Karnataka utilising Survey of India toposheets, LANDSAT-7, and IRS-P6-LISS-III datasets within a remote sensing and GIS framework. The study utilised the Maximum Likelihood Classification (MLC) method, complemented by ground truth validation, to generate a thematic map of the watershed, precisely illustrating land use and land cover (LULC) patterns. The results demonstrated that the execution of the Integrated Watershed Management Project positively influenced land conditions and elevated the quality of life for the local populace. This study highlights the significance of remote sensing-based monitoring in assessing the efficacy of watershed interventions. This approach can guide sustainable urban water resource planning, including rainwater harvesting strategies, particularly in regions experiencing analogous anthropogenic and ecological challenges, such as Kolkata.

Chokkavarapu and Mandla (2017) examined land use and land cover (LULC) alterations from 2005 to 2013 in a micro-watershed in Telangana utilising multi-temporal LISS III satellite images and GIS methodologies. Utilising supervised classification with verified training data and post-classification comparison methods, they noted substantial increases in agricultural area, scrub/deciduous forest, and water bodies. In contrast, wasteland and degraded forests exhibited a downward trend. Their findings illustrated the efficacy of watershed management measures in improving land production and ecological equilibrium. This study underscores the efficacy of remote sensing in evaluating the impact of watershed improvements, serving as a crucial method for informing sustainable urban water practices, including rainwater collection, particularly in dynamic urban settings such as KMC, the studied area.

Thilagavathi et al. (2015) examined land use and land cover (LULC) alterations in the Salem Chalk Hills, Tamil Nadu, utilising LANDSAT TM and IRS P6 LISS IV MX imagery from the years 2002 and 2012. Six land use and land cover categories were discovered with high classification accuracy by image processing and field validation. The research indicated that mining activities and swift urban expansion substantially transformed land use patterns, leading to heightened urban development and diminished agricultural and aquatic zones. These findings highlight the influence of human activities on land alteration, especially in growing metropolitan areas. These patterns are essential to evaluate in urban planning and water management strategies, since the depletion of agricultural and water retention areas can directly influence rainwater harvesting capacity and runoff dynamics in urban areas like the studied area, KMC.

Poongothai et al. (2014) examined land use and land cover (LULC) alterations in the Kiliyar sub-watershed of Tamil Nadu with satellite imagery and topographic maps from the years 1995, 2003, and 2009. The study sought to examine the magnitude and trends of land use and land cover changes and to ascertain their underlying causes. Results indicated significant alterations in wasteland, woodland, and aquatic ecosystems throughout the research period, predominantly driven by natural and human-induced variables. The study underscored the necessity of conserving forests and aquatic ecosystems for sustainable watershed development. These findings are essential for guiding urban water management plans, especially in incorporating rainwater harvesting systems in areas where rapid land use and land cover changes jeopardise ecological stability and hydrological processes.

Desai et al. (2009) investigated land use and land cover (LULC) alterations in Pune metropolitan, Maharashtra, emphasising the difficulties arising from fast and unregulated urbanisation. The research highlighted that unregulated urban growth endangers sustainable city development and requires strategic planning. The authors illustrated how sophisticated methods such as remote sensing (RS) and geographic information systems (GIS) may efficiently monitor urban growth patterns and their environmental consequences through spatial data. Their work emphasises the essential requirement for incorporating technical methods in the management of urban infrastructure and environmental resources. Such insights are pertinent for cities like Kolkata, where sustainable urban water management, including rainwater collection, relies on comprehending and regulating urban development.

Prakasam C. (2010) conducted a study titled “Land Use/Land Cover Change Detection through Remote Sensing Approach: A Case Study of Kodaikanal Taluk, Tamil Nadu.” This research examines the alterations in land use and land cover in Kodaikanal taluk over 40 years (1969 - 2008). The research was conducted utilising a remote sensing methodology, employing the SOI taluk map of Kodaikanal from 1969, together with Landsat imagery from May 2003 and

April 2008. The current study reveals that forest coverage was approximately 70 percent in 1969, which declined to 33 percent by 2008. The agricultural land, developed areas, cultivated land, and wasteland have seen significant transformation. Developed land (settlements) has risen from 3 percent to 21 percent of the overall area. The Kodaikanal region is recognised as a significant biodiversity area in India. Proper land use planning is crucial for the sustainable growth of Kodaikanal taluk.

Currently, the majority of research has utilised hydrological and hydrodynamic models to evaluate the effects of urbanisation on watershed hydrology. Research regularly demonstrates that urbanisation results in heightened runoff and peak flow within urban watersheds, exacerbating the intensity of urban flood occurrences (Damodaram et al., 2010; Jacobson, 2011; Qin et al., 2013; Hou et al., 2019). Moreover, urban expansion interferes with the natural interplay among base flow, surface water, and groundwater, especially in peri-urban areas, potentially intensifying water resource issues. These findings underscore the essential requirement for cohesive urban water management measures to alleviate the detrimental hydrological impacts of fast urban expansion.

1.5.3. Implementation and Impact of Rainwater Harvesting:

Rainwater Harvesting (RWH) implementation and its impact studies were collected, and a critical review was carried out, as shown in the following sections:

Akuffobea-Essilfie et al. (2020) examine the factors influencing the implementation of rainwater harvesting in Ghana, focusing on both the challenges and opportunities for its adoption. The investigation looks into approaches and methods for enhancing the acceptability and implementation of roof rainwater harvesting (RWH) systems in Ghana, aiming to bolster water security and availability. The study utilizes a qualitative method to explore the perspectives shared by various stakeholders involved in a workshop focused on the potential for expanding successful rainwater harvesting technology. This study identifies several key drivers, including promoting local fabrication industries to design and develop components for rainwater harvesting (RWH) installations. It also highlights using a cluster approach in implementing RWH technology to improve cost-effectiveness and encourage broader adoption of the system. Additionally, the study emphasizes the role of media, such as television and radio, in disseminating the socioeconomic and environmental benefits associated with RWH systems. This paper illustrates the importance of the RWH system as a mechanism for achieving water security in Ghana.

Mrtijn Kuller et al. (2017) assessed the feasibility of rainwater harvesting to meet non-potable water requirements at Schiphol Airport, Netherlands, with an extensive runoff loss model initially introduced by Van de Ven (1998). The model calculates runoff (Pn) by subtracting initial loss (il) from total precipitation (P), thereby considering elements that diminish usable rainfall. This quantitative methodology offers a dependable foundation for evaluating rainwater availability, illustrating how modelling can enhance system design in urban environments. These approaches provide essential insights for tailoring rainwater harvesting to areas such as Kolkata, where precise runoff calculation is vital for effective water resource management.

Hayssam et al. (2017) examined the feasibility of rooftop rainwater collection in Lebanon by calculating the volume of collectable rainwater based on total rooftop area, average annual precipitation, and runoff coefficient. Their research indicated that the adoption of rooftop rainwater collection might mitigate almost 70% of the current water supply shortfall, underscoring the substantial role of decentralised rainwater collection in urban water sustainability. This strategy emphasises the necessity of including rooftop water harvesting in metropolitan areas like Kolkata, where alleviating water scarcity is essential.

Owusu and Teye (2015) investigated the viability of rainwater harvesting as a sustainable remedy for urban water scarcity in Accra, Ghana. Their research highlighted that incorporating rainwater harvesting technologies can substantially augment urban water supply, reducing strain on current infrastructure and improving water security. The findings underscore the practical advantages of decentralised rainwater harvesting methods in swiftly urbanising cities, providing significant insights for analogous metropolitan regions like the city of Kolkata that encounter similar issues.

Chao-Hsien Liaw et al. (2014) established a framework to evaluate the national rainwater harvesting potential from residential structures in Taiwan. The research divided the nation into rainfall zones to compute average yearly precipitation and assessed rooftop areas of residences to determine the total amount of collectable rainwater. The research employed a comprehensive household case study to provide a scientific framework for assessing large-scale rainwater capture capacity, highlighting the viability of rainwater collecting as an auxiliary domestic water supply. This paradigm can guide urban water management policies in areas like Kolkata, enabling the optimised design and planning of rainwater harvesting systems.

Nilufa Sultana et al. (2015) examined the quality of harvested rainwater in Kuala Lumpur, Malaysia, within the framework of the Storm Water Management Manual for Malaysia

(MSMA) and an eco-hydrology initiative. Their review conformed to the Interim National Water Quality Standards (INWQS) and the Malaysian Department of Environment’s Water Quality Index, offering a thorough assessment of the appropriateness of accumulated rainwater for diverse applications. The study emphasises the necessity of including water quality monitoring into rainwater harvesting systems to provide a safe and sustainable urban water supply, an essential consideration for the design of effective systems in cities such as Kolkata.

Guido Petrucci and colleagues (2012) investigate the application of rainwater harvesting as a strategy to manage stormwater runoff in suburban regions. This experimental case study investigates the broad impact of rainwater harvesting on runoff, highlighting the potential of this technique for managing stormwater sources. The analysis utilizes a dynamic rainfall run-off simulation model, specifically the storm water management model (SWMM 5), which has been calibrated based on rainfall run-off data collected from two measurement campaigns conducted before and after the equipment installation.

Yie-Ru Chiu (2012) presented the Simulation-Based Spatial System (SBSS) model as a proficient instrument for designing rooftop rainwater harvesting systems (RWHS) in urban settings. This model assesses the hydraulic efficiency and economic viability of RWHS, offering a thorough methodology for system optimization. The study emphasised the SBSS as a crucial innovation promoting the widespread implementation of rainwater harvesting technology, particularly in metropolitan regions experiencing water constraints. These modelling frameworks are essential for devising sustainable water management plans for cities such as Kolkata.

C. Vialle et al. (2011) in their paper on the modelling of a roof runoff harvesting system: A case study involving a family of four, examined the use of rainwater for toilet flushing through a rainwater harvesting system. The results indicated an impressive water-saving efficiency of 87% over the course of a year. This study demonstrates that a rainwater collection system plays a crucial role in decreasing the consumption of potable water. This study demonstrates that collecting rainwater from the rooftops of single-family homes can conserve 42 m^3 of potable water annually. The model was utilized to determine the ideal tank size for a single-family household, revealing that a storage capacity of around 5 m^3 is suitable.

Yong-chao Zhou et al. (2010) created a computational model to assess the efficacy of Domestic Rainwater Harvesting Systems (DRHS) in Zhoushan, China. Their simulation-based methodology examined the impact of fluctuations in the ratio of water demand to average yearly collected runoff and storage capacity to runoff on system performance. The study offered significant insights into optimising rainwater harvesting designs for home water supply by reconciling storage and demand, emphasising the necessity of model-based evaluations for efficient system planning. This study provides a pragmatic paradigm relevant to analogous metropolitan environments, such as Kolkata, where effective water demand management is essential.

Ju Young Lee et al. (2010) examined the regulatory frameworks and practical implementations of urban rainwater harvesting through a case study at Seoul National University in South Korea. The research tackled significant urban environmental issues, such as flood prevention, water conservation, and emergency water supply, by implementing a rainwater harvesting system. The system, intended for a catchment area of 2,098 m^2 and featuring a 200 m^3 concrete tank, effectively provided water for 70 toilets, demonstrating the efficacy and advantages of extensive urban rainwater reclamation. This instance illustrates how integrated rainwater harvesting systems can enhance urban sustainability, providing insights pertinent to densely populated cities such as Kolkata.

Sinwane and Kunene (2010) investigated the feasibility of rainwater harvesting (RWH) in the rural Makapa village of Swaziland, uncovering significant problems pertinent to urban environments as well. Although RWH systems were universally present in the 126 examined residences, hardly 8% utilised captured rainwater throughout the year due to the restricted capacity of storage tanks. The research underscored that tank size substantially impacted the length of water availability, emphasising the economic and infrastructural limitations that affect system efficacy. These findings highlight a significant difficulty for urban rainwater collection, especially in low-income metropolitan locations, where spatial constraints and the cost of sufficient storage frequently influence system efficacy and dependability.

Oni et al. (2008) examined the feasibility of rainwater harvesting (RWH) for home water supply in urban, semi-urban, and rural areas of Edo State, Nigeria. The study, which examined 31 families via questionnaires, determined that rainwater harvesting was less common in metropolitan areas due to greater accessibility to potable water and elevated groundwater levels. Notwithstanding this, 92% of participants from all regions relied on water vendors throughout the arid season, while merely 8% indicated that captured rainwater provided for their needs throughout the year. Notably, 31.5% of rural households engaged in the sale of accumulated water, highlighting its economic importance. These findings underscore that although metropolitan regions may not presently prioritise rainwater harvesting due to existing infrastructure, the system possesses inherent capacity to address water requirements during periodic deficits and to bolster resilience in neglected communities.

Rees et al. (2000) emphasised the increasing worldwide acknowledgement of Domestic Rooftop Water Harvesting (DRWH) systems, especially regarding cost-effective applications in East Africa. Their study delineated the essential components of DRWH systems—roof, storage tank, gutters, and filters or first flush diverters—and underscored the significance of appropriate system design and water management. Although merely 40% of the collected samples conformed to WHO microbiological guidelines, the contamination was primarily ascribed to secondary processing rather than the rainfall itself. The study, while concentrating on rural environments, underscores a crucial principle relevant to urban contexts: rainfall is among the safest and most cost-effective sources of drinkable water, contingent upon proper post-harvest management. This finding is particularly pertinent in urban areas with sporadic municipal supply, where decentralised harvesting methods might augment demand.

Zhua et al. (2004) examined the quality of rainwater collected from diverse catchment surfaces, highlighting the significance of storage length and self-purification in enhancing water quality. Their findings indicated that rooftop catchments using ‘first flush’ methods markedly improved the safety of accumulated rainwater by reducing organic pollutants and other impurities. Significantly, rainwater accumulated immediately after a rainstorm event had minimal organic matter levels, confirming its appropriateness for residential use. This study emphasises the necessity of incorporating effective system design and maintenance, such as first flush devices and sufficient storage, in rainwater harvesting systems, especially in urban environments where maintaining water quality is essential for domestic use.

Harda et al. (2006) assessed the efficacy of diverse rainwater harvesting (RWH) systems in Gujarat, utilising both the water balance method and the water table fluctuation method to measure groundwater recharge. Their investigation indicated a restricted recharge efficiency, necessitating around 104.3 mm of cumulative rainfall to attain merely 1 mm of groundwater recharge. This discovery underscores the limitations of specific RWH structures regarding infiltration capability, especially in areas with limited permeability or inadequate design optimisation. The research underscores the significance of localised hydrological evaluations and the necessity for enhanced rainwater harvesting structure designs to boost recharge efficacy, particularly in semi-arid urban environments.

Glendenning and Vervoort (2011) examined the hydrological effects of rainwater harvesting (RWH) at the watershed scale in the Arvari River basin, Rajasthan, India. The study utilised a conceptual water balance model to examine the trade-offs between localised water advantages and wider hydrological impacts. Their models indicated that while rainwater harvesting (RWH) improves groundwater recharge and promotes the sustainability of irrigated agriculture, it simultaneously diminishes downstream streamflow. This underscores the importance of reconciling localised water security with downstream water availability, particularly in arid and semi-arid regions where integrated watershed management is essential.

Aijaz (2010) critically analysed the escalating issues of urban water supply in India due to rapid population expansion and urbanisation. The study utilised case studies from Delhi, Mumbai, and Kolkata to illustrate how escalating urban demands exert pressure on existing infrastructure, thereby affecting quality of life, economic efficiency, and sustainable urban growth. The study highlighted structural deficiencies in water governance and policy, including the shortcomings in planning and investment that obstruct fair and effective water distribution in Indian urban areas.

A case study titled ‘Domestic Rooftop Water Harvesting- A Case Study’ was conducted in Dhule town by Dwivedi and Bhanduria (2009). From a total of 50 households, 43 single-story households were chosen for the study. The respondents indicated in the study that rainwater harvesting serves as an optimal solution for issues concerning water quality and quantity. The results indicated that the minimal rainfall during the non-monsoon period in the region rendered domestic rainwater harvesting systems insufficient to meet year-round water demand. The study indicated that a rainwater harvesting system with a capacity of 125 meters or more can meet the demand effectively.

Raju et al. (2007) examined the increasing dependence on groundwater and the consequent decline in water quality in the urban areas of Hubli, Dharwad, Belgaum, and Kolar. The study, published as a working paper, highlighted that the deficiencies in municipal water delivery systems have resulted in unsustainable groundwater extraction, exacerbated by contamination hazards. Their findings highlight the critical necessity for comprehensive urban water management strategies that address both supply enhancement and quality assurance.

Meera and Mansoor (2006) examined the water quality features of rooftop rainwater harvesting systems, highlighting that the quality of harvested rainwater is profoundly affected by the techniques employed in collection and storage. Their research showed pollution issues predominantly linked to the storage phase of rooftop runoff. When stored under appropriate circumstances, rainfall can comply with the drinking water quality requirements set by the World Health Organisation. This underscores the essential importance of maintenance and management techniques in guaranteeing the safety and utilisation of accumulated rainwater.

Shrivastava (2000) in his research paper titled “Water Management and Need for Rainwater Harvesting” stated that water resource development projects are essential for economic growth and prosperity to address the increasing demands of the population, while water conservation primarily seeks to align demand with supply. Water conservation strategies can be categorized as demand-oriented, supply-oriented, or management-oriented. The choice of strategy may vary based on the specific field of water use, such as domestic, irrigation, or industrial applications. One significant supply-oriented strategy is domestic rooftop rainwater harvesting technology.

Athavale (2003), in his book Water Harvesting and Sustainable Supply in India, emphasised that rainwater is typically devoid of dissolved solids and detrimental chemicals like arsenic and fluoride. He observed that specific regions in India—namely Andhra Pradesh, Madhya Pradesh, Gujarat, and Rajasthan exhibit fluoride concentrations in groundwater surpassing the permissible threshold of 1.5 microgrammes per litre, whereas areas in West Bengal and Bangladesh demonstrate arsenic levels exceeding the safe limit of 50 microgrammes per litre. In these regions, rainwater collection is advised irrespective of groundwater accessibility. Athavale additionally cited the definition of water harvesting from the working group of the Rajiv Gandhi National Drinking Water Mission, which includes the collection and storage of precipitation, surface water, and groundwater, as well as initiatives to minimise losses due to evaporation and seepage. The concept includes hydrological studies, engineering measures, and the installation of several water conservation structures, including agricultural ponds, check dams, percolation tanks, and subterranean dams. Furthermore, soil and water conservation techniques such as contour bunding, terrace farming, management of seawater intrusion, and reduction of groundwater flow to the sea constitute essential elements of sustainable water harvesting strategies.

Since May 2001, the Government of Tamil Nadu has vigorously promoted rainwater harvesting (RWH) across the state to address the growing gap between water supply and demand. To formalize this initiative, legislation was enacted in October 2002, followed by an ordinance in June 2003, mandating the installation of rainwater harvesting systems in all existing buildings.

These systems mainly collect rooftop runoff and channel it to existing or abandoned wells situated within residential, governmental, and private properties. State and national agencies have initiated public awareness campaigns and established regulatory frameworks to reduce the extensive and unregulated mining of groundwater resources (Sundaram et al., 2008).

The Central Groundwater Board (CGWB, 2007) launched many pilot programs to advance economical artificial groundwater recharge technology. Diverse recharge structures, such as check dams, recharge shafts, percolation ponds, and subsurface dykes, were established in various hydrogeological contexts to augment groundwater availability. In Tamil Nadu, seven percolation tanks and a subsurface dyke were erected, exemplifying the actual implementation of recharge techniques in regional water management.

1.5.4. Rainwater harvesting structures and methods

Due to the prevalence of droughts and floods in India, several water harvesting structures tailored to distinct eco-regions have been established. Although the techniques for harvesting rainwater vary by region, the primary goal remains the conservation of water for use during periods of scarcity. This section emphasises the diverse traditional, technological, and hybrid water harvesting structures in India.

Murty and Madan (2011) delineate the fundamental prerequisites for excavating agricultural ponds, underscoring the importance of meticulous site selection for their effective establishment. They categorise four specific categories of agricultural ponds—excavation ponds, watershed ponds, spring-fed ponds, and off-stream storage ponds—based on water source, geographical position, and land topography. These minor agricultural water features, such as ponds, tanks, and reservoirs, facilitate irrigation, animal requirements, and fish production, hence serving a crucial function in agricultural water management.

Yadav et al. (2010) delineate the significant structures for rainfall harvesting and management. Structures referred to as 'cisterns,' commonly known as tanks in the desert region of Rajasthan, are subterranean reservoirs typically built from concrete or brick. They are employed to collect and hold runoff water. Likewise, farm ponds are diminutive storage facilities utilised for the collection and retention of runoff water. Structures such as 'Johads' are built following the curves of mountain slopes to capture and retain rainwater. In addition to these buildings, the historic practice in the Jodhpur region has been the Nadi system of water accumulation. It is a diminutive excavated village pond employed to capture limited rainfall in arid desert regions to alleviate the scarcity of potable water. To satisfy irrigation and potable water requirements, safeguard land from erosion caused by runoff, refill groundwater, and preserve the ecosystem, structures such as small earthen dams, sunken structures/dugouts, and check dams have been constructed in the Bilwara region of Rajasthan.

Ravikumar et al. (2003) examined rooftop rainwater collection at Chennai Airport utilising Geographic Information Systems (GIS). They evaluated surface runoff using the Soil Conservation Service (SCS) methodology and engineered rainwater collection systems for the airport's terminal structures. Thematic maps were digitised utilising MapInfo GIS software, facilitating roof drainage demarcation inside a GIS framework. Artificial recharge structures, including recharge shafts, wells, and pits, were developed to enhance groundwater recharge based on the site's topography and lithology.

Guled et al. (2003) assert that the technique of rainwater harvesting and its application for various purposes is not novel to India. Substantial evidence of human understanding concerning water harvesting has been identified in southern India. Given that 20% to 25% of yearly precipitation is lost as runoff, surface water harvesting facilities such as farm ponds, nala bunds, and percolation tanks are advantageous for rural agricultural communities. This book highlights that, despite the geometric advantages of circular farm ponds, which provide maximum storage capacity, square and rectangular ponds are more practical for collecting runoff.

Kadirvelu (2002) assessed the efficacy of rainwater harvesting (RWH) at the Marina campus of Madras University, constructing structures adapted to local soil conditions. Water levels in three open wells were monitored before and after the adoption of Rainwater Harvesting (RWH) during pumping, with comparisons conducted against a nearby observation well overseen by the Tamil Nadu Water Supply and Drainage Board (TWAD). Results indicated enhancements in both groundwater volume and quality. A benefit-cost ratio of 2.38 signifies the economic feasibility of the system, illustrating that rainwater harvesting significantly influenced water supply and quality while providing a favourable cost-benefit equilibrium.

1.5.5. Government Policies related to rainwater harvesting:

Shukala (2000) indicated that the execution of Rainwater Harvesting (RWH) can be categorised into three components: public motivation, governmental incentives, and the establishment of regulations and laws. The enforcement of regulations is essential; currently, building permits are issued under the Bhumi Vikas Niyam, 1984. The Government has amended this regulation, stipulating that every building or residence constructed on a plot of

2400 square feet or larger must have Rainwater Harvesting (RWH) systems. This is compulsory for new structures. The Indore Municipal Corporation has mandated the implementation of Rainwater Harvesting systems for existing residences and buildings with a plot area of 2400 square feet or more.

The Central Pollution Control Board (CPCB) (2001), based in Delhi, under the Government of India, has released a book titled ‘Concepts and Practices for Rainwater Harvesting’, which elucidates the principles and methodologies associated with rainwater harvesting. This document will become beneficial for the design and implementation of rainwater harvesting and utilisation systems. It is essential to develop rainwater harvesting practices across the country to ensure safe water security for our country. While initiatives to address water scarcity through the conventional methods of extracting freshwater from rivers and subterranean aquifers are ongoing, rooftop rainwater collection in urban areas is increasingly seen as a viable means to augment traditional water sources.

The Centre for Science and Environment (CSE, 2003) in New Delhi has released a publication titled ‘Water Harvesting Manual for Urban Areas: Case Studies from Delhi and Mumbai’. This manual has been developed to provide essential information for initiating water harvesting practices. The handbook is designed straightforwardly to be accessible to average residents, in addition to architects, engineers, and other professionals interested in water harvesting implementation. Thus, the CSE has actively engaged in promoting awareness regarding the importance of community-based rainwater harvesting for several years.

Athavale (2003) in his book, ‘Water Harvesting and Sustainable Supply in India’, provides valuable insights that can assist decision-makers in acquiring pertinent information to make informed choices regarding optimal water harvesting techniques. It will also emphasise the importance of implementing integrated, scientific, and meticulously planned approaches to handling water resources to ensure an equitable supply of water.

Madhava et al. (2006) asserted that effective methods for subsurface water retention, soil moisture conservation, and groundwater recharge technologies should be appropriately incorporated into water resource management. Water resource management is essential for the sustainable development of watersheds, which is achievable solely via the application of diverse rainwater collecting systems.

Singh (2012) asserts that the Indian Constitution guarantees the right to life as a basic right under Article 21, which has been judicially interpreted to encompass the right to clean air and water. He emphasises the necessity for a centralised legislative framework to facilitate effective water resource management. The government has implemented a number of programs because water is a crucial resource, including the 1992 Policy Statements on Environment and Development, the National Water Policy, and the National Conservation Strategy. The Andhra Pradesh government implemented strategies that minimise rainwater wastage and sustain the level of groundwater. All state governments ought to embrace such efforts to enhance water levels.

Srivastava and Dubey (2012) asserted that the National Water Policy 2002 is an amended iteration of the 1987 policy, incorporating numerous beneficial components that were lacking in the prior edition. Water is classified as a state subject, which necessitates that state governments develop their policies regarding this resource.

Rai (2012) states that water is a limited and valuable resource. To distribute water resources, such as rivers that flow through several states, the Indian government established a number of water management bodies and agencies, including the Central Water Commission, Central Ground Water Board, National Water Development Agency, National Policy Guidelines, and the National Commission for Integrated Water Resource Development Plan. The 11th Five-Year Plan (2002-2012) established guidelines for the effective management of water resources in the nation. The Jal Abhiyan Program was initiated in December 2005 to generate significant awareness around water scarcity. This plan phase also emphasised water collection structures.

The Government of Karnataka, through the Department of Rural Development and Panchayat Raj, has initiated an extensive rooftop rainwater harvesting (RWH) program to address the shortage of potable water in rural schools, focusing on 23,683 institutions statewide. These schools were carefully selected due to the lack of available drinkable water sources. The initiative aims to provide each student with 1.5 litres of drinking water every day, utilizing rainwater harvested from school rooftops. The Engineering Departments of the individual Zilla Panchayats or the District Nirmithi Kendras supervise the construction and technical implementation of the RWH systems (Government of Karnataka, 2020).

In 2002, the Government of India, through the Central Public Works Department (CPWD), released a detailed guidebook entitled Rainwater Harvesting & Conservation, which outlines technical and strategic directives for the efficient use of rainwater resources. The guideline emphasizes the need to collect and preserve rainwater at the site of rainfall, promoting decentralized water management to enhance water sustainability and reduce reliance on traditional sources (CPWD, 2002).

In 2011, the Government of India initiated the National Water Mission as one of the eight missions under the National Action Plan on Climate Change (NAPCC), aiming to enhance water conservation, reduce waste, and guarantee equitable distribution of water resources both among and within states. The Mahatma Gandhi National Rural Employment Guarantee Act (MGNREGA) has been utilised to execute water conservation activities inside its developmental projects. The government has implemented block-level water conservation programs to enhance decentralised water management and alter rural and urban environments. In accordance with these initiatives, the Ministry of Water Resources, River Development, and Ganga Rejuvenation commenced the Jal Kranti Abhiyan in June 2015, subsequently launching the Jal Swavalambhi Abhiyan on January 27, 2016, to galvanise community-driven efforts for sustainable water management (Ministry of Jal Shakti, 2016).

The National Water Policy (NWP) of 2012, developed by the Ministry of Water Resources, Government of India, defines water as an "economic good" to encourage its efficient, egalitarian, and sustainable utilisation. The strategy establishes a thorough framework for the planning, development, and efficient utilisation of water resources nationwide. It emphasises the significance of participatory methodologies, especially the inclusion of farmers in water conservation initiatives, while addressing critical issues such as flood and drought mitigation and soil erosion control (Ministry of Water Resources, 2012).

In 2019, the Government of India initiated the Jal Shakti Abhiyan (JSA) to tackle these issues by emphasising water conservation, rainwater harvesting, and groundwater recharge in 1,592 water-scarce blocks across 256 districts (Ministry of Jal Shakti, 2021). Nevertheless, the emergence of the COVID-19 pandemic obstructed the comprehensive execution of JSA in 2020.

In 2020, the ‘Catch the Rain’ campaign was launched under the JSA initiative, advocating for the establishment of Rain Water Harvesting Structures (RWHS) with the tagline ‘Catch the rain, where it falls, when it falls’. The effort underscores community involvement and the necessity for frameworks adapted to local climatic and subsoil conditions to enhance water retention (NITI Aayog, 2021). Research indicates that decentralised and community-oriented water management strategies markedly improve water security, particularly when executed before the monsoon season (Shah, 2009; Agarwal & Narain, 1997).

The management of sustainable water resources is becoming increasingly crucial due to climate variability and escalating agricultural demand (Falkenmark & Rockström, 2006). Decentralized rainwater accumulating and small-scale irrigation schemes have proven effective in countries reliant on monsoon precipitation (Agarwal & Narain, 1997). In 2011–12, the Government of West Bengal launched the 'Jal Dharo-Jal Bharo' program to harness rainwater and reduce runoff by constructing minor irrigation projects (WRIDD, 2020). This concept promotes community engagement, revitalization of traditional water bodies, and modern irrigation design. Research shows that localized water management can boost agricultural output, reduce reliance on groundwater, and enhance climate resilience (Kerr, 2002; Batchelor et al., 2003). The WRIDD plays a critical role in facilitating the scientific planning and execution of the program, providing a replicable framework for other monsoon-dependent areas (WRIDD, 2020).

1.6. Research Gaps:

After reviewing the extensive literature, we realize that numerous studies have been conducted on rainwater harvesting techniques, their implementation, structure, and impact, initiated by the government at both the central and state levels, as well as by non-governmental groups. These studies were primarily executed in arid and semi-arid, rain-fed regions; however, it is noteworthy that even areas with abundant rainfall experience water scarcity during dry seasons, while streets are often flooded during the rainy season. This has led to significant issues with both the quantity and quality of groundwater. Despite numerous studies on rainwater harvesting across various regions of India, there is a lack of research addressing the potential volume of rainfall that can be captured within the Kolkata Municipal Corporation, especially the quantification of rooftop rainwater harvesting. Additionally, there is a dearth of studies focused on economically viable methods of rainwater harvesting. Furthermore, there has been insufficient research on reducing urban flooding and capturing rainwater to store it in tanks and holding structures, representing the research gap.

1.7. Statement of Problems:

This study addresses the deficiency of research regarding the implementation of rainwater harvesting within the Kolkata Municipal Corporation (KMC). The groundwater level in the Kolkata Municipal Corporation has significantly decreased over the years. In the study region, groundwater extraction by the Kolkata Municipal Corporation (KMC) escalated from 121.5 million litres per day in 1986 to 209.7 million litres per day in 1998, persisting until 2004.

Since 2005, the Kolkata Municipal Corporation has been progressively substituting groundwater supplies with surface water supply. Consequently, there has been a decrease in the volume of groundwater extraction since 2005 (Kolkata Municipal Corporation, 2006). In 2006, groundwater extraction by Kolkata Municipal Corporation-owned tube wells decreased to 144.30 million litres per day (Kolkata Municipal Corporation, 2006). Kolkata is the most water-challenged city in India, experiencing regular urban flooding during the monsoon due to inadequate rainwater management, while residents endure water scarcity during dry months. The issue is exacerbated by high human density, temporal variability of precipitation, and the escalating depletion and contamination of both surface and groundwater resources. Given the aforementioned factors present in the study area, planners, policymakers, hydrologists, water managers, local communities, geographers, and researchers must recognise that rain is a valuable and essential natural resource that necessitates meticulous management.

1.8. Objectives:

The main objectives of the present study are as follows-

1. Analysis of the long-term rainfall trend and its variability over 120 years of Monthly and Annual Rainfall in Kolkata Municipal Corporation (KMC).
2. Analysis of Land Use and Land Cover Changes within Kolkata Municipal Corporation (KMC).
3. Estimation of the potential amount of rainfall that can be harvested on rooftops within KMC.
4. Dimensioning the Rooftop Rainwater Harvesting Structure based on estimation of assured rainfall
5. Assessment of Various Policy Support with Sustainable Development Goals (SDGs) and People's Perception regarding Rooftop Rainwater Harvesting (RRWH)

1.9. Materials and Methods:

1.9.1. Database:

Data is a collection of information that characterises objects and phenomena in relation to spatial and temporal contexts. It is essential to assess the current status and future potential of rainwater harvesting in the study area. Therefore, a robust primary and secondary database, essential for the research, has been collected. The significant sources and databases utilised for this research are as follows:

I. Rainfall data has been retrieved from a web-based spatial data portal, the Water Resource Information System of India (*India Water Resources Information System*, 2016) for water-related data dissemination

II. Topographic maps and census data are obtained from different government offices.

III. Depth to groundwater level has been retrieved from the Central Ground Water Board (CGWB).

IV. The coordinates and dimensions of the numerous observation structures have been measured using GPS, tape, and a distometer.

V. Satellite images have been exported from Google Earth Engine and USGS Earth Explorer.

VI. People's perceptions regarding the implementation of rainwater harvesting and the current status of various multi-complex buildings in the study area concerning rainwater harvesting structures have been collected through a field survey.

1.9.2. Methodology:

To achieve the objectives, the obtained data were processed and presented in the form of maps, tables, charts, and figures. The present study is primarily driven by quantitative analysis, machine learning analysis, and applications of GIS and remote sensing. This study utilises long-term rainfall data to analyse trends and variability through various statistical techniques implemented in Python and MS Excel. The trend of annual rainfall and its magnitude were assessed using a non-parametric Mann-Kendall test and Sen's slope estimator. The total area under examination is 187 km², determined through vectorisation of the Kolkata Municipal Corporation (KMC) map in UTM projection and WGS84 datum using ArcMap 10.2. The study started in the year 2018, and it was important to have an idea regarding the land use and land cover (LULC) of KMC in order to set the objectives of the research. Hence, 2019 Sentinel data, which have a spatial resolution of 10 metres, were used to generate the LULC map of KMC. The land use land cover changes of the study area have been assessed by classifying the Landsat TM data for 1990, 2000, 2011, and 2021. The land use and land cover (LULC) map of the study area has been generated utilising ERDAS IMAGINE 2014, based on the Sentinel 2A (2019) image. The rooftop area of the chosen buildings, including government-aided colleges and universities, has been determined through the use of Google Earth Pro and manual measurements taken with a distometer and tape. In order to verify the value of the runoff coefficient, an experiment was carried out on the concrete rooftop of the building, and based on the results, the runoff coefficient for this study has been determined to be 0.8.

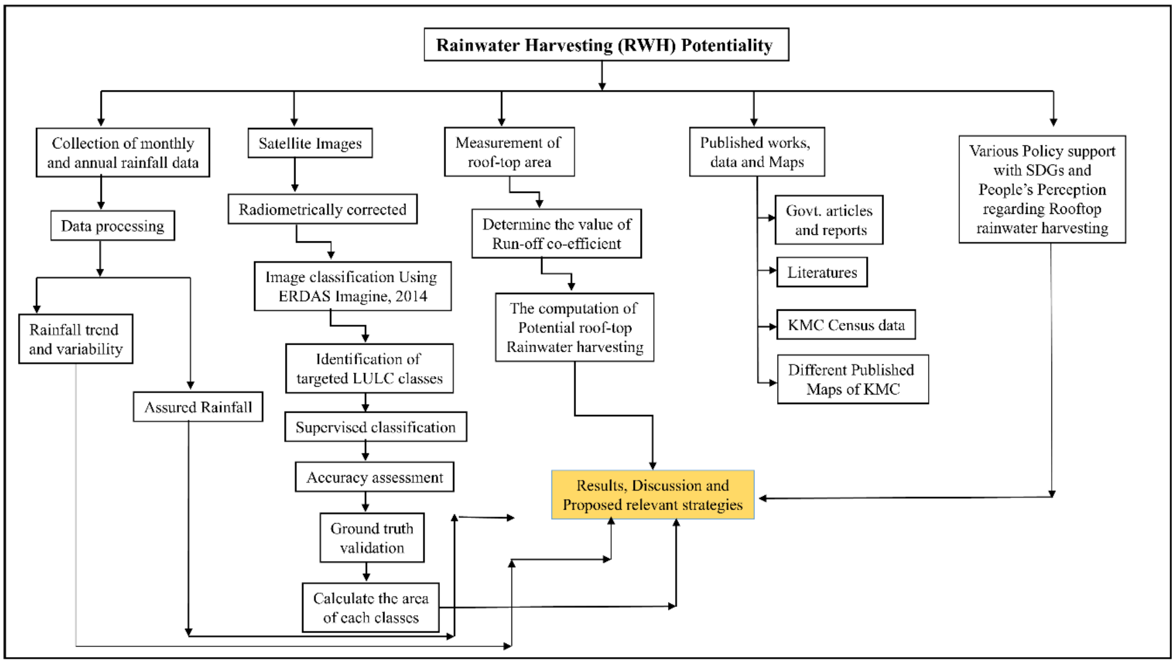

Figure 1.3: Methodological flow chart of the study

1.10. Limitation of the Study:

The current study encounters certain limitations related to time and resources during its execution. Several challenges emerge during the investigation of Rainwater Harvesting prospects in KMC, including a large area that is not physically accessible for survey, a lack of information regarding building architecture and plans from both individuals and proprietors of big hotels, shopping malls, etc. However, significant attention has been devoted to ensuring that the study proceeds systematically. In addition to this, rainwater harvesting can only be effective when the quantity and frequency of rainfall, along with the size of the catchment area, are adequate to produce sufficient water for the intended use.

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CHAPTER 2

PRESENT STATUS OF WATER SUPPLY SCENARIO

2.1. Introduction:

Kolkata, traditionally rich in water resources from its position on the Hooghly River delta, is presently facing considerable difficulties with its water supply system. Although the city generates over 2,180 million litres of water daily, adequate for its estimated 5 million inhabitants and supplementary daily commuters, it encounters challenges of significant wastage and inequitable distribution. Reports suggest that approximately 23 % of the delivered water is wasted due to leaks and inefficiencies in the distribution system, resulting in dependence on water tankers, especially in disadvantaged regions (Kolkata Municipal Corporation, 2016). The excessive exploitation of groundwater has led to a notable decrease in water tables, with levels falling by almost 2.1 meters from 2017 to 2021. The depletion has resulted in the encroachment of brackish water and elevated levels of arsenic and salt in the groundwater, presenting health hazards and jeopardising the future reliability of the water supply (Bandyopadhyay, 2023). The population of Kolkata is currently over 4.6 million and continues to increase. According to the 2011 census, 4,496,694 people were living in the KMC region. The massive infrastructure development projects that have been carried out by the public and private sectors in various locations along the EM bypass, as well as in additional areas of Kolkata, such as Jadavpur, Garia and Behala, outside of the city proper and northern congruent parts, are major problems for such a population influx. As a result, the demand for residential water has escalated to an unusually high level. This has led to a significant need for the provision of drinkable water, especially in these expanding regions.

In response to these difficulties, the Kolkata Municipal Corporation (KMC) has implemented strategies to diminish groundwater reliance by two-thirds by 2026. Plans entail the establishment of new booster pumping stations and the replacement of deteriorating pipelines to improve the efficiency and coverage of the surface water supply system (Ray, 2025).

2.2. Materials and Methods:

This study adopts a descriptive-analytical approach to evaluate the current condition, difficulties, and prospects of the water supply system in the Kolkata Municipal Corporation (KMC) area. It primarily relies on secondary data, meticulously gathered from credible sources, including official government documents like the Action Plan to Reduce Water Losses (2015–

2020) by KMC (Kolkata Municipal Corporation, 2016), technical reports from the Central Ground Water Board (2007) and other relevant scientific literature (Sikdar, Banerjee, & Chakraborty, 2022). Additional information was acquired from news articles and official announcements concerning advancements in water infrastructure (Ray, 2025; Roy, 2025). Quantitative data, including daily water demand, production capacity, losses and groundwater extraction, were analysed with statistical tools to identify disparities between demand and supply as well as long-term trends. Moreover, qualitative assessment methods were employed to analyse the spatial distribution of infrastructure, policy frameworks and administrative responses to increasing water demand. Particular emphasis was placed on water-scarce periphery areas such as Garia, Jadavpur, and Behala, which are experiencing rapid population growth and infrastructural development. Where applicable, GIS-based spatial data, including KMC’s digital water line mapping project, has been utilised to examine pipeline networks and areas susceptible to leakage (Anandabazar Online Correspondent, 2024). However, constraints include the lack of direct household consumption records and real-time data regarding pipeline performance. Despite these limitations, the technique offers a scientifically rigorous and culturally relevant framework for comprehending the dynamics of Kolkata's urban water supply and assessing current initiatives aimed at ensuring its sustainability.

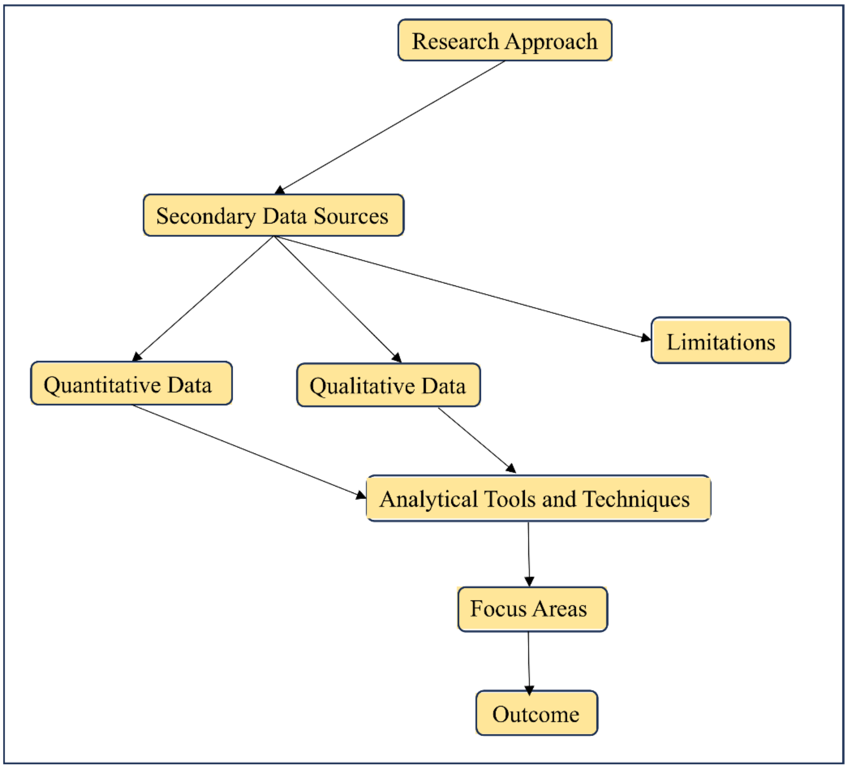

Figure 2.1: Methodological framework for the study of the present water supply scenario within the Kolkata Municipal Corporation

2.3. Sources of Water Supply:

Kolkata has two types of water sources: surface water and subsurface water. The city's water supply relies on both surface water from the Hugli River and groundwater sources.

2.3.1. Surface Water Sources:

The primary surface water supply for the Kolkata Municipal Corporation (KMC) is the Hugli River. The western portion of the city is located along the right branch of the Hooghly River, which is perennial in nature. Therefore, the city enjoys a relatively fortunate position compared to numerous other cities in India. The Hugli River begins in the Farakka Barrage on the Ganges River, situated almost 200 km north of Kolkata, and runs in a north-south direction towards the sea. It serves as the prime source of drinkable surface water for Kolkata, supplied by the historic Palta Water Works along with other water treatment plants (Table 2.b). The Palta Water Works, currently renamed as the Indira Gandhi Water Treatment Plant, with an extensive area of 480 acres, was the inaugural intake station established between 1864 and 1870 for the generation and distribution of water. Commencing with a capacity of 6 MGD (million gallons per day), filtered water was produced using sedimentation in pre and final settling tanks.

2.3.2. Subsurface Water Sources:

Officially, 15% of Kolkata's water is obtained from groundwater, while actual usage in households may range from 25% to 30% derived from groundwater sources (Basu, 2015). The Central Groundwater Board (Central Ground Water Board, 2007) Booklet indicates that the groundwater utilisation for domestic and industrial purposes within the KMC area is approximately 320 MLD. In 2006, groundwater withdrawal by KMC was 144.30 MLD, which decreased to 114 MLD by 2011 (Central Ground Water Board, 2007). P.K. Sikdar, of the Indian Institute of Social Welfare and Business Management (IISWBM), noted that groundwater availability is rapidly diminishing in the city. In 2006, groundwater withdrawal by KMC was 144.30 MLD, which decreased to 114 MLD by 2011. KMC aims to minimise and deter groundwater usage. Groundwater availability is rapidly diminishing in the study area (Sahu et al., 2013), which may result in soil subsidence due to a subsurface layer of approximately 40 meters of clay, followed by sand that could collapse. He stated, “In the 1950s, groundwater flowed from north to south; however, a shift occurred three decades ago when a groundwater pressure trough emerged in the south-central region of Kolkata due to excessive groundwater extraction, causing water to flow into the trough from all directions.”

2.4. Process of Water Supply and its distribution:

The primary water supply for Kolkata comes from the Hugli River. KMC treats the water in various water treatment plants (WTPs) according to their capacity after extracting it from the river. Once the water has been treated, it is delivered to a number of pumping stations for short-term storage before being distributed around the city.

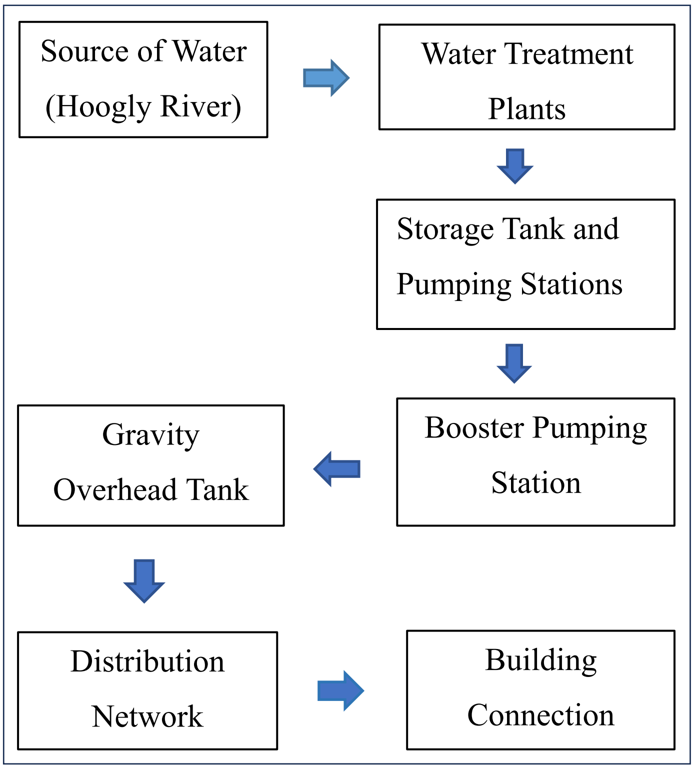

Figure 2.2: Basic flow chart of water distribution system within KMC

The water supply authority divides the city into seven zones according to best engineering principles and hydraulic patterns. The zones are Central, North, South, Jadavpur unit, S.S. unit, Garden Reach unit and Tube Well (areas that rely on tube wells for groundwater extraction). Water is distributed via a network of pipes across the city for final use by both domestic and industrial consumers. The water supply department provides water for shipping, tanker distribution, daily usage, and emergency maintenance operations.

2.5. Basic statistics of the water supply scenario within KMC:

Urban water management plays a vital role in sustainable development, especially in densely populated and swiftly expanding urban areas such as Kolkata. The Kolkata Municipal Corporation (KMC), tasked with the provision of potable water within its jurisdiction, is encountering mounting challenges to satisfy the rising demand from both resident and transient populations. Grasping the quantitative aspects of water supply, like production capacity, demand, usage patterns and system losses, is crucial for assessing the effectiveness and sustainability of the city's water infrastructure. The following statistics summary (Table 2.a) offers essential insights into the scale and operational dynamics of the KMC water supply system, establishing a baseline for evaluating current challenges and developing informed policy and infrastructure responses.

Table 2.a: Basic statistics of water supply scenario within KMC

Parameter	Value
Total Area (in sq. km)	187
Total Population (as per 2011 Census)	4,560,694
Water Demand (in litres/day) *	1,181,688,000
Water Generated (in litres/day)	1,434,640,000
Water Supplied (in litres/day)	1,181,688,000
Domestic Use (63% of total supplied, in litres/day)	744,463,440
Industrial & Commercial Use (35% of total supplied, in litres/day)	413,590,800
Social Use (2% of total supplied, in litres/day)	23,633,760
Volume of Water Losses (in litres/day)	366,452,000
Estimated Water Loss Percentage (per day)	23.67%

*Considering @ 150 lpcd, @ 40 lpcd for the floating population of 60 Lakh, and 20% of domestic demand as ICI consumption

Source: Action plan (2015-2020), KMC

The water supply systems within the KMC reveal a multifaceted interplay of demand, generation, distribution, and loss, highlighting both successes and systematic inefficiencies. The KMC covers an area of 187 square kilometres and accommodates a population of around 4.56 million as per the 2011 census. The daily water requirement is approximately 1.18 billion litres. This figure is derived from a per capita consumption of 150 litres per day, with adjustments made for a transient population of 6 million at a rate of 40 litres per capita. Additionally, 20% of the domestic water demand is linked to industrial, commercial, and institutional consumption (ICI). KMC produces around 1.43 billion litres of water daily above the reported demand, suggesting a theoretical adequacy in supply (Kolkata Municipal Corporation 2016). Nonetheless, despite this capability, the actual volume supplied aligns with the demand at 1.18 billion litres per day, exhibiting notable segmentations: domestic use accounts for 63% (744.46 million litres), industrial and commercial use comprises 35% (413.59 million litres), and social purposes represent 2% (23.63 million litres). A significant issue emerges from the reported daily water losses of roughly 366.45 million litres, being an estimated 23.67% of the total generated volume. These findings highlight an urgent necessity for infrastructural enhancements and leakage management to improve efficiency and sustainability in the water supply system within KMC.

2.6. Existing Water Treatment Plant (WTP):

The water supply system in the study area (KMC) is fundamentally supported by water treatment plants, which play a crucial role in purifying and distributing potable water throughout the area. KMC manages multiple significant water treatment plants (WTPs), each designed with different capacities to address the various water needs. These plants serve as indicators of the city's infrastructural capacity while also revealing potential areas of underutilisation or inefficiencies. Table 2.b specifies the production capacities and present production of the key water treatment plants under KMC, offering valuable insight into the operational status and performance of KMC's water treatment infrastructure.

Table 2.b: Existing Water Treatment Plants with their capacity and present production

Sl. No.	Water Treatment Plant	Production Capacity in MGD (Million Gallons per Day)	Present Production in MGD (Million Gallons per Day)
1	Indira Gandhi Water Treatment Plant, (Palta)	242	234
2	Garden Reach Treatment Plant	185	130
3	Jai Hind Jal Prakalpa – Dhapa	30	27
4	Jorabagan Water Treatment Plant	08	05
5	Watgunge Water Treatment Plant	05	04

Source: KMC Officials

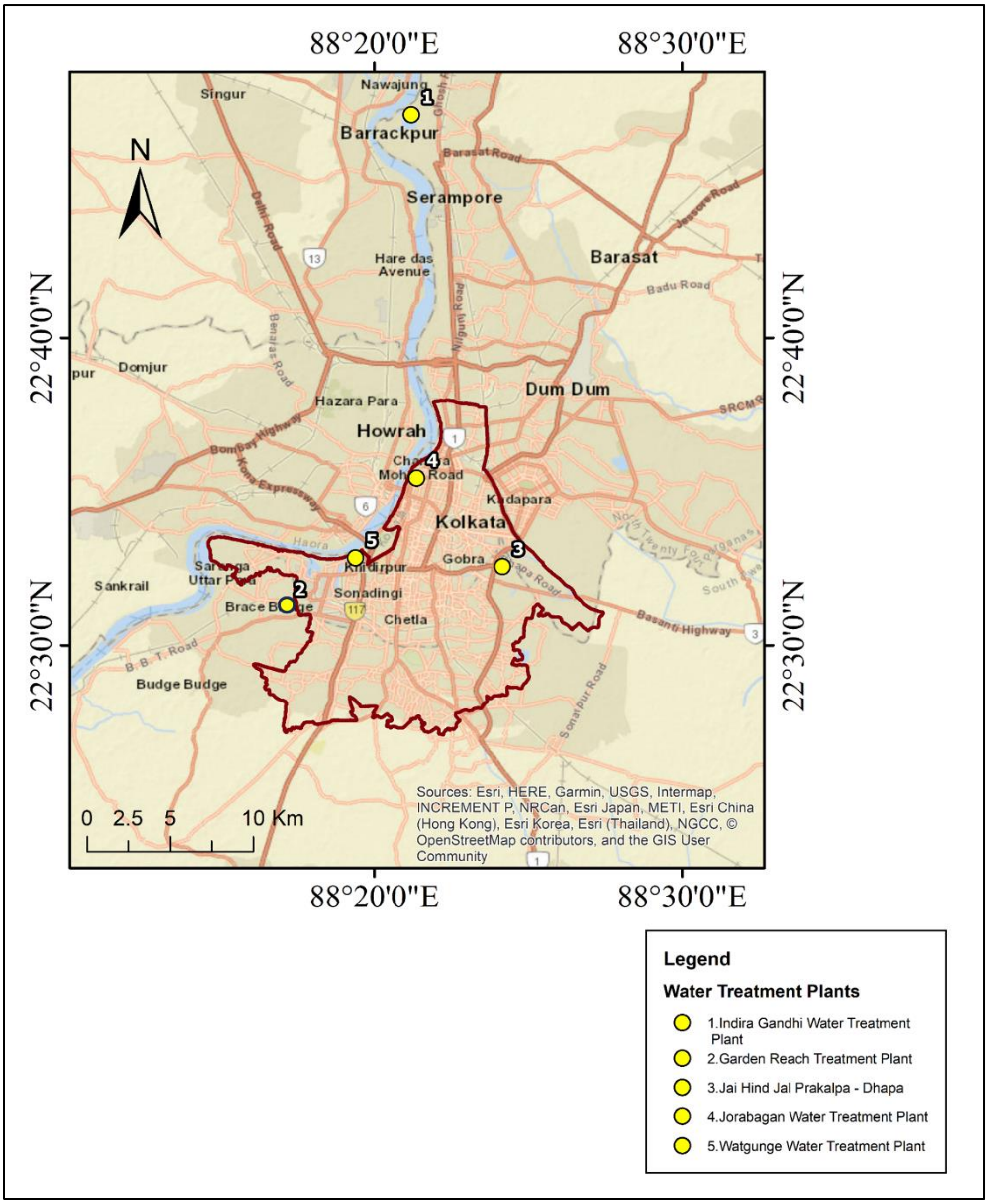

Figure 2.3: Location of Existing Water Treatment Plants under KMC

1. Indira Gandhi Water Treatment Plant, Palta:

Originally called Palta Water Works, these water works were renamed as the Indira Gandhi Water Treatment Plant in 2002. The Palta Water Works, with an extensive area of 480 acres, was the inaugural intake station established between 1864 and 1870 for the generation and distribution of water. Over the years, the plant's capacity has been augmented, and the present capacity of the waterworks is 242 MGD (Million Gallons per Day). Three pumping stations are used to extract raw water from the Hooghly River, which is then processed by a number of clarifiers, settling tanks, filter beds and chlorinators. Five transmission mains convey treated water from Palta to the Tala Reservoir and Pumping Station, located 23 km south of Palta. Tala serves as the primary reservoir and pumping station for Palta water works, facilitating the distribution of water throughout the urban supply area.

2. Garden Reach Water Treatment Plant (GRWTP):

Garden Reach Water Works (GRWW) is situated on the western boundary of Kolkata within Borough XV. The total production capacity of the Garden Reach Water Treatment Plant is 242 MGD (Million Gallons per Day). In addition to being sent straight to the city service grid's Core Calcutta (CC) and South Suburban (SS), treated water from the Clear Water Reservoir (CWR) is diverted to reservoirs at the Booster Pumping Station (BPS), which is situated in Behala Chowrasta.

3. Jai Hind Jal Prakalpa – Dhapa (JHJP):

The Jai Hind Jal Prakalpa water treatment plant is situated in Dhapa, Kolkata. The initial groundwork for the water treatment facility was established in 2008. The construction of the water treatment facility was meticulously planned to serve millions of residents along the Eastern Metropolitan Bypass.

4. Jorabagan Water Treatment Plant (JWTP):

The total production capacity of the Jorabagan Water Treatment Plant is 8 MGD (Million Gallons per Day). The plant was established approximately twenty years ago to address the water crisis affecting significant areas of north Kolkata. The KMC water supply department officials selected the Mallickghat pumping station as the raw water source for this facility.

5. Watgunge Water Treatment Plant (WWTP):

The construction of this 5MGD water treatment plant and booster pumping station at Watgunj Square is being facilitated by advanced technology, aimed to fulfil the filtered water needs of the residents in the Watgunj and Hastings areas.

Apart from that, the Water Treatment Plant, which are under construction, are:

1. Garden Reach Water Works – 25 MGD Capacity.
2. Indira Gandhi Water Treatment Plant – Palta – 20 MGD

2.7. Current initiatives taken to enhance the water supply:

The Kolkata Municipal Corporation has launched several major initiatives to modernise and improve the city's water supply system. These projects aim to ensure the fair distribution of safe drinking water, lower reliance on groundwater, and fewer transmission losses due to ageing infrastructure.

1. Allocation of Funds to improve the Infrastructure and Water Supply (2024-2026):

KMC has allocated more than ₹ 700 crores for the execution of 22 water-related initiatives throughout the city. This encompasses the establishment of new water treatment facilities (WTPs), the setup of new booster pumping stations, and the creation of water reservoirs. A major segment of this budget is allocated for the replacement of outdated, leaky pipelines with contemporary solutions to mitigate water loss. The Corporation underlined the dedication of providing citizens with clean drinking water, particularly in areas that now depend on groundwater ('KMC to Invest', 2024).

2. Upgrade the Water Treatment Plant (WTP):

The Kolkata Municipal Corporation (KMC) upgrade the capacity of the Dhapa water treatment plant (WTP) from 30 million gallons per day (MGD) to 50 MGD (Roy, 2025). This expansion intends to provide drinkable water to regions including Topsia, Anandapur, Naskarhat, Kasba, Madurdaha, Kalikapur, Mukundapur, and Patuli (Times News Network, 2019) In addition, a new 10 MGD water treatment plant is currently being constructed near Garia's Dhalai Bridge, with the objective of addressing water shortages in the Tollygunge-Jadavpur area These initiatives have been scheduled to be completed before summer 2026 (Team MP, 2024).

3. Building new Reservoirs and Booster Pumping Stations:

KMC plans to construct several booster pumping stations with related reservoirs to help underprivileged communities suffering with water shortages. The Foundation stones have been set in January 2025 for stations in Kasba (Ward 106) and Santoshpur (Ward 103); other stations have been scheduled for Garia (Ward 100) and Tollygunge (Ward 97) (Roy, 2025).

4. Treated Surface Water in Place of Tubewells:

KMC designated 10 wards (13, 65, 67, 89, 97, 99, 100, 103, 110 and 130) for initiatives to substitute groundwater-sourced tubewells with treated surface water in December 2024. This effort entails the installation of semi-underground reservoirs and booster pumping stations, with an estimated total expenditure of around ₹ 60 crores. Land for such initiatives has been designated, and the execution is scheduled to occur in phases (Mullick, 2024).

5. Digital Water Line Mapping:

KMC started building an extensive digital map of the water pipelines in the city in August 2024. This project seeks to record information including pipeline locations, diameters, valve placements and connections, hence enabling effective maintenance and future planning (Anandabazar Online Correspondent, 2024)

6. Preventing Leakage with Pipeline upgradation:

KMC started a ₹ 364-crore initiative in February 2024 to strengthen old pipelines using a jacketing approach, hence tackling water loss brought on by ageing infrastructure. Covering worn-out pipes with protective coatings to stop leaks and extend their life by 30-40 years constitutes this approach. Targeting important thoroughfares including SP Mukherjee Road, Ballygunge Circular Road, and Gariahat Road, the project is being carried out in stages (Ray, 2024).

7. Lessening of Groundwater Dependency:

KMC intends to substantially diminish groundwater extraction in the Tollygunge-Garia area by 2026. Presently, over 24.3 million gallons of groundwater are extracted every day for 20 wards in this region. The objective is to reduce this by increasing surface water availability through the development of the Dhapa water treatment facility and the establishment of a new plant near Dhalai Bridge in Garia. Furthermore, 40 semi-subterranean water reservoirs and capsule booster pumping stations are proposed, with 15 already finished and 25 now under development (Ray, 2025).

2.8. Conclusion:

The present study emphasises the dynamic and complicated interactions of KMC's urban water supply, a system under growing strain from fast population increase, urban development, and ageing infrastructure. Kolkata's water consumption is predicted to grow dramatically in the next years, given a population above 4.6 million and an expected steady increase. Particularly in densely inhabited and freshly growing districts like Jadavpur, Garia, Behala, and those along the EM Bypass, this increase has already put great strain on both surface and groundwater supplies. Historically, the main surface water source for the city, the Hooghly River, has offered a consistent foundation for the delivery of drinking water. However, especially in southern areas of the city, excessive groundwater extraction has caused worrisome aquifer level decreases, which have formed a groundwater trough and changed normal flow patterns.

The Kolkata Municipal Corporation (KMC) has acknowledged these developing issues and started a multi-pronged approach to modernise, enlarge, and stabilise the water supply system. Among the projects are the growth of significant water treatment facilities like those at Dhapa and Palta, the building of new reservoirs and booster pumping stations, the replacement of ageing pipeline systems, and the move from tubewell-sourced water to treated surface water in several wards. Especially, KMC's promise of more than 700 crores between 2024 and 2026 shows a major dedication to solving infrastructure weaknesses as well as supply shortages. Additionally, the strategic implementation of digital water line mapping and enhanced leakage reduction via pipeline jacketing shows a progressive strategy that combines data-driven planning with conservation engineering. Despite these initiatives, ongoing challenges, such as around 24% water loss, swift urban growth, and lagging infrastructure in outlying regions, emphasise the necessity for sustained monitoring, maintenance, and community involvement.

In conclusion, although significant advancements have been achieved, the sustainable future of Kolkata's water supply depends on the city's capacity to integrate technological innovation, environmental stewardship, and effective administration. Proactive strategies such as rainwater collecting, greywater recycling and decentralised treatment systems should be further investigated to enhance current initiatives and tackle potential water security issues in a swiftly urbanising city.

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CHAPTER 3

ANALYSIS OF RAINFALL TREND, VARIABILITY AND FORECASTING

3.1. Introduction:

The study of rainfall trend, variability, and forecasting is critically important in Indian cities like Kolkata, which have high water demand. Rainfall is the primary source of water for those whose entire existence is reliant on it. Rainfall forecasting has become a significant concern in recent years, attracting the attention of government agencies, industries, risk assessment agencies, and the research community. It is the primary source of groundwater, which slowly seeps into the ground and raises the water table. Therefore, the proper trend analysis, its variability, and forecasting are necessary for the planners regarding the sustainable use of rainwater. The analysis of long-period rainfall data provides information about the temporal pattern and its mutability. A piece of detailed knowledge about the trend and capricious nature of rainfall is an imperative prerequisite for planners regarding urban water management to reduce the gap between water demand and availability. The term ‘climate’ is typically used to refer to the average weather, or more precisely, to the statistical description of important parameters over timescales ranging from months to thousands or millions of years (IPCC-SAR, 1995). The World Meteorological Organization (WMO) specifies 30 years as the traditional time frame for averaging these variables. One of the fast-paced components of climate change is rainfall. The amount and pattern of rainfall obtained in each region are significant in determining the quantity of water required to meet the demands of various sectors, including agriculture, manufacturing, household and hydropower. The study of rainfall pattern analysis in highly urbanized areas is of great importance for various purposes, such as flood forecasting, water resource management, hydrological modelling, climate change adaptation and planning. Effective Global Circulation Models (GCMs) were used to determine the type and pattern of annual maximum precipitation events in the Kolkata Metropolitan Area. The rainfall data from the Alipore Kolkata station (1901–2013) were considered for analysis in that study, and the results showed that the rainfall in the specified area follows a natural pattern of variability and oscillation (Malik et al., 2020). The Bhilangana River Basin in the Uttarakhand Himalayas was studied to detect spatio-temporal patterns and changeability in yearly, periodic, and monthly rainfall associated with the number of rainy days. According to the findings, the catchment decreased by 15.75 millimetres of rainfall per decade on average between 1983 and 2008 at all surface observatories (Banerjee et al., 2020). The seasonal rainfall trends from 1901 to 2002 and the inclination were determined using the Mann-Kendall test, while the magnitude of these trends was assessed using the Theil-Sen slope estimator (Kundu & Mondal, 2019). Long-term spatial and chronological rainfall patterns based on 102 years of rainfall data from 12 meteorological stations of Gangetic West Bengal between 1901 and 2002 were analysed on weekly, seasonal, and annual scale, revealing that the average annual precipitation increased by 2.61 percent and the post-monsoon precipitation increased considerably by 33.87 percent between 1901 and 2002. (Ghosh, 2018). The Indian Meteorological Department's monthly rainfall data, spanning from 1901 to 2000, was utilised to generate district-wise annual rainfall variance statistics throughout West Bengal. A surplus of 1.5-2 percent was observed throughout the state (Das et al., 2018). Global climate transformation and the risk of intensifying droughts and floods will influence long-term rainfall patterns affecting water supply (Pal et al., 2017).The Mann-Kendal, Sen's slope, and sequential Mann–Kendall tests were used to analyse seasonal and annual rainfall chronological trends and their fluctuations through time in Bangladesh, in order to determine the abrupt changes in rainfall data over 50 years (Bari et al., 2016). The climatic variability was analysed in South West England based on present and historical climatic data, which shows that the study on local climate modification has great importance, as the trends that initiate in localities can differ from nationwide and worldwide estimates (Kosanic et al., 2014). To measure rainfall and temperature trends over thirteen districts of Uttarakhand the M-K test with Sen's slope estimate were used which revealed an increasing inclination of precipitation and temperature in some months while a decreasing trend in the alternative months, implying inconsistent inclusive variations in the region (Yadav et al., 2014). To fit a model on the monthly and periodic rainfall pattern over the Langat River basin, Malaysia, from 1970 to 2012 Holt's assessment was applied, which showed an upward trend in March, July, and November while showing a declining trend in May and September (Huang et al., 2015). In order to detect trends of temporary rainfall changes over India, the non-parametric Mann-Kendall test was used and the magnitude of the trend was determined using the Sen's slope estimator (Kumar et al., 2010). The temporal rainfall shifts were analysed in the north-east part of Cuttack, Orissa, with a statistical test that displayed an upward trend over a few months and a downward trend over another few months and with insignificant changes to the region in general (Mondal et al., 2012). A study was performed to detect the precipitation trends and variability in Scotland. In accomplish their objectives in detail, the CUSUM and chronological Mann-Kendall test were incorporated (Afzal et al., 2011). To understand climatic variability, climatic records availability are required for a long-term period (Brunet & Jones, 2011). Awareness of historical and tropical climate change has gained significant consideration by enhancing and expanding a wide variety of database and more advanced data analysis around the globe (Kumar et al., 2010). Historical rainfall shifts over the Indian Himalayas were carried out where the Mann Kendall test was used to monitor the trends and reveals a rising trend in the period of 1902-1964 while rainfall patterns were declining from 1965 to 1980 (Manatsa et al., 2008). The prediction of South Asian summer monsoon precipitation shows an increasing trend based on the multi-model ensemble technique (Kripalani et al., 2007). The interannual and short-term climate variability over the Southeast Asian region were investigated and understood using seasonal and annual rainfall data from 135 stations over durations ranging from 25 to 125 years (Kripalani & Kulkarni, 1997). A total of 135 years of monthly data (1871–2005) for 30 Indian sub-divisions (sub-regions) were used to examine rainfall trends on a monthly, seasonal and annual scale. Current studies (Hwakins, 1980; Monirul Qader Mirza, 2002; Shrestha et al., 2000) indicate that although the frequency of rainy days and annual rainfall have decreased in many parts of Asia, the occurrence of more intense rainfall events has increased. Rainfall prediction models can aid in preserving people's lives and property while indirectly supporting the country's economy. Effectively forecasting long-term rainfall and quantification is essential for water resource planning and management (Huang et al., 1998; Serinaldi & Kilsby, 2012; W. Zhang et al., 2018). Long-term rainfall data prediction in meteorology can aid decision-making processes carried out by organizations responsible for catastrophe risk avoidance (Poornima & Pushpalatha, 2019). Rainfall prediction is a challenging endeavour due to the non-linear character of climate processes. In recent years, data-driven (empirical) approaches have surpassed knowledge-driven (physical) approaches in terms of popularity (Ouyang et al., 2016). The effective use of several data-driven models in hydrology has opened new dimensions for the application of deep neural networks for time series analysis. Box and Jenkins proposed the autoregressive integrated moving average model (ARIMA), generally known as the Box–Jenkins model, for time-series forecasting (Box, G. E. P., & Jenkins, 1976). The Autoregressive model, Autoregressive Moving Average (ARMA), and Autoregressive Integrated Moving Average (ARIMA) models have all been extensively used in hydrological forecasting (Ayuba et al., 2018). ARIMA is an enlarged form of the ARMA model, and it is one of the most effective models with a long history of use (Bari et al., 2015; Rahman et al., 2017; Wanders et al., 2017). Sequential modelling was employed to forecast monthly precipitation in India and demonstrate that a deep learning network can be used successfully for time series analysis in the realm of hydrology and related fields (Kumar et al., 2019). A comparative study using machine learning techniques has been used to build models for rainfall prediction (Oswal, 2019). A comparative study of various statistical and deep learning techniques were carried out to forecast long-term pollution trends in Kolkata and it was discovered that statistical methods such as auto-regressive (AR), seasonal auto-regressive integrated moving average (SARIMA), and Holt-Winters outperformed the deep learning methods (Nath et al., 2021). The rainfall intensity of Coonoor in the Nilgiri district of Tamil Nadu was predicted using regression techniques and other statistical models. The regression techniques employed for prediction were Support Vector Regression (SVR), Random Forest (RF), and Decision Tree (DT), demonstrating that Random Forest is the best regression strategy for rainfall prediction (Tharun et al., 2018). A comparison of ANFIS, ARIMA, and the proposed fuzzy-based curve fitting for weather forecasting was conducted using SSE, R^2, RMSE, and MAE, revealing that the curve fitting based on fuzzy logic outperforms ANFIS and ARIMA (Srikanth et al., 2016). Statistical downscaling local polynomial regression was used to derive future rainfall estimates in the catchment of the Idukky reservoir in Kerala, India (George et al., 2016). The rainfall in the city of Bengaluru, India, was forecasted using seasonal Naive, triple exponential smoothing and seasonal ARIMA time series models where many scale dependent error predictions methods and inferential analysis were used to assess the accuracy of forecasts from these time series models and the results suggest that the seasonal autoregressive moving average model delivers more accurate results (Joshi & Tyagi, 2021). A comparison of four different machine learning algorithms (K-Nearest Neighbor, Logistic Regression, Random Forest Classifier, and Support Vector Machine) in solar flare forecasting shows that Logistic Regression and Support Vector Machine algorithms perform exceptionally well in forecasting active region flaring potential (Sinha et al., 2021). Recent studies have utilised non-linear models, including artificial neural networks (ANNs) and classification and regression trees (CART), to predict precipitation in various climate conditions (Bhattacharya & Bhattacharyya, 2023; Choubin et al., 2018; Litta et al., 2013). Forecasting rainfall directly impacts the security and economic stability in any region, which is typically a complex phenomenon. Indian cities like Kolkata, one of the country's largest cities, have more than 80 percent built-up area (Alam & Majumder, 2022). Due to the extensive coverage of the built-up area of the Kolkata Municipal Corporation (KMC), the city frequently faces a water crisis during non-monsoon periods, while it is prone to urban floods during the monsoon season. Hence, the management of rainwater in a sustainable way should be a major focus of research in this area. Rainwater harvesting may serve as an alternative method to reduce urban floods and, at the same time, maintain the water supply to create favourable conditions to meet the water demand of the city. Therefore, in order to invest for rainwater harvesting or any other sustainable planning to meet the water demand of KMC, rainfall forecasting is of utmost importance. Though many works have been done on rainfall forecasting but there is a lack of studies in comparative analysis of various degree of polynomial curve and ARIMA to find the best fit model in the study area to better forecast the rainfall. Therefore, this study also aims to identify the optimal model by evaluating the root mean square error (RMSE) and examining the relationship between the coefficient of determination (R^2) and RMSE in identifying the best fit model. The focus of this study is to determine the optimum model for forecasting rainfall using different techniques like the auto-regressive integrated moving average (ARIMA) and other statistical regression techniques. In this study, a comparative analysis of ARIMA and other statistical techniques, such as different degrees of polynomials, has been used in Rainfall Prediction in Kolkata (KMC), West Bengal. For this purpose, 120 years of monthly and annual rainfall data of IMD (Indian Meteorological Department) from 1901 to 2020 of Kolkata has been retrieved from the Indian water portal ‘Water Resource Information System’ (WRIS) and tries to forecasting rainfall using ARIMA, and different degree of Polynomial regression for identification of the best model. This study aims to determine the rainfall trend, variability, and forecasting in Kolkata, a highly urbanized district in West Bengal, as well as in India. The monthly and yearly patterns of rainfall, as well as their variability in different periods and annual forecasting, have been analysed. This incorporates comprehension of the region's rainfall patterns, their variability, and the optimal model for forecasting. The realisation of the uncertainties, patterns, and best forecasting associated with rainfall would provide a database for improved water demand management.

3.2. Materials and Methods:

Monthly rainfall statistics have been retrieved for 120 years from 1901 to 2020 for Kolkata Municipal Corporation (KMC) from a web-based spatial data portal, the Water Resource Information System of India (India Water Resources Information System, 2016), for water-related data dissemination. The rainfall data, which has been used in this study, is IMD grid data of Kolkata. The monthly rainfall data have been combined to total rainfall at periodic and yearly scales for the analysis of trend, its variability, and forecasting with the best fit model. In this study, the long-term rainfall data have been used to analyze their trend and variability with the help of different statistical techniques using Python and MS Excel. To determine the trend of annual rainfall and its magnitude, a non-parametric Mann-Kendall test and Sen's slope estimator were applied. In this analysis, Python (version 10.3), a high-level, general-purpose programming language, has been used to measure the trend with Mann-Kendall test and calculate Sen's Slope. The time series rainfall data has been analysed monthly and annually. Mean, Standard deviation, and coefficient of variation have been used to detect rainfall variability in the study area. Finally, the various graphical methods have been used in this study. On the other, several statistical approaches have been used to study rainfall forecasting, including Autoregressive Integrated Moving Average Method (ARIMA) using Python linear (Ordinary Least Squares Method) and polynomial regression in MS Excel. Finally, to find the best-fit model, the Root Mean Square Error (RMSE) has been calculated using observed and forecasted rainfall data from 2001 to 2020. The methodological framework of the study is shown in Figure 3.1. The process of forming assumptions about the future values of investigated variables is known as forecasting (Box, G. E. P., & Jenkins, 1976). The serial correlation effect has been checked, as it plays a vital role in assessing and ultimately reducing the uncertainty of rainfall forecasting, before being examined in detail.

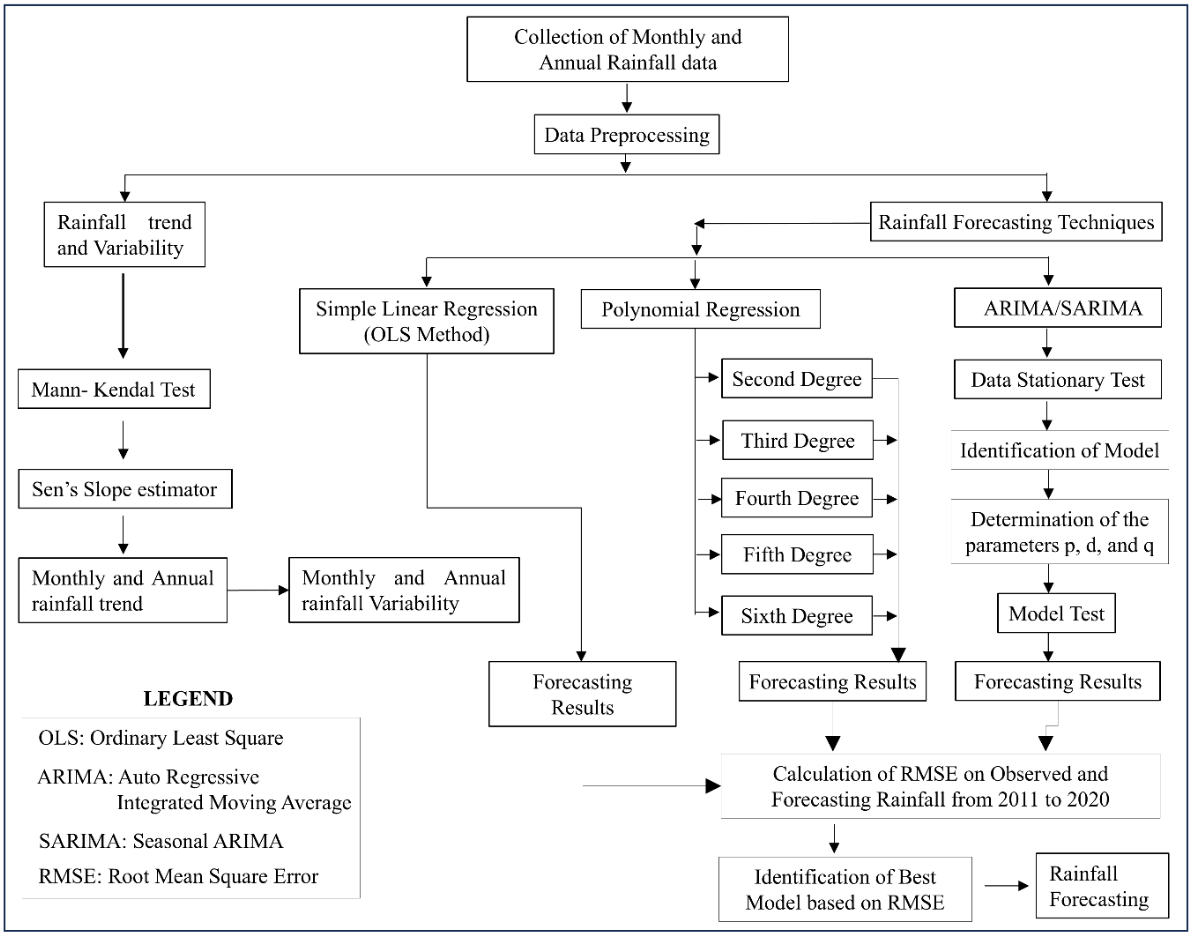

Figure 3.1: Methodological flow chart of the study of rainfall trend, its variability and forecasting with the best fit model.

3.2.1. Trend Analysis:

The trend is characterized as the overall development of an arrangement over an extended period. It is the needy component's drawn-out shift over a considerable period (Hwakins, 1980). Factual trends attempt to predict future developments of a specific variable by analyzing historical patterns. The original Mann-Kendall test has been employed to determine whether there is a significant trend in 120 years of rainfall data over the research area, and Sen's slope estimator was utilised to assess the magnitude of the trend in the current analysis. For a long time, the settled trend tests, such as the Original Mann-Kendall, have been used to classify global precipitation shifts.

3.2.1.1. Mann-Kendall (M-K) Test:

The Mann-Kendall test is a non-parametric statistical tool commonly used in the analysis of trends in climate and hydrological time series data. In the field of environmental chronology, this test was widely adopted (Kendall, 1975; Mann, 1945). This test has the advantage of being a non-parametric test that does not necessitate the series data to be uniformly spread. It is also worth mentioning that the test lacks sensitivity to sudden breaks in time sequence. The rainfall data are independent and randomly ordered; therefore, according to the null hypothesis, H_0 shows no pattern, while the alternative hypothesis, H1, indicates a trend (increasing or decreasing). The Mann-Kendall test does not make any assumptions about normalcy and reveals the direction, not the magnitude of significant trends. (Mann, 1945). For a given data set Xi = x1, x2…, xn, the Mann–Kendall assessment statistic S is computed as follows:

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} \mathrm{sign}(x_j - x_i) \qquad \text{(I)}$$

Where x_j and x_i denote yearly rainfall amounts in years, with j higher than i, and n the number of years. The following formula is used to find the value of sign (x_j - x_i):

$$\mathrm{sign}(x_i - x_j) = \begin{cases} -1 & \text{if} \quad (x_j - x_i) < 0 \\ 0 & \text{if} \quad (x_j - x_i) = 0 \\ 1 & \text{if} \quad (x_j - x_i) > 0 \end{cases} \qquad \text{(II)}$$

This statistic represents the sum of the positive and negative differences for all evaluated variances. The test is carried out with a standard estimation (Z statistics) for large samples (N>10), with the mean and variance as follows:

$$S \text{ has an average of } E[S] = 0 \tag{III}$$

The following equation is used to determine the variance of S:

$$\mathrm{Var}(S) = \frac{n(n-1)(2n+5) - \sum_{k=1}^{m} t_k(k)(k-1)(2k+5)}{18} \tag{IV}$$

Where n is the number of years, m is the number of tied groups in the rainfall data sets, and t_k is the number of the k_{th} tied group's data points. To detect a significant trend, standardised test statistics, Z, are used. The values of S and VAR(s) are utilised to measure test statistics Z, which is as follows:

$$Z = \begin{cases} \frac{S-1}{\sqrt{\mathrm{Var}(S)}} & \text{if } S > 0 \\ 0 & \text{if } S = 0 \\ \frac{S+1}{\sqrt{\mathrm{Var}(S)}} & \text{if } S < 0 \end{cases} \tag{V}$$

This particular test has been determined with the function *mk.original_test (df)* by importing pymannkendall library in Python. The Z-value is used to determine whether a trend is statistically significant. A positive Z number denotes an upward trend, while a negative value denotes a downward trend. The statistically significant trend test is commenced at a specified significance level α. When $|Z| > Z_{1-\frac{\alpha}{2}}$ Reject the null hypothesis, and the time series shows a significant trend.

3.2.1.3. Sen's Slope Estimator:

A non-parametric approach to compute the rate or the degree of inclination in the time series data was developed. In this method, the slope β_i, is determined as the following equation from all data sets:

$$\beta_i = \frac{x_j - x_k}{J - k} \qquad \text{for } k = 1,2,3, \ldots, N \tag{VI}$$

Where x_j and x_k are the respective data values at the time of j and k (j>k). There would be the same number as N = n(n-1)/2 slope estimates β_i if there are n values x_j in the time series. The median of these N estimates of β_i is Sen's evaluator of slant. β_i's N estimates are positioned from the smallest to the largest, and Sen's slope estimator is determined as follows:

$$\beta\mathrm{med} = \begin{cases} \beta_{i\left(\frac{N+1}{2}\right)} & \text{When N is odd} \\ \frac{1}{2}\,\{\beta i._{\frac{N}{2}} + \ \beta i(N+2)/2\} & \text{When N is even} \end{cases} \tag{VII}$$

The Sen's estimator is measured as βmed =βi (N+1)/2 if N is odd and βmed= [βi N/2+ βi (N+2)]/2 if N is even. In the end, βmed is measured at a 100 (1-α) percent confidence interval by a two-tailed test, and then the non-parametric assessment will achieve an actual slope. In the time series a positive value of β_i denotes an upward or progressive trend, whereas the negative value of β_i suggests a downward or regressive trend. This approach has been used to measure the factual slope of a current trend such as the sum of change per year, and the test was carried out in this study using the Python 3.10 version.

3.2.1.4. Autocorrelation Effect:

In a normal Mann-Kendall test, it is assumed that the recorded dataset is serially independent. However, some substantial autocorrelation coefficients may occur in the time series data and hence it is required to test autocorrelation while examining a series of historical data. To test autocorrelation, the Durbin-Watson (DW) statistic has been applied by using the function durbin_watson (model.resid), which has been imported from the statsmodels library in python to determine whether the residuals of the regression model are autocorrelated or not. The following formula has been used to obtain the Durbin-Watson test statistic:

$$d = \sum_{t=2}^{T} \left((e_t - e_{t-1})^2\right) / \sum_{t=1}^{T} e_t^2 \qquad \text{(VIII)}$$

where, *T* is the total number of observations. The value of the test statistic is approximately equal to 2(1-r), where r is the sample autocorrelation of the residuals. The Durbin-Watson statistic will always fall within the range of 0 to 4. The values between zero and less than two indicate positive autocorrelation. In contrast, values between two and four indicate negative autocorrelation, with a value of 2.0 denoting the absence of any such correlation in the sample. If the data is autocorrelated, the modified M-K test must be used to detect the trend instead of the original Mann-Kendall test.

3.2.2. Rainfall Forecasting and Model Selection:

This study examines and contrasts various forecasting methodologies, including the Autoregressive Integrated Moving Average (ARIMA) model and several regression models (linear and polynomial, ranging from second to sixth degree), to determine the most effective approach for predicting rainfall in the Kolkata Municipal Corporation (KMC) region. The models were evaluated using historical rainfall data from 2001 to 2020, with a focus on their performance as measured by the Root Mean Square Error (RMSE). The primary objective is to identify the optimal model that integrates statistical validity with forecasting precision, hence enhancing the reliability of rainfall prediction methods for urban water resource management.

3.2.2.1. The Auto-Regressive Integrated Moving Average (ARIMA):

Autoregressive Integrated Moving Average (ARIMA) or Box-Jenkins have been extensively used as forecasting techniques. The autocorrelation function (ACF) and partial autocorrelation function (PACF) of the sample data were proposed as the main tools for determining the ARIMA model's order (Box, G. E. P., & Jenkins, 1976). The model is expressed as ARIMA (p, d, q), where p represents the order of the auto regressive process, d represents the order of the stationary data and q represents the order of the moving average process (P. G. Zhang, 2003). The ARIMA model is implemented in the following steps (Box, George E. P.; Jenkins, Gwilym M.; Reinsel, 1994).

(i) Identification of Model:

When time series data are stationary, the ARIMA model is useful. The first step is to determine whether the time series data is stationary or not before proceeding further. Before forecasting with ARIMA, it is necessary to make the time series stationary if it has a trend or seasonality component.

(ii) Identification of PACF and ACF parameters:

To use the ARIMA model, it is necessary first to identify the value of d (for stationary data), the number of residual lag values (q), and the dependent lag value (p). The key tools for detecting q and p, as well as correlation, are ACF (autocorrelation function) and PACF (Partial autocorrelation function), which display the plots of ACF and PACF values for various lag. The partial autocorrelation coefficient measures the similarity between Xt and Xt-k, whereas the lag effect times 1, 2, 3…, k-1 are assumed to be constant.

(iii) Build the optimal ARIMA Model:

There can be different ARIMA models based on the outcomes of the stationary detection and the determination of ACF and PACF. Hence, the auto-regressive parameters are determined. To identify the best order of the model in this analysis, the auto_ARIMA function has been used, which automatically gives the optimum order for this model. In Python, the auto_ARIMA function finds the best order for the model's parameters by employing a quick maximum likelihood estimation approach and a stepwise search based on minimum AIC (Akaike

Information Criteria). The AIC is a fine-tuned technique for estimating the likelihood of a model to predict future values based on in-sample fit (Akaike, 1974). The best order of the model is the one that produces the lowest AIC among all the other orders.

(iv) Forecasting:

After obtaining the optimal model, forecasting for the subsequent period is possible. Forecasting using this method is frequently more efficient than forecasting using other time series methods.

(V) Residual Diagnostics to check the Model:

In a time-series analysis every observation may be predicted using all prior observations, which are referred to as fitted values and the residuals are that which is deviated over after a model has been fitted. The linear regression hypothesis is tested using residual analysis, which determines if the error follows a normal distribution. The standardized residual graph, normal Q-Q plot and Histogram plus estimate density have been plotted in this study to check the white noise of the residuals.

(a) Standardized Residual Graph:

The standardized residuals are calculated by dividing the raw residuals by the overall standard deviation of the raw residuals which produces a consistent measure of prediction error. It is a metric that indicates how strong the gap between observed and predicted values is. This plot clarifies that the residuals are dispersed in a random fashion and the residuals can be demonstrated to be independent if the sequence does not display patterns like trend or periodicity.

(b) Normal Q-Q Plot:

Normal Q-Q (quantile-quantile) plots are extremely useful for graphically analysing and comparing two probability distributions by plotting their quantiles against one another. It is useful to verify the assumption that the dependent variable is normally distributed or not. If it is not normally distributed, then it is required to explain how the assumption is broken and what data points are involved. If the points on the graph are nearer to a 45-degree straight line, the usual assumptions about allocation are met. The normal odds graph has been utilised in this investigation to see if the residuals satisfy the normal distribution assumption or not.

(c) Histogram plus estimated density (Kernel Density Estimators):

The histogram, along with estimated density, has been used to assess whether the residuals are normal or not, depending on the interval values employed to categorise the data. A density plot is a continuous, smoothed form of a histogram derived from data. Kernel density estimation (KDE), the most frequent technique of estimation, has been used in this work.

3.2.2.2. Linear and Polynomial Regression:

Regression analysis is a type of predictive modelling that is commonly used for forecasting, time series modelling and determining causal relationships between variables. In this work, a 'least squares' method has been utilised to find the best-fit line to estimate rainfall using a linear regression model, which is expressed as follows:

$$\mathrm{y = a + bx} \tag{IX}$$

where, y represents estimated rainfall, 'a' represents intercept and 'b' represent slope which is coefficient of x.

In this study polynomial regression have been applied to forecast the rainfall. In this study, the rainfall is treated as a dependent variable y, which is modelled as an nth degree polynomial of x, where time is treated as an independent variable x. When the pattern of rainfall trend is linear, the simple linear regression procedure works. However, if the data is non-linear, linear regression will not be able to create a best-fit line and will fail in such cases, hence polynomial regression has been applied in this study.

3.2.2.3. Model Validation with RMSE (Root Mean Squared Error):

Lastly, to validate the above models, compare the predicted values to the actuals and calculate the root mean squared error to find out the best fit model for forecasting the rainfall.

The square root of Mean Squared Error (MSE) is RMSE, which measures the absolute fit of the prediction model to the data. As a result, the model's projected values are compared to the observed data points to determine how accurate the model is. So, the RMSE is the average prediction error, which is expressed as follows:

$$\mathrm{RMSE} = \sqrt{\frac{\sum_{i=1}^{N} (x_i - \hat{x}_i)^2}{N}} \tag{X}$$

Where, RMSE is Root Mean Square Error, N is the number of data points, i is the ith variable, x_i is the actual rainfall and $\hat{x}_i$ is the forecast rainfall.

3.3. Results and Discussions:

The outcomes of this chapter are structured to demonstrate the historical trend analysis of rainfall along with the comparative assessment of forecasting models. The analysis begins with an assessment of the temporal trends in annual and monthly rainfall over a 120-year period (1901–2020). This is accomplished through the application of statistical methods, including the Mann-Kendall trend test and Sen's slope estimator, which provide valuable insights into the direction and magnitude of changes in rainfall patterns. Box and whisker plots illustrate the monthly variability and seasonal dispersion, emphasising key periods of rainfall fluctuation. The discussion thereafter transitions to the assessment of rainfall forecasting models, wherein the efficacy of ARIMA and multiple polynomial regression models is scrutinised through Root Mean Square Error (RMSE) as the primary indicator. This comprehensive analysis highlights the evolving rainfall patterns in the study area (KMC) and determines the most effective forecasting method, thereby facilitating enhanced planning for the sustainable management of water.

3.3.1. Annual Rainfall Trend Analysis:

In this study of 120 years of annual rainfall analysis, the highest rainfall has been found in 1962 (3588.19 mm), and the lowest annual rainfall was recorded in 2012 (385.33 mm) from 1901 to 2020. The mean annual rainfall and standard deviation for 120 years are 1591.86 mm and 390.371 mm, respectively.

3.3.1.1 Autocorrelation Check:

The Durbin-Watson (D-W) statistic has been used to examine the autocorrelation effect over 120 years of annual rainfall using python. This test yielded a value of 2.00, demonstrating that the data series are serially independent and therefore performing the original M-K test seem to have no bias on the trend analysis results.

3.3.1.2. Mann-Kendall test (M-K):

The annual rainfall trends have been obtained using the non-parametric ordinary M-K test. To assess the presence or absence of a trend at a 5% level of significance, the M-K test was performed using Python (version 3.10). The results of this test from 1901 to 2020 are presented below in Table 3.a.

Table 3.a: Result of Mann-Kendall trend test in Python 3.10

Mann-Kendall trend test Result	
Trend	Increasing
h	TRUE
P	0.00577
Z	2.76044
Kendall’s Tau	0.17058
S	1218
var (s)	194366.6667
Alpha (α)	0.05

The M-K assessment displayed that Kendall's tau is 0.17058 and the p-value is 0.00577 at 5 % significance level. In this study, the rainfall trend has been analysed over time period from 1901 to 2020. Kendall's tau, which ranges from 0 to 1 (0 represents no relationship and 1 represents perfect relationship), measures the non-parametric relationship between the columns of ranked data shows that there is a trend of total annual rainfall during the years from 1901 to 2020. Here, the derived p-value is less than the level of significance alpha = 0.050, indicating that the null hypothesis H_0 is rejected and the alternative hypothesis Ha is accepted. This also suggests a trend in rainfall during testing, which is supported by the test results. The results also show that the Z value is 2.76044, confirming an increasing annual rainfall trend over time.

3.3.1.3. Sen’s Slope Estimator:

The Sen's slope estimator has been adapted to compute the magnitudes of the trends for the yearly rainfall series in the study area from 1901 to 2021. The Sen's slope estimate (Table 3.b) shows a marginally increasing trend in annual rainfall over the area under study, with a Sen's slope of 2.4807. The Sen's slope of 2.48 implies that the rainfall is increasing at a rate of 2.48 millimetres annually. Figure 3.2 shows the Theil-Sen Regression line, plotted in red, with a 95% confidence interval shown in a dotted line.

Table 3.b: Sen's Slope Estimation

	Sen's Slope Estimation Results
Intercept	1396.12447
Slope	2.48152

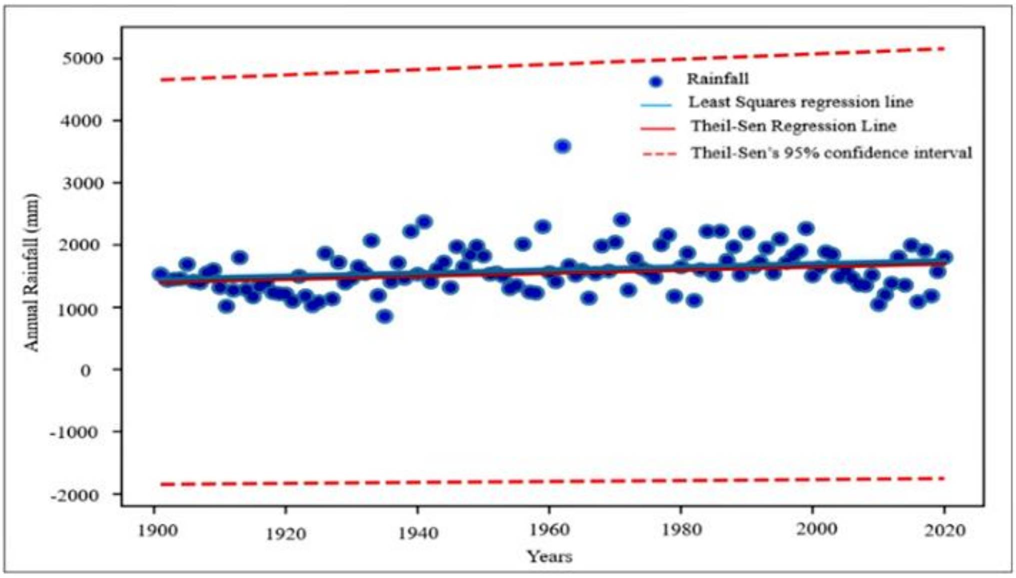

Figure 3.2: Trend of Annual Precipitation total from 1901 to 2020 with Sen's slope Estimation using Python.

3.3.2. Monthly Rainfall Trend Analysis:

The trend of monthly rainfall over 120 years is obtained by linear regression, as illustrated in Figure 3.3. In this section, the month-wise rainfall trend has been plotted using linear regression over the entire time series data. From the analysis, it has been found that rainfall increased in the month from May to December, while it decreased over the months of January to April. In October highest increasing trend of rainfall is observed at the rate of 0.5537 millimetres per year, while a declining trend is detected in February by a maximum of 0.1118 mm per year (Figure 3.3). From monthly rainfall trend analysis, it is observed that during June, i.e., the initial month of monsoon, the amount of rainfall is slightly increasing at a rate of 0.1306 mm per year (Figure 3.3). It is also noted that particularly in the pre-monsoon period except May, there is a negative trend of rainfall over the years which need to take as a great concern by the planners because the issue of water shortage also happened in this period.

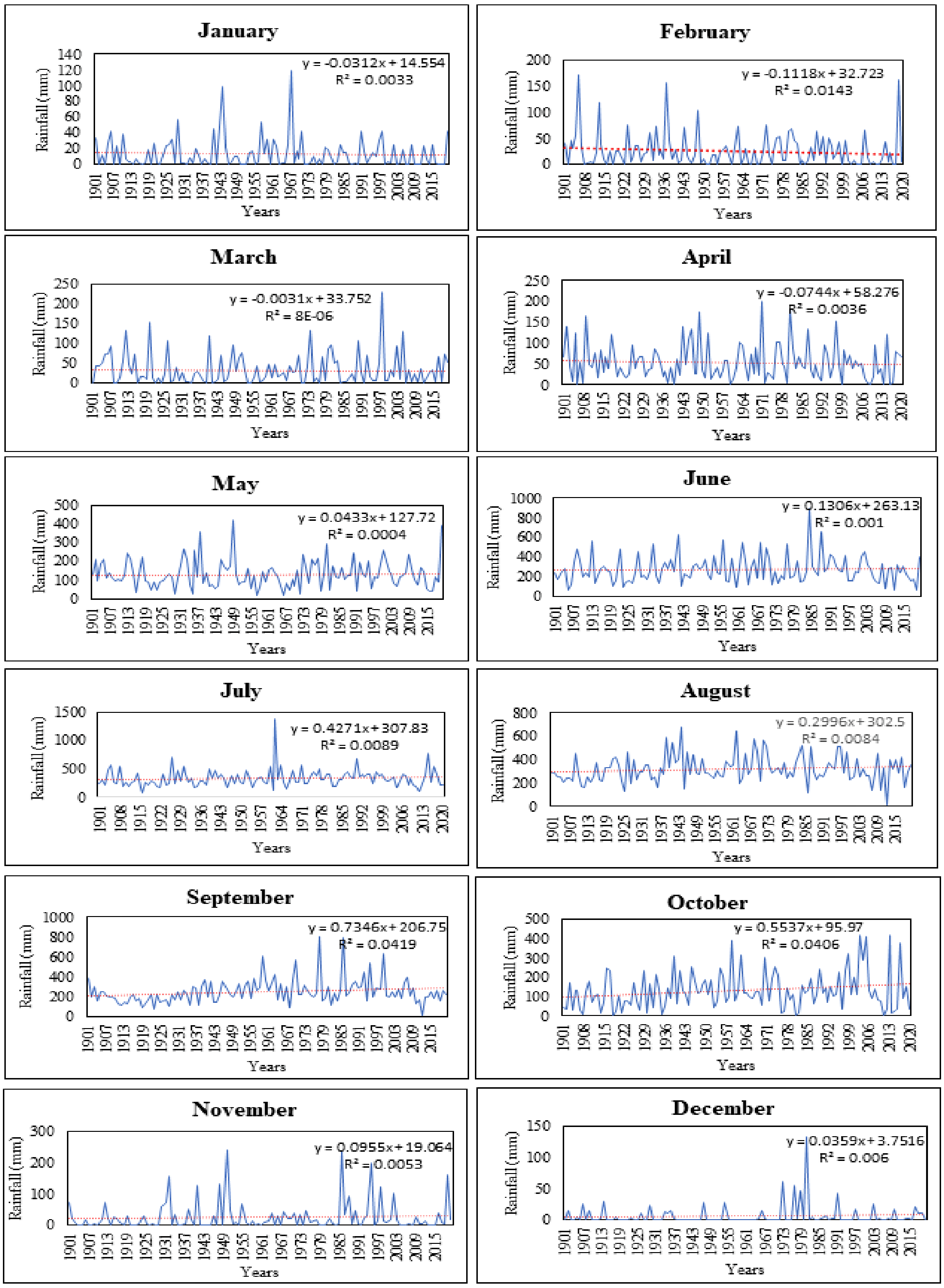

Figure 3.3: Monthly Rainfall totals with trend line during the years from 1901 to 2020.

It is crucial to analyse monthly rainfall trends and their unpredictability as it helps decision-makers to manage urban water resources in a sustainable way.

3.3.3. Annual Rainfall Variability:

Exploring rainfall variability is an essential parameter for researchers and decision-makers in their decision-making processes related to water conservation and solving water-related problems.

Table 3.c: Phase-wise (fourth phase) temporal change of variability of annual rainfall over 120 years from 1901 to 2020

Years	1901-1930	1931-1960	1961-1990	1991-2020
Mean annual rainfall (millimetres)	1373.94	1632.83	1773.122	1590.10
Standard Deviation (millimetres)	218.56	345.83	473.61	368.87
Coefficient of Variation (%)	15.91	21.18	26.71	23.20

Here, in Table 3.c., the coefficient of variation has been determined for the analysis of annual rainfall variability. Therefore, the total time periods of 120 years from 1901-2020 have been divided into four phases, each phase comprises 30 years (Table 3.c) of total annual rainfall. In this analysis, it has been detected that the mean annual rainfall increased from the first to the second phase and from the second to the third phase, but declined in the fourth phase compared to the third. It has also been observed that the coefficient of variation has increased from the first to the second and from the second to the third phase, but decreased in the fourth phase as compared to the third phase. So, it can be deciphered that the overall annual rainfall variability has been increasing over the years. Usually, it is seen that the coefficient of variation is lowest in the first phase (1901-1930) with 15.91 % and highest in the third phase in the years 1961-1990 with 26.71 %. This increasing coefficient of variation implies that the inconsistency of temporal precipitation increases and needs more concern about water management in the study region, though the variability has decreased in the last phase.

3.3.4. Monthly Rainfall Variability:

The Box and Whisker plot depicts the monthly variation of 120 years of rainfall from 1901 to 2020. Box and whisker plots have a compact appearance (Tukey, 1977), that allows us to compare many variables next to each other, which can be hard to decipher, to use more comprehensive illustrations, like the bar chart (Banacos, 2011). A middle horizontal line depicts the median, the box's upper and lower horizontal lines depict the interquartile range, and the whisker plot shows the range value.

Table 3.d: Statistical characteristics of Monthly Rainfall Variability and analysis table for Box and Whisker Plot.

Months	**Minimum (mm)**	**Quartile 1 (mm)**	**Median (mm)**	**Quartile 3 (mm)**	**Maximum (mm)**	**Mean (mm)**	**SD (mm)**	**CV (%)**
January	0.00	0.08	3.04	21.75	118.43	12.67	18.82	148.63
February	0.00	2.99	17.05	35.40	171.80	25.96	32.40	124.81
March	0.00	4.33	18.62	48.19	229.95	33.56	39.18	116.75
April	0.00	21.84	43.37	73.04	199.71	53.78	43.10	80.14
May	17.13	82.17	119.36	167.05	416.99	130.35	73.41	56.32
June	54.79	171.55	249.66	330.89	898.01	271.03	139.63	51.52
July	86.00	239.77	312.79	395.46	1381.09	333.67	156.43	46.88
August	22.10	250.73	298.55	380.62	681.37	320.62	113.44	35.38
September	13.83	176.39	223.73	298.28	812.08	251.19	124.32	49.49
October	0.00	62.87	110.64	177.66	418.16	129.47	95.16	73.50
November	0.00	0.00	6.95	27.60	240.67	24.84	45.52	183.22
December	0.00	0.00	0.00	2.21	132.19	5.92	16.05	270.96

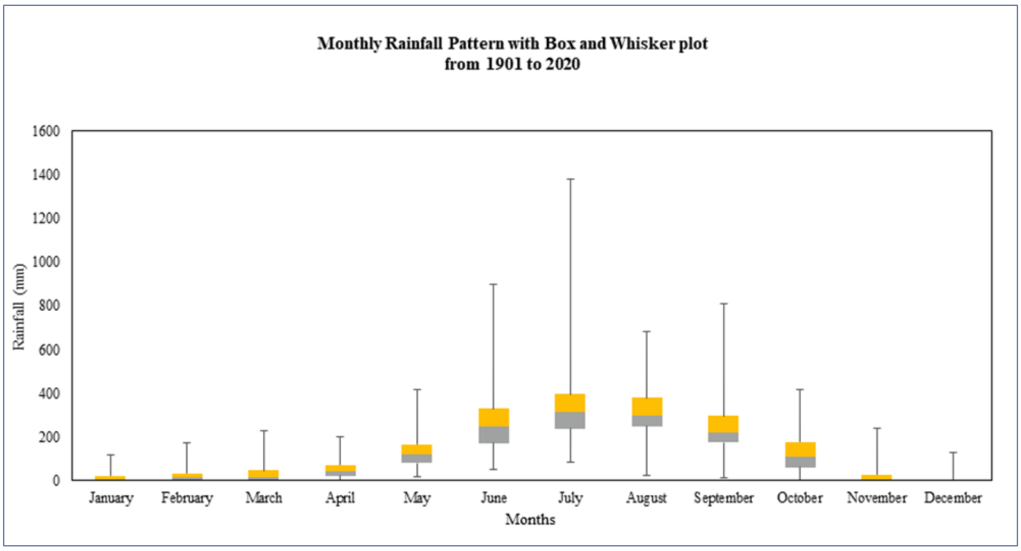

Figure 3.4: Monthly Rainfall Pattern with Box and Whisker plot from 1901 to 2020.

Box and Whisker plot are a common approach to depict the distribution of data based on a five-number summary. The minimum, first quartile, median, third quartile and maximum make up the five-number summary. The middle line of the box represents the median value of the dataset, and each box has lines extending from it to capture the range of the remaining data. Half of the values of the box is higher than the median, while the other half are lower. The above figure (Figure 3.4) illustrates that July has the highest median monthly rainfall, while December has the lowest. The length of each whisker in the above figure is a measure of the dataset's outer range, just as the extent of the interquartile range (as represented with the box in figure 3.4) is quintessential of the dataset's centre half's relative dispersion (10th to 25th percentile and 75th to 90th percentile). The above figure shows that the higher dispersion in the middle half of the datasets is in the monsoon period. The whisker depicts how markedly different the extremes are from the remainder of the dataset. Significant dispersion of relative outliers has been observed in this analysis, with the highest extreme values occurring in June, July, and September. This scenario is evident from the box and whisker plots (Figure 3.4), which show that the datasets are not customarily detailed. The analysis shows that the area's rainfall is decidedly capricious, which increases over time.

The analysis of the long-term rainfall trend and its variability will be supportive to examine the viability of rain harvesting implementation. For instance, there will be less demand for storage in an area, where rain falls throughout the years, which will lower the cost of the system. On the other hand, the cost of the system will be significant when rain falls during short-term periods of high intensity. In this approach, research on rainfall trends and in particular on variability is essential to estimate the rainfall storage capacity, which eventually helps to address the water crisis.

3.3.5. Rainfall Forecasting with ARIMA Model:

In this study, the ARIMA model has been implemented in Python language and used to forecast rainfall. To achieve the best results, the basic parameters of this model p, d, and q has been determined, which are dependent on the nature of the time series data. To determine the best order for this model, import the *auto_arima* package from the *pmdarima.arima* library and use the *stepwise_model.aic* function, which finds the optimum order for the model automatically as shown in the following (Table 3.e):

Table 3.e: Identification of the optimum order for the best model of ARIMA using python

Identifying the order of ARIMA model with performing a stepwise search to minimize AIC		
Model	Order	AIC
ARIMA	ARIMA (2,1,2)	1763.918
	ARIMA (0,1,0)	1838.171
	ARIMA (1,1,0)	1794.501
	ARIMA (0,1,0)	1836.175
	ARIMA (1,1,1)	1760.029
	ARIMA (0,1,2)	1760.155
	ARIMA (1,1,2)	1762.026
	ARIMA (0,1,1)	**1757.651**
	ARIMA (1,1,2)	1760.055

The above results (Table 3.e) shows that the optimum order for the best model is 0, 1, 1 for the parameters of p, d and q respectively, which has the lowest AIC that is 1757.65 among the other orders. It has been then used as the order of the model with the function of stats ARIMA (df, order = (0,1,1) to get best results of the model. After determining the best model to forecast rainfall, it is necessary to validate the results. Therefore, the data has been divided into training data from 1901-2000 and test data from 2001-2020. After that, it produces the predicted annual rainfall for the above-mentioned 20-year periods, which is shown in the following table (Table 3.f), and then plots the actual and forecasted annual rainfall, which is shown in the following (Figure 3.5):

Table 3.f: Forecasted annual rainfall from 2001 to 2020 as computed by the author with the ARIMA model using Python

Years	Annual Rainfall (mm)	Years	Annual Rainfall (mm)	Years	Annual Rainfall (mm)	Years	Annual Rainfall (mm)
2001	1806.57	2006	1762.87	2011	1594.92	2016	1503.62
2002	1751.94	2007	1739.23	2012	1316.87	2017	1450.18
2003	1800.19	2008	1708.44	2013	1515.97	2018	1509
2004	1804.12	2009	1676.96	2014	1427.7	2019	1470.8
2005	1778.07	2010	1661.78	2015	1415.65	2020	1482.85

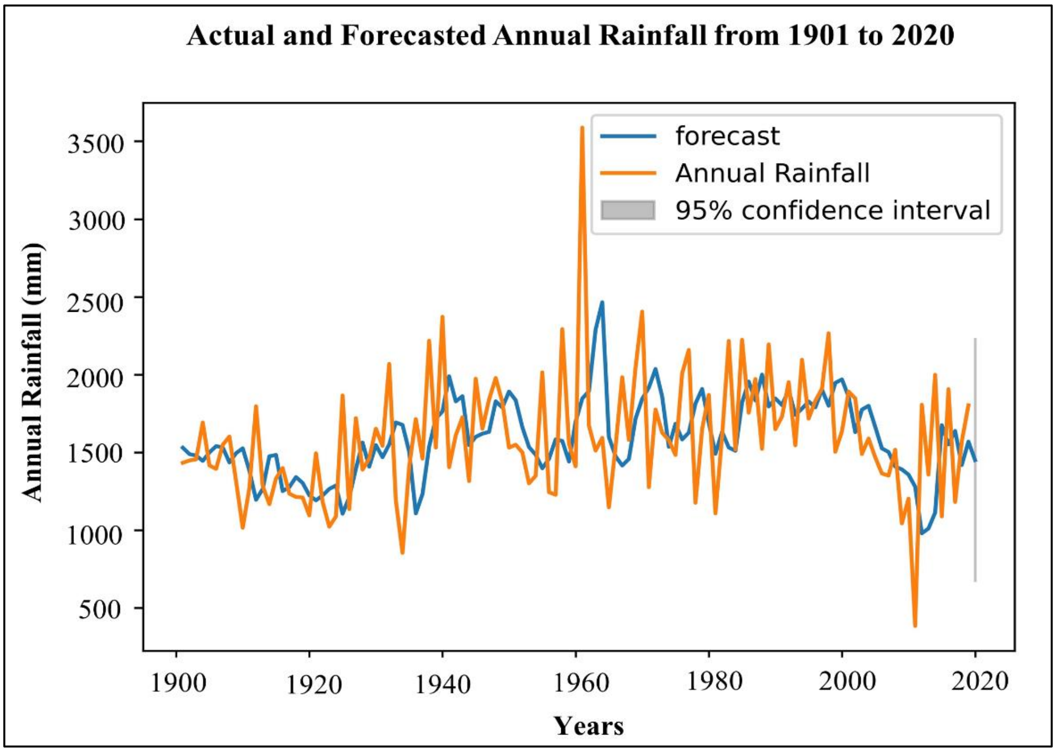

Figure 3.5: Actual and forecasted annual rainfall plotted using Python based on 120 years of annual rainfall (mm) data

The ARIMA model can be used for modelling and forecasting rainfall. To enhance the accuracy of the new model and forecasts, it must constantly update the previous data with new data and validate the results against observed data. This information about forecasting rainfall can be used for urban planning purposes, such as flood management and rainwater conservation, in the research region.

3.3.6. Residual Diagnostics to check the Model:

In this study, the standardized residuals, typical Q-Q plot, and histogram plus estimated density have been plotted to assess the model residual diagnostics, which are shown in the following (Figure 3.6):

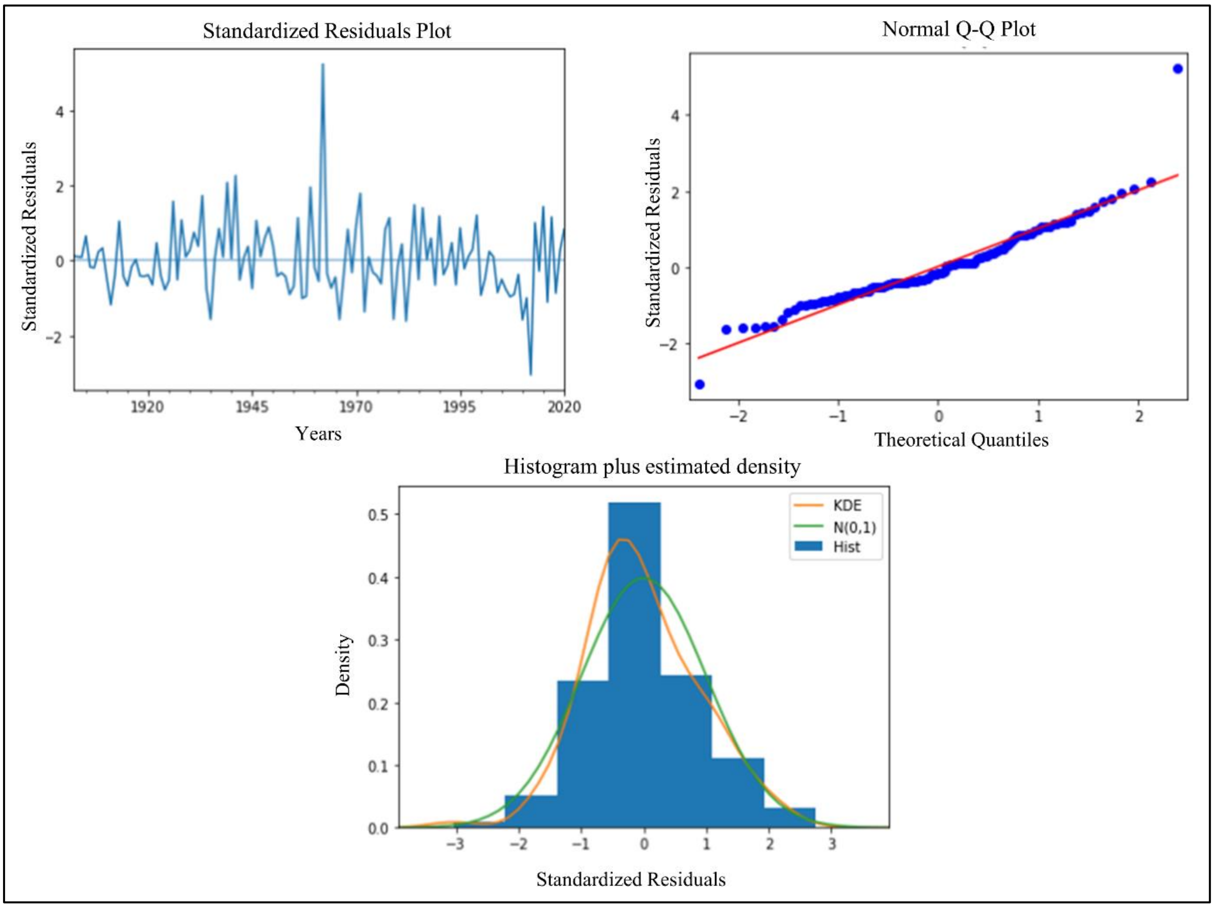

Figure 3.6: Results of Residual Diagnostics plotted using python

The above normalized residual plot reflects that the residuals are independent since they are scattered in a random form, which is a prerequisite assumption for the ARIMA model to forecast the values. Here, the x-axis represents the forecasted value made by the model and the y-axis represents the accuracy of the prediction with standardized residuals. The larger the distance from the zero line reflects the worse prediction while the closer to zero reflects the better prediction. Except for two values for 1962 and 2012, the plot in this model indicates a reasonable prediction because all of the values are between zero and plus or minus two.

The normal Q-Q plot indicates that all of the values with the exception of the first one or two and the last one is just around the 45-degree line, confirming the model's assumption that the data is normally distributed across the years 1901 to 2020.

The histogram plot, along with the estimated density, indicates that the residuals are normally distributed, confirming the model's assumption for predicting rainfall in this study. The normal density plot is shown on the green line, and the Kernel density estimation (KDE) plot is shown on the orange line, where the probability density function is represented on the y-axis.

3.3.7. Linear and Polynomial Regression:

In this study, simple linear regression and second-to-sixth-degree polynomial regressions have been employed (Figure 3.7) to forecast the rainfall to determine the best model for effective forecasting. First, the 20 years of rainfall from 2001 to 2020 have been forecasted on the basis of 100 years of rainfall from 1901 to 2000, applying all of the above-mentioned techniques and then validated with actual rainfall from 2001 to 2020. So, in order to validate or to determine the best regression model, the RMSE between actual rainfall and forecasted rainfall has been calculated with the R-squared value for each of these regression models. The following are the graph of the last 20 years' projected annual rainfall from 2001 to 2020:

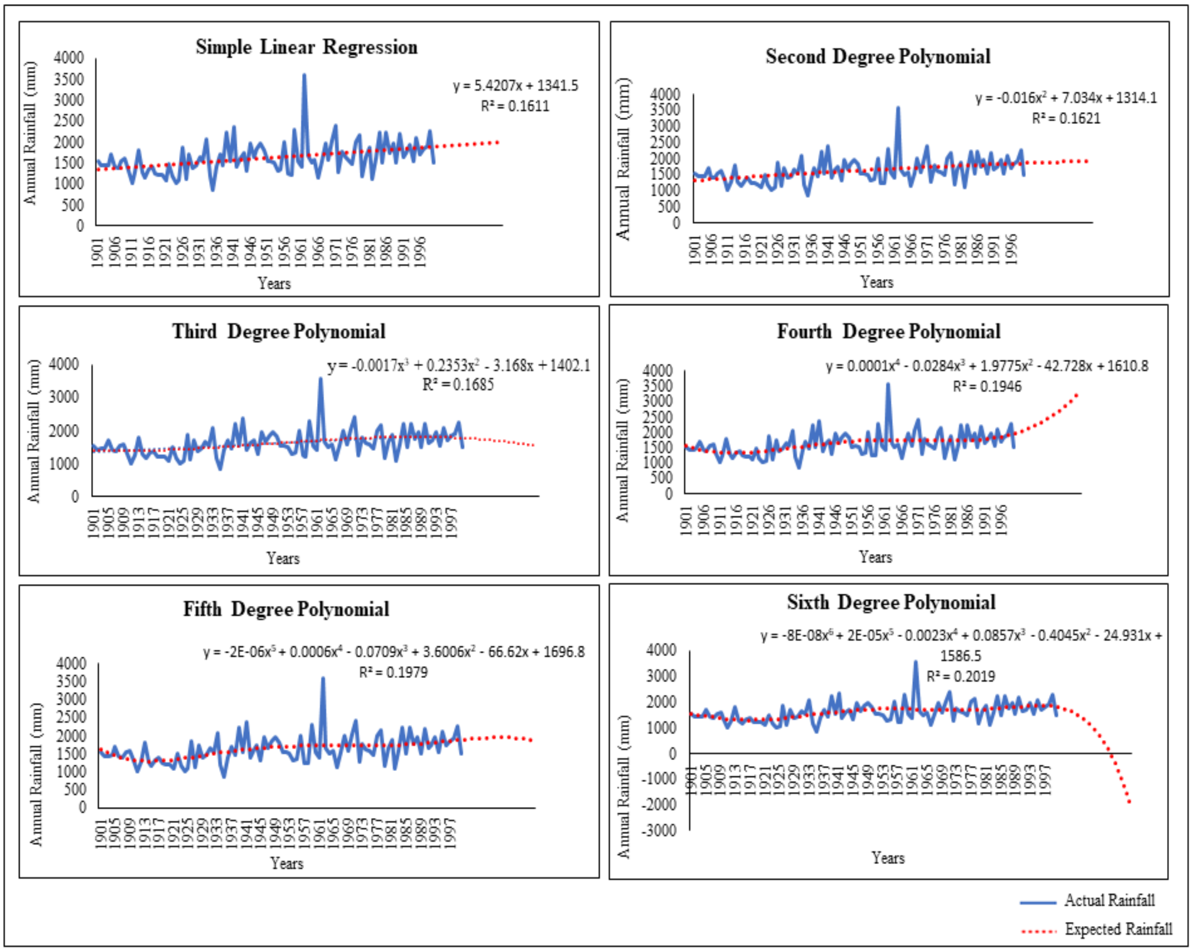

Figure 3.7: Linear and second to sixth degree Polynomial Regression line plotted in Excel

So, based on the above equations, the forecasted annual rainfall over the last 20 years from 2001 to 2020 has been determined for each regression model, which is as follows (Table 3.g):

Table 3.g: Forecasted annual rainfall from 2001 to 2020 as computed by the author in Excel

Years	**Forecasted Annual Rainfall (mm) using various regression techniques**					
	Linear trend	Second Degree Polynomial	Third Degree Polynomial	Fourth Degree Polynomial	Fifth Degree Polynomial	Sixth Degree Polynomial
2001	1346.92	1321.12	1399.17	1570.02	1633.71	1561.25
2002	1352.34	1328.10	1396.69	1533.03	1577.40	1535.67
2003	1357.76	1335.06	1394.67	1499.65	1527.47	1510.20
2004	1363.18	1341.98	1393.08	1469.64	1483.54	1485.22
2005	1368.60	1348.87	1391.93	1443.11	1445.22	1461.07
2006	1374.02	1355.73	1391.20	1419.62	1412.14	1438.03
2007	1379.44	1362.55	1390.87	1399.10	1383.97	1416.36
2008	1384.87	1369.35	1390.94	1381.40	1360.36	1396.26
2009	1390.29	1376.11	1391.41	1366.38	1341.00	1377.88
2010	1395.71	1382.84	1392.25	1353.87	1325.56	1361.36
2011	1401.13	1389.54	1393.46	1343.73	1313.74	1346.79
2012	1406.55	1396.20	1395.03	1335.82	1305.27	1334.21
2013	1411.97	1402.84	1396.95	1329.99	1299.86	1323.67
2014	1417.39	1409.44	1399.20	1326.11	1297.26	1315.14
2015	1422.81	1416.01	1401.79	1324.03	1297.20	1308.60
2016	1428.23	1422.55	1404.69	1323.62	1299.45	1303.98
2017	1433.65	1429.05	1407.89	1324.74	1303.77	1301.18
2018	1439.07	1435.53	1411.40	1327.27	1309.95	1300.11
2019	1444.49	1441.97	1415.19	1331.08	1317.77	1300.62
2020	1449.91	1448.38	1419.26	1336.04	1327.04	1302.56

3.3.8. Identification of Best Model and Forecasting up to 2050:

In this study, the coefficient of determination (R^2) and Root Mean Square Error (RMSE) have been computed and considered to determine the optimum model for forecasting rainfall. The minimum RMSE is found with the fifth-degree polynomial equation, as shown in Table 3.h. among all the regression models. It is important to note that though the R^2 (coefficient of determination) has increased with increasing degree of curvature from the straight line to sixth degree polynomial equation with higher R^2 being 0.2019 at sixth-degree polynomial equation but the lower RMSE is found at the fifth-degree polynomial equation. The value of R^2 for the sixth-degree polynomial is maximum (Table 3.h) to express the degree of explained variance, but the value of RMSE is not the least for the sixth-degree polynomial, which signifies that the sixth-degree polynomial regression is over-fitting the 120 years of dataset. The RMSE for the fifth-degree polynomial is the least (Table 3.h) among all the polynomial equations, indicating that the fifth-degree curve is the best fit for forecasting the data, as it is neither an underfit nor an overfit curve with its datasets. R-squared indicates how well a regression model explains the observed data or how well the data fits the regression model. However, a big value of r-square does not always indicate a good regression model, which is proved in this study, as the quality of the statistical measure is dependent on several factors, including the nature of the variables used in the model, the units of measure used for the variables, and the data transformation used. The lowest RMSE has been found with fifth-degree polynomial regression techniques, which is 364.83, compared to the other techniques or models. The forecasted annual rainfall for 2050, derived from the fifth-degree polynomial equation identified as the optimal model, is 1629.8 mm. Although the ARIMA model has been used in this study and met all the requirements for forecasting rainfall, but did not produce the best results. The r-squared value and RMSE have been shown in the following (Table 3.h).

Table 3.h: Order of ARIMA and Root mean square error with R square of various regression techniques calculated by the author

Trend Line/Model	**Equation/order**	**R^2**	**Root Mean Square Error (RMSE)**
ARIMA	P, d, q (0,1,1)	---	420.95
Linear trend Line	$y = 5.4207x + 1341.5$	0.1611	383.90
Second Degree Polynomial	$y = -0.016x^2 + 7.034x + 1314.1$	0.1621	388.23
Third Degree Polynomial	$y = -0.0017x^3 + 0.2353x^2 - 3.168x + 1402.1$	0.1685	377.75
Fourth Degree Polynomial	$y = 0.0001x^4 - 0.0284x^3 + 1.9775x^2 - 42.728x + 1610.8$	0.1946	367.16
Fifth Degree Polynomial	$y = -2E{-}06x^5 + 0.0006x^4 - 0.0709x^3 + 3.6006x^2 - 66.62x + 1696.8$	0.1979	**364.83**
Sixth Degree Polynomial	$y = -8E{-}08x^6 + 2E{-}05x^5 - 0.0023x^4 + 0.0857x^3 - 0.4045x^2 - 24.931x + 1586.5$	**0.2019**	372

An analysis of the long-term rainfall trend and its variability is a prerequisite to determining the feasibility of rainwater harvesting. In this regard, identifying the most suitable model for forecasting rainfall is necessary. The results obtained through this study's analysis may help planners in the sustainable management of the water resources in the study area. The forecast must provide administrators with significant confidence to develop policies in KMC regarding rainwater harvesting, aiming to reduce urban flooding and manage the city's water resources sustainably. Even the same study can be applied to other cities, where the best forecasting model can be used for water resource management.

3.4. Conclusion:

The chapter examined the yearly and monthly rainfall trends and their variability over 120 years of rainfall data for the Kolkata Municipal Corporation (KMC). The aim was to analyse the temporal patterns of rainfall on an annual and monthly basis, and evaluate the consistency and predictability of rainfall behaviour to guide water resource management techniques in an urban setting. The Mann-Kendall test indicated a statistically significant upward trend in yearly precipitation, with a Kendall's tau of 0.17058 and a Z-value of 2.76. Sen's slope demonstrated an annual increase of 2.48 mm. Monthly trend analysis indicated an increase in rainfall from May to December and a decrease from January to April. Box and whisker plots (Figure 3.4) revealed increased variability and dispersion throughout the monsoon months, especially in June and July. A temporal study across four phases revealed an escalation in annual rainfall variability until the third phase, followed by a reduction in the most recent period. Artificial water storage systems are proposed to overcome rainfall irregularity and alleviate water stress during dry months. The study evaluated ARIMA against linear and polynomial regressions (up to the sixth degree) using root mean squared error (RMSE) for data spanning 2001–2020 from a forecasting perspective. The fifth-degree polynomial regression exhibited the lowest RMSE among all models, signifying the highest predicting precision. Despite the sixth-degree polynomial exhibiting a superior R^2 value, its elevated RMSE rendered it less effective than the fifth-degree model. Although the ARIMA model satisfied its statistical assumptions, it did not surpass polynomial regression in this case.

The findings of this chapter offer significant insights into the changing patterns of rainfall in Kolkata, emphasising both upward trends and seasonal fluctuations. Furthermore, the analysis indicates that fifth-degree polynomial regression provides a reliable and effective method for rainfall forecasting in the region, surpassing ARIMA and other lower-order regression models.

These findings can significantly enhance urban water resource planning, particularly in a city frequently faced with urban flooding and water scarcity.

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CHAPTER 4

ANALYSIS OF LAND USE AND LAND COVER CHANGES

4.1. Introduction:

Land use is a critical aspect for ensuring long–term economic development along with social benefits. The built environment of Kolkata was connected to urbanisation in the prehistoric and medieval periods because of centralized monarchical rule, religious motivation, and commercial behaviours. However, modern urbanisation has experienced a different type of built environment since the Industrial Revolution, notably with the ‘Growth Mania’ following the Second World War and the ‘Hypergrowth Mania’, which was coined by Daly, began in the 1980s (Tan et al., 2010). Urbanization has a significant hydrological influence because it affects runoff and other hydrological properties (Barron et al., 2013; Jacobson, 2011; McGrane, 2016; Redfern et al., 2016; Remondi et al., 2016). Cities all across the world are implementing food water management strategies to mitigate the ecological damage caused by impervious run-off as a result of the population growth (Vizzari et al., 2018). Human demand for land use has increased throughout time. Urbanization is a human-induced process that changes land use and land cover (LULC), as well as the amount and quality of surface and groundwater resources, particularly in peri-urban areas (Maiti & Agrawal, 2005; Mohan et al., 2011). As a result of urbanisation, agriculture, deforestation, and other human activities, the Earth's terrain has been drastically altered, posing numerous challenges (Solomon et al., 2007). The most critical is the growth in concrete surface area, which has a substantial impact on the environment and worsens living circumstances (Yin et al., 2005). An effort has been made to analyse the key urban changes that took place in Kolkata and their effects on the environment and urban water security using geospatial tools during 1990 and 2021 (John et al., 2020; Mukherjee et al., 2018; Parveen & Ilahi, 2022). The combination of human endeavours and environmental conditions results in landuse. On the other hand, land cover is either naturally occurring or the result of changes in land use brought on, particularly, by human activity (Mukhopadhaya, 2016; Reveshty, 2011). The rising population and housing densities are accompanied by shifting societal requirements and priorities (T et al., 2012). Massive land use/land cover (LULC) changes have been accelerated in recent decades by rapid urban growth, resulting in a negative impact on the ecosystem and the environment on a local, regional, national, and international scale (Lambin et al., 2001; Mahmood et al., 2010; Moniruzzam et al., 2018; Rousta et al., 2018, 2020; Weng, 2001). Additionally, this has a variety of effects on urban floods and urban hydrology (Chen et al., 2015; Sanders et al., 2008). Changes in land use and land cover can affect the dynamics of the vegetation, the surface or subsurface aqueous system, and the flow conditions of streams (Graniel et al., 1999; McGrane, 2016). The increase in impervious surface area caused by the changes in land use and cover slows down the rate of infiltration, which reduces groundwater recharge and lowers the water level. Previous studies have demonstrated that anthropogenic activities have a significant impact on urban water quality and quantity as well (Chen et al., 2015; Díaz-Caravantes & Sánchez-Flores, 2011; Tripathi et al., 2019).

The single and primary underlying causes of global land-cover change are not the population or poverty. Changes in land cover are instead influenced by how people react to economic opportunities as mediated by institutional considerations (Lambin et al., 2001). Urbanisation-induced LULC has significantly increased and drawn public attention as a result of today's rapid economic growth and population growth. As a result, pertinent studies have emerged as key areas of research, particularly for future city planning (Chang et al., 2018). Numerous studies have studied the land use and land cover alterations and analyzed how they affected the dynamics of the land surface over various Indian towns (Arunprakash et al., 2017; Khatun & Sivaramakrishnan, 2022; Mondal & Banerjee, 2021; Mukherjee et al., 2018; Naikoo et al., 2020; Nath et al., 2021; Vinayak et al., 2021). Therefore, this study has made an effort to analyse the changes in land use and cover using remote sensing, GIS, and Google Earth Engine from 1990 to 2021.

4.2. What is the necessity of Land Use Land Cover Analysis?

The increasing population and activities have further intensified pressure on the limited land and soil natural resources. The lifestyle of humans has undergone a swift transformation, resulting in the significant conversion of important land resources for agriculture, construction, and other uses, thereby compromising the ability of these resources to support the growing human population. Rapid urbanisation has transformed open land and water bodies into concrete surfaces for various uses, significantly affecting infiltration rates. The land use and land cover of an area have significantly impacted the local environment and economic development. In the contemporary era, humanity has initiated measures for economic advancement through industrialisation, urbanisation, land commercialisation and transportation development. These forces have resulted in significant alterations in land use and land cover, adversely impacting natural resources both locally and globally. The physical environment and economic development are the primary determinants of land use trends in any region. In the current time, the prolonged manmade alterations have drastically modified the Earth's landscape. A large-scale land use change has occurred, resulting in significant impacts on the natural environment and posing threats to landscape stability, land degradation, and geo-diversity (Rockstrom, 2009). Land Use Land Cover (LULC) analysis is crucial for the planning, management, and assessment of initiatives at the local, regional, and national levels. This information enhances comprehension of land use and is crucial for the formulation of policies and programs necessary for development planning. Monitoring land use and land cover patterns over time is essential for ensuring sustainable development. To attain sustainable urban development and to regulate the erratic growth of towns and cities, it is essential for the relevant authorities to create planning models that ensure the most rational and optimal use of every available piece of land. This necessitates the current and historical land use and land cover data for the region. LULC maps facilitate the examination of alterations occurring within our ecosystem and environment. Having detailed information about Land Use/Land Cover within the study unit enables the formulation of effective policies and the initiation of programs aimed at environmental preservation.

4.3. Materials and Methods:

4.3.1. Data used:

The study is mostly based on the analysis of secondary data, which have been collected from numerous sources, including databases available at the official website of Kolkata Municipal Corporation, data on groundwater level, and census statistics. The secondary data from a variety of sources has been obtained to meet the objectives of this article (Table 4.a). Multispectral Landsat images for the years 1990, 2000, 2011, and 2021 have been used as one of the secondary sources of data to measure the changes in land usage and land cover. Google Earth Engine (GEE) has been used to retrieve the Landsat satellite images for 1990, 2000, 2011 and 2021, which are detailed in Table 4.a. In this study, a combination of Landsat 5 and Landsat 8 data with a 30-meter spectral resolution has been utilised. To avoid any seasonal variations in vegetation dynamics and land use activities, the images were only taken during a fixed time frame i.e., in January. Additionally, the 2019 Sentinel data, which have a spatial resolution of 10 metres, were used to generate the ward-wise LULC map of KMC.

Table 4.a: Temporal and technical specifications of Landsat Imagery used in the study

Satellite Images	Product Identifier	Sensor	Pixel size
Landsat 5 (1990)	ee.ImageCollection ("LANDSAT/LT05/C02/T1_TOA")	TM Collection 2 Tier 1 TOA reflectance	30 meters
Landsat 5 (2000)	ee.ImageCollection ("LANDSAT/LT05/C02/T1_TOA")	TM Collection 2 Tier 1 TOA reflectance	30 meters
Landsat 5 (2011)	ee.ImageCollection ("LANDSAT/LT05/C02/T1_TOA")	TM Collection 2 Tier 1 TOA reflectance	30 meters
Landsat 8 (2021)	ee.ImageCollection ("LANDSAT/LC08/C02/T1_TOA")	Operational Land Imager (OLI) TOA reflectance	30 meters

4.3.2. Methodology:

To understand the dynamic changes in land use and land cover in the study area, various software and a cloud-based geospatial analysis platform have been utilised to perform different tasks (Table 4 b). The various methods that have been used to accomplish the objective of this chapter have been described and graphically presented in Figure 4.1.

Table 4.b: Software tools and their application in LULC analysis

Software	Applications
Google Earth Engine	Export RGB images
ArcGIS 10.2 pro	Masked the AOI (Area of Interest)
Erdas Imagine 2014	Supervised classification and accuracy assessment

To analyse the Land Use and Land Cover (LULC) classification and its change detection from 1990 to 2021, multi-temporal Landsat images with a spatial resolution of 30 metres have been used in this study. Landsat images from 1990, 2000, 2011, and 2021 have been obtained via Google Earth Engine (GEE) platform. Then, the images were radiometrically corrected and mosaicked before classification. The Landsat imagery was specifically chosen for temporal change detection in LULC patterns because of the unavailability of better-resolution satellite imagery (Sentinel 2A) over the entire temporal range (1990-2021). To complement the change detection analysis and obtain a more detailed and accurate depiction of the existing LULC pattern at the ward level, high-resolution Sentinel-2A imagery (10-metre spatial resolution) for the year 2019 was utilised, which was obtained from the USGS Earth Explorer. Sentinel data facilitated the detailed classification and quantification of distinct land-use land-cover (LULC) types across 141 wards of KMC, allowing for a more precise spatial evaluation that was previously unattainable with lower-resolution Landsat data. Hence, Landsat data were predominantly employed for the detection of long-term land use and land cover changes, whereas Sentinel-2A imagery offered improved spatial resolution, essential for ward-specific land use and land cover classification and analysis for the year 2019. This integrative method assured historical accuracy and geographical precision in assessing urban land dynamics within the Kolkata Municipal Corporation.

Then, the images were masked using ArcGIS Pro, and supervised classification was performed with ERDAS Imagine, employing the maximum likelihood method. Primary land use and land cover classes have been determined based on visual interpretation for the classification of land use and land cover. After that, an accuracy assessment was performed to evaluate the percentage of accuracy in classification. For accuracy assessments, a minimum of 100 spectral signatures for each class of land use have been collected using a random pixel selection. The ERDAS IMAGINE software has been used to conduct the accuracy assessment. In the accuracy assessment tool of ERDAS IMAGINE software, the LULC map of the different years has been opened and then some random point has been taken as a GCP point. To show the value of each class the point has been taken in accordance with its value and then both the Kappa accuracy and the Overall accuracy of the report were assessed.

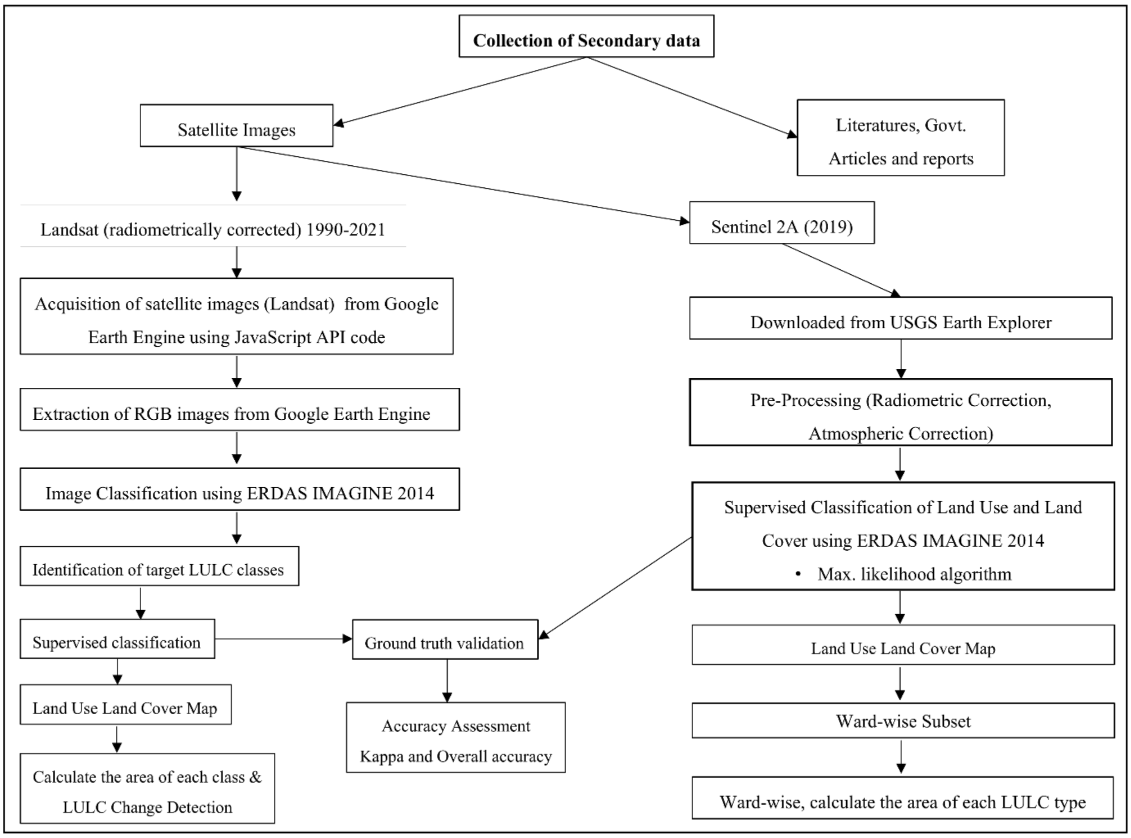

Figure 4.1: Methodological Framework for the analysis of LULC changes

4.4. Results and Discussions:

This chapter delineates the results of the Land Use and Land Cover (LULC) change analysis performed for the Kolkata Municipal Corporation (KMC) from 1990 to 2021. The systematic examination of spatial and temporal alterations across essential land cover categories, specifically built-up areas, vegetation, water bodies, agricultural land, and fallow land, has been conducted using multi-temporal satellite imagery, supervised classification approaches, and GIS tools. The findings indicate substantial urban growth, characterised by a notable rise in developed regions, alongside a decline in open spaces and vegetation. These alterations signify the evolving characteristics of urban development and its environmental consequences. This discourse analyses the data on urban expansion, ecological sustainability, and water resource management, offering insights essential for informed urban planning and policy formulation.

4.4.1. Analysis of Land Use Land Cover Changes from 1990 to 2021:

To track the changes of land use and land covers in KMC the supervised classification has been generated. The five classes of LULC have generally been taken into consideration in this study to determine the changes from 1990 to 2021. In this study, classes such as built-up areas, vegetation, water bodies, agricultural land, and fallow land have been taken into account. The changes to these classes between 1990 and 2021 have been shown in Figure 4.2.

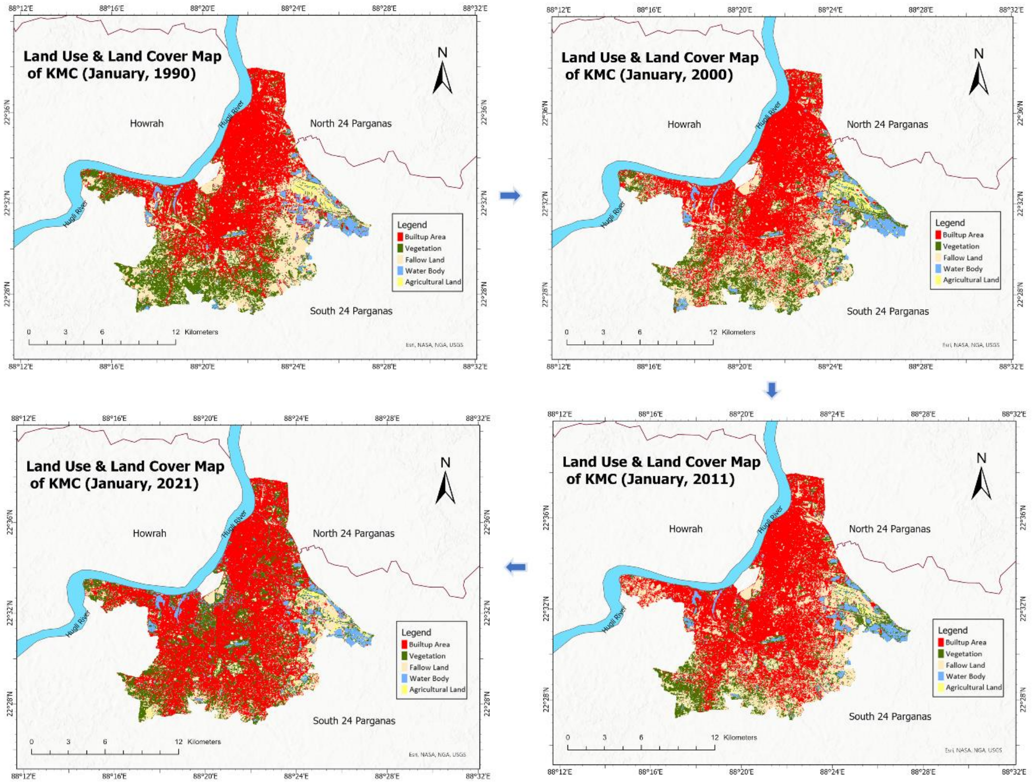

Figure 4.2: Land use and Land cover changes and their spatial variation in KMC from 1990 to 2021.

The primary land use and land cover classes have changed both spatially and temporally between 1990 and 2021 as shown in Figure 4.2 by the LULC classification of KMC. The LULC classification map illustrates how between 1990 and 2021 the built-up area in the study region expanded while the vegetation cover declined. After classification of the aforementioned LULC map the area of each class has been computed to identify the changes in the aforementioned major land uses and land covers. The results are displayed in Table 4.c.

Table 4.c: Changes in land use and land covers along with their spatial variation within KMC between 1990 and 2021

Area under LULC classes in KMC								
LULC Classes	**1990**		**2000**		**2011**		**2021**	
	Area in Sq. Km.	Area in %	Area in Sq. Km.	Area in %	Area in Sq. Km.	Area in %	Area in Sq. Km.	Area in %
Built-up area	83.68	45	86.36	46.64	98.63	53.27	106.20	57.36
Vegetation	41.11	22.20	30.93	16.70	23.73	12.81	35.78	19.32
Water body	10.35	5.59	11.96	6.45	9.75	5.26	10.13	5.47
Agricultural land	2.40	1.29	2.98	1.61	1.81	0.98	2.91	1.56
Fallow land	47.99	25.92	52.90	28.60	51.30	27.70	30.16	16.29
Total	185.15	---	185.15	---	185.15	---	185.15	---

The computed LULC classes reveal that from 1990 to 2021, the Kolkata Municipal Corporation (KMC) experienced substantial alterations in land use and land cover (LULC), indicative of the fast urbanisation and evolving land dynamics in the area. The most significant change was the ongoing growth of the built-up area, which rose from 83.68 km^2 (45%) in 1990 to 106.20 km^2 (57.36%) in 2021. This growing trend highlights the increasing strain of urban development propelled by population growth, infrastructural expansion, and the demand for residential and commercial properties. In contrast, Fallow land suffered a large reduction, shrinking from 47.99 km^2 (25.92%) in 1990 to 30.17 km^2 (16.29%) in 2021, showing that most of this space has been converted to urban use. The vegetation is mostly concentrated in the south and south-eastern part of KMC. The largest area of vegetation cover loss has been detected in 2011, which was only 23.7285 square kilometres a decline of roughly 19.38 square kilometres compared to 1990. Initial vegetation cover drops from 41.11 km^2 (22.20%) in 1990 to 23.73 km^2 (12.81%) in 2011; by 2021, it shows a partial rebound to 35.78 km^2 (19.32%).

This variation has been ascribed to the encroachment of urban infrastructure and subsequent conservation or greening efforts. Water bodies exhibited relative stability during the research period, encompassing around 5.5% of the total area, indicating minimal modification or effective conservation measures. Agricultural land, however consistently limited, experienced tiny fluctuations, culminating in a modest increase from 2.40 km² (1.29%) in 1990 to 2.91 km² (1.56%) in 2021. The analysis indicates a significant tendency of urban expansion that compromises open spaces and vegetation, highlighting the necessity of sustainable urban planning to reconcile development with environmental conservation.

To validate the classification results, the accuracy assessment report has been computed and displayed in table 4.d.

Table 4.d: Accuracy assessment report, computed by author

Accuracy assessment report				
Accuracy report	1990	2000	2011	2021
Overall accuracy	88.3	87.4	83.68	88.57
Kappa accuracy	80%	84%	81%	80%

The accuracy of the land use and land cover classification for the years 1990, 2000, 2011, and 2021 has been evaluated using overall accuracy and the Kappa coefficient. The overall accuracy of the classification has been found to be between 83.68% and 88.57%, a broad spectrum of reliability that reflects the overall situation of the classification. Likewise, the Kappa coefficient values remained consistently high, ranging from 80% to 84%, indicating a significant agreement between the reference data and the categorised data. Reflecting strong categorisation consistency for that year, the peak Kappa value was found in 2000 at 84%. Despite modest variations, the accuracy metrics over the years indicate that the land cover classifications are dependable and accurate, hence substantiating the validity of the temporal LULC change analysis conducted in this research.

4.4.2. Existing Land Use Pattern of Kolkata Municipal Corporation (KMC):

The Kolkata Municipal Corporation's land use and land cover map has been generated using ERDAS IMAGINE 2014, utilising the Sentinel-2A (2019) image. The overall built-up area (Figure 4.3) in KMC accounted for 70.05 per cent of the total area in 2019. The current land use and land cover (LULC) pattern of the Kolkata Municipal Corporation (KMC), indicates a landscape predominantly characterised by urban development. The extensive built-up area in KMC, combined with a diminishing trend in groundwater level, raises concerns about the area's long-term water availability (Mukherjee, Bebermeier, & Schütt, 2018). As a result, this study becomes critical for the city's long-term viability.

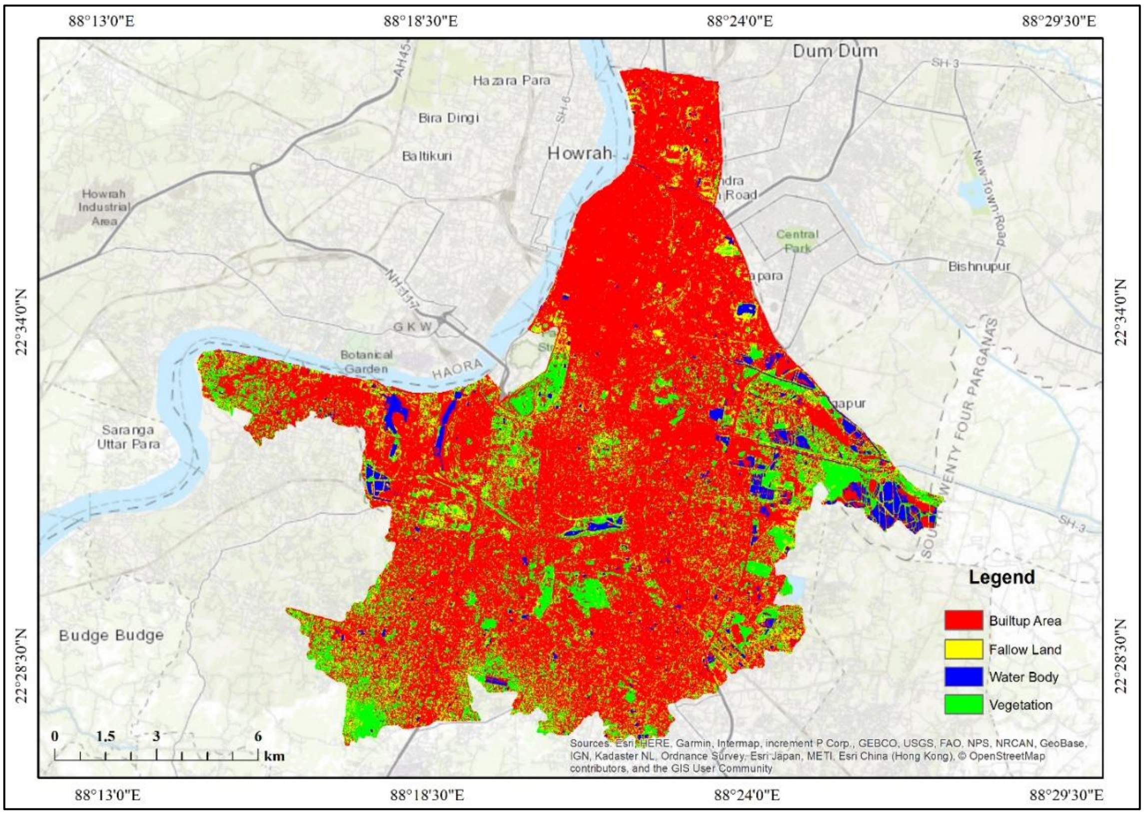

Figure 4.3: Land use Land cover map (2019) of the study area. Prepared by the author based on Sentinel 2A image, which was downloaded from USGS Earth Explorer.

4.4.2.1. Ward-wise classification and measurement of each LULC within KMC:

The ward-wise Land Use/Land Cover (LULC) classification shows different spatial patterns in land use throughout the research area. The comprehensive ward-wise Land Use/Land Cover (LULC) categorisation offers an in-depth insight into the geographical distribution of built-up areas, which are essential markers of urbanisation and human impact on land. It reflects severe urban development and infrastructure expansion; built-up areas have been predominantly found in several central wards. In several central wards, the built-up area has been found to be above 90%, which demonstrates how quickly cities are growing and expanding their infrastructure. A closer investigation reveals that the percentage of built-up area gradually declines from the urban core towards the periphery, giving way to larger areas of farmland, open spaces, and natural vegetation. The elevated levels of impervious surfaces signify extensive residential, commercial, and infrastructural land use, with minimal to no remaining open space, vegetation, or water bodies. This intense urban density illustrates years of unchecked growth and the saturation of developable land (Mukherjee, Bebermeier, & Schütt, 2018).

In contrast, peripheral and semi-urban wards, especially in the southern and eastern peripheries of KMC, display comparatively lower built-up densities. These regions preserve greater expanses of open ground, greenery, and, in certain instances, minor agricultural plots, indicating persistent shifts from rural to urban land use classifications (Mondal & Banerjee, 2021). Wards 57, 63, and 108 have a more varied land use and land cover profile, incorporating a mix of green spaces, fallow lands, and water bodies, frequently linked to peri-urban dynamics (Naikoo et al., 2020).

The spatial variation in land use and land cover composition has a significant impact on environmental sustainability and urban planning. Areas with sparse vegetation and water bodies encounter heightened difficulties associated with heat stress, flooding, and diminished groundwater recharge. The lack of natural buffers in these regions underscores the vulnerability of densely populated areas to environmental degradation (Chen et al., 2015). Conversely, wards with comparatively greater green cover or open spaces are viable areas for implementing green infrastructure, rainwater harvesting systems, and ecological conservation initiatives.

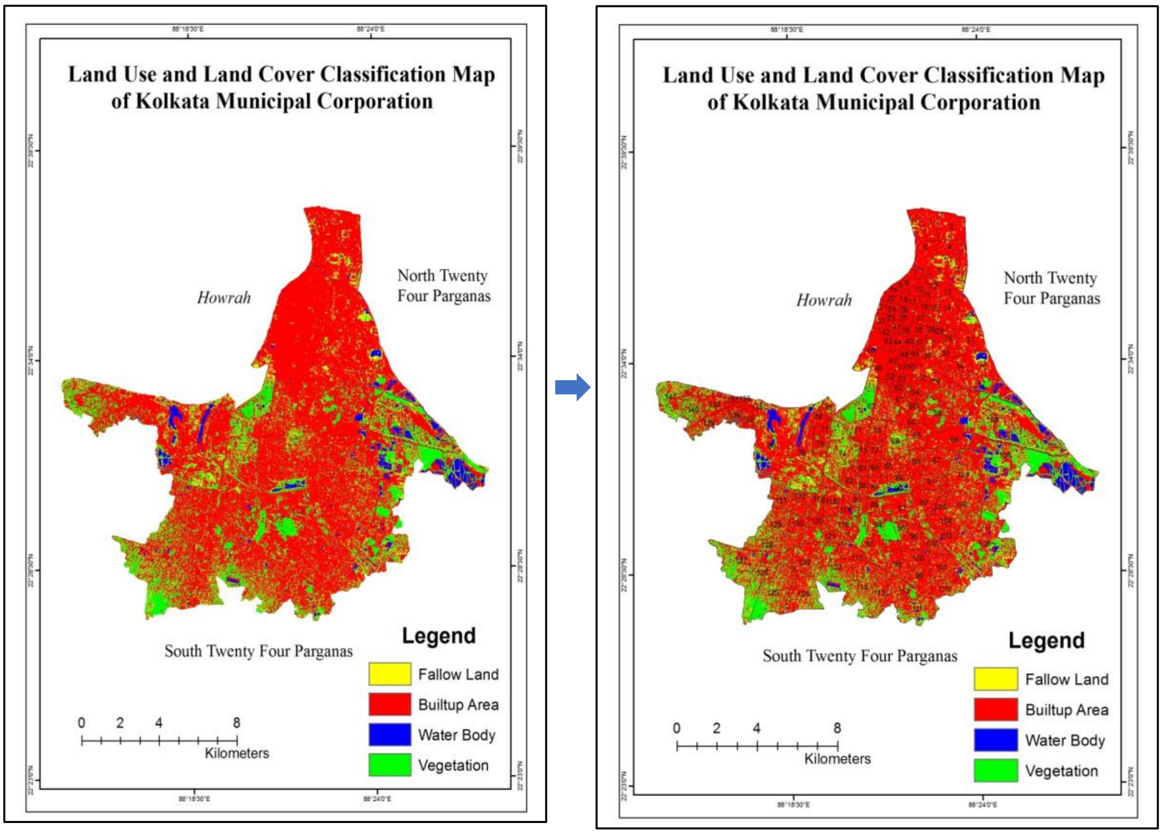

Figure 4.4: Ward-wise classification and measurement of each LULC within KMC

In specific wards, the constructed area coexists with remnants of vegetation or open ground, indicating transitional land-use zones where urban expansion is ongoing. These transitional zones are particularly significant to urban planners, as they exemplify locations where development control measures, zoning rules, and sustainability efforts can have the greatest influence. Vegetation is low in heavily urbanised wards, indicating possible issues connected to the urban heat island effect, loss of biodiversity, and lower ecological resilience. The lack of open and green areas in such wards highlights the pressing need for integrated land-use planning, including environmental buffers, public spaces, and green infrastructure.

Table 4.e: Ward-wise classification and measurement of each LULC within Kolkata

Ward No	Fallow Land (sq.km.)	Built-up Area (sq.km.)	Water Body (sq.km.)	Vegetation (sq.km.)	Sum (sq.km.)	Percentage of Built-up area
1	0.09	1.35	0.02	0.01	1.47	92.17
2	0.13	1.54	0.02	0.02	1.71	90.09
3	0.20	0.93	0.03	0.05	1.21	76.85
4	0.05	0.90	0.02	0.01	0.98	92.51
5	0.33	1.04	0.01	0.05	1.44	72.67
6	0.13	1.63	0.01	0.02	1.80	90.77
7	0.01	0.42	0.01	0.00	0.44	94.24
8	0.00	0.35	0.00	0.00	0.36	98.88
9	0.00	0.28	0.00	0.00	0.28	99.26
10	0.00	0.43	0.00	0.00	0.44	99.12
11	0.00	0.33	0.00	0.00	0.33	98.62
12	0.03	0.44	0.01	0.01	0.49	90.10
13	0.02	0.73	0.01	0.01	0.77	94.74
14	0.05	0.92	0.01	0.01	0.98	93.31
15	0.04	0.47	0.00	0.01	0.52	88.83
16	0.00	0.35	0.00	0.00	0.35	98.98
17	0.00	0.36	0.00	0.00	0.36	99.66
18	0.00	0.24	0.00	0.00	0.24	99.76
19	0.00	0.24	0.00	0.00	0.24	99.75
20	0.00	0.30	0.00	0.00	0.30	99.69
21	0.01	0.32	0.00	0.00	0.33	97.76
22	0.01	0.46	0.00	0.00	0.48	96.46
23	0.00	0.13	0.00	0.00	0.13	99.67
24	0.00	0.20	0.00	0.00	0.20	99.48
25	0.00	0.39	0.00	0.00	0.39	99.80
26	0.01	0.34	0.00	0.00	0.35	97.55
27	0.01	0.41	0.00	0.00	0.43	96.95
28	0.01	0.39	0.00	0.00	0.41	96.38
29	0.01	0.34	0.00	0.00	0.35	96.34

30	0.04	0.53	0.00	0.01	0.57	91.81
31	0.12	1.22	0.01	0.02	1.37	89.04
32	0.25	1.25	0.04	0.08	1.63	76.91
33	0.28	1.25	0.14	0.06	1.73	72.03
34	0.05	0.74	0.01	0.01	0.81	90.92
35	0.09	0.89	0.00	0.02	1.00	89.14
36	0.10	0.84	0.01	0.03	0.98	85.97
37	0.01	0.30	0.00	0.00	0.32	95.74
38	0.01	0.48	0.00	0.00	0.49	97.93
39	0.00	0.20	0.00	0.00	0.20	99.66
40	0.00	0.35	0.00	0.00	0.36	98.30
41	0.01	0.25	0.00	0.00	0.26	95.65
42	0.00	0.25	0.00	0.00	0.25	100.00
43	0.00	0.26	0.00	0.00	0.26	99.66
44	0.01	0.46	0.00	0.00	0.47	98.30
45	0.17	1.25	0.03	0.06	1.52	ther.59
46	0.19	1.13	0.01	0.08	1.41	80.58
47	0.00	0.41	0.00	0.00	0.42	99.44
48	0.00	0.26	0.00	0.00	0.26	99.52
49	0.00	0.25	0.00	0.00	0.25	98.24
50	0.00	0.38	0.00	0.00	0.39	98.97
51	0.01	0.31	0.00	0.00	0.32	96.91
52	0.00	0.24	0.00	0.00	0.24	98.72
53	0.00	0.35	0.00	0.00	0.36	98.79
54	0.01	0.46	0.00	0.01	0.48	95.87
55	0.13	0.82	0.01	0.02	0.98	83.25
56	0.05	0.57	0.00	0.03	0.66	86.54
57	0.30	1.86	0.37	0.28	2.81	66.26
58	1.50	5.89	0.90	2.44	10.73	54.88
59	0.14	1.46	0.02	0.36	1.98	73.88
60	0.04	0.42	0.00	0.03	0.49	85.70
61	0.04	0.56	0.00	0.03	0.63	88.43
62	0.01	0.34	0.01	0.01	0.36	95.19
63	0.49	1.97	0.07	1.35	3.87	50.77
64	0.05	0.76	0.00	0.04	0.86	88.69
65	0.10	1.08	0.00	0.09	1.26	85.51
66	0.10	2.12	0.08	0.11	2.41	88.28
67	0.11	1.53	0.02	0.11	1.77	86.52
68	0.06	0.78	0.00	0.06	0.90	87.33
69	0.34	1.30	0.01	0.37	2.02	64.37
70	0.07	0.66	0.00	0.06	0.79	83.90
71	0.11	0.76	0.01	0.14	1.02	74.39
72	0.02	0.53	0.00	0.02	0.58	91.16
73	0.03	0.44	0.00	0.03	0.50	88.29
74	0.71	1.58	0.02	1.00	3.32	47.68
75	0.09	0.39	0.01	0.06	0.55	70.70

76	0.01	0.40	0.01	0.01	0.43	92.81
77	0.02	0.49	0.00	0.16	0.67	72.86
78	0.03	0.58	0.00	0.06	0.67	86.70
79	0.38	1.98	0.16	0.34	2.86	69.33
80	1.30	5.34	0.91	1.01	8.56	62.38
81	0.92	0.99	0.00	0.12	2.03	48.59
82	0.07	0.74	0.00	0.08	0.88	83.83
83	0.02	0.43	0.01	0.02	0.47	90.46
84	0.02	0.40	0.00	0.02	0.44	92.09
85	0.04	0.62	0.00	0.04	0.71	88.11
86	0.10	0.74	0.00	0.08	0.92	80.14
87	0.08	0.50	0.05	0.12	0.74	67.10
88	0.04	0.45	0.01	0.04	0.53	84.63
89	0.04	0.45	0.00	0.06	0.55	81.64
90	0.13	0.61	0.18	0.29	1.22	50.46
91	0.05	0.81	0.01	0.05	0.92	87.57
92	0.13	1.41	0.01	0.11	1.66	84.78
93	0.13	1.51	0.03	0.20	1.88	80.57
94	0.13	0.81	0.01	0.75	1.70	47.49
95	0.07	0.60	0.00	0.19	0.85	69.83
96	0.04	1.05	0.01	0.06	1.16	90.21
97	0.20	1.31	0.00	0.55	2.06	63.54
98	0.09	1.01	0.01	0.06	1.17	86.33
99	0.12	1.12	0.01	0.09	1.34	83.87
100	0.05	0.87	0.01	0.03	0.96	90.17
101	0.13	1.42	0.02	0.08	1.65	86.19
102	0.08	0.76	0.01	0.12	0.97	78.51
103	0.73	0.86	0.02	0.03	1.65	52.35
104	0.08	0.88	0.00	0.06	1.03	85.55
105	0.04	0.56	0.01	0.01	0.62	89.79
106	0.22	1.55	0.01	0.15	1.93	80.42
107	0.32	2.16	0.04	0.33	2.86	75.67
108	1.40	4.42	1.84	3.31	10.97	40.33
109	1.22	3.67	0.26	1.58	6.73	54.55
110	0.26	1.25	0.05	0.20	1.77	70.93
111	0.38	1.32	0.06	0.43	2.19	60.29
112	0.16	1.26	0.02	0.23	1.67	75.92
113	0.22	1.11	0.01	0.24	1.58	70.21
114	0.45	1.27	0.03	0.52	2.27	56.11
115	0.12	1.16	0.03	0.11	1.42	81.81
116	0.09	0.92	0.01	0.21	1.22	75.06
117	0.03	0.56	0.03	0.09	0.71	78.82
118	0.07	0.84	0.00	0.09	1.01	83.77
119	0.05	0.57	0.00	0.10	0.72	78.20
120	0.03	0.60	0.01	0.05	0.70	86.80
121	0.12	1.10	0.02	0.19	1.44	76.66

122	0.41	1.80	0.10	0.86	3.18	56.73
123	0.21	1.28	0.02	0.27	1.79	71.79
124	0.42	1.67	0.03	0.46	2.57	64.87
125	0.49	1.56	0.03	1.12	3.21	48.71
126	0.61	1.48	0.03	1.06	3.18	46.47
127	0.52	1.48	0.07	0.90	2.98	49.77
128	0.24	1.25	0.01	0.35	1.85	67.56
129	0.24	1.26	0.01	0.40	1.91	65.71
130	0.04	0.66	0.01	0.06	0.77	86.05
131	0.12	1.27	0.01	0.18	1.58	80.76
132	0.06	0.67	0.02	0.10	0.85	78.40
133	0.02	0.43	0.00	0.03	0.49	88.86
134	0.13	0.62	0.01	0.08	0.84	73.61
135	0.01	0.18	0.00	0.01	0.19	93.30
136	0.03	0.41	0.02	0.05	0.51	80.06
137	0.03	0.34	0.00	0.02	0.39	86.28
138	0.06	0.75	0.00	0.12	0.93	80.48
139	0.10	0.94	0.01	0.23	1.28	73.39
140	0.15	0.73	0.01	0.44	1.33	55.00
141	0.48	1.39	0.04	0.83	2.74	50.73
Sum	21.75	130.06	6.29	27.56	185.66	70.05

The ward-specific Land Use and Land Cover (LULC) classification (Table 4.e), when assessed in relation to rooftop rainwater harvesting (RRWH) capacity, indicates substantial consequences for sustainable urban water management. The built-up areas, consisting of rooftops, paved surfaces, and impermeable structures, are essential for both generating surface runoff and providing physical infrastructure for rainwater harvesting. The classification indicates that central and highly urbanised wards exhibit a significant concentration of built-up area, reflecting dense residential, commercial, and institutional facilities. The comprehensive presence of impermeable surfaces signifies an unexploited potential for Rainwater Harvesting (RRWH), especially via rooftop systems capable of capturing and storing rainwater for non-potable applications or groundwater replenishment. The rainwater harvesting potential increases with the percentage of built-up area. Rainfall occurrences in wards with more than 50–60% land under built-up usage produce a significant amount of runoff, much of which is lost as surface runoff or directed into overloaded drainage systems. However, particularly in water-stressed urban areas like KMC, when combined with RRWH systems, even a small portion of this volume can greatly increase water availability at the household or community level. In addition, the spatial concentration of built-up areas in these wards offers logistical benefits, including access to rooftops, current water infrastructure, and community network elements that support the execution of decentralised harvesting systems.

On the other hand, peripheral wards with moderate to low built-up area ratios might not have the same degree of RRWH potential, but they have other benefits. Typically, these regions maintain more open space that can be utilised for recharge pits, percolation tanks, and larger storage systems, thereby supporting rooftop projects. RRWH can be incorporated into planning systems for future housing projects, educational institutions, and public facilities in these areas, thereby producing a more comprehensive water management approach that integrates developed and underdeveloped land resources. The elevated built-up density in central wards frequently corresponds with heightened water demand and restricted groundwater recharge as a result of soil sealing. This disparity intensifies urban water insecurity, particularly in arid seasons. Implementing rooftop rainwater harvesting in these wards can help restore the natural hydrological cycle by enhancing aquifer recharge and reducing reliance on external water sources. Furthermore, RRWH may mitigate urban flooding hazards by capturing peak runoff during monsoon events, a growing concern in densely populated areas where stormwater systems are often insufficient.

The ward-specific built-up data offers a spatially precise basis for prioritising RRWH interventions. Prioritise wards with the highest percentages of built-up area for rooftop harvesting programs, bolstered by policy incentives, awareness campaigns, and community-based implementation approaches. Municipal authorities can amalgamate LULC data with precipitation patterns, rooftop area assessments, and socio-economic variables to build ward-level RRWH action plans. This data-driven design aligns with national urban initiatives and sustainable development objectives (SDG 6), which emphasize effective water utilization, climate change resilience, and community involvement. This ward-wise LULC analysis facilitates micro-level urban governance by pinpointing priority locations for policy intervention. Wards characterised by significant built-up density may be prioritised for rooftop greening or vertical landscaping initiatives, whilst peripheral wards could be safeguarded against unregulated urban expansion through the implementation of zoning restrictions and ecological zoning overlays (Tripathi, Pingale, & Khare, 2019). The distribution of built-up areas serves not only as an indicator of urban expansion but also as a strategic metric for assessing rainwater collection capacity. Utilising this potential through strategically designed RRWH systems has a twin advantage: alleviating urban water shortages and fostering ecological sustainability in rapidly urbanising regions. The ward-level LULC assessment provides insights into the existing urban footprint and highlights regions where sustainable urban development strategies can be effectively applied. By synchronising land use planning with ecological capacity at the ward level, municipal authorities can enhance their management of growth, infrastructure development, and environmental preservation concurrently.

4.5. Conclusions:

This chapter has rigorously analysed the spatial and temporal dynamics of land use and land cover (LULC) in the specified area, using remote sensing and GIS techniques. Over the specified period, notable changes in land use and land cover types have been identified through the classification and interpretation of satellite images. The outcomes reveal a clear pattern of land transformation, especially emphasising the rise in built-up areas and the simultaneous reduction of agricultural and vegetated land. These alterations highlight the continuing urbanisation and human footprint in the area.

The use of multi-temporal satellite imagery, paired with supervised classification techniques and comprehensive accuracy assessments, has produced consistent knowledge on the degree and character of LULC changes over the specified periods. The ward-wise analysis highlights the regional heterogeneity of land use, indicating that the peripheral areas still maintain some biological land uses, despite increasing development pressure. The decline in natural land cover, coupled with an increase in impermeable surfaces, has substantial consequences for urban hydrology, groundwater replenishment, ecological equilibrium, and overall environmental resilience. Moreover, the observed geographical and temporal patterns offer essential insights into the dynamics of land surface changes and their possible consequences for environmental sustainability and resource management. The recorded decline in ecologically important land use types, including vegetation cover and agricultural land, highlights the pressing need for integrated land management plans that strike a balance between development and preservation. Overall, this chapter provides a solid foundation for future studies in this field and contributes significant empirical data to the broader discussion on land cover change.

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CHAPTER 5

RAINWATER HARVESTING POTENTIAL (RWHP) OF KMC

5.1. Introduction:

Water is an essential natural resource that possesses multifaceted utility. In light of current circumstances, the daily utilization of water has become limited and necessitates prudent conservation measures. The issue of water scarcity is considered to be one of the most pressing global water challenges. (William A. Jury and Henry Vaux, 2005). Urban water resources in emerging nations may be compromised due to population growth, urbanization, and climate change. (Murad et al., 2007; O'Hara & Georgakakos, 2008; Wheida & Verhoeven, 2007). The growing water demand has prompted cities to focus on capturing rainwater for irrigation and other non-drinking applications, as well as recharging their groundwater supplies. (Abdulla, 2020; Aladenola & Adeboye, 2010; Bashar et al., 2018; Mahmood & Hossain, 2017). Rainwater harvesting systems are efficient, minimal-impact development techniques that improve both run-off management and water supply (Rui & Guo, 2018). In metropolitan areas, it is often used as a secondary water supply for non-potable purposes such as flushing toilets, washing clothes, watering plants, washing cars, and preventing flooding. (Hanson & Vogel, 2014; Van Der Sterren et al., 2012). Plans for collecting and using rainwater are effective when combined with initiatives to improve aquifer recharge and water demand management (UNEP-IETC, 1999). It has been broadly accepted in multiple nations all over the world, including India (S. Biswas et al., 2021; K. Pavan Kumar & B. Srimuruganandam, 2017; Said, 2014); Bangladesh (B. K. Biswas & Mandal, 2014); Australia (Amos et al., 2016; Hajani & Rahman, 2014), Egypt (Gado & El-Agha, 2020), and Portugal (Lúcio et al., 2020). Instead of a wide range of climatic situations and applications, even those in Australia have shown the usefulness of the RWH system in water savings and conservation (Rahaman et al., 2012). The potential for collecting rainwater is determined by several factors, including the rooftop area, the depth of the precipitation, the capacity of the rooftop to store water and the run-off coefficient. (Farreny et al., 2011). A balance equations model can be used to pretend the operation of the RWH system at the scale of a building or a residence to accurately assess the water savings potential of RWH (Lúcio et al., 2020). A significant source of worldwide anxiety is the potential for a water disaster (Mekonnen & Hoekstra, 2016). Most of the world's population is projected to face water scarcity within the next twenty years. (Wang et al., 2018). This scenario is even more problematic in developing nations in arid or semi-arid regions where climate change can create various climatic zones with high frequency and variability of precipitation and drought (Christensen et al., 2007). Shallow tube wells linked to electrified pumps made illegal groundwater drafting, leading to qualitative water stress. This situation has increased the chance of a health crisis related to arsenic exposure for a significant portion of the population. (Banerjee & Jatav, 2017; A. Biswas et al., 2019; Chakraborti et al., 2009; Malakar et al., 2016; Pal et al., 2009). After analysing the groundwater condition, many studies employed remote sensing and geographic information systems to identify potential sites for RWH with artificial recharge. (Buraihi & Shariff, 2015; Elewa et al., 2012; Haldar & Majumder, 2022; Kumar & Jhariya, 2017; Setiawan & Nandini, 2022; Waghaye et al., 2023). High-cost arsenic remediation facilities offered momentary respite but were not suggested as a long-term remedy (Jiang et al., 2013; Shan et al., 2018). Therefore, a higher level of effort is necessary to implement rooftop rainwater harvesting to address the problem of water contamination.

Installing a rainwater collection system to handle the demands of the flushing, laundry, plant growth, major construction requirements and any other purposes is one of the most efficient ways to preserve water in metropolitan areas. The effective strategy for mitigating flooded roadways, replenishing aquifers, and addressing the needs of urban populations is the collection of rainwater during rainfall events. The process of accumulating run-off from roofs and other impermeable surfaces is known as 'rainwater harvesting' (Pacey, A; Cullis, 1986). This approach involves implementing strategies to facilitate the infiltration of rainwater into the soil, as opposed to allowing it to run off the surface, through flood control measures and the construction of small reservoirs. The collected run-off water can subsequently be utilised for potable or non-potable purposes. A subset of rainwater harvesting is rooftop rainwater harvesting. Rainwater harvesting (RWH) is common and equally popular in the Western and Eastern world. It might be a viable alternative source of potable and non-potable water in areas where a more centralized water supply system is not feasible or if there is a water shortage situation. Urbanization and the accompanying construction activities have negatively impacted the traditional resilient pond-based rainfall harvesting (RWH) agriculture method and taken over suburban natural watercourses, drainage channels, and green spaces, impeding the groundwater recharge zones.

Kolkata experiences a considerable amount of surface run-off during almost every monsoon season as of insufficient harvesting measures. The excess water can be utilised efficiently for non-potable purposes. Adopting Rainwater Harvesting (RWH) as a supplementary water source is imperative as the government has not yet created a system that is free of arsenic, affordable, and user-friendly. Furthermore, the practice of openly disposing of arsenic mitigation filters poses several risks due to the ecological impact of the filters' heavily contaminated sludge (Chakraborti et al., 2009; Sayl et al., 2020; Surajit et al., 2020). RWH also significantly and favorably can reduce the pluvial urban flood, which is highly frequent in urban areas like Kolkata.This chapter intends to estimate the potential for rainwater harvesting by considering the government higher education institutions within Kolkata Municipal Corporation (KMC) and evaluate the significance of rooftop rainwater harvesting techniques for non-potable purposes in urban areas. The research posits that rainwater harvested from rooftops is suitable for toilet flushing, and calculations were conducted to assess whether the flushing demand could be satisfied.

5.2. Materials and Methods:

Generally, there are two types of rainwater harvesting: roof-based and land-based. In this study, the prime focus is on the assessment of rooftop rainwater harvesting potential within KMC. The following steps (Figure 5.1) have been carried out to study the feasibility of the implementation of rainwater harvesting techniques in the study area:

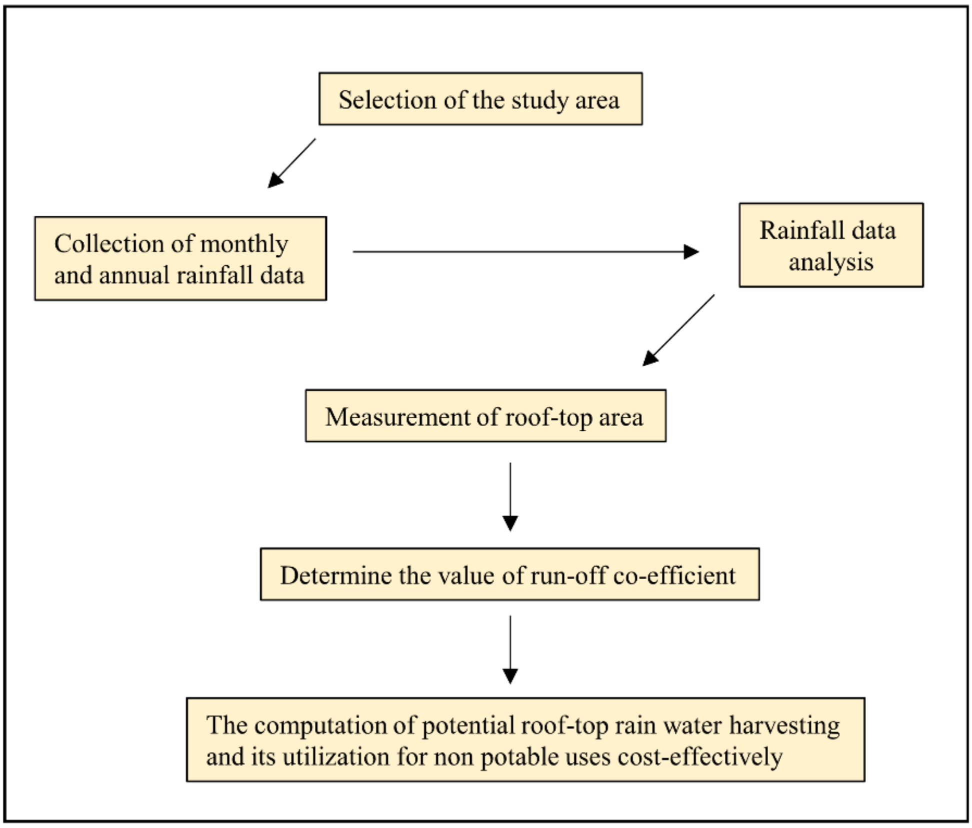


Figure 5.1: Methodological flow chart of the study

5.2.1. Collection of Rainfall data and its analysis:

The adoption of a rainwater harvesting system necessitates an assessment of the rainfall pattern and its variability over the study area. The pattern and variability of the rainfall often determine the viability of a rainwater harvesting system. In this study, a web-based spatial data portal has retrieved 30 years of monthly and annual rainfall from 1991 to 2020 from WRIS (Water Resources Information Systems) to calculate the rainfall variability. Various statistical techniques have been computed to understand the pattern and variability of rainfall. The coefficient of variation of the monthly rainfall has been used to calculate the intra-annual variability, which is represented as follows:

$$\mathrm{CV} = \frac{\mathrm{Sd}}{\bar{\mathrm{X}}} \times 100 \qquad \text{(I)}$$

where,

CV represents the coefficient of variation of the monthly rainfall
Sd represents the standard deviation and
$\bar{x}$ represents the mean monthly rainfall

5.2.2. Measurement of rooftop area:

First, determine the rooftop area to get an idea of how much water can be captured when it rains on a surface. In the current study, the rooftop area of selected buildings, such as government-aided colleges and universities has been calculated using Google Earth Pro and measured manually with the help of a distometer. All the rooftops of selected buildings were not accessible to measure accurately. On the ground, the length and width of that building from the outside have been measured carefully. After that, multiply the length by the breadth, which gives us the area of that specific building. In addition to that, some of the buildings were not accessible to measure the length and width from outside the building accurately. In this instance, the rooftop area was measured using digitization with the assistance of Google Earth Pro.

Figure 5.2: Measurement of rooftop area

5.2.3. Run-off Coefficient:

The run-off coefficient measures the amount of run-off to rainfall. The value of this parameter is greater in regions with limited infiltration and higher run-off, whereas it is comparatively lower in areas that are permeable and densely vegetated. It is a dimensionless factor that is determined by considering the impracticality of capturing the entire run-off of rainwater from the catchment surface. Due to evaporation or surface retention, a sizable quantity of run-off is constantly lost from the catchment surface. It can be computed as the following:

$$\mathrm{C_r} = \mathrm{v_r} \,/\, \mathrm{v_c} \qquad \text{(ii)}$$

Where $\boldsymbol{C_r}$ represents the run-off coefficient, $\boldsymbol{v_r}$ represents the run-off volume and $\boldsymbol{v_c}$ represents the rainfall volume on the catchment. The selection of rooftop materials can significantly influence the values of the run-off coefficient. In the research area, level cement or brick roofs are the most often used rooftops (Figure 5.3). An experiment has been conducted on the rooftop of the building which is concrete in nature (figure 5.3) for verification of the runoff coefficient ($\boldsymbol{C_r}$) value. The average value obtained from the experiment was 0.82 which justified the value of $\boldsymbol{C_r}$ to many previous studies (Ghisi et al., 2009; Liaw & Tsai, 2004; Tabassum et al., 2013) and based on that, the runoff coefficient for this study has been considered as 0.8.

Figure 5.3: Measurement of Runoff Coefficient. A and B illustrate the measurement of water discharge from-a tap, whereas C and D depict the collection of rooftop runoff on the ground.

5.2.4. Computation of potential rainwater harvesting:

The total amount of water that a specific catchment receives from rainfall is referred to as its rainwater legacy, and the amount that can be properly harvested is referred to as its water harvesting potential. The equation (equation iii) was used to calculate the potential monthly amount of rainfall that can be collected by each institution adopting from (Ghisi et al., 2006). The equation is revised in the following form:

$$\mathrm{RWHP} = \frac{\mathrm{AR} * \mathrm{RA} * \mathrm{Rc}}{1000} \qquad \text{(iii)}$$

where,

RWHP represents monthly Rainwater Harvesting Potential (in cubic metres)

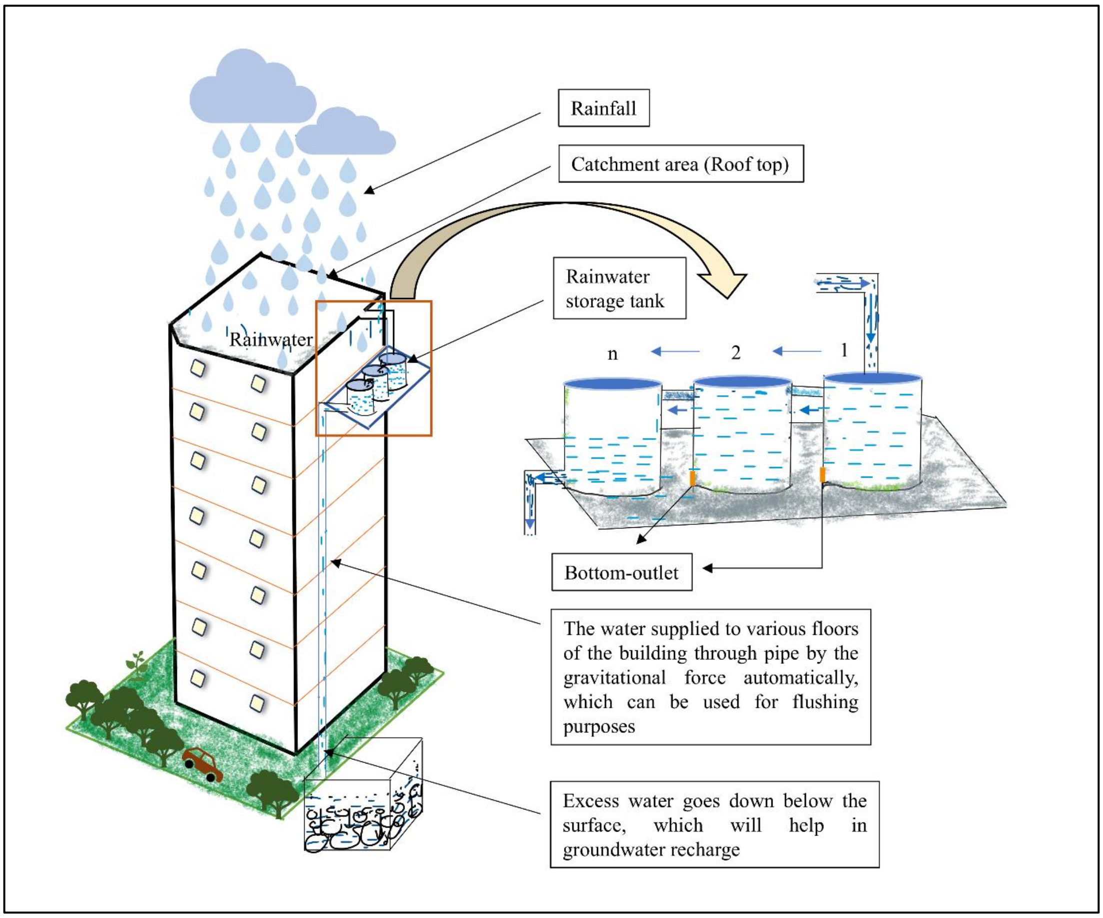
AR Average Rainfall (in millimetres)

RA represents the Rooftop Area (in square metres)

RC represents the Run-off coefficient (unitless)

5.2.5. Supply and distribution of the harvested rainwater:

An important part of the rainwater harvesting system is the efficacy of the supply and distribution of the rainwater harvested on the rooftops of the buildings. According to the schematic diagram, i.e., figure no. 5.4. it is represented that the rainwater accumulates on the rooftop of the buildings. It is necessary to have a planar slope towards a particular outlet through which the total water may drain out of the rooftop. A wire gauge placed at the mouth of the collecting pipe of the outlet will help in the primary physical purification of the drained rainwater. The water will move into the storage tanks through the pipe connecting the outlet of the roof and the storage tanks. The storage tanks are expected to be kept at the (m-1) floor of the multi-stored building so that the water may travel under the force of gravity, where 'm' represents the number of the storey of the building. The water will start accumulating in the first tank. Once the first tank is almost filled up, the water should move to the second tank through a connecting pipe that should be connected at the uppermost part of the interconnecting tanks. Similar process will be repeated from the second tank to the third tank up to 'n' number of tanks, where 'n' represents the number of tanks. This 'n' should be a function of the daily maximum rainfall and assured rainfall to avoid over flow of water while at the very same time 'n' should be restricted to such a number that there is a sufficient flow of water during rainfall. This process of water transfer from the first tank to the n^{th} tank will ultimately lead to the physical purification of the accumulated rainwater through the process of sedimentation and decantation. Once this process is completed, the water should flow out from the end storage tank i.e., the n^{th} tank to be distributed for using purpose. Since, one of the objectives of the study is to reduce the cost of the daily expenses of the rainwater harvesting system (RWHS). Hence, the water should be allowed only for such purposes where the physical purification of the collected rainwater be adequate, such as for toilet flushing, cleaning, gardening, etc. The pipeline coming out of the n^{th} tank or the end storage tank should be connected at the bottom of the n^{th} tank so that water flows out of pressure where water pressure is a function of the height of the water column, density of water and acceleration due to gravity. As the storage tanks are supposed to be positioned at the extended portion of the 'm-1'th stored building, hence the water will flow through the pipeline from 'm-1' stored up to the ground floor. Since, our study involves only HEI within KMC hence the computations and the designs are focused to supply the water for toilet flushing. Another major objective of the study is to make the total system unmanned or fully automatic so that there is no dependency on any person to operate the system as rainfall itself is an erratic phenomenon. The pipeline coming out from the end storage tank should be connected to 'T' shaped connector of a whose one end should be connecting the cistern for toilet flushing. The other end of the 'T' shaped connector should be connected to the municipal water supply system. The pipeline from the storage tank should have a diameter double that of the diameter of the pipeline coming from the municipal water supply system. This 'T' shaped connector should also have a valve installed within it in such a way that when the water will flow from the storage tank the valve will automatically close the municipal water supply pipeline due to differential acting water pressure as there is a difference of diameters of the pipeline systems. Once the water supply from the storage tanks ceases, the valve will automatically open up the water supply system from the municipal source. In this way the total RWHS will operate on an unmanned basis and without any external source of energy except the gravitational force. Finally, it is essential to note that any excess water will be directed toward the surface chamber during heavy rainfall, which will help to recharge the groundwater. It is also necessary to clean the storage tanks once a year during the dry season for better functioning of the RWHS.



The water supplied to various floors of the building through pipe by the gravitational force automatically, which can be used for flushing purposes

Excess water goes down below the surface, which will help in groundwater recharge

Figure 5.4: Schematic representation of rooftop rainwater harvesting, prepared by the author.

In this study, it is considered that the usable water tank is the last tank, in which a pipe has been installed at the bottom of the tank, and the preceding 'n' number of tanks are mostly utilised for physical purification of the accumulated rainwater through the process of sedimentation and decantation. However, each tank can be equipped with an outlet pipe connected at the bottom of the tank, in addition to the overflow and inflow pipes shown in Figure 5.4. This bottom outlet pipe will allow gravitational drainage of the residual water when needed, ensuring that nearly the entire volume of stored rainwater can be utilised. In dry periods or during regular maintenance, a manual valve at the bottom outlet may be opened to drain and use the residual trapped water for non-essential activities, such as gardening or floor cleaning. This procedure can moreover enhance regular tank sanitation, fostering system cleanliness and operational durability (Fewkes & Butler, 2000).

5.3. Results and discussion:

The rainfall pattern and its variability of KMC have been analysed for 30 years of rainfall from 1991 to 2020 in the study area to identify the sustainability of the RWHS within KMC. The monthly mean rainfall and the coefficient of variation have been calculated to understand the rainfall pattern and its variability, which is shown in Table 5.a. The findings reveal that the average annual rainfall throughout the study period has been found to be roughly 1590 mm., with the monsoon months (June to September) comprising nearly 70% of the overall rainfall.

Table 5.a: Monthly rainfall variability of the study area over 30 years of rainfall from 1991 to 2020

Months	Mean Monthly rainfall (mm)	Standard deviation (mm)	Coefficient of variation (%)
January	14.46	13.94	96.40
February	13.92	32.33	232.26
March	35.94	47.2	131.33
April	47.39	38.06	80.3
May	133.77	74.46	55.66
June	254.34	108.81	42.78
July	330.19	126.34	38.26
August	312.23	108.27	34.68
September	258.19	119.77	46.39
October	154.14	124.43	80.73
November	26.92	49.07	182.26
December	5.14	10.02	194.94
Annual	1590.1	368.87	23.2

Source: Computed by author based on the rainfall data of 1991-2020 retrieved from WRIS

The highest mean monthly rainfall has been found for the month of July (330.19 mm), while the lowest mean monthly rainfall has been found for the month of December. The coefficient of variation has been calculated to determine the variability of rainfall over the study area, expressed as a percentage. The intra-annual variability ranges between 34.68% and 232.26%. The maximum and minimum variability have been found in the months of February and August, respectively. From the analysis of table 5.a. it is indicated that there is high uncertainty of rainfall over the region during the non-monsoon months while the lowest variability has been recorded in the monsoon period, i.e., in the months of June, July, August and September, indicating more stable and reliable rainfall, favourable for effective rainwater harvesting. Table 5.a. also shows that the annual rainfall variability over 30 years of rainfall is 23.2%, which is lower than the monthly rainfall variability of KMC. The rainfall stability improves the long-term reliability of rainwater harvesting (RWH) system design, reducing the risk associated with fluctuating climatic patterns in the study area. The analysis of rainfall patterns and variability indicates that, despite the concentration of seasonal rainfall, it is sufficiently reliable for implementing a sustainable rainwater harvesting system, especially when properly sized to handle substantial inflows during monsoon seasons and minimal inflows during dry periods. This understanding of rainfall variability helps to ensure the feasibility of the rainwater harvesting system and to design the storage requirement to harvest the rooftop rainwater at the time of rainfall.

The incorporation of catchment area assessment is crucial in developing a rainwater harvesting (RWH) system. It plays a significant role in evaluating the viability and efficiency of rainwater harvesting systems since it directly impacts the amount of rainwater that can be captured and used. In this study, the rooftop area has been considered as a catchment area to harvest rainwater. The rooftop area of all the colleges under the University of Calcutta and the 9 other university campuses within KMC have been measured in square metres, which are shown in tables 5.b. and 5.c. respectively.

Table 5.b: Rainwater harvesting potentiality in various colleges within the study area

Name of the Colleges	**Mean annual rainfall (in millimeters)**	**Run-off coefficient**	**Rooftop area (sq. metres)**	**Volume of rainwater harvesting potential (m^3/annum)**
Acharya Girish Ch. Bose College	1590	0.8	1000	1272.00
Acharya Jagadish Ch. Bose College	1590	0.8	949	1207.13
City College/Rammohan College/Ananda Mohan College	1590	0.8	2000	2544.00
Bangabasi College/Bangabasi Evening College/Bangabasi Morning College	1590	0.8	917	1166.42
Basanti Devi College	1590	0.8	993	1263.10
Bengal Music College	1590	0.8	215	273.48
Bethune College (Govt.)	1590	0.8	663	843.34
Calcutta Girls' College	1590	0.8	316	401.95
Charuchandra College	1590	0.8	587	746.66
Chittaranjan College	1590	0.8	225	286.20
City College of Commerce & Business Administration	1590	0.8	411	522.79
Deshbandhu College for Girls	1590	0.8	1019	1296.17
Goenka College of Commerce & Business Administration (Govt.)	1590	0.8	1214	1544.21
Gokhale Memorial Girls' College	1590	0.8	573	728.86
Government College of Arts & Crafts	1590	0.8	834	1060.85
Govt. General Degree Girls College (Govt.)	1590	0.8	176	223.87
Gurudas College	1590	0.8	1234	1569.65
Sivanath Sastri College/Prafulla Chandra College/Heramba Chandra College	1590	0.8	947	1204.58
Heritage College (Self-Finance)/Heritage Law College	1590	0.8	2225	2830.20
Asutosh College/Syamaprasad College/Jogamaya Devi College	1590	0.8	2129	2708.09

Jogesh Chandra Chaudhuri College/Jogesh Chandra Chaudhuri Law College	1590	0.8	547	695.78
Khudiram Bose Central College	1590	0.8	927	1179.14
Kidderpore College	1590	0.8	339	431.21
Lady Brabourne College (Govt.)	1590	0.8	3200	4070.40
Loreto College	1590	0.8	3118	3966.10
Maharaja Sris Chandra College/Maharaje Manindra Ch. College/Maharani Kasiswari College	1590	0.8	1012	1287.26
Milli-AL-Ameen College for Girls	1590	0.8	575	731.40
Maulana Azad College (Govt.)	1590	0.8	2093	2662.30
Muralidhar Girls' College	1590	0.8	843	1072.30
Naba Ballygunge Mahavidyalaya	1590	0.8	405	515.16
Netaji Nagar College for Women	1590	0.8	849	1079.93
Netaji Nagar College (Evening)/Netaji Nagar Day College	1590	0.8	1402	1783.34
New Alipore College	1590	0.8	1154	1467.89
Kolkata Police Law Institute (Self-Financed)	1590	0.8	494	628.37
Rani Birla Girls' College	1590	0.8	405	515.16
Savitri Girls' College	1590	0.8	236	300.19
Scottish Church College	1590	0.8	1640	2086.08
Seth Anandram Jaipuria College	1590	0.8	1493	1899.10
Seth Soorajmull Jalan Girls' College	1590	0.8	881	1120.63
Shyambazar Law College (Self-Financed)	1590	0.8	206	262.03
Sir Gurudas Mahavidyalaya	1590	0.8	924	1175.33
Sister Nibedita Government General Degree College for Girls	1590	0.8	1635	2079.72
South Calcutta Girls' College	1590	0.8	579	736.49
South Calcutta Law College	1590	0.8	236	300.19
Sri Shrikshayatan College	1590	0.8	2257	2870.90
State Institute of Physical Education for Women	1590	0.8	900	1144.80
St. Paul's Cathedral Mission College	1590	0.8	651	828.07

St. Xavier's College (Autonomous)	1590	0.8	3120	3968.64
Surendranath College/Surendranath College for Women/Surendranath Evening College/Surendranath Law College	1590	0.8	3012	3831.26
Taradevi Harakhchand Kankaria Jain College (Self-Financed)	1590	0.8	1813	2306.14
The Bhawanipur Education Society College	1590	0.8	1474	1874.93
Umesh Chandra College	1590	0.8	687	873.86
Vedanta College	1590	0.8	706	898.03
Victoria Institution (College)	1590	0.8	379	482.09
Vidyasagar College/Vidyasagar College for Women/Vidyasagar Evening College	1590	0.8	2075	2639.40
Vijaygarh Jyotish Roy College	1590	0.8	1685	2143.32
Women's Christian College	1590	0.8	500	636.00
Women's College, Calcutta	1590	0.8	449	571.13
Behala College	1590	0.8	1078	1371.22
Vivekananda College	1590	0.8	1081	1375.03
Vivekananda College for women	1590	0.8	1349	1715.93
K. K. Das College	1590	0.8	191	242.95
Sarsuna College	1590	0.8	1596	2030.11
Metiabruz College	1590	0.8	289	367.61
Kishore Bharati Bhagini Nivedita (Co-Ed) College	1590	0.8	346	440.11
Dinabandhu Andrews College	1590	0.8	1023	1301.26
Harimohan Ghose College	1590	0.8	141	179.35
Total volume of rainwater harvesting potential (m^3/annum)				89831.18

Source: Measured and computed by the author

Table 5.c: Rainwater harvesting potential in various universities within the study area

Name of the Universities		Mean annual rainfall (in millimeters)	Run-off coefficient	Rooftop area (sq. meters)	Volume of rainwater harvesting potential (m^3/annum)
University of Calcutta	Asutosh Siksha Prangan (College Street Campus)	1590	0.8	9209	11713.85
	Rashbehari Siksha Prangan (Rajabazar Science College Campus), University of Calcutta	1590	0.8	3501	4453.27
	Taraknath Palit Siksha Prangan (Ballygunge Science College Campus)	1590	0.8	7565	9622.68
	Sahid Kshudiram Siksha Prangan (Alipore Campus)	1590	0.8	3535	4496.52
	B.T. Road Campus (Econamic dept)	1590	0.8	3057	3888.50
	Hazra Road Campus (Law College Campus)	1590	0.8	897	1140.98
	University Health Service, Goenka Hospital Diagnostic Research Centre	1590	0.8	1182	1503.50
Rabindra Bharti university	Rabindra Bharti university (Main Campus)	1590	0.8	2225	2830.20
	Rabindra Bharti university (Joarsanko Dwarakanath Tagore Lane)	1590	0.8	4183	5320.78
Aliah University	Aliah University (Park Circus Campus)	1590	0.8	2023	2573.26
	Aliah University (Old Campus Talatala Campus)	1590	0.8	2079	2644.49
Jadavpur University (Main Campus)		1590	0.8	48912	62216.06
Presidency University		1590	0.8	9848	12526.66
The Sanskrit College & University		1590	0.8	2702	3436.94
West bengal university of animal and fishery secience		1590	0.8	1883	2395.18

west bengal university of teacher's training, education planning and administration, Kolkata	1590	0.8	269	342.17
National Institute of Pharmaceutical Education and Research, Kolkata	1590	0.8	453	576.22
Total volume of rainwater harvesting potential (m^3/annum)				131681.25

Source: Measured and computed by the author

After the measurement of all the rooftops of all university campuses and colleges within the study area the annual rainwater harvesting potentiality has been computed (table 5.b and 5.c). The average annual rainfall, which has been computed for 30 years of annual rainfall from 1991 to 2000 is 1590 millimeters. The run off coefficient for all the rooftops is considered as 0.8 to calculate the rainwater harvesting potential. The volume of rainwater that can be harvested has been computed in cubic metres per annum. It is found that Jadavpur University main campus has the highest annual potential for rooftop rainwater harvesting of 62216.06 cubic meters (Table 5.c). As Jadavpur University has the highest potential of RWH hence a water budget between the rainwater harvesting potential and the total demand for non-potable use of water on monthly basis has been generated for Jadavpur University main campus. The total rooftop area at Jadavpur University (Main campus) is 48912 square metres (Table 5.c). The rooftops of several structures and others land use patterns on the main campus of Jadavpur University are depicted in Figure 5.5.

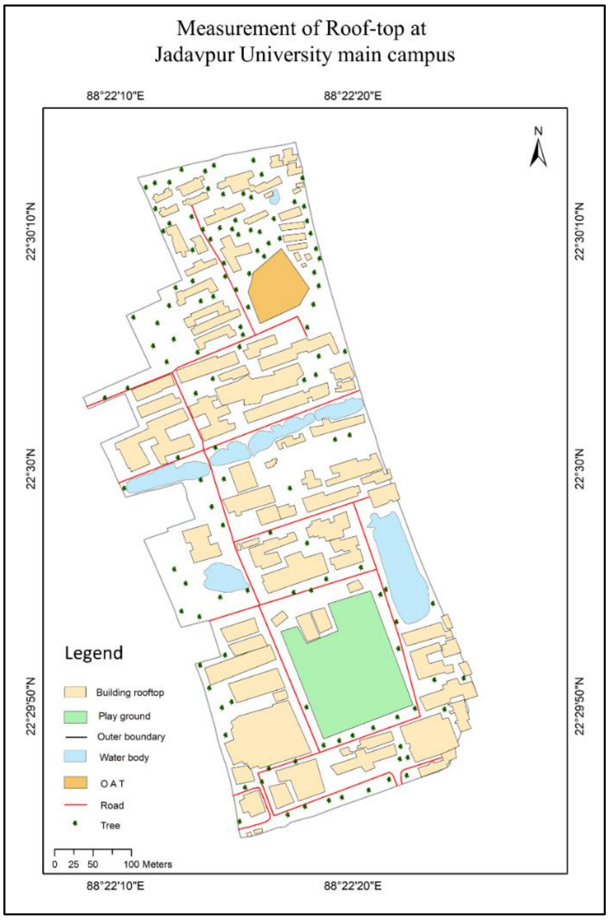


Figure 5.5: Measurement of rooftop area at Jadavpur University main campus, Kolkata

In this connection, a survey was done to collect the data from the university authorities on several parameters, which are as follows (Table 5.d):

Table 5.d: Statistical facts about the number of persons at Jadavpur University (Main campus)

Number of Students (approx.)	12291
Number of Teaching staff (approx.)	1514
Number of non-teaching staff (approx.)	639
Number of Research Scholars (approx.)	701
Total	15145

Source: Collected by the author from Jadavpur University authorities for 2021-2022 academic session as on 09-06-2023

A dependability analysis based on this monthly water demand for non-potable uses (mostly for toilet flushing) at this university campus has been conducted to ascertain the RWH's practical effectiveness. Calculations have been done for non-potable use of water, especially for toilet flushing, considering the 90% attendance of the total stakeholders of the university. The 90% of the total number of persons are 90/100 × 15145 = 13630. The water quantity required for a single flush has been determined to be 10 litres, as observed during a field visit. It is also assumed that each individual utilises the flush once per day. So, the total water demand per day for flushing use only are 13630 (persons) × 10 (litres) = 136300 litres and the monthly demand will be as 136300 litres × 20 days (considered) = 2726000 litres, which is equal to 2726 cubic metres. Taking into account a monthly average non-potable water demand of 2726 cubic metres, it has been discovered that from the month of May to October, the rooftop rainwater harvesting potential surpassed monthly demand, attaining complete reliability. On the other, from November to April, reliability significantly decreased due to diminished rainfall (Table 5.e).

Table 5.e: Monthly total rooftop rainwater harvesting potential of Jadavpur University main campus, Kolkata

Months	Mean Monthly rainfall (mm)	Runoff coefficient	Total Rooftop area of Jadavpur University main campus (sq. metre)	Volume of rainwater harvesting potential (m^3/month)
January	11.04	0.8	48912	431.99
February	20.87	0.8		816.63
March	35.94	0.8		1406.32
April	47.39	0.8		1854.35
May	133.77	0.8		5234.37
June	254.38	0.8		9953.79
July	330.19	0.8		12920.20
August	312.23	0.8		12217.44
September	258.19	0.8		10102.87
October	154.14	0.8		6031.44
November	26.92	0.8		1053.37
December	5.14	0.8		201.13
Total (Annual) rainwater harvesting potential (m^3/month)				62223.89

Source: Computed by author.

In the study, it has been found that the total volume of rainwater harvesting potential is maximum in the month of July and minimum in the month of December, i.e., 12920.20 and 201.13 cubic metres respectively. The aforementioned monthly fluctuation in the volume of rainwater harvesting potential (m^3/month) indicates that there is a significant volume of rainfall can be accumulated during June, July, August, and September. This significantly uneven monthly distribution of rainwater harvesting potential also highlights the imperative for substantial storage capacities to collect efficiently and retain excess rainwater during the peak monsoon months for progressive use in lean months. On the other hand, in the month of December, January and February, the rainwater harvesting potential is low. So, the water demand for toilet flush only is 2726 cubic metres and the rainwater which can be collected at the rooftop only in the month of May to October is sufficient enough to supply the required water demand (Table 5.e). The demand for water for toilet flushing and the potential for rainwater harvesting at Jadavpur University main campus has been graphically represented in Figure 5.6. The graph illustrates that the demand for toilet flushing remains constant at 2726 cubic metres throughout the year, while the potential for rainwater harvesting fluctuates every month. In the month of January to April and November to December the RHP is lower than the demand but in the months of May to October the RWHP is higher than the demand. Particularly in the months of June to September the RWHP is very high compared to demand. Therefore, the overall annual system reliability has been estimated at roughly more than 50% indicating that half of the annual non-potable water needs could be satisfied only by rooftop captured rainwater, without additional municipal supply, in a typical year. Particularly during monsoon months (June to September), the available rainwater not only satisfied toilet flushing but also surpassed the need for other cleansing water on numerous occasions. This excess volume generates further potential for secondary applications, such as floor sanitation, gardening, or regulated groundwater replenishment. Hence, it is imperative for planners and policymakers to prioritize the months of June, July, August and September for the implementation of rooftop rainwater harvesting systems. This approach can serve multiple purposes and alleviate the burden on primary water sources such as pumping and supply by KMC.

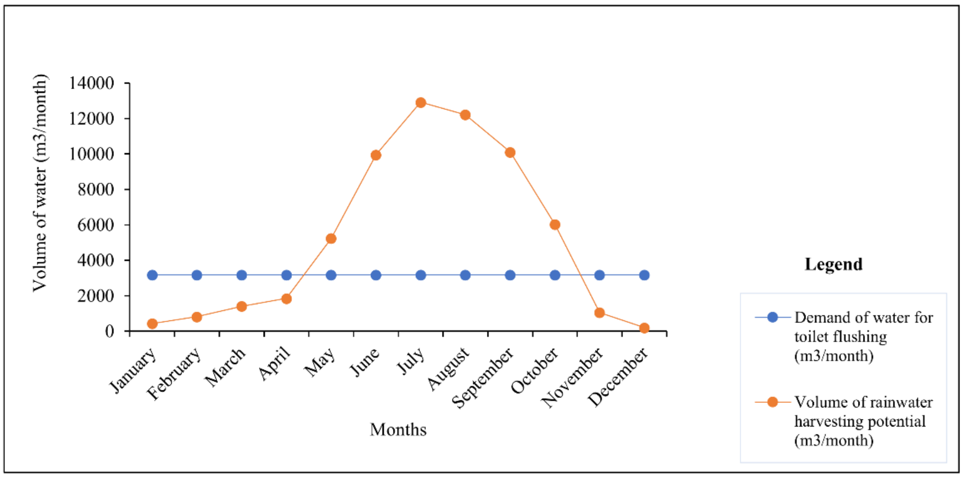


Figure 5.6: Month wise demand of water for toilet flushing and rainwater harvesting potential at Jadavpur University main campus

As per the official data, on an average, in the working days the total consumption of water per day is 1789 cubic metres. In this study, the total working days per month has been considered as 20. So, the monthly total water demand is 1789 × 20, that is 35780 cubic metres. The percentage of RWHP with respect to total demand of water has been calculated and portraited in table 5.f. This table shows that in the months of June to September large amount of water can be supplied by rooftop rainwater harvesting, which can reduce the pressure on primary sources to meet the demand of water.

Table 5.f: The percentage of RWHP with respect to total water demand

Months	**Total demand of water (m^3/month)**	**Volume of rainwater harvesting potential (m^3/month)**	**Percentage of water that can supply by rooftop rainwater harvesting (%)**
January	35780	431.99	1.21
February	35780	816.63	2.28
March	35780	1406.32	3.93
April	35780	1854.35	5.18
May	35780	5234.37	14.63
June	35780	9953.79	27.82
July	35780	12920.2	36.11
August	35780	12217.44	34.15
September	35780	10102.87	28.24
October	35780	6031.44	16.86
November	35780	1053.37	2.94
December	35780	201.13	0.56

Source: Computed by the author

Apart from that in the months of rainy season, the study area (Jadavpur University main campus) frequently becomes inundated. Figure 5.7 depicts the inundation of the southern end of the university campus. So, if the rooftop rainwater can be collected through rainwater harvesting techniques, it can be used for non-potable purposes like for toilet flushing undergoing physical purification process and on the other hand, it can reduce the flooding situation at the time of rainfall.

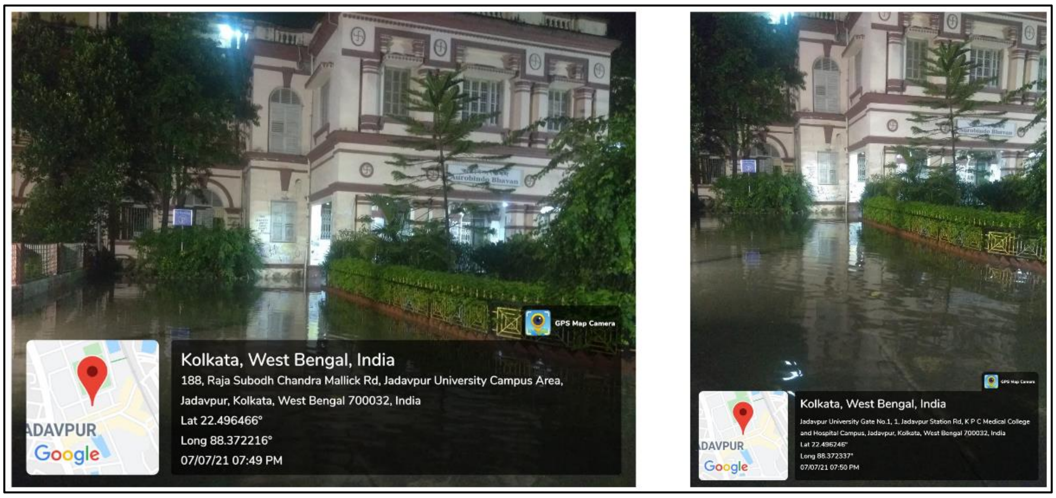


Figure 5.7: Inundation of the southern end of the Jadavpur University main campus in the month of July, captured by the author.

Based on the findings presented in Figure 5.6 it has been observed that the months of June to September exhibit a surplus of water for the campus of Jadavpur University. Again, it is evident from table 1 that the months having less variability is during the monsoon season i.e. from June to September.

Table 5.g: Rainwater Harvesting Potential in Higher Educational Institutions within KMC during monsoon months

Years	Monsoon Months	Average rainfall (in millimeters)	Total average rainfall (in millimeters)	Runoff coefficient	Total rooftop area of all the colleges	RWHP (cubic metre)	Total rooftop area of all the Universities	RWHP (cubic metre)	Total rooftop area of all Higher educational institutions	RWHP (cubic metre)
1991-2020	June	254.38	1154.99	0.8	70622	65254	103523	95654	174145	160908
	July	330.19								
	August	312.23								
	September	258.19								

Source: Computed by author

Hence, considering the intersection of the two datasets, the four months i.e.; June to September, have been considered for calculating the significance of the RWHS of the selected Higher Educational Institutions within the study area. So, considering the monsoon months, i.e., from June to September, the total RWHP of 160908 cubic metres has been calculated in table 5.g.

Table 5.g. shows that the total average rainfall of June to September months for 30 years of rainfall is 1154.99 millimetres and based on that amount of rainfall the RWHP has been calculated. The RWHP of all the colleges under university of Calcutta within the study area has been found as 65254 cubic metres, that is 65254000 litres, while on all the universities 95654 cubic metres, i.e.; 95654000 litres of rainwater can be harvested.

In this study, the emphasis has been given to use the harvested rainwater for toilet flushing. Hence, we calculate the number of flushing that we can use by harvesting rainwater automatically. This study sets particular emphasis on the utilization of harvested rainwater for the purpose of toilet flushing. Therefore, the calculation of the quantity of flushing that can be facilitated through automated utilization of harvested rainwater is conducted. Thus, in order to determine the potential for rainwater harvesting on rooftops for the purpose of toilet flushing, it is necessary to take into account the standardized size of the flushing tank and the average frequency of toilet usage per individual on a daily basis. Based on the available data, an analysis has been conducted to determine the feasibility of utilizing harvested rainwater for toilet flushing during the monsoon months, specifically focusing on the main campus of Jadavpur University.

Table 5.h: Average daily Rainwater Harvesting Potential (RWHP) within Jadavpur University main campus during monsoon months in terms of total number of persons can be supplied by rooftop harvested rainwater.

Total RWHP (in litres) in monsoon months (June-September)	Average daily RWHP (in litres) in monsoon months (June-September) (45194296.70 litres /122 days)	Discharge from cistern per flush (in litres)	Use of flush in number of times per day and its volume of water		Total number of persons using cisterns for ‘n’ number of times (370445/V)
			Number of times ‘n’	volume of water in litre (v)	
45194296.70	370445	10	1	10	37044
			2	20	18522
			5	50	7409
			10	100	3705

Source: Computed by the author

5.4. Conclusion:

Water crisis has become a significant issue in urban areas due to rising water consumption. On the other hand, the study area not only faces water crisis in the dry months but also pluvial flooding at the time of rainfall. There is no way for the authorities to decrease water consumption, but they can increase the water supply and improve the capacity to store rainfall underground to alleviate the current crisis. The usage of many technologies is now required to address this kind of challenge. Rainwater harvesting can serve as a viable solution for concurrently addressing the issue of water scarcity and the problem of pluvial flooding. Therefore, the present study aimed to investigate the effectiveness of rooftop rainwater harvesting to promote water sustainability. The water that will be gathered has solely been intended for non-potable purposes and doesn't require any additional purification. The cost to establish a rainwater collecting system is primarily the initial expenditure in construction and a little more for maintenance. It is expected that this study will help policymakers in implementing a cost-effective Rainwater Harvesting (RWH) system. Specifically, the study explores the automatic circulation of rainwater from storage tanks using the effect of gravitational force. Therefore, implementing rainwater harvesting techniques within KMC can be most effective for water sustainability.

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CHAPTER 6

DIMENSIONING THE ROOFTOP RAINWATER HARVESTING STRUCTURE (RRWH$_{SR}$)

6.1. Introduction:

Rooftop rainwater harvesting serves as a cost-effective source of indoor water and represents a sustainable water management strategy. It can help decrease runoff volume and peaks while alleviating water scarcity during dry periods. Especially in urban and semi-urban regions, rainwater harvesting (RWH) has proven to be a sustainable way to solve the water shortage. RWH system efficiency and efficacy mostly rely on the appropriate dimensioning of its components, particularly the top structure comprising the catchment area, conveyance systems, and initial storage or filter units. Accurate dimensioning guarantees that rainwater harvesting systems fulfill requirements without excessive or insufficient component design. Fewkes and Butler (2000) assert that the ideal design of rainwater harvesting systems must equilibrate water supply, demand, and cost-effectiveness. The dimensions of the upper structure are crucial since they dictate the volume of rainwater that may be collected. This is contingent upon various elements, including roof area, rainfall intensity, runoff coefficient, and local rainfall trend (Jenkins, 2007). The rooftop or catchment area serves as the principal element for rainwater harvesting. Research indicates that an area of at least 50-80 m² is typically sufficient for a modest household system in urban environments (Kumar et al., 2012). Recent advancements in modeling technologies have facilitated more accurate dimensioning. Software like SWMM (Storm Water Management Model), Rainwater, and RHMS enables users to simulate rainfall-runoff and enhance rainwater harvesting solutions (Campisano et al., 2017). These instruments amalgamate regional precipitation data, roofing attributes, and utilisation trends.The drainage system, principally gutters and drains, must be dimensioned according to maximum rainfall intensity. Inadequately sized gutters may lead to overflow losses. Gutter sizing recommendations typically include a minimum diameter of 100 mm for regions with high rainfall (Pacey & Cullis, 1986). Filtration systems, typically installed prior to storage tanks, must be appropriately sized to prevent blockage and maintain the quality of the water. Research conducted in Chennai, India, indicated that appropriately sized rainwater harvesting systems might satisfy as much as sixty percent of yearly residence water requirements (Sivanappan, 2006). Lima et al. (2020) illustrated that inadequately designed systems in Brazil resulted in overflows during intense rainfall or water scarcity during arid conditions, underscoring the necessity for precise dimensioning. Urban centres such as Kolkata encounter significant issues pertaining to water supply, seasonal inundation, and overloaded municipal systems. Rainwater harvesting (RWH) provides a decentralized method to augment water supply and mitigate runoff. The efficacy of these systems is fundamentally reliant on the sizing of the upper structure, encompassing the catchment area, conveyance system, and principal filtering elements. In urban environments, rooftops function as the principal catchment zones. In Kolkata, typical residential buildings include concrete or asbestos roofs, with runoff coefficients between 0.7 and 0.9 (CPCB, 2020).

Kolkata experiences an average yearly rainfall of around 1,600 mm, predominantly during the monsoon period from June to September (IMD, 2021). Although ample rainfall, the city encounters intermittent water shortages attributable to inadequate delivery and dependence on groundwater. Urban growth and the proliferation of impermeable surfaces have diminished natural recharge and heightened runoff, rendering rainwater harvesting especially beneficial (Ghosh & Ghosh, 2019). Kolkata experiences a yearly average precipitation of 1,582 mm, primarily occurring from June to September (IMD, 2021). Urban development and impervious surfaces have exacerbated runoff, while groundwater levels have diminished due to excessive extraction (CGWB, 2020). The city's architectural forms—spanning from individual residences to high-rise apartments—require scalable and flexible rainwater harvesting designs. Rooftops function as essential catchment regions, with designs ranging from flat concrete slabs to sloped asbestos or tiled roofs, which affects runoff efficiency. In urban centres such as Kolkata, instruments like SWMM (EPA), the RWH Calculator from the Ministry of Jal Shakti, and iRAIN (IIT Bombay) assist in evaluating system performance. These instruments amalgamate precipitation data, roof dimensions, storage specifications, and user demand profiles to facilitate accurate sizing (Biswas et al., 2020). PVC downpipes with diameters ranging from 75 to 100 mm are frequently applied; however, they often fail to manage peak rainfall exceeding 50 mm per hour, leading to surplus and wastage (Sengupta & Pal, 2021). This demonstrates the necessity for tailored hydrological simulation when designing conveyance frameworks.

The objective of this chapter is to present a methodology for dimensioning rainwater harvesting tanks based on the rainfall data, area of rooftops, types of rooftops, and other parameters. Establishing the appropriate dimensions for a rainwater harvesting tank is essential, as it significantly influences the system's effectiveness, ensuring an optimal equilibrium between rainwater collection and the avoidance of superfluous expenses and potential water quality concerns arising from excessive storage. An appropriately sized tank will consistently supply sufficient harvested rainwater to meet specified requirements, such as toilet flushing, car washing, gardening, or even boosting domestic water demands based on rainfall patterns and water usage. An excessively large tank incurs redundant initial expenses, whereas a tank that is insufficiently sized may fail to accommodate adequate water storage during significant rainfall, resulting in potential overflow and water wastage. Conversely, a properly sized tank optimizes the capacity of roof catchment areas, effectively capturing maximum rainwater during precipitation events and reducing dependence on municipal water sources. This study attempts to figure out the ideal dimensions of storage tanks based on assured weekly and monthly rainfall and water consumption.

6.2. Materials and Methods:

This section delineates the scientific approach employed for sizing the tank of rainwater harvesting (RRWH), specially tailored to the climatic and architectural context of the study area (KMC). The methodology incorporates long-term rainfall data analysis, hydrological calculations, and empirical modeling to ascertain the ideal tank dimensions based on assured rainfall, catchment area, and runoff attributes. The optimal dimensions for the storage tank in rooftop rainwater harvesting have been determined by calculating the assured rainfall for the study area.

6.2.1. Data collection:

The principal dataset consists of 120 years of historical weekly and monthly precipitation data (1901–2020) for the Kolkata Municipal Corporation (KMC) area. In order to assess the assured rainfall at 50%, 60%, and 70% in the study area, 120 years of weekly and monthly rainfall data from 1991 to 2020 were retrieved from WRIS (Water Resources Information Systems), a web-based spatial data portal. The temporal rainfall distribution throughout the monsoon season was structured and analysed using standard meteorological week classifications provided by the India Meteorological Department (IMD).

6.2.2. Assured Rainfall estimation:

Assured rainfall refers to the minimum amount of rainfall anticipated to occur at a certain probability level, typically set at 50%, 60%, and 70%, frequently utilised for strategic planning and water resources management. It's an idea for evaluating the dependability or consistency of rainfall. This analysis is essential for planning or ascertaining the best tank size for rooftop rainwater harvesting in a certain region. A study indicates that an area is expected to receive a minimum of 30 mm of rainfall per week with a 60% probability during any specified time frame is classified as ‘assured rainfall’ at that probability level. This provides a solid foundation for the development of water infrastructure in regions experiencing fluctuating rainfall patterns.

The ‘standard meteorological week’ given by the ‘India Meteorological Department’ has been taken into consideration in this study to determine the weekly assured rainfall. Here, the computation has been done for weekly and monthly assured rainfall, and the tank size was determined based on 60% assured rainfall. The weekly assured rainfall has been computed particularly during the rainy season, spanning from week 18 to week 44, as delineated by the India Meteorological Department, to determine the assured rainfall at a specified probability of 60%. Opting for 60% assured rainfall as the design basis offers a prudent and practical estimation that strikes a balance between excessive design, resulting in avoidable capital expenditures, and insufficient design, causing regular overflows or shortages. This also takes into account climatic variability, which is a crucial factor in urban areas reliant on monsoons, such as Kolkata. The chart of ‘standard meteorological week’, which has been followed in this study to assess the assured rainfall given by the Indian Meteorological Department, are in Table 6.a. The calculation of monthly assured rainfall was conducted to evaluate cumulative storage needs and reinforce the rationale behind seasonal design considerations.

Table 6.a: Standard Meteorological Weeks (SMW)

Week No.	**Dates**	**Week No.**	**Dates**
1	01 Jan – 07 Jan	27	02 Jul –08 Jul
2	08 Jan – 14 Jan	28	09 Jul – 15 Jul
3	15 Jan – 21 Jan	29	16 Jul – 22 Jul
4	22 Jan – 28 Jan	30	23 Jul – 29 Jul
5	29 Jan – 04 Feb	31	30 Jul – 05 Aug
6	05 Feb – 11 Feb	32	06 Aug – 12 Aug
7	12 Feb – 18 Feb	33	13 Aug – 19 Aug
8	19 Feb – 25 Feb	34	20 Aug – 26 Aug
9*	26 Feb – 04 Mar	35	27 Aug – 02 Sep

10	05 Mar – 11 Mar	36	03 Sep – 09 Sep
11	12 Mar – 18 Mar	37	10 Sep – 16 Sep
12	19 Mar – 25 Mar	38	17 Sep – 23 Sep
13	26 Mar – 01 Apr	39	24 Sep – 30 Sep
14	02 Apr – 08 Apr	40	01 Oct – 07 Oct
15	09 Apr – 15 Apr	41	08 Oct – 14 Oct
16	16 Apr – 22 Apr	42	15 Oct – 21 Oct
17	23 Apr – 29 Apr	43	22 Oct – 28 Oct
18	30 Apr – 06 May	44	29 Oct – 04 Nov
19	07 May – 13 May	45	05 Nov – 11 Nov
20	14 May – 20 May	46	12 Nov – 18 Nov
21	21 May – 27 May	47	19 Nov – 25 Nov
22	28 May – 03 Jun	48	26 Nov – 02 Dec
23	04 Jun – 10 Jun	49	03 Dec – 09 Dec
24	11 Jun – 17 Jun	50	10 Dec – 16 Dec
25	18 Jun – 24 Jun	51	17 Dec – 23 Dec
26	25 Jun – 01 Jul	52**	24 Dec – 31 Dec

* Week No. 9 will be 8 days during leap year

** Week No. 52 will always have 8 days

Source: India Meteorological Department

6.2.3. Tank Sizing:

To establish a suitable range of tank sizes, calculations were performed for both the maximum and minimum storage capacities. The maximum storage has been determined using the daily mean of the monthly average rainfall recorded throughout the monsoon season. The calculation of minimum storage was derived from the daily mean of 60% assured rainfall during the corresponding months. The optimal storage volume was determined by calculating the average of the minimum and maximum values, resulting in a design approach that effectively avoids both overflow and underutilisation.

6.3. Results and Discussion:

This section outlines the findings obtained from the statistical analysis of long-term rainfall data and examines the implications of reliable rainfall for the design and implementation of rooftop rainwater harvesting systems in the Kolkata Municipal Corporation (KMC) area. The analysis underscores the fluctuations in rainfall over various months and standard meteorological weeks, pinpointing the most reliable times for rainwater harvesting. The results establish a basis for identifying the most effective tank sizing, guaranteeing that the system operates efficiently even in less favorable climatic conditions. This chapter analyses the statistical results and connects them with practical design aspects for urban rainwater harvesting systems.

6.3.1. Weekly Mean and Assured Rainfall:

This study aims to establish the optimal tank size for rooftop rainwater harvesting by calculating the weekly assured rainfall and comparing it with the weekly mean rainfall. When determining the dimensions of a rooftop rainwater-harvesting tank in the research area, it is essential to reconcile storage capacity with the variability and dependability of precipitation. Assured rainfall, when integrated with roof area and water demand, facilitates precise tank sizing to fulfill user requirements without excess. The dataset covers the period from Week 18 to Week 44, encompassing the entire monsoon cycle from early May to the end of October. The Mean Rainfall (MR) and Assured Rainfall (AR%) at various probabilities (50%, 60%, 70%) provide valuable insights into both the amount and predictability of rainfall. The Assured Rainfall (AR%) values at 50%, 60%, and 70% provide valuable insights into the historical probability of specific levels of rainfall occurring. Table 6.b presents the weekly assured rainfall data of the study area over 120 years of rainfall from 1901 to 2020.

Table 6.b: Weekly Mean Rainfall (MR) and Assured rainfall (AR %) within Kolkata Municipal Corporation (KMC) over 120 years of rainfall from 1901 to 2020.

Number of Weeks	**Mean Rainfall (mm)**	**Assured Rainfall (%)**		
		50	**60**	**70**
18	21.68	17.17	10.46	3.26
19	31.17	20.7	13.21	7.38
20	24.64	17.3	11.46	8.47

21	34.32	23	16.7	10.21
22	36.86	27.8	21.13	13.47
23	53.26	35.96	28.66	20.21
24	64.06	49.57	38.99	26
25	74.43	57.88	46.81	38.38
26	71.82	57.24	41.26	34.34
27	77.76	61.5	55.2	43.31
28	70.39	58.14	50.05	40.25
29	72.9	61.62	50.45	40.01
30	80.24	73.9	61.41	49.46
31	80.62	62.59	54.84	44.24
32	74.51	64.76	53.93	45.81
33	72.12	57.58	52.23	42.5
34	66.28	59	47.8	40.28
35	67.54	57.6	46.34	42.37
36	63.07	50.73	41.76	33.8
37	57.14	45.66	35.47	26.56
38	52.63	46.25	36.34	28.89
39	59.36	37.09	27.54	19.51
40	42.63	29.19	22.16	13.42
41	31.43	18.07	12.23	8.77
42	29.65	10.54	5.91	2.16
43	18.63	2.65	0.97	0
44	11.87	0	0	0

The data presented in Table 6.b. indicates a notable disparity between the mean rainfall and the assured rainfall. Occasionally, a sudden surge of rainfall during a specific period can elevate the average rainfall levels. Consequently, the assured rainfall levels of 50%, 60%, and 70% consistently fall short of the mean rainfall.

The weekly mean rainfall for Kolkata (1901–2020) reveals a clear monsoon rhythm. A significant increase in mean rainfall (37 to 74 mm) from weeks 22 to 25 and enhanced reliability (from 13% to 38% at 70% assured rainfall) signify the shift from unpredictable pre-monsoon showers to consistent rainfall. From weeks 26 to 31, the highest rainfall volume ranged from 71.82 mm to 80.62 mm, demonstrating both substantial and relatively stable mid-season precipitation. Between Weeks 32 and 38, a progressive decrease in both intensity and confidence indicates the monsoon's withdrawal. From Weeks 39 to 44, a swift decline in mean rainfall (from 60 to 12 mm) and near-zero guaranteed probabilities suggests the onset of the dry season. The ten-week core monsoon, spanning from Week 24 to Week 33, provides the most reliable water supply for urban needs. The early (Weeks 18–21) and late (Weeks 39–44) periods exhibit significant variability, rendering them inappropriate for rain-dependent operations, including rooftop rainwater harvesting.

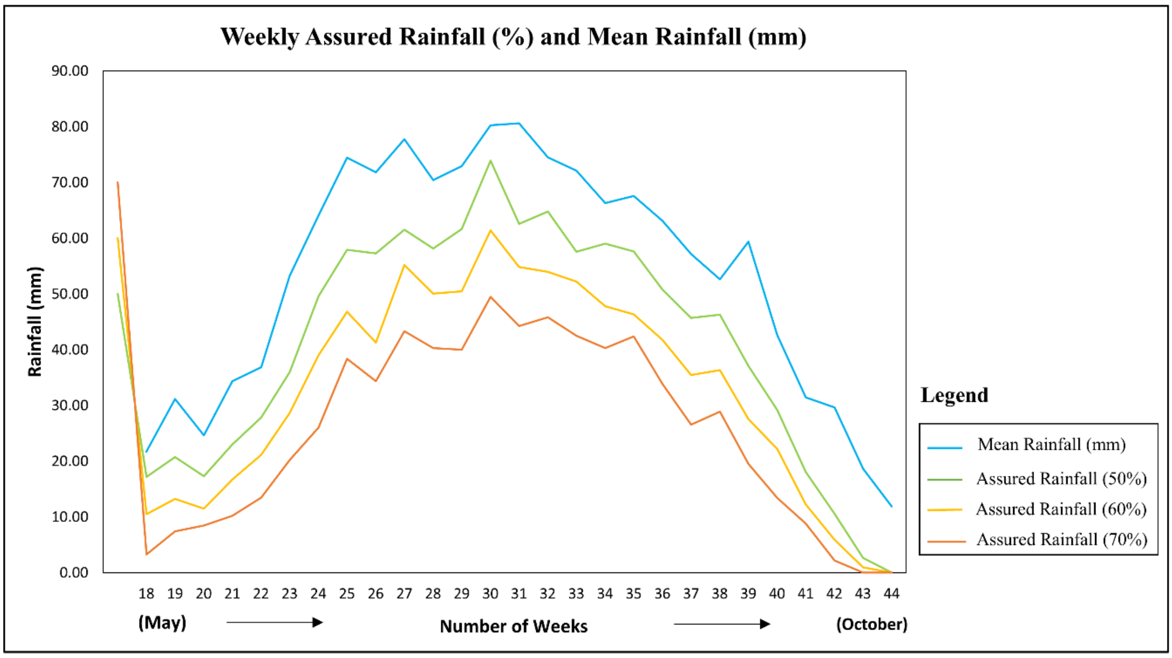

Figure 6.1: Weekly Mean Rainfall (MR) and Assured Rainfall (AR%) within Kolkata Municipal Corporation (KMC) over 120 years of monthly rainfall from 1901 to 2020.

6.3.2. Monthly Mean and Assured Rainfall:

Table 6.c, titled ‘Monthly Mean and Assured Rainfall within Kolkata Municipal Corporation (KMC)’, employs a 120-year dataset from 1901 to 2020, providing significant insight into the seasonality and reliability of rainfall in Kolkata, which is crucial for the design of effective rooftop rainwater harvesting (RRWH) systems. Both the monthly mean rainfall and the assured rainfall at 50%, 60%, and 70% probability levels have been calculated (Table 6.c), allowing

for an evaluation of average circumstances as well as rainfall reliability, which is essential for effective water resource planning.

Table 6.c: Monthly Mean Rainfall (MR) and Assured Rainfall (AR%) within Kolkata Municipal Corporation (KMC) over 120 years of monthly rainfall from 1901 to 2020.

Months	**Mean Rainfall (mm)**	**Assured Rainfall (%)**		
		50 %	**60 %**	**70 %**
Jan.	12.67	3.01	0.89	0.2
Feb.	25.96	17.01	9.06	4.41
Mar.	33.56	17.41	13.07	6.32
Apr.	53.78	41.59	36.77	25.88
May.	130.35	119.26	105.37	87.81
Jun.	271.03	249.4	216.16	180.93
Jul.	325.33	312.12	273.41	249.69
Aug.	320.62	297.9	278.23	256.05
Sep.	247.86	222.65	202.35	181.25
Oct.	129.47	110.51	92.76	73.89
Nov.	24.84	6.63	2.34	0.26
Dec.	5.92	0	0	0

The analysis indicates a significant seasonality, characterized by a substantial concentration of rainfall during the monsoonal period from June to September. The four months in question play a significant role in the total annual precipitation, with July recording a mean monthly rainfall of 325.33 mm and August following closely at 320.62 mm. More significantly, the 60% guaranteed rainfall throughout these months—which ranges from 216.16 mm in June to 278.23 mm in August, which confirms the relative dependability and temporal concentration of precipitation in monsoon season. Further possibility for early season water collection is suggested by the modest rainfall in the pre-monsoon months of April and May, with assured values of 36.77 mm and 105.37 mm, respectively, with 60% assured rainfall. In contrast, the post-monsoon and winter months (November to March) exhibit minimum to insignificant precipitation, with guaranteed values often below 10 mm for the most of these months and virtually no rainfall in December. This prolonged drought highlights the necessity for sufficient storage capacity to satisfy residential or institutional water requirements during times of scarcity. Employing 60% guaranteed rainfall as a design criterion guarantees system resilience under conservative climatic scenarios, providing a safeguard against inter-annual fluctuation and climatic unpredictability. The data together demonstrate the viability of Rainwater Harvesting (RRWH) in Kolkata, emphasising the essential requirement for strategic tank sizing and demand management to successfully address the extended dry season.

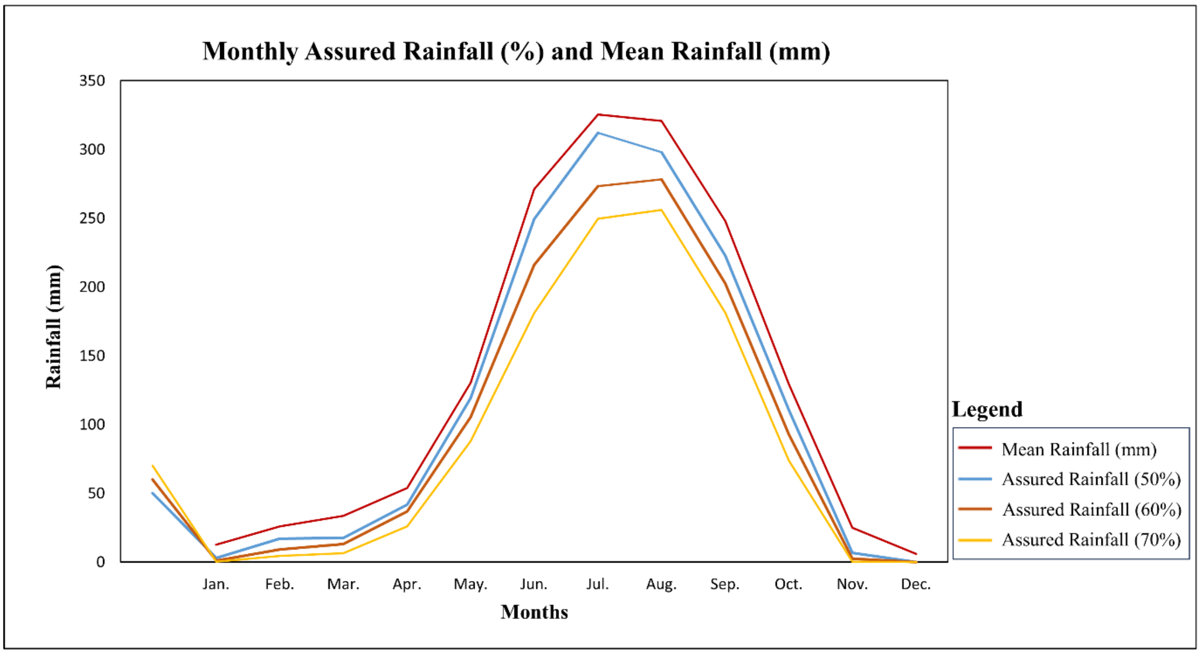

Figure 6.2: Monthly Mean Rainfall (MR) and Assured Rainfall (AR %) within Kolkata Municipal Corporation (KMC) over 120 years of monthly rainfall from 1901 to 2020

6.3.3. Proposed dimension of the tank size for rooftop rainwater harvesting (RRWH):

The storage capacity and the number of tanks should be structured and arranged in such a way that it reduces overflow from tanks while, at the same time, there should be adequate flow of water from the tanks to the cistern to maintain optimal utilisation. In this study, the 60% assured rainfall has been used to determine the optimal tank size for rooftop rainwater harvesting. This study examines the 60% guaranteed rainfall during the June–September southwestern monsoon season and converts it into daily averages. The minimum, maximum, and optimal storage capacity for a rainwater harvesting tank are calculated using a 100 m² rooftop catchment and a runoff coefficient of 0.8.

Hence, the proposed tank storage should be as follows:

Maximum storage capacity = Daily mean rainfall during monsoon x Catchment area x Runoff Coefficient (0.8)

Minimum storage capacity = Daily mean of 60% assured rainfall during monsoon x Catchment area x Runoff Coefficient (0.8)

Table 6.d: Daily mean of 60% assured rainfall during monsoon

Area of Rooftop (considered)	Months	Assured Rainfall in mm (60%)	Mean of 60 % Assured rainfall in mm.	Daily mean of 60% assured rainfall in mm. (242.54/30)	Monthly Mean Rainfall (mm)	Grand Mean of Mean monthly Rainfall (mm)	Daily mean rainfall in mm. (291.21/30)
100 sq. metre	June	216.16	242.54	8.08	271.03	291.21	9.71
100 sq. metre	July	273.41			325.33		
100 sq. metre	August	278.23			320.62		
100 sq. metre	September	202.35			247.86		

The monthly 60% assured rainfall depths, together with their monthly, daily, and overall grand means, are summarised in the above table (Table 6.d).

Here, the area of the rooftop is considered 10m x 10m = 100 sq. m.

Maximum storage capacity = 9.71 x 100 x 0.8 = 776.8 litre

Minimum storage capacity = 8.08 x 100 x 0.8 = 646.4 litre

So, the tank storage should vary from 646.4 litre to 776.8 litre.

Ideal storage capacity should be = (Minimum storage + Maximum Storage)/2 = (646.4 litre + 776.8 litre)/2 = 711.6 litre.

Size of the tanks = 711.6 / n   where n is the number of tanks, which will depend on the size of the catchment area & $n \geq 2$

Thus, an optimal capacity of roughly 712 litres tank will equilibrate low and high daily rainfall throughout the monsoon seasons for rooftop rainwater harvesting. This optimal sizing will reduce overflow losses during peak rainfall and prevent underutilisation during low rainfall, hence improving the effectiveness and sustainability of rainwater harvesting systems. This idea facilitates scalable implementation across diverse roof dimensions and urban environments, considerably enhancing decentralized water management, alleviating strain on municipal supplies, and bolstering climate resilience in urban areas like in Kolkata Municipal Corporation (KMC).

6.4. Conclusion:

This study develops a scientific technique for sizing rooftop rainwater harvesting (RRWH) tanks utilising long-term reliable rainfall data. This research provides a scientifically robust approach for tank dimensioning by analysing 120 years of historical rainfall data and computing assured rainfall at 50%, 60%, and 70% probability levels, ensuring practicality and resilience. It highlights the necessity of equilibrating storage capacity with rainfall dependability and urban water requirements, facilitating the best utilisation of collected rainwater while circumventing excessive infrastructure expenses. By using 60% assured rainfall as a design guideline, the suggested tank capacities are guaranteed to continue operating even in conservative climates, improving system dependability and lowering the possibility of overflow or underutilisation. Analysis of monthly rainfall over a year indicates obvious seasonality, with monsoon months (from June to September) contributing most of the rainfall. This can be very useful information, especially to plan out storage, as the water harvested during these months must last the dryer months. The optimal storage capacity for a 100 m^2 rooftop catchment area with a runoff coefficient of 0.8 is around 712 litres, providing a balanced solution between maximum and minimum storage needs. This sizing guarantees effective collection and use of rainfall, diminishing dependence on municipal water sources, and promoting sustainable urban water management. This method confirms not only resistance during dry spells but also a scalable strategy for tank sizing that can be tailored to various catchment regions and local rainfall traits. Eventually, this work greatly helps to develop and put into place efficient RRWH systems in monsoon-dependent areas, such as within the Kolkata Municipal Corporation.

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CHAPTER 7

VARIOUS POLICY SUPPORT WITH SUSTAINABLE DEVELOPMENT GOALS (SDGS) AND PEOPLE'S PERCEPTION

7.1. Introduction:

Rainwater harvesting (RWH) has attained international significance as a sustainable water management approach that corresponds with the Sustainable Development Goals (SDGs), specifically SDG 6 (Clean Water and Sanitation), SDG 11 (Sustainable Cities and Communities), and SDG 13 (Climate Action). In Australia, towns such as Adelaide have adopted extensive rainwater harvesting systems that diminish reliance on centralised water sources and assist in stormwater management, thus promoting urban sustainability and climate resilience (Mitchell et al., 2008). Berlin, the capital of Germany, incorporates rainwater harvesting via green roofs and permeable urban infrastructure, exemplifying water-sensitive urban design in accordance with both SDG 11 and SDG 13 (Wagner & Breil, 2013). In Singapore, RWH constitutes a component of the national water plan that integrates rainwater harvesting with reclaimed water to improve water security in accordance with SDG 6 (PUB Singapore, 2020). A good example of policy-driven alignment with SDGs 6 and 11 is Chennai, India, where a law requiring rooftop rainwater collection has effectively increased groundwater recharge and urban resilience (Ranganathan et al., 2010). These examples highlight the adaptability of RWH as a decentralised, economical solution for sustainable water availability and climate adaptation in many geographic settings.

The depletion of water resources is a significant problem for urban India and is predicted to precipitate a severe catastrophe in the future, as the urban population is expected to increase from 377 million in 2011 to 600 million by 2031 (Amarasinghe et al., 2004). Therefore, the sustainability of urban water supplies is becoming crucial in India, particularly in rapidly urbanising cities such as Kolkata. The situation is exacerbated by climate unpredictability, excessive groundwater extraction, uncontrolled urban expansion, and inadequate infrastructure, leading to significant water stress and flooding problems (Amarasinghe et al., 2004). As India progresses towards a water-resilient future, the incorporation of stringent water policies, the implementation of decentralised water management technologies such as rooftop rainwater harvesting (RRWH), and the proactive engagement of communities have become essential. RRWH, as a decentralised and ecologically sustainable water conservation method, alleviates urban water stress by improving groundwater recharge, diminishing runoff, and augmenting municipal supply systems (Bhattacharya & Roy, 2018; Ghosh & Ghosh, 2019). India's dedication to the United Nations 2030 Agenda for Sustainable Development is evident in its compliance with various Sustainable Development Goals (SDGs), especially SDG 6 (Clean Water and Sanitation), SDG 11 (Sustainable Cities and Communities), and SDG 13 (Climate Action) (NITI Aayog, 2021; UNDP India, 2020; Ghosh & Ghosh, 2019). These objectives support climate-resilient infrastructure, efficient water use, and fair access to safe water-goals that interact with national frameworks including the National Water Policies (1987, 2002, 2012), the draft 2020 on National Water Policy, and urban missions like AMRUT and the Jal Jeevan Mission. The National Water Policy (2012), for instance, particularly supports rainwater collecting, aquifer recharge, and participation of stakeholders to improve urban water resilience (Ministry of Water Resources, 2012). The policy frameworks stress not only infrastructure improvements but also reforms to government and community engagement.

In Kolkata, the Kolkata Municipal Corporation's (KMC) building codes requiring rainwater harvesting in new constructions (KMC, 2019), alongside state-level initiatives such as ‘Jal Dharo-Jal Bharo,’ seek to promote rainwater harvesting and groundwater recharge in urban and peri-urban areas (Government of West Bengal, 2004). Notwithstanding these regulatory frameworks, effective implementation is frequently hindered by insufficient public knowledge, infrastructural limitations, and inadequate institutional coordination (Bhattacharya & Roy, 2018; Chakraborty & Mukherjee, 2016).

The public's view and behavioural inclinations about the adoption of RRWH systems substantially impact the efficacy of these programs. A recent empirical study within KMC indicates a significant public endorsement of Rainwater Harvesting (RRWH), with 80% of respondents supporting the mandatory implementation of such systems. However, insufficient technical understanding, awareness of incentives, and regulatory ambiguity persist as significant difficulties (Chakraborty & Mukherjee, 2016). Surveys of commercial establishments, including malls, hospitals, and hotels, indicate limited adoption of Rooftop Rainwater Harvesting (RRWH) systems, despite significant rooftop capacity, underscoring a disparity between legislative objectives and practical execution.

This chapter aims to examine the convergence of policy, sustainability and community perception about rooftop rainwater harvesting within KMC. It investigates the function of national and state water policies in promoting sustainable urban water management, assesses the city's advancement in attaining pertinent Sustainable Development Goals (SDGs), and evaluates the determinants affecting community and institutional acceptance of Rooftop Rainwater Harvesting (RRWH) systems. This study seeks to provide practical ideas for improving urban water sustainability in the study area (KMC) and comparable cities using a combination of policy analysis with Sustainable Development Goals (SDGs) and empirical fieldwork.

7.2. Methodology for Policy Analysis Incorporating SDGs and People's Perceptions on Rooftop Rainwater Harvesting (RRWH):

A multi-faceted analytical approach has been employed to perform a thorough analysis of policies that promote Rooftop Rainwater Harvesting (RRWH) within the framework of Sustainable Development Goals (SDGs). This incorporates a comprehensive policy analysis methodology that commences with a thorough examination of national and state-level policy documents, including the National Water Policies of 1987, 2002, 2012, and the Draft NWP 2020, to delineate the progression of regulatory ideologies and priorities over time. A special focus has been put on the alignment of these policies with Sustainable Development Goals 6 (Clean Water and Sanitation), 11 (Sustainable Cities and Communities), and 13 (Climate Action). In addition, sectoral initiatives including Jal Jeevan Mission, Jal Shakti Abhiyan, AMRUT, and AMRUT 2.0, along with state programs such as 'Jal Dharo-Jal Bharo' and the Kolkata Municipal Corporation's building regulations, are rigorously evaluated for their policy objectives, execution strategies, and institutional collaboration. Comparative case studies from global cities such as Adelaide, Berlin, and Singapore have been used to provide context for the effectiveness and innovation of policies in RRWH practices. The analysis incorporates stakeholder perceptions, concentrating on public and institutional responses in the study area to evaluate the effectiveness of these policy frameworks. This combined approach, integrating document review, policy mapping, comparative assessment, and perception analysis, will provide a comprehensive understanding of the interactions among policy, sustainability, and public engagement in advancing RRWH.

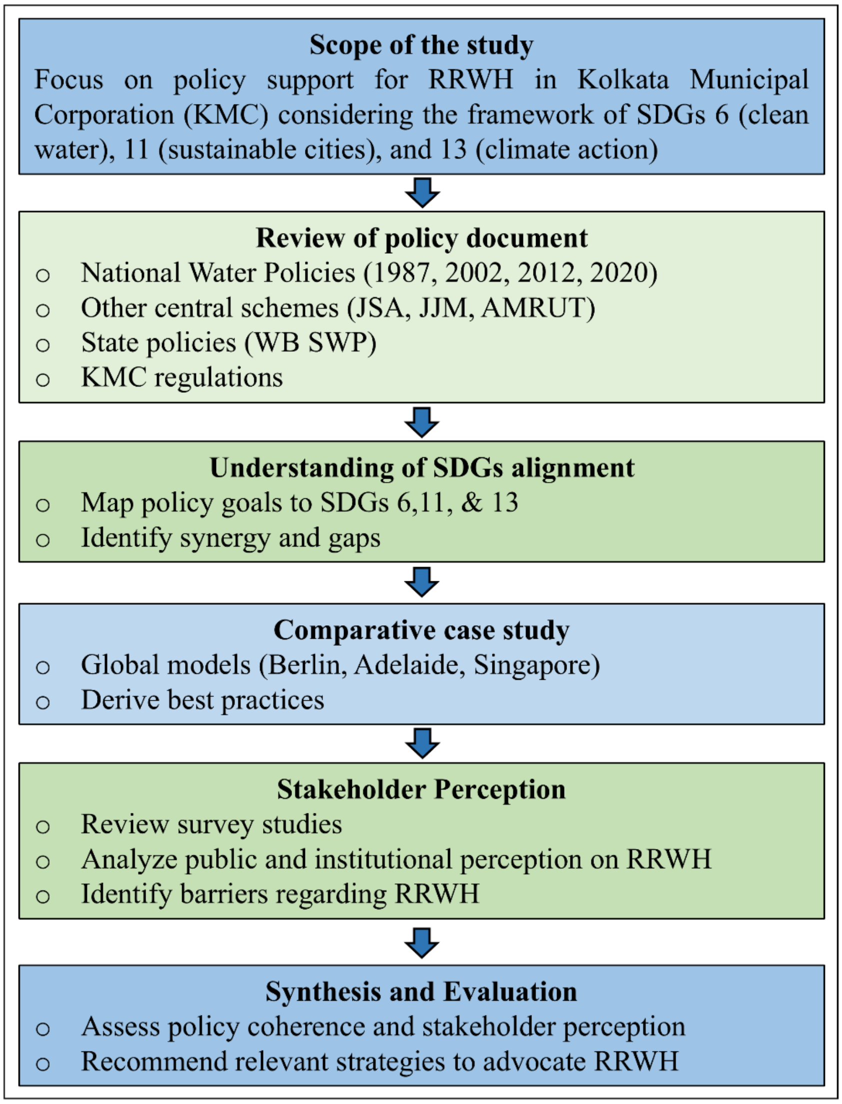


Figure 7.1: Methodological Framework for Policy Analysis Incorporating SDGs and People's Perceptions on Rooftop Rainwater Harvesting (RRWH)

7.2.1. People's Perception and Institutional Practices of RRWH:

A comprehensive field study was conducted within the Kolkata Municipal Corporation (KMC) area to extensively assess the awareness, perception, and implementation status of Rooftop Rainwater Harvesting (RRWH) among urban households and significant institutional buildings, including malls, hospitals, and hotels. The household section included a convenience sampling of 600 respondents, sourced from designated municipal wards that reflect varied socio-economic and geographical situations. This methodology ensured a comprehensive and representative comprehension of public sentiments, awareness of rainwater harvesting policies, and behavioural intentions towards the adoption of RRWH. An institutional survey was concurrently conducted in targeted malls, hospitals, and hotels utilising purposive sampling, based on their extensive rooftop areas, significant water demand, and compliance with municipal building code regulations. These institutions were selected to evaluate infrastructure preparedness, adherence to RRWH requirements, and perceived operational difficulties. The household and institutional surveys collectively deliver an in-depth assessment of the practical, perceptual and policy-related aspects of RRWH in the urban context of KMC.

The field survey aimed to document community opinions and institutional practices concerning Rooftop Rainwater Harvesting (RRWH) in KMC. The study employed a mixed-method sampling strategy that incorporated both random (not statistically random) and purposeful sample procedures, specifically designed for the unique characteristics of the target groups—households and institutions. A total of 600 respondents were randomly selected from intentionally identified municipal wards for the household survey. The wards were selected based on geographic variety, population density and disparities in water access conditions. Households within each ward were randomly selected to prevent selection bias. The poll focused on heads of families or adult decision-makers, guaranteeing that the replies represented informed viewpoints on water consumption and rainwater harvesting system adoption. A semi-structured questionnaire was conducted in person, addressing demographics, water usage patterns, awareness of rainwater harvesting policies, perceived advantages and obstacles, and readiness to implement rainwater harvesting systems. Responses were documented using standardised formats and subsequently processed for analysis. This methodology guaranteed a comprehensive and representative comprehension of public sentiments, awareness of rainwater harvesting policies and behavioural intentions towards the adoption of RRWH.

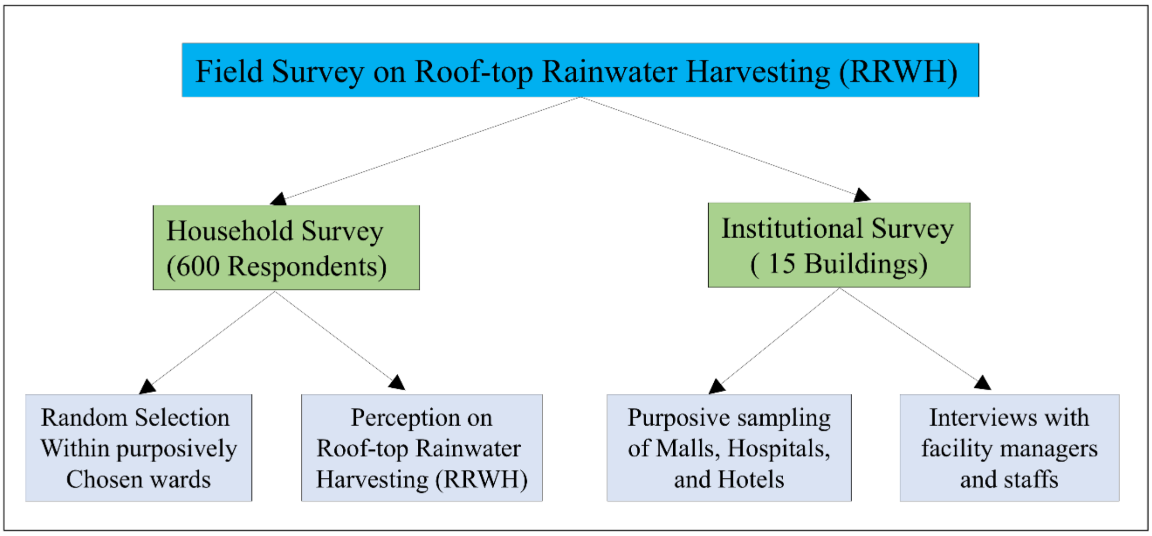


Figure 7.2: Sampling framework for Rooftop Rainwater Harvesting (RRWH)

A purposeful sample of 15 institutions, including malls, hospitals, and hotels (five from each category), was selected based on their significant water demand, extensive rooftop area, and regulatory significance under Kolkata Municipal Corporation (KMC) building regulations. Institutional representatives, including facility managers, engineers and administrative personnel, were interviewed utilising a distinct instrument aimed at evaluating the status of RRWH implementation, compliance motivation, infrastructural constraints and perceived environmental and economic effects. The institutional interviews were performed in person using a predefined questionnaire (schedule). The data from both components were systematically compiled in MS Excel and subjected to analysis for descriptive statistics and thematic insights. This study used both qualitative and quantitative techniques to acquire sufficient data to fit the stated objective. Based on data collected from the study area, the study evaluates community perceptions and attitudes toward rainwater harvesting, considering various demographic, economic, quality and water supply scenarios. The obtained data has been compiled, and several charts and graphs have been generated to facilitate comprehension of the different variables. Throughout the process, ethical standards were meticulously followed, ensuring voluntary participation, informed consent, and the protection of confidentiality for every person who participated.

7.3. Results and Discussion:

7.3.1. Rooftop Rainwater Harvesting (RRWH) and Sustainable Development Goals (SDGs):

Rooftop Rainwater Harvesting (RRWH) plays a crucial role in advancing the Sustainable Development Goals (SDGs), particularly SDG 6 (Clean Water and Sanitation), SDG 11 (Sustainable Cities and Communities), and SDG 13 (Climate Action). The installation of RRWH systems aligns with the broader objectives of SDG 6, which prioritises access to clean water and efficient water utilisation, while also facilitating climate adaptation strategies promoted by SDG 13. Additionally, RRWH enhances sustainable urban infrastructure, a key aspect of SDG 11, by promoting decentralised water systems and alleviating environmental pressure. Thus, Rooftop Rainwater Harvesting Systems (RRWH) in urban development not only bolsters global sustainability objectives but also tackles local issues of water scarcity and climate resilience. The contribution of RRWH in attaining the Sustainable Development Goals 6, 11, and 13 has been discussed below:

7.3.1.1. Sustainable Development Goals:

In 2015, global leaders reached a consensus on 17 objectives, officially termed the Sustainable Development Goals (SDGs). The SDGs aim to foster a better world by 2030 through the eradication of poverty, the combating of inequality, and the urgent response to climate change.

India, as the signatory to the United Nations' 2030 Framework for Sustainable Development, has synchronised numerous national and state-level water projects with the Sustainable Development Goals (SDGs). Three Sustainable Development Goals are especially pertinent to the study area are as follows:

SDG 6: Clean Water and Sanitation:

The sixth objective of sustainable development (SDG 6) seeks to 'Ensure availability and sustainable management of water and sanitation for all, often referred to as the 'water goal''. The connection of water resource management transcends this specific objective, profoundly aligning with other Sustainable Development Goals (SDGs). SDG 6, which emphasises clean water and sanitation, is essential as access to safe water and sanitation is a fundamental human right, critical for health, well-being, and sustainable development, influencing poverty, education, and economic growth. Access to fresh water, both in adequate amounts and of high quality, is crucial for every facet of life and the advancement of sustainable development. Specifically, eight targets must be achieved by 2030 according to SDG 6, which include: access to clean water, sanitation and hygiene, water quality and wastewater management, water efficiency and scarcity, integrated water resources management, protection of water ecosystems, international cooperation and capacity building, and local participation in water and sanitation management.

Rooftop rainwater harvesting (RRWH) directly promotes SDG 6 by enhancing access to safe and sustainable water resources. In various cities, especially where municipal supply is inadequate or inconsistent, Rainwater Harvesting (RRWH) functions as an auxiliary water source suitable for both potable and non-potable applications. It alleviates stress on groundwater and surface water resources while promoting the objective of enhancing water-use efficiency and integrated water resources management (UN-Water, 2018).

SDG 11: Sustainable Cities and Communities:

RRWH aids in the development of inclusive, secure, resilient, and sustainable urban environments, which are the fundamental aims of SDG 11. This decentralised method of harvesting rainwater from rooftops aids in stormwater management, mitigates urban flooding, and alleviates pressure on drainage systems. It advocates for sustainable urban planning and the implementation of green building methods, particularly in densely populated cities where infrastructure development is difficult (UN-Habitat, 2020).

Kolkata's initiatives for stormwater drainage, waste disposal, and water-sensitive urban planning align with SDG 11, which advocates for inclusive, secure, resilient, and sustainable urban environments. Rainwater harvesting systems, urban lakes, and climate-resilient infrastructure enhance urban water resilience (UNDP India, 2020).

SDG 13: Climate Action:

RRWH is essential for climate adaptation as it alleviates the effects of extreme weather phenomena, including droughts and floods. This localised water conservation strategy bolsters community resilience against climate-induced water stress and diminishes the carbon footprint linked to extensive water pumping and treatment facilities. Consequently, RRWH facilitates the construction of climate-resilient infrastructure, a principal emphasis of SDG 13 (IPCC, 2022).

Water resource management is crucial to Kolkata's climate adaption efforts, particularly due to pluvial flooding and seasonal water scarcity. Policies promoting green infrastructure and rainwater harvesting are consistent with the necessity to enhance resilience against climate-induced water risks (Ghosh & Ghosh, 2019).

RRWH is a multifaceted strategy that enhances water supply while promoting environmental stewardship, infrastructure durability, and enduring urban sustainability. The incorporation of this element into urban policy and planning is essential for attaining the Sustainable Development Goals and guaranteeing a secure and adaptable future for expanding urban populations. Thus, RRWH functions as a multifaceted solution that enhances water security, urban sustainability, and climate action.

7.3.2. Government policies supporting Rooftop Rainwater Harvesting (RRWH):

7.3.2.1. National Water Policies in India:

The Ministry of Water Resources of the Government of India has systematically enhanced its institutional backing for rooftop rainwater harvesting (RRWH) via various national and state-level policy initiatives to ensure reliability, effectiveness, and equality in water allocation. The inaugural National Water Policy was enacted in September 1987. It underwent review and revision in 2002 and subsequently in 2012.

7.3.2.1.1. National Water Policy,1987:

India implemented its inaugural National Water Policy (NWP) in 1987, signifying a key advancement in the nation's water resources management strategy. This policy was formulated in reaction to escalating apprehensions regarding water scarcity, ineffective water utilisation, and the absence of a unified approach among states. The 1987 policy underscored the necessity of recognising water as a precious natural resource, highlighted the significance of water conservation, and advocated for the national development of water resources (Ministry of Water Resources, 1987). A key aspect of the 1987 strategy was the acknowledgement of water as a limited and precious resource, necessitating comprehensive planning and coordinated management. The strategy promoted planning at the river basin level, the development of surface and groundwater resources, the minimisation of water losses, and the encouragement of traditional water-saving methods, including rainwater accumulation.

Although the 1987 policy did not specifically address urban water management, its ideas were especially relevant for metropolitan places like Kolkata, given the broad national framework it offered. By the late 1980s, Kolkata, with its reliance on the Hooghly River and groundwater sources, started to feel the strain of increasing urbanisation, waterlogging and ineffective water delivery infrastructure. The emphasis of the strategy on the combined use of surface and groundwater and accumulated rainwater has set the stage for the next water management actions in the city. Though the late 1980s and 1990s saw slow large-scale implementation in Kolkata, the NWP 1987 increased awareness of the urgent need for urban water resource planning, particularly in flood-prone deltaic areas like Kolkata. Kolkata (KMC), which already struggled with pollution in the Hooghly River and leakages in municipal water supply lines, saw particular relevance in the focus on maintaining water quality and cutting waste. Moreover, the NWP's emphasis on drinking water will eventually affect state-level initiatives and laws meant to provide safe and sufficient water for all city dwellers. In the early years, little application of the policy's suggestions in Kolkata was seen because of poor institutional coordination, inadequate infrastructure and low public knowledge (Chattopadhyay, 1995).

Although urban-specific methods were more distinctly articulated in the amended plans of 2002 and 2012, the 1987 policy functioned as a foundational document that impacted both national and state-level water planning, particularly in West Bengal and Kolkata.

7.3.2.1.2. National Water Policy, 2002:

The National Water Policy (NWP) 2002 constituted a significant revision of India's initial 1987 policy, addressing developing issues related to water scarcity, sustainability, climatic variability, and the imperative for effective water governance. The amended strategy placed increased focus on democratic methodologies, equitable water allocation, and demand-side water management, while expressly acknowledging urban and industrial water requirements (Ministry of Water Resources, 2002). This strategy acknowledged water as an economic commodity—a contentious yet significant transition aimed at fostering effective and equitable utilisation through pricing and regulation (Ministry of Water Resources, 2002).

It promoted private sector involvement in water infrastructure, supported community-based strategies, and highlighted the necessity for participatory irrigation management (PIM). The policy indicated an increasing recognition of the necessity for integrated water resource management (IWRM) and emphasised the significance of the conjunctive utilisation of surface and groundwater. Critics contend that although the strategy delineated overarching objectives, it was deficient in robust implementation mechanisms (Iyer, 2003).

Kolkata (KMC), an urban area experiencing periodic water shortages, recurrent urban flooding, and dependence on both surface water (Hooghly River) and groundwater, established the foundation for localised water resource management techniques through the 2002 policy. In accordance with the strategy, the Kolkata Municipal Corporation (KMC) implemented measures to require rainwater collection in new constructions, particularly post-2007, and commenced investigations into decentralised water supply systems. Due to the decline of groundwater levels in specific wards of Kolkata, the focus on aquifer recharge and conjunctive use became especially pertinent (Chakraborti et al., 2009). Moreover, the increasing urban populace of Kolkata, alongside deteriorating water infrastructure and contaminated stormwater systems, necessitated enhancements in wastewater recycling, a fundamental aspect of the 2002 policy. The NWP endorsed the concept of demand-side management, which subsequently impacted the following initiatives focused on public awareness, metered supply, and the reduction of non-revenue water.

7.3.2.1.3. National Water Policy, 2012 (NWP 2012):

The National Water Policy (2012) developed a more innovative and inclusive foundation by prioritising sustainability, environmental adjustment, decentralised governance, and the reusing and recycling of water. It passionately promoted rainwater accumulation, aquifer replenishment, and community engagement in water management. It emphasised a transition from a supply-driven to a demand-driven paradigm. It prioritised ecological sustainability and inter-sectoral water distribution, incorporating measures for ecosystem protection (Ministry of Water Resources, 2012). The policy recognised the escalating issues of urbanisation and emphasised the necessity for integrated urban water management, encompassing rooftop rainwater harvesting (RRWH). The strategy, despite its extensive vision, encountered obstacles in execution due to insufficient cooperation among central, state, and local institutions (Cullet & Gupta, 2009). Emphasising water as an economic, ecological, and social resource, with a keen eye on sustainability, equality, and efficiency, the National Water Policy (NWP) 2012 marks a notable change in India's water administration.

The policy encourages urban local governments to implement decentralised and participatory methods in water planning, which is especially crucial for metropolitan areas such as Kolkata. In accordance with the guidelines provided in national water policy frameworks, it is advised that every state set up an independent water regulatory body to independently oversee and regulate water tariffs and pricing structures. In addition to tariff control, such an authority might be assigned broader functions, including the distribution and monitoring of water resources, regulatory oversight of procedures, assessment of agency performance, and the formulation of policy reform suggestions. Gradually, the state's conventional function as a direct water supplier should evolve into that of a service facilitator and operator, therefore enhancing the capabilities of institutions tasked with the design, execution, and control of water services. Although nations often possess the legal and institutional capabilities to formulate comprehensive water-related policies and regulations, there was an urgent necessity for the establishment of a cohesive regional framework that delineates fundamental principles for water administration. This framework would facilitate the implementation of significant state-level legislation and encourage decentralised government by enabling local entities to manage water resources effectively. This legislation must recognise water as a limited and essential public resource, governed as common property under the public trust theory, to guarantee food security, sustainable livelihoods, and fair socio-economic development for all (Sakthivel et al., 2015).

Additionally, it is imperative to diminish the significant disparity in water resource management between urban and rural regions. If techno-economically viable, desalination should be advocated in urban and industrial regions to augment the supply of accessible water.

Kolkata, being a swiftly urbanising metropolis, faces many difficulties that the 2012 policy directly tackles, including the following issues:

- The NWP 2012 emphasises the need to reuse stormwater and enhance urban drainage systems, which is especially important in Kolkata, a city usually flooded during monsoons because of poor drainage and silted canals.
- The plan emphasises aquifer recharging and the conjunctive utilisation of surface and groundwater, which is particularly pertinent to the periphery regions of Kolkata, where groundwater over-extraction and arsenic poisoning pose significant challenges (Das et al., 2014).
- In accordance with the NWP's directives, the Kolkata Municipal Corporation (KMC) implemented legislation requiring rainwater harvesting systems in new projects and advocated for rooftop systems, particularly in water-scarce wards. Nonetheless, enforcement has been irregular owing to insufficient awareness and technical proficiency (Chakraborty & Mukherjee, 2016).
- The 2012 strategy promotes grassroots leadership, which corresponds with KMC's efforts to engage local ward committees and NGOs in water conservation campaigns, although these efforts are still in their nascent phases.

Thus, the National Water Policy 2012 establishes a comprehensive framework for urban water management in Kolkata; however, its efficacy is contingent upon localised implementation, capacity enhancement and civic participation.

7.3.2.1.4. New National Water Policy (NWP), 2020:

The Draft National Water Policy (2020) signifies a transformative change in India's water governance by adopting a comprehensive, sustainability-focused strategy. The 2020 draft, in contrast to previous iterations, highlights water as a common-pool resource necessitating decentralised, democratic, and ecologically friendly management. A primary initiative is the advocacy for solutions based on the environment, such as rooftop rainwater harvesting (RRWH), wetland protection, and urban green infrastructure, to tackle water scarcity and enhance adaptation to climate change (Ministry of Jal Shakti, 2020). The proposed approach transcends conventional supply-side strategies, emphasising demand management, water efficiency, and the reuse and recycling of resources, especially in urban environments. It fervently supports the incorporation of rainwater collection into building regulations and urban planning. The policy advocates for reforms in water governance, encompassing independent water regulatory authorities at the state level, extensive aquifer mapping, and enhanced data transparency via digital platforms. Although it is a draft, it gained significant appreciation for its progressive goal; however, apprehensions persist over its implementation owing to institutional and political issues (Saraswat, 2024).

This marked the inaugural instance in which the government solicited a group of independent experts to formulate the policy. The primary recommendations of this proposed National Water Policy are as follows:

- Allow local rainwater harvesting more attention in order to collect the rain where and when it falls.
- Integrate rainwater collection with the delineation, notification, safeguarding, and restoration of traditional local water sources in both rural and urban settings.
- Highlight ‘nature-based solutions’ for water storage and provision.
- Provide water via revitalising catchment areas and promote this through remuneration for ecological services, particularly for vulnerable communities in the upstream mountainous regions.
- Change up our cropping pattern to incorporate fewer water-demanding crops that complement local agroecology.
- All non-potable applications in urban areas, including gardening, landscaping, vehicle washing, fire safety, flushing, and more, must be switched to treated wastewater.
- As the nation runs out of land for additional large dam building and water tables and groundwater quality are declining in many regions, it is necessary to address the change in emphasis on the supply side.

Thus, The Draft National Water Policy 2020 provides a progressive framework that tackles the complex water issues encountered by urban areas such as Kolkata. The successful execution in the city depends on efficient government, community engagement, and the use of novel water management strategies.

7.3.2.2. Other Central schemes and programmes:

7.3.2.2.1. Jal Shakti Abhiyan (2019–Present):

The Jal Shakti Abhiyan (JSA), a nationwide initiative started in 2019 by the Ministry of Jal Shakti, aims to encourage rainwater collection and water conservation, particularly in India's water-stressed districts. The initiative emphasises five principal intervention areas: (1) water conservation and rainwater collection, (2) restoration of traditional and other water sources, (3) reuse and recharge structures, (4) watershed development, and (5) extensive afforestation (Ministry of Jal Shakti, 2020). It employs a mission-oriented strategy, utilising the involvement of national and state government entities, non-governmental organisations, and local communities.

In urban and institutional contexts, rooftop rainwater harvesting (RRWH) is given particular attention, and its adoption is promoted by means of awareness campaigns, technical assistance, and incorporation into municipal building codes. The effort is closely aligned with SDG 6 (Clean Water and Sanitation) and SDG 13 (Climate Action) by fostering community-level water resilience and decentralised approaches to water scarcity. In 2021, the JSA initiated the 'Catch the Rain' campaign, promoting the principle 'Catch the rain, where it falls, when it falls,' hence emphasising the significance of site-specific rainwater harvesting and groundwater recharging (UNDP India, 2021). The initiative, however, in its nascent stages, has demonstrated potential in enhancing water literacy and revitalising old conservation methods.

This project in Kolkata has catalysed numerous municipal rainwater harvesting schemes and educational activities focused on water conservation and efficiency.

7.3.2.2.2. Jal Jeevan Mission (JJM):

The Jal Jeevan Mission (JJM), initiated by the Government of India in 2019, is a transformative program designed to guarantee universal access to clean and sufficient drinking water via individual household tap connections by 2024, with a primary focus on rural regions. The mission is based on the ideas of community engagement, resource sustainability, and decentralised governance, which are essential for enduring water security. However, the JJM is not applicable for urban areas like the Kolkata Municipal Corporation (KMC), as it specifically targets rural areas. By concentrating on the amalgamation of water supply infrastructure with source enhancement strategies like rainwater harvesting and groundwater recharge, JJM tackles both supply-side and demand-side issues in rural water management. The focus on capacity building and behavioural change communication promotes community ownership, hence improving accountability and sustainability at the grassroots level. In water-scarce regions and among disadvantaged populations, the initiative is crucial for diminishing waterborne infections, improving quality of life, and guaranteeing equitable access to a critical resource. Furthermore, the mission corresponds with overarching objectives of public health, gender equity, and the promotion of rural livelihoods, as women and girls who frequently shoulder the responsibility of water collection are poised to gain substantially from enhanced water accessibility (Ministry of Jal Shakti, 2020).

7.3.2.2.3. Atal Mission for Rejuvenation & Urban Transformation (AMRUT):

In 2015, the government of India launched the Atal Mission for Rejuvenation & Urban Transformation (AMRUT), a water-focused national urban mission, with the goal of providing universal access to water in 500 Mission cities over five years, with an extension until March 2023 for project completion. AMRUT's goal is to have 100% of families with access to water by the end of the mission, compared to 64% at the beginning. In order to attain universal coverage, 139 lakhs water tap connections were required. In tandem with other programs, AMRUT has installed 115 lakh new water tap connections so far.

7.3.2.2.4. Atal Mission for Rejuvenation & Urban Transformation 2.0 (AMRUT 2.0):

The Atal Mission for Rejuvenation and Urban Transformation 2.0 (AMRUT 2.0), initiated in October 2021, is a principal initiative of the Government of India designed to enhance water supply, sewage systems, and urban infrastructure, emphasising sustainable water management and conservation. AMRUT 2.0 enhances the accomplishments of AMRUT (initiated in 2015) and is closely aligned with the Jal Jeevan Mission (Urban) and the Sustainable Development Goals (SDG-6), which prioritise clean water and sanitation.

In Kolkata, the activities under AMRUT 2.0 are promising, particularly in rainwater harvesting, sewage treatment plants, and the regeneration of water bodies; nevertheless, the success of these efforts' hinges on effective implementation, citizen engagement, and inter-agency collaboration. The amalgamation of conventional water knowledge with contemporary infrastructure and policy frameworks will be essential for sustainable water management in the metropolis.

7.3.2.2.5. Central Ground Water Board guideline:

The Central Ground Water Board (CGWB), functioning under the Ministry of Jal Shakti, has released comprehensive guidelines to encourage Rooftop Rainwater Harvesting (RRWH) throughout India, especially in urban and water-scarce regions. These guidelines highlight RRWH as a vital approach for groundwater replenishment and sustainable urban water management. The CGWB advocates for the use of Rainwater Harvesting Systems in all new constructions- residential and commercial, with a roof area over 100 square meters (CGWB, 2015). The guidelines delineate technical specifications for the construction of efficient Rainwater Harvesting (RRWH) systems, encompassing site-specific recharge structures, filter units, storage tanks, and silt traps. The CGWB recommends diverse methods for groundwater augmentation, including recharge pits, trenches, percolation tanks, and injection wells, contingent upon soil type, rainfall patterns, and land availability. In municipalities experiencing diminishing groundwater levels, the Board requires Rainwater Harvesting Systems (RRWH) in accordance with state-specific construction regulations, frequently linking it to the endorsement of architectural plans.

CGWB emphasises the necessity of public awareness initiatives, training programs, and institutional collaborations to promote the adoption of RRWH. These guidelines align with national initiatives under Jal Shakti Abhiyan and facilitate the achievement of SDG 6 through localised water resource management and adaptation to climate change.

7.3.2.3. Schemes and initiatives adopted at the State level, West Bengal:

West Bengal's state-level water governance is directed by its policy manuals and urban development requirements.

7.3.2.3.1. West Bengal State Water Policy (2004):

The West Bengal State Water Policy promotes the integrated management of surface and groundwater, the conservation of wetlands, and the regulation of pollution. It underscores public engagement, cost recuperation, and the integrated utilisation of various water sources (Govt. of West Bengal, 2004). The strategy promotes rainwater collection and groundwater replenishment, especially in metropolitan regions experiencing water scarcity, such as Kolkata.

7.3.2.3.2. Kolkata Municipal Corporation (KMC) Water Regulations:

The Kolkata Municipal Corporation has introduced building regulations requiring rainwater harvesting systems in new structures beyond 500 m² (KMC, 2019). Notwithstanding the regulation, enforcement has been erratic, characterised by inadequate compliance monitoring. Numerous studies indicate the necessity for capacity-building among municipal officials and developers to guarantee the appropriate design and management of harvesting systems (Bhattacharya & Roy, 2018).

7.3.2.3.3. East Kolkata Wetlands (EKW) Conservation Act (2006):

The East Kolkata Wetlands, recognised as a Ramsar Site, are essential for water management in Kolkata. These wetlands inherently purify sewage and replenish groundwater. The East Kolkata Wetlands Management Authority was established to implement the East Kolkata Wetlands (Conservation and Management) Act, 2006, which limits construction and encourages sustainable utilisation of the wetlands for aquaculture and agriculture (Dey & Banerjee, 2019). The preservation of EKW exemplifies ecological infrastructure that bolsters urban water security.

7.3.2.3.4. Jal Dharo-Jal Bharo:

A programme called ‘Jal Dharo-Jal Bharo’ was initiated in 2011-12, focusing on the preservation of valuable water resources. This initiative aims to enhance the availability of these resources through extensive rainwater harvesting and the management of surface water runoff, facilitated by the construction and oversight of Minor Irrigation structures. A program titled ‘Jal Dharo-Jal Bharo’ was initiated in 2011-12 with the objective of conserving valuable water resources by extensively harvesting rainwater and mitigating surface water runoff, thereby enhancing the availability of essential water resources through the development and oversight of minor irrigation frameworks (Government of West Bengal, 2012). The Water Resources Investigation & Development Department of GoWB has played a crucial role in the program's successful execution by building and maintaining minor irrigation structures, which improve the availability of valuable water resources, and by collecting rainwater on a large scale and preventing surface runoff.

The Department of Water Resources Investigation & Development is implementing water harvesting structures through various funding plans. It is concurrently involved in the re-excavation of tanks and other water bodies under the MGNREGA program in collaboration with the P&RD (Panchayat and Rural Development) Department, Government of West Bengal. Various structures, such as check dams, water harvesting tanks, and surface flow minor irrigation schemes, are being created to mitigate surface runoff and facilitate the utilisation of stored water for agriculture and other purposes. DWRID has initiated a mass awareness campaign in various districts of West Bengal to conserve valuable water resources through the ‘JAL DHARO-JAL BHARO’ program, aimed at enhancing public knowledge on rainwater conservation and its efficient utilisation.

The ‘Jal Dharo-Jal Bharo’ program has launched a mass awareness campaign in Kolkata and other districts of the state to inform the public about the value of conserving water through effective irrigation techniques, artificial recharge, pollution control to maintain quality, and promoting active participation to ease the water crisis.

This initiative is being promoted through daily newspapers and hoardings displayed in multiple locations across Kolkata and other districts. The State Water Investigation Directorate, which is part of the Water Resources Investigation & Development Department, has created a documentary video called ‘JAL DHARO JAL BHARO’ in six languages: Bengali, English, Hindi, OI Chiki (Santhali), Nepali, and Urdu.

The Kolkata Municipal Corporation (KMC) has mandated rooftop rainwater collection for any new building beyond 500 m^2. However, execution remains irregular. A pilot project in Salt Lake revealed that appropriately designed rainwater harvesting systems could decrease municipal water reliance by 30–40% during the monsoon (Bhattacharya & Roy, 2018).

7.3.3. People’s Perception and Institutional Practices of RRWH:

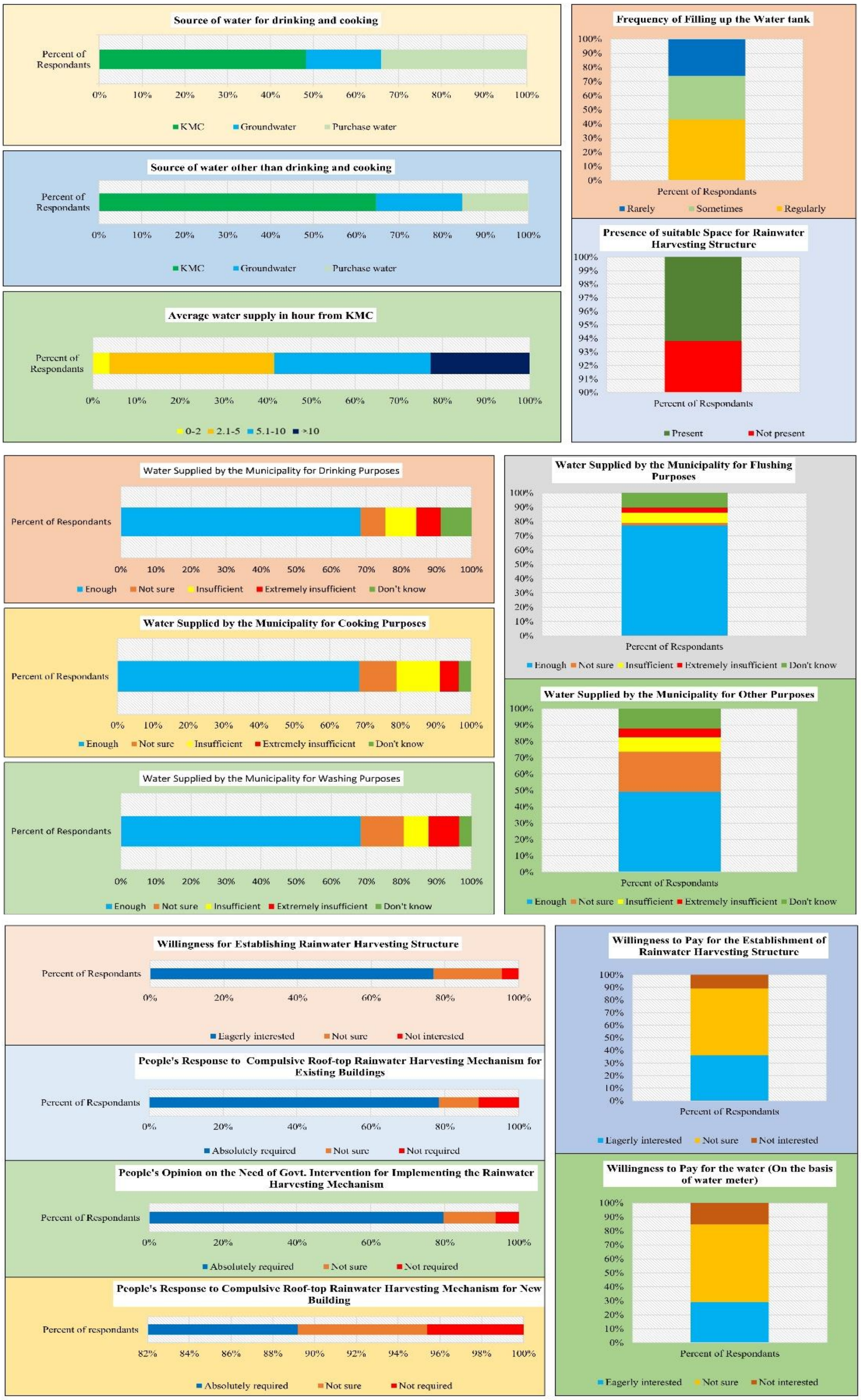
Public awareness and community engagement are essential for the effective implementation of Rooftop Rainwater Harvesting (RRWH) systems, especially in urban areas such as Kolkata Municipal Corporation (KMC), where water scarcity, flooding, and excessive groundwater extraction present significant sustainability issues. Although municipal legislation requiring rainwater harvesting systems in new constructions, implementation remains uneven, primarily affected by public awareness, attitudes, and the tendency to invest in these systems. Community engagement is influenced by socio-economic status, kind of infrastructure, and availability of information, necessitating the creation of tailored awareness campaigns and incentive frameworks. Enhancing public involvement via education, policy implementation, and participatory planning is crucial for integrating RRWH as a sustainable urban water management strategy in KMC. It possesses significant potential for rainwater harvesting, as demonstrated by an illustrative calculation that can be scaled from a single building to encompass the entire city. The community's active participation in this situation can greatly increase rainwater harvesting's efficacy. Communities can collaborate to design and execute rainwater harvesting systems, including the construction of harvesting pits, installation of rooftop systems, and establishment of green spaces. Public involvement in the planning and execution process is essential.

Rapid urbanization frequently happens without a thorough evaluation of its effects on the environment, which has a major impact on water resource sustainability. KMC is fortunate to have the Hooghly River, which is extremely valuable to us and serves as the city's primary supply of drinkable surface water. Conversely, KMC has been facing significant water stress in recent years, particularly during the summer months. Rainwater harvesting (RWH), as a sustainable remedy for water stress, possesses significant potential in the study area.

The availability of open spaces in Kolkata is limited, and many built-up areas are not suitable for rainwater harvesting due to constraints related to space, design, accessibility, and safety considerations. However, the city possesses numerous governmental infrastructures, including colleges, universities, large shopping malls, hospitals and residential communities, where the potential for implementing rooftop rainwater harvesting is significant. Implementing rainwater harvesting enables metropolitan regions to enhance water awareness, demonstrate environmental responsibility, and more effectively meet their water needs by capturing precipitation at its origin. Rooftops are one of the most prevalent and appropriate locations for rainwater collection in urban settings. Rainwater can be efficiently harvested from residential, commercial, and industrial structures through the implementation of appropriate structures and systems.

7.3.3.1. People’s Perception on Water Supply and Implementation of Rooftop Rainwater Harvesting (RRWH):

The perceptions and attitudes of the populations in the study area about rooftop rainwater harvesting have been investigated under various demographic and economic scenarios. Figure 7.3 illustrates the perceptions and attitudes of individuals regarding different facets of RRWH. The information is categorised into various statements concerning RRWH, along with the corresponding percentages of responses (strongly agree, agree, disagree, maybe) for each statement. Figure 7.3 illustrates that the key findings uncovered a multifaceted mosaic of community perceptions concerning RRWH. The data indicates a strong acceptability of RRWH, with nearly 80% of individuals fully endorsing mandatory rainwater harvesting.



Source of water for drinking and cooking

Source of water other than drinking and cooking

Average water supply in hour from KMC

Frequency of Filling up the Water tank

Presence of suitable Space for Rainwater Harvesting Structure

Water Supplied by the Municipality for Drinking Purposes

Water Supplied by the Municipality for Flushing Purposes

Water Supplied by the Municipality for Cooking Purposes

Water Supplied by the Municipality for Other Purposes

Water Supplied by the Municipality for Washing Purposes

Willingness for Establishing Rainwater Harvesting Structure

Willingness to Pay for the Establishment of Rainwater Harvesting Structure

People's Response to Compulsive Roof-top Rainwater Harvesting Mechanism for Existing Buildings

People's Opinion on the Need of Govt. Intervention for Implementing the Rainwater Harvesting Mechanism

Willingness to Pay for the water (On the basis of water meter)

People's Response to Compulsive Roof-top Rainwater Harvesting Mechanism for New Building

Figure 7.3: People's Perception on Water Supply and Implementation of Rooftop Rainwater Harvesting (RRWH)

The objective was to gather information from individuals regarding their perceptions of the water supply service, associated issues, and proposed enhancements for rainwater harvesting utilisation. Consequently, enquiries were made into the current state of available resources, expenditures on water usage, and related matters. During the observation, it was determined that the extensive roof areas of the houses or flats possess potential for Rainwater Harvesting (RRWH). Figure 7.3 shows the responses of individuals about a variety of factors, including sources of water supplied for different uses, average duration of water supply, whether the supplied water is enough or not for different uses, and their opinions about rainwater harvesting:

The perspective study indicates that about 30 percent of people do not use the water supplied by the KMC for drinking and cooking purposes. The majority of the people possess applicable knowledge and a willingness to incorporate RRWH systems, notwithstanding certain challenges. The lack of social awareness initiatives regarding the application and advantages of Rainwater Harvesting (RWH), coupled with insufficient knowledge of the technology, regulations, and training, has been recognised as a major obstacle to the implementation of RWH in Kolkata. The entire urban water development model of the expanding town may be changed by some form of incentive system, awareness-raising, compliance enforcement, and simplification of the integration process through the combined efforts of beneficiaries. The initial stage in fostering community engagement in rainwater collection is to raise awareness among ordinary people and various institutions regarding the significance and benefits associated with rainwater accumulation. Awareness campaigns can be planned at the local and neighbourhood level, involving government organizations, educational institutions, and residential societies. To promote community engagement, the government can offer incentives to individuals and communities who implement rainwater harvesting systems. This may encompass subsidies, tax incentives, or alternative financial inducements to promote the adoption of rainwater collection devices. Active participation from individuals and communities is likely to render rainwater harvesting an effective solution to the water crisis in Kolkata. The engagement of both beneficiaries and bureaucrats is crucial for achieving environmental sustainability in municipal water management, mitigating water stress linked to new urban development, and promoting sustainable cities. To achieve this, social awareness campaigns must be revitalized to encompass individuals who are unaware and in a state of uncertainty. The existing roof catchment can satisfy the annual drinkable or non-drinkable water needs of a considerable population. Rooftop Rainwater Harvesting (RRWH) systems with sufficient storage capacity can effectively manage educational institutions, commercial buildings, places of worship, recreation, and other establishments that require more non-potable water. Domestic rainwater harvesting may be strategically designed to manage non-potable water demands based on the user's proposed applications of rainwater. The lack of societal comprehension concerning the implementation and benefits of rainwater harvesting systems is a key factor hindering the adoption of rooftop rainwater harvesting systems. The official accountable, namely the urban development body overseeing water management, should mitigate this by reducing the participation of superfluous parties. Raising awareness will ultimately foster a culture of water conservation and promote the understanding of water as a limited resource. The subsequent major challenges encompass the absence of access to scientific knowledge, rules, and training related to rainwater harvesting and its implementation. Addressing knowledge deficiencies, augmenting capacity, and delivering training on the installation of rainwater harvesting systems are crucial for optimising their effective functioning through the coordinated efforts of beneficiaries and officials.

Considering the land-use patterns in the study area, the appropriate authorities must identify and inform the beneficiary about the specific roof area allocated for use as a catchment for domestic rainwater harvesting systems and groundwater recharge. Therefore, it is imperative to establish a social engagement strategy that enables the planning and execution of rainwater harvesting systems and wastewater reuse in all forthcoming urban developments, irrespective of water scarcity, to guarantee climate resilience and sustainability. In conclusion, the integration and implementation of rainwater harvesting (RWH) must prioritise stringent compliance by beneficiaries, along with effective enforcement and monitoring by relevant authorities, bolstered by increased social awareness and incentive systems.

7.3.3.2. Present status of RRWH at Multi-Story Mall, Hotels and Hospitals:

In this study, a first survey was conducted at numerous large malls, hotels, and hospitals to assess the present status of RRWH. The existing status of RRWH in some selected large multi-story buildings, such as malls, Hotels, and hospitals is the follows:

Table 7.a: The existing status of RRWH in five selected large malls

Sl. No.	**Name of the Mall**	**Location**	**Total rooftop area (sq. metre)**	**Rainwater Harvested (Yes/No)**
1	South City Mall	375, Prince Anwar Shah Rd, South City Complex, Jadavpur, Kolkata, West Bengal 700068	15,354	Yes
2	Mani Square Mall	164/1 Maniktala Main Road, Eastern Metropolitan Bypass, Kolkata, West Bengal 700054	8,536	No
3	Quest Mall	33, Beck Bagan Row, Park Circus, Ballygunge, Kolkata, West Bengal 700017	7,500	Yes
4	Acropolis Mall	Sector 1, 1858/1, Rajdanga Main Rd, East Kolkata Twp, Kolkata, West Bengal 700107	4,942	N/R
5	E-mall	Central Avenue, Biplabi Anukul Chandra St, Bowbazar, Kolkata, West Bengal 700072	4,299	No

Table 7.a shows data on the installation of rooftop rainwater harvesting (RRWH) systems at the chosen eight major malls in Kolkata. Among them only two malls, South City Mall and Quest Mall have implemented RRWH techniques, with enormous rooftop spaces of 15,354 and 7,500 square meters, respectively. Acropolis Mall was one mall that provided no information regarding the RRWH application. Though some of them, like Mani Square Mall (8,536 sq. m), E-mall (4299 sq. m), have significant rooftop spaces that may be efficiently used for water harvesting, but do not have any RRWH system in place. These data indicate a limited adoption of rainwater collecting systems among big commercial buildings within KMC. This highlights a missed opportunity for sustainable water management in an urban setting and suggests that increased awareness, incentives, or administrative actions are required to support RRWH systems in such infrastructure.

Table 7.b: The existing status of RRWH in some selected large hotels

Sl. No.	Name of the Hotels	Location	Total rooftop area (sq. metre)	Rainwater Harvested (Yes/No)
1	The Oberoi Grand	15, Jawaharlal Nehru Rd, New Market Area, Dharmatala, Taltala, Kolkata, West Bengal 700013	10,040	N/R
2	ITC Sonar and Royal Bengal	1, JBS Haldane Ave, Tangra, Kolkata, West Bengal 700046	7332	No
3	The Lalit Great Eastern Kolkata	Dalhousie Square 1, 2,3, Old Court House St, Ward Number 1, Kolkata, West Bengal 700069	5,282	No
4	Taj Bengal Kolkata	34-B, Belvedere Rd, Alipore, Kolkata, West Bengal 700027	4,310	No
5	JW Marriott Hotel	4A, JBS Haldane Ave, Tangra, Kolkata, West Bengal 700105	2,867	N/R

Table 7.b, showing the current state of rooftop rainwater harvesting (RRWH) at chosen large hotels in Kolkata, shows a total absence of RRWH utilisation among the surveyed hotels. Among the five chosen hotels, none have implemented RRWH. The Oberoi Grand and JW Marriott Hotel have not provided information regarding their status. For example, The Oberoi Grand has a rooftop area of approximately 10,040 square meters while The Lalit Great Eastern Kolkata offers 5,282 square meters of ample space for a rainwater collection system.

Though the hospitality sector is getting more attention on sustainability, this study shows a notable lack of environmental efforts, implying that RRWH is still not well-known among Kolkata's hotels. The lack of RRWH systems in all large hotels shows a lack of awareness or policy enforcement. It highlights the need for more advocacy, incentives, and regulatory assistance to encourage water conservation efforts in this resource-intensive industry.

Table 7.c: The existing status of RRWH in some selected large hospitals

Sl. No.	Name of the Private Hospitals	Location	Total rooftop area (sq. metre)	Rainwater Harvested (Yes/No)
1	SSKM Medical College and Hospital	Acharya Jagadish Chandra Bose Rd, Bhowanipore, Kolkata, West Bengal 700020	33,875	No
2	Peerless Hospital	360, Pancha Sayar Rd, Sahid Smirity Colony, Pancha Sayar, Kolkata, West Bengal 700094	8,831	No
3	KPC Medical College & Hospital	Kpc, 20, Raja Subodh Chandra Mallick Rd, Jadavpur, Kolkata, West Bengal 700032	6,244	No
4	Apollo Multispecialty Hospitals	58, Canal Circular Rd, Kadapara, Phool Bagan, Kankurgachi, Kolkata, West Bengal 700054	6,153	No
5	Medica Superspeciality Hospital	127, Eastern Metropolitan Bypass, Nitai Nagar, Mukundapur, Kolkata, West Bengal 700099	4,200	No

Table 7.c., on the status of RRWH in some chosen hospitals, also highlights the absence of rainwater collecting system deployment in the healthcare sector. Out of the 17 public and private hospitals surveyed, none have implemented RRWH, including SSKM Medical College and Hospital (33,875 sq. m), Apollo Multispecialty Hospitals (6,153 sq. m), and KPC Medical College & Hospital (6,244 sq. m), have not implemented any Rainwater Harvesting (RRWH) structure. The prevalent non-adoption of RRWH within the healthcare sector is particularly alarming because of the persistent and elevated water demand in hospitals. The data highlights an urgent necessity for the incorporation of sustainable water management practices in healthcare institutions. Promoting RRWH in hospitals can substantially enhance urban water resilience, alleviate strain on municipal water supplies, and accord with overarching environmental sustainability objectives.

As a whole, Tables 7.a., 7.b., and 7.c demonstrate the inadequate implementation of RRWH in the vast majority of buildings. Moreover, numerous respondents were reluctant to reveal information concerning the true condition of rooftop rainwater harvesting activities. Only South City Mall and Quest Mall replied, indicating that they have established rooftop rainwater collecting, which is utilised for various non-potable applications, including car washing, landscaping, and floor cleaning. Despite the considerable potential for rooftop rainwater harvesting in these structures, the execution of such systems has not conformed to standards due to the lack of rigorous rules and efficient oversight by government authorities. In contrast, some recommendations have been derived from them based on our questionnaire. In contrast, several recommendations have been derived from them based on our questionnaire, and additional information has been gathered, which is discussed in this study.

In conclusion, only 2 of the 15 institutional buildings in the sample had functional rainwater harvesting systems. Others attributed non-compliance to infrastructure limitations, the absence of required enforcement, and insufficient awareness among management. Almost all respondents recognised the possible environmental and economic advantages of RRWH. A prevalent theme in interviews was the necessity for technical support and financial incentives to facilitate wider implementation.

7.3.3.3. Comparative Analysis:

The comparison between residences and institutions demonstrated a mutual acknowledgement of the advantages of RRWH, while also revealing disparities in motivation and capacity. Households, particularly in outdated structures, reported structural constraints, whereas institutions encountered administrative obstacles and deficiencies in financial planning. Both groups expressed a pronounced preference for government-initiated support programs, encompassing subsidies, awareness initiatives, and technical assistance. The findings indicate that although a policy framework is in place, the practical facilitation mechanisms are inadequately established, hindering extensive adoption in both domains. These insights highlight the necessity for a cohesive, community-oriented, and institutionally endorsed approach to enhance the implementation of RRWH in the study area.

7.3.4. Connection between various policies and people's perception with gaps and opportunities:

India's water policy framework exhibits robust institutional backing for Rooftop Rainwater Harvesting (RRWH) via national initiatives including the National Water Policies (1987, 2002, 2012), the Draft National Water Policy (2020), Jal Shakti Abhiyan, Jal Jeevan Mission, and urban initiatives such as AMRUT and the Smart Cities Mission. At the state level, initiatives like West Bengal’s ‘Jal Dharo-Jal Bharo’ and the Kolkata Municipal Corporation’s building laws render Rainwater Harvesting (RRWH) legally and administratively pertinent. These strategies promote decentralised water saving, enhanced groundwater recharge and urban climate resilience.

However, despite this strong policy framework, public perception and engagement remain inconsistent. Field investigations and surveys undertaken in Kolkata indicate that although awareness of Rainwater Harvesting (RRWH) is on the rise, its practical application remains constrained. A considerable number of inhabitants endorse the RRWH conceptually, acknowledging its advantages in flood mitigation and groundwater replenishment (Bhattacharya & Roy, 2018). However, practical implementation is obstructed by issues including substantial initial expenses, insufficient incentives, inadequate technical expertise, and ineffective regulatory enforcement (Chakraborty & Mukherjee, 2016).

7.3.5. Comprehensive Effects of Rooftop Rainwater Harvesting (RRWH) on Urban Drainage, Waterlogging Alleviation, and Community Participation:

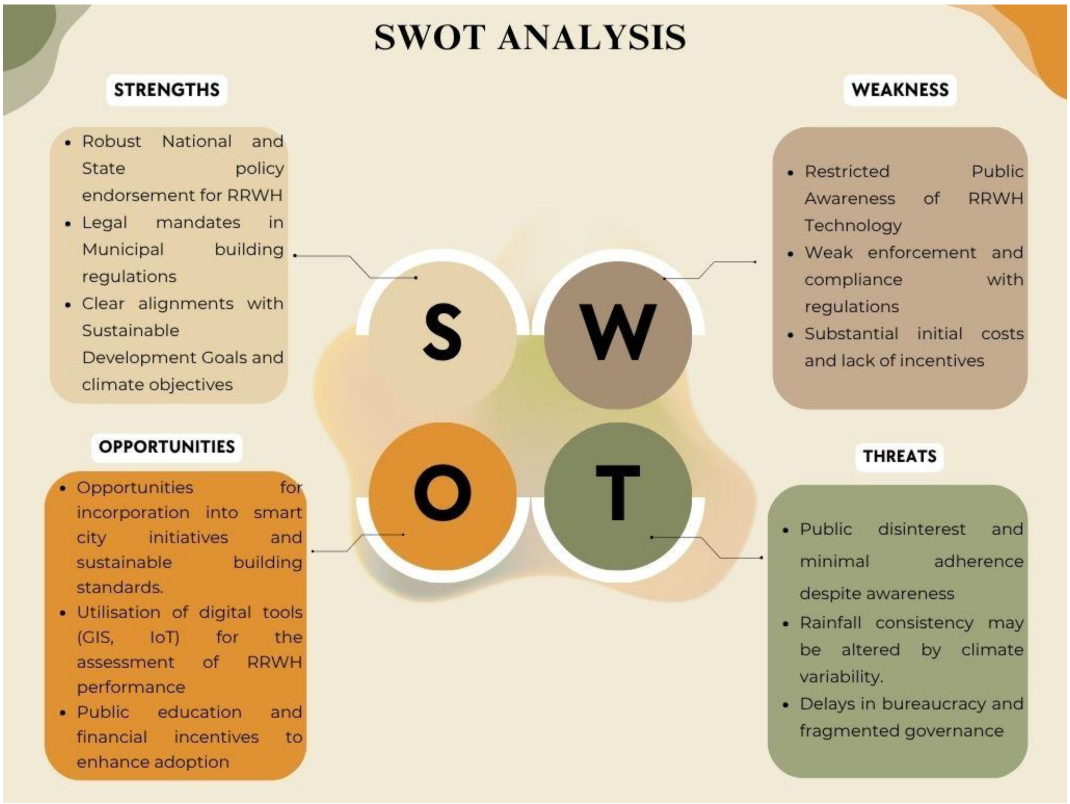
The primary objective of constructing rainwater harvesting systems is to absorb and store rainwater, thereby diminishing the volume of stormwater runoff that enters the drainage system. This reduction in runoff can relieve stress on the drainage infrastructure during intense precipitation events. Rainwater harvesting (RWH) systems can mitigate excess water accumulation in low-lying locations by collecting rainwater on-site, hence diminishing the risk of waterlogging situations.

Societies and institutions can significantly contribute to grassroots water conservation efforts by conducting awareness campaigns or events. These programs have the potential to spread, encouraging regular people to implement sustainable water management techniques like rooftop rainwater collection, which will ultimately support the greater objective of environmental preservation and water security.

Community engagement is essential for the effective execution of rainwater harvesting systems. Following the field study, it is evident that additional education and outreach may be necessary to underscore the need for water conservation and the advantages of rainwater harvesting (RWH). Generally, when the community actively participates, they are more likely to assume ownership of the project and ensure its long-term sustainability. Active community engagement and enthusiasm for the project significantly enhance the probability of good system maintenance and utilisation, hence ensuring its long-term sustainability. Therefore, assessing the degree of community engagement in rainwater harvesting (RWH) is crucial to this study. Various critical indicators and approaches have been utilised to assess the efficacy of rainwater harvesting systems in preserving water resources.

7.3.6. SWOT analysis of RRWH Policies and People's Perception Integration:

A SWOT (Strengths, Weaknesses, Opportunities, and Threats) study offers a systematic approach to thoroughly review the existing state of Rooftop Rainwater Harvesting (RRWH) within KMC, focusing on policy execution and public perception. Although policy directives at both national and state levels endorse the use of Rainwater Harvesting (RRWH) through regulatory mandates and sustainability objectives, grassroots participation is inconsistent due to practical and socio-behavioural obstacles. This analysis identifies the internal strengths and limitations of the current system, together with external opportunities and threats that affect the efficacy of RRWH as a decentralised urban water management method. The SWOT framework functions as a strategic instrument to connect policy objectives with community action, while also guiding future planning, awareness campaigns, and governance reforms. Figure 7.1 below illustrates the graphical depiction of the SWOT Analysis for the integration of Rooftop Rainwater Harvesting (RRWH) policy and public perception.



STRENGTHS

- Robust National and State policy endorsement for RRWH
- Legal mandates in Municipal building regulations
- Clear alignments with Sustainable Development Goals and climate objectives

WEAKNESS

- Restricted Public Awareness of RRWH Technology
- Weak enforcement and compliance with regulations
- Substantial initial costs and lack of incentives

OPPORTUNITIES

- Opportunities for incorporation into smart city initiatives and sustainable building standards.
- Utilisation of digital tools (GIS, IoT) for the assessment of RRWH performance
- Public education and financial incentives to enhance adoption

THREATS

- Public disinterest and minimal adherence despite awareness
- Rainfall consistency may be altered by climate variability.
- Delays in bureaucracy and fragmented governance

Figure 7.4: SWOT Analysis of Rooftop Rainwater Harvesting (RRWH) Policy and Public Perception within Kolkata Municipal Corporation (KMC)

The SWOT analysis (Fig. 7.1) of Rooftop Rainwater Harvesting (RRWH) within the study area indicates robust governmental support and strategic compatibility with national sustainability objectives, while facing challenges in practical implementation. The strengths are rooted in robust policy frameworks, local mandates, and alignment with global objectives such as the Sustainable Development Goals (SDGs). However, deficiencies such as insufficient public knowledge, inadequate enforcement measures, and an absence of financial incentives impede effective implementation. Conversely, substantial prospects arise from the integration of Rooftop Rainwater Harvesting (RRWH) with smart city planning, the enhancement of digital monitoring systems, and the advancement of educational initiatives and subsidies to increase adoption. However, challenges such as public indifference, skewed rainfall pattern, climatic rainfall variability and fragmented governance frameworks present significant concerns to the enduring efficacy and expansion of RRWH systems. This analysis highlights the necessity for a multi-stakeholder, incentive-based strategy to address policy and perception gaps and improve urban water resilience.

In conclusion, although the policy framework for Rainwater Harvesting in India is conceptually robust and aligns with sustainability objectives, its effectiveness hinges on enhancing public involvement, institutional coordination, and establishing financial and social incentives to translate awareness into action.

7.3.7. Recommendation for the installation of a rooftop rainwater harvesting system in residential societies:

The installation of a rooftop rainwater harvesting (RRWH) system is beneficial for residential societies, especially in Kolkata, where water supply is constrained and demand is rising. Establishing a rainwater harvesting (RWH) system is recommended for several reasons, including its ability to facilitate water percolation into the soil, refilling the groundwater table, and promoting the sustainable utilisation of this vital water resource.

The policy, that can be proposed for implementing RRWH within the study area, is as follows:

1. The KMC, which already mandates the implementation of RRWH systems in buildings with rooftop areas exceeding 500 sq. m., should be strictly enforced.
2. Government agencies might support institutions that use RRWH systems financially through tax breaks, financial subsidies, or green building certification benefits.

3. Plan outreach and training for building managers, facilities engineers, and owners on the advantages and technical features of RRWH.
4. Integrate RRWH implementation plans as a prerequisite for new building or expansion approvals.
5. Provide financial and technical assistance in retrofitting RRWH infrastructure in current buildings, especially in the hotel and medical sectors.
6. Encouraging public-private partnerships.
7. Required to integrate RRWH with other urban sustainability measures

7.4. Conclusion:

Rooftop Rainwater Harvesting (RRWH) is an essential element of sustainable urban water management, especially in water-stressed and highly populated cities within the study area (KMC). This chapter has examined the interaction between national and local policy frameworks, sustainable development goals, and community perceptions in influencing the implementation of RRWH systems. Despite the robust framework established by regulations at many levels, implementation deficiencies remain due to insufficient public knowledge, inadequate incentives, and feeble regulatory enforcement. Community engagement is crucial yet underexploited, underscoring the necessity for inclusive planning, focused awareness initiatives, and financial support systems. A SWOT analysis highlights the inherent strengths and external obstacles confronting RRWH activities. Looking forward, the incorporation of RRWH into urban infrastructure planning, supported by robust governance and public participation, is crucial for developing resilient, water-secure cities that match with India's sustainable development objectives. This paradigm can be applied to any new urban growth and involves both functionaries and beneficiaries in managing the water demand. This will lessen the need for institutional reforms and the involvement of an excessive number of stakeholders, which are seen to be the obstacles to the incorporation of RWH and wastewater recycling in many developing nations. Thus, this chapter enhances the comprehensive understanding of urban water sustainability within KMC by analysing the interactions among policies, Sustainable Development Goals (SDGs), and community behaviour regarding rooftop rainwater harvesting (RRWH).

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PRINCIPAL OBSERVATIONS AND RESEARCH FINDINGS

8.1. Introduction:

The final chapter intends to integrate the insights obtained from the previous analysis regarding the rainfall assessment, the feasibility of rooftop rainwater harvesting (RRWH) systems, rainwater harvesting structures and methodologies, various policies pertaining to rainwater harvesting, and the people's perception on RRWH in the study area. A holistic approach is crucial for formulating practical suggestions derived from the findings and interpretations developed throughout the study. The studies adopted a mixed-methods approach, incorporating field surveys, organized discussions with general people and municipal officials, and statistical analysis through primary and secondary data sources.

Kolkata, a densely populated urban center in the lower Ganga delta, confronts significant issues with water scarcity, inequitable municipal water distribution, and excessive groundwater extraction (Ghosh & Majumder, 2018). Moreover, the study area is characterized by unpredictable monsoon patterns and excessive reliance on centralized water supply infrastructure. The reliance on the KMC (Kolkata Municipal Corporation) water delivery system has increased, while seasonal monsoonal rainfall continues to be underutilized at both household and institutional levels. This contradiction is especially evident in Kolkata, where rainfall rather than being collected, exacerbates surface runoff and urban flooding. The urban water cycle in Kolkata has grown increasingly uneven, with rooftop rainwater predominantly pouring unused into the city's overburdened drainage system (Roy et al., 2021). In this context, RRWH provides a feasible decentralized water management plan that corresponds with sustainable development objectives and local ecological conditions. Despite numerous government programs advocating for Rainwater Harvesting, its implementation at the household and community level is constrained by insufficient incentives, operational challenges, and inconsistent policy enforcement (Chatterjee & Roy, 2021; Banerjee et al., 2020). Factual data and opinions were combined in this chapter to outline significant findings that explain current conditions and future recommendations for development.

This chapter comprises three sections: critical observations from fieldwork and stakeholder interaction; findings relevant to objectives; and a series of actionable recommendations designed to enhance water security and resilience within the study area.

8.2. Principal Observations:

The principal observations of the study on rooftop rainwater harvesting potential have been derived from a primary field survey. A wide range of individuals, from household communities to government representatives, were interviewed to collect the data.

1. The study indicated that a considerable percentage of respondents, at both household and institutional levels, were acquainted with the concept of rooftop rainwater harvesting and acknowledged its environmental and economic advantages. Nevertheless, this understanding did not convert into prevalent practice. The implementation is restricted, suggesting that although informative outreach may have achieved some success, practical and motivational obstacles persist in obstructing actual acceptance.
2. Significant initial expenses linked to the implementation of the RRWH system, coupled with insufficient technical expertise and the lack of robust support framework, were consistently identified as primary barriers. In older residential buildings and smaller institutions, there were notable concerns raised by maintenance. The identified constraints seem to play a crucial role in shaping the disparity between intention and execution.
3. In the survey of various commercial and institutional establishments, including malls, hospitals and hotels, it was found that raly a limited number had implemented rainwater recycling and harvesting systems. This adaption was primarily seen newer buildings that incorporated design features to accommodate such systems, some entities, in spite of regulatory requirements, have not adopted RRWH because of minimal enforcement pressure, lack of administrative interest or inherent structural highlights the necessity for enhanced regulatory enforcement and technical support.
4. It is promising to note that both households and institutional participants have demonstrated a favourable disposition towards the future adaption of RRWH, Contingent upon receiving adequate guidance, financial support, and policy backing. This suggests hidden possibilities for broad adoption, which could be benefitted through focused initiatives and educational outreach.
5. Despite robust advocacy of rainwater harvesting (RWHS across national, state and municipal policy frameworks, the study identified a significant implementation gap. Regulations are in place, nevertheless, enforcement in inadequate, and awareness of these policies in inconsistent. The actual effect of these policies has been limited,

highlighting the necessity for improved alignment between policy formulation and implementation at the local level.

8.3. Major Findings:

This chapter provides a systematic summary of the major findings from each objective of the study on rooftop rainwater harvesting (RRWH) potential. It emphasizes the essential insights acquired from literature review, field survey, technological evaluation and data analysis. The objective wise major findings have been concisely summarized to demonstrate the attainment of study objectives and the potential of RRWH as a sustainable solution to urban water scarcity and management issues.

8.3.1. **Findings from the first objective** (Analysis of Rainfall trends, their Variability, and forecasting):

1. The analysis revealed a statistically significant upward trend in annual rainfall, as determined by the Mann-Kendall test ($p = 0.00577$; $Z = 2.76044$), with a Kendall's tau of 0.17058, signifying a persistent increase in rainfall over the past century. The Sen's slope estimator calculated this growth at around 2.48 mm/year, indicating a total increase of nearly 300 mm throughout the reported duration. This tendency increases the prospective feasibility and dependency of rainwater harvesting systems as a sustainable water supply in KMC.
2. The research revealed significant monthly fluctuations, with precipitation rising throughout the monsoon and post-monsoon months (May–December) and declining during the pre-monsoon dry season (January–April), particularly in February (−0.1118 mm/year). These trends indicate that rainwater harvesting systems must be engineered to prioritize monsoonal collection and dry season storage, guaranteeing year-round functionality despite seasonal variations.
3. Throughout the four phases of 30-year intervals during 120 years of rainfall, the coefficient of variation (CV) increased from 15.91% to 26.71%, reaching its zenith during 1960-1990 interval before seeing a slight decline. The increasing variability underscores the necessity for adaptable and flexible storage options in rainwater harvesting systems to manage fluctuations and mitigate overflow or underutilisation.
4. Box and whisker plots reveal substantial dispersion and extreme rainfall events during monsoon months (June–September), with July showing the highest median rainfall. Such concentration of rainfall events presents both a challenge and an opportunity,

requiring robust collection and drainage systems but also offering a high yield potential for rainwater harvesting if appropriately timed and captured (Tukey, 1977; Banacos, 2011).

5. The comparative analysis of forecasting models indicated that the fifth-degree polynomial regression model had the lowest RMSE (364.83 mm) and outperformed ARIMA (RMSE 420.95 mm) in forecasting the annual rainfall. Precise forecasting is essential for the strategic design and optimization of rainwater harvesting systems, facilitating pre-monsoon preparation and improved demand-supply equilibrium (Srikanth et al., 2016; Joshi & Tyagi, 2021).
6. Forecasts based on the optimal model suggest an anticipated annual precipitation of roughly 1629.8 mm by 2050. This projection reinforces the need for investing in extensive rainwater collection infrastructure, as precipitation continues to adequately address urban water shortages and alleviate urban flooding (Malik et al., 2020; Nath et al., 2021).

8.3.2. **Findings from the second objective** (Analysis of Land Use and Land Cover Changes):

1. From 1990 to 2021, the built-up area within KMC increased markedly from 83.68 km^2 (45%) to 106.20 km^2 (57.36%). This expansion signifies the mounting pressures of urbanization propelled by population growth, infrastructure requirements, and real estate development. The expansion primarily encroached upon natural land categories, indicating a transition to more impermeable urban environments.
2. The vegetation covers significantly decreased from 41.11 km^2 (22.20%) in 1990 to 23.73 km^2 (12.81%) in 2011. By 2021, a partial recovery was noted, with vegetation expanding to 35.78 km^2 (19.32%). This trend indicates initial deterioration from urban encroachment, succeeded by potential conservation, afforestation, or green development efforts in the subsequent decade.
3. The area of fallow land diminished substantially, decreasing from 47.99 km^2 (25.92%) in 1990 to 30.16 km^2 (16.29%) in 2021. The reduction of open spaces indicates their transformation into developed land for urban infrastructure, which directly affects urban liveability, stormwater management, and ecological equilibrium.
4. Ward wise study demonstrates significant disparities in land usage trends. The central KMC wards are highly urbanized, with built-up areas above 90%, but the periphery wards maintain areas of vegetation and open ground. This geographical variability signifies varying phases of urban transformation and provides essential insights for

localized planning interventions, including rooftop rainwater harvesting (RRWH) and the construction of green infrastructure.

8.3.3. **Findings from the third objective** (Rainwater Harvesting Potential):

1. An assessment of 30 years of rainfall data (1991-2020) indicates that Kolkata receives an average annual precipitation of roughly 1590 mm, with nearly 70% of this amount happening during the monsoon season (June to September). The temporal concentration of precipitation provides a reliable opportunity for rainwater capture, rendering rooftop rainwater harvesting (RRWH) an effective technique for urban water management, particularly during the peak rainfall season.
2. The research measured the rooftop areas of government-supported institutions and university campuses under the Kolkata Municipal Corporation (KMC) to assess their rainwater harvesting capacity. The findings indicate that the total RWHP during the monsoon months surpasses 160,000 cubic meters. Jadavpur University's main campus was the foremost contributor among all institutions, achieving an annual RWHP above 62,000 cubic meters, highlighting the unexploited potential of institutional of institutional rooftops for sustainable water supply.
3. The analysis examined the quantity of collected rainwater in relation to the water requirements for toilet flushing, which is the primary non-potable application. At Jadavpur University, the harvested rainwater during the monsoon season has the potential to fully satisfy or even surpass the monthly flushing requirement (approximately 2,726 m^3/month). Throughout the year, rainwater harvesting has the potential to meet over 50% of the university's total non-potable water demand, highlighting its effective application.
4. Despite the generally high levels of rainfall, there is notable variability within the year, as rainfall amounts can change dramatically from one month to the next. For example, the RWHP varies significantly, with values as low as 201 m^3 in December and exceeding 12,900 m^3 in July. This variation requires the establishment of sufficient storage infrastructure to collect surplus rainwater during the monsoon months and utilise it effectively in the dry season, thereby improving the system's reliability throughout the year.
5. The finding indicates that RRWH operates as a low-energy, gravity-driven system, which contributes to its cost-effectiveness and long-term sustainability. Upon installation, the system functions autonomously, requiring no external power or

personnel. It employs straightforward physical processes like sedimentation and decantation to render the water suitable for toilet flushing, cleaning, and gardening, providing a cost-effective alternative to traditional municipal water supply systems.

6. In addition to its importance in conserving water, RWHP significantly contributes to the mitigation of urban flooding. The investigation highlights that establishments such as Jadavpur University encounter recurrent pluvial flooding in the monsoon season. By channelling rooftop runoff into storage systems, RRWH mitigates surface water buildup, contributing to flood risk management. Therefore, its implementation plays a crucial role in enhancing water security and fostering climate resilience in areas experiencing rapid urbanization.

8.3.4. **Findings from the fourth objective** (Dimensioning the Rooftop Rainwater Harvesting Structure):

1. The investigation is based on an extensive analysis of 120 years of historic rainfall data (1901-2020), facilitating a statistically sound estimation of assured rainfall across different probability levels (50%, 60%, and 70%). The analysis demonstrated distinct seasonality in rainfall Patterns, particularly during weeks 24 to 33 and from June to September, which were recognized as the most dependable times for rainwater harvesting. This establishes the foundation for identifying ideal tank dimensions that correspond with both maximum and guaranteed rainfall intervals.
2. The design of the tank size utilised a practical threshold of 60% assured rainfall in the study. This probability level provides a balanced approach, maintaining system reliability under moderately conservative climate conditions while avoiding overdesign and unnecessary expenses. This method guarantees sufficient storage capacity for most rainfall occurrences while also reducing unnecessary infrastructure and financial waste.
3. The optimal tank size was determined by averaging the highest and minimum daily rainfall storage requirements for a 100 square metre rooftop catchment area with a runoff coefficient of 0.8. The research determined the ideal tank capacity to be roughly 712 litres, optimizing collection efficiency during intense rains while ensuring sufficient storage during drier seasons. This dimensional strategy improves water accumulation efficacy across varying rainfall intensities.
4. The analysis indicates that inadequately sized tanks—either excessively large or insufficiently small—can result in inefficiencies, including overflow during intense rainfall or underutilization during arid conditions. The paper provides a scalable and

adaptive approach for tank sizing by estimating the daily average of both actual assured rainfalls, thereby mitigating frequent system failures and water loss.

5. The study illustrates significant intra-annual and weekly fluctuations in rainfall patterns in the study area, highlighting a considerable reduction in reliable rainfall during the early and late monsoon weeks (weeks 18-21 and weeks 39-44). This unpredictability highlights the necessity of context-specific tank design that accounts for both average rainfall and the statistical confidence of rainfall occurrence, hence ensuring the year-round operational stability of rooftop rainwater harvesting systems.
6. The dimensioning model created in this study demonstrates scalability and adaptability across different building types and urban contexts. This approach utilises extensive rainfall data and hydrological analysis to create rainwater harvesting systems that are effective, cost-efficient, and robust. The results offer a valuable framework for urban planners and policymakers to adopt tailored rainwater harvesting systems in water-scarce cities such as Kolkata.

8.3.5. **Findings from the fifth objective** (Various Policy Support with Sustainable Development Goals and People's Perception)

1. India possesses an extensive array of national and state-level policies, including the National Water Policies (1987, 2002, 2012, Draft 2020), Jal Jeevan Mission, and 'Jal Dharo-Jal Bharo,' which advocate for rainwater harvesting. However, the execution continues to be disjointed and uneven, mainly as a result of inadequate enforcement, insufficient technical expertise, and a lack of public awareness within local communities.
2. RRWH plays a crucial role in advancing the objectives of SDG 6 (Clean Water and Sanitation), SDG 11 (Sustainable Cities and Communities), and SDG 13 (Climate Action). This approach improves water availability, minimizes urban runoff and flooding, and bolsters climate resilience, establishing it as an essential strategy for sustainable urban water management within the study area (KMC).
3. Field surveys reveal that more than 80% of urban residents advocate for mandatory RRWH, acknowledging its capacity to alleviate water stress. However, a significant barrier to adoption has surfaced due to a pervasive deficiency in technical knowledge, awareness of benefits, and comprehension of incentives, underscoring the necessity for focused awareness and training initiatives.

4. The effectiveness of RRWH is significantly influenced by the engagement of the community and the implementation of financial incentives, including subsidies and tax benefits. The analysis suggests incorporating RRWH into building approval processes and encouraging collaborations between the public and private sectors to enhance its adoption in residential and commercial areas.

8.4. Suggestions:

This section presents pragmatic and data-informed recommendations for improving the implementation and efficacy of rooftop rainwater harvesting (RRWH) systems within the Kolkata Municipal Corporation. Drawing from a comprehensive study of rainfall trends, land use patterns, rainwater harvesting potentialities, tank size dimensioning, and public sentiments, some objective-specific and pragmatic recommendations for future planning and implementation are proposed.

1. Strategic incorporation of rooftop rainwater harvesting into urban water management:

In light of the mounting challenges facing KMC's urban infrastructure, exacerbated by population growth, unpredictable rainfall patterns, and the depletion of groundwater resources, incorporating rooftop rainwater harvesting (RRWH) into urban water management is advisable.

2. Design rainwater storage tanks employing 60% assured rainfall for maximum effectiveness:

The analysis establishes that a 60% assured rainfall serves as a dependable foundation for optimizing both the cost and operational effectiveness of rainwater harvesting systems. Therefore, it is recommended to utilise 60% assured rainfall as a benchmark for the sizing of the tanks throughout KMC, particularly in public and institutional structures. This approach prevents both underutilisation and overflow, guaranteeing consistent utility throughout the year from a water source reliant on monsoon conditions.

3. Combine land use planning with water harvesting policies:

It is recommended to combine land use planning with water harvesting policies. It is essential for new urban developments to include obligatory rainwater harvesting infrastructure, particularly in areas characterized by high density and significant runoff. The implementation of this strategy will effectively address the reduction in natural groundwater recharge and counteract the adverse hydrological effects associated with urban expansion.

4. Developed designs for unmanned systems based on gravitational principles:

The study presents a well-structured, gravity-fed rainwater harvesting system design that is both economical and self-sufficient in energy use. Therefore, it is advisable to advocate for the implementation of gravity-fed, automated rainwater harvesting systems within public and educational institutions. This will reduce operational expenses, remove the necessity for manual involvement, and enhance the sustainability of the systems.

5. Implement awareness initiatives and offer financial incentives:

It is recommended to carry out organized awareness initiatives, supply technical resources, and extend financial support for both residential and commercial users to adopt rainwater harvesting systems.

6. Employ Geographic Information Systems (GIS) and predictive tools for strategic planning:

It is recommended to employ Geographic Information Systems (GIS) and predictive tools for targeting to enhance effectiveness. It is recommended to utilize spatial land use and land cover data alongside rainfall forecasting models to prioritize rainwater harvesting effectively in areas that are susceptible to flooding and experiencing water scarcity.

7. Establish monitoring and maintenance protocols as standard practices:

It is recommended to establish a mandatory annual inspection and maintenance of RRWH systems within municipal regulations, which will help to extend the lifespan of the system and foster user trust. Municipal teams at the ward level can take responsibility for supervising pre-monsoon maintenance and post-monsoon inspection of rainwater harvesting systems to ensure their efficacy and sustainability.

8.5. Conclusions:

The present study offers a thorough evaluation of Rooftop Rainwater Harvesting (RRWH) as a sustainable water management strategy within the Kolkata Municipal Corporation (KMC). KMC confronts escalating issues in providing a dependable and equitable water supply due to rising urbanization, unpredictable rainfall patterns, and diminishing groundwater levels. The study incorporates various aspects, including analysis of rainfall trends and variability, changes in LULC, assessment of rooftop areas, strategies for tank dimensioning, and assessment of various policies and people's perception to assess the viability and efficacy of Rooftop Rainwater Harvesting (RRWH) in this swiftly urbanizing environment. The findings jointly emphasize that RRWH is both technically feasible and an environmentally sustainable option. The effective incorporation of RRWH in KMC depends on a combination of precise scientific planning, adaptive policy development, community engagement, and institutional dedication. Rooftop rainwater collecting should be redefined as an essential element of urban water management rather than a supplementary choice. When augmented by spatial planning tools, predictive modeling, and stakeholder engagement, Rainwater Harvesting (RRWH) can substantially propel Kolkata's advancement towards Sustainable Development Goals (SDGs), particularly SDG 6 (Clean Water and Sanitation), SDG 11 (Sustainable Cities), and SDG 13 (Climate Action). The research presents a scalable, policy-compliant, and climate-resilient model for RRWH that can be extended to other monsoon-dependent urban areas encountering analogous water management issues.

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Supplementary Materials

Table 1: Calculation of weekly assured rainfall (50%, 60% and 70%) and mean rainfall over 120 years of weekly rainfall

Number of Years	Weekly Rainfall (mm) in ascending order with Date & number of weeks																										
	30 Apr - 06 May	07 May - 13 May	14 May - 20 May	21 May - 27 May	28 May - 03 Jun	04 Jun - 10 Jun	11 Jun - 17 Jun	18 Jun - 24 Jun	25 Jun - 01 Jul	02 July - 08 July	09 July - 15 July	16 Jul - 22 Jul	23 Jul - 29 Jul	30 Jul - 05 Aug	06 Aug - 12 Aug	13 Aug - 19 Aug	20 Aug - 26 Aug	27 Aug - 02 Sep	03 Sep - 09 Sep	10 Sep - 16 Sep	17 Sep - 23 Sep	24 Sep - 30 Sep	01 Oct - 07 Oct	08 Oct - 14 Oct	15 Oct - 21 Oct	22 Oct - 28 Oct	29 Oct - 04 Nov
	18	**19**	**20**	**21**	**22**	**23**	**24**	**25**	**26**	**27**	**28**	**29**	**30**	**31**	**32**	**33**	**34**	**35**	**36**	**37**	**38**	**39**	**40**	**41**	**42**	**43**	**44**
1	0	0	0	0	0	0	0	0.46	4.69	3.08	0.42	2.31	1.63	9.52	3	0.19	2.2	0	0.02	0.44	0	0	0	0	0	0	0
2	0	0	0	0	0	0	0.38	2.55	5.19	4.6	3.63	2.31	2.83	10.17	7.3	7.86	7.06	0	1.06	4.2	0.01	0.55	0	0	0	0	0
3	0	0	0	0	0	0	1.16	4.4	6.24	6.99	3.7	4.25	4.07	12.45	9.56	9.12	9.1	0.4	3.11	4.55	0.06	0.63	0	0	0	0	0
4	0	0	0	0	0	0.17	3.03	7.37	11.27	8.25	9.96	5.58	7.07	12.9	16.03	11.31	9.88	1.39	7.52	7.9	0.31	0.66	0	0	0	0	0
5	0	0	0	0	0	1.2	3.67	10.35	11.29	8.35	10.13	12.5	14.08	14.6	17.89	11.38	11.31	9.71	11.28	8	1.53	1.18	0	0	0	0	0
6	0	0	0	0	0	1.71	4.1	12.03	12.29	13.2	11.47	14.25	17.1	14.81	19.8	13.25	11.93	14.54	11.71	8.12	4.2	1.92	0	0	0	0	0
7	0	0	0	0	0	4.87	4.41	12.54	13	13.95	12.66	16.97	21.31	15.39	20.14	15.76	13.95	14.63	12.96	8.12	4.5	2.12	0	0	0	0	0
8	0	0	0	0	0	5.88	4.42	13.32	13.62	14.13	13.23	17.46	22.07	17.96	21.28	16.44	14.89	15.16	14.4	8.44	6.6	2.5	0	0	0	0	0
9	0.01	0	0	0.14	0	5.99	4.42	15.01	15.01	14.65	13.76	18.46	22.96	18.45	25.99	17.41	15.69	16.24	15.29	8.92	6.79	3.2	0.04	0	0	0	0
10	0.02	0	0	0.3	0.07	6.51	7.07	17.93	15.08	15.69	18.4	19.27	23.62	18.93	27.07	19.6	15.95	17.58	15.51	9.14	8.39	3.35	0.09	0	0	0	0
11	0.04	0	0	0.5	0.29	6.64	8.5	18.07	15.4	17.72	18.47	19.87	25.12	22.77	28.54	21.64	16.85	18.6	16.34	9.45	10.08	3.98	0.1	0	0	0	0
12	0.07	0	0	0.7	1.12	6.86	9.29	19.08	15.62	18.26	18.97	22.94	25.49	25.4	29.6	22.91	18.84	23.74	16.91	11.29	11.01	5.68	0.49	0	0	0	0
13	0.2	0.08	0	0.89	1.61	7.17	10.55	19.52	17.85	22.91	21.51	22.99	26.43	25.84	29.94	24.02	19.04	24.11	18.94	12.47	11.73	5.79	1.44	0.15	0	0	0
14	0.31	0.26	0	2.23	1.8	7.24	10.71	19.84	18.22	24.03	22.05	23.36	28.08	26.13	30.99	24.31	19.66	25.33	19.31	12.55	12.09	6.92	1.58	0.18	0	0	0
15	0.31	0.27	0	2.35	2	8.59	10.72	20.74	19.2	24.29	22.27	23.67	29.73	27.88	31.62	24.9	21.2	26.61	19.36	13.83	12.54	7.74	2.2	0.2	0	0	0
16	0.36	0.36	0.01	2.98	2.22	8.62	11.65	21.03	20.6	24.58	23.15	23.74	29.73	28.14	31.79	27.04	21.61	27.2	19.44	14.27	12.69	9.17	3.21	0.3	0	0	0
17	0.37	0.41	0.2	3.09	3.18	8.8	13.31	21.87	21.45	24.66	23.96	25.93	29.85	29.68	32.76	27.81	21.65	27.22	19.88	14.96	14.2	10.29	3.86	0.56	0	0	0
18	0.42	0.5	0.36	3.19	4.25	10.21	15.86	22.39	21.53	27.83	24.91	26.33	32.13	29.92	32.8	28.52	26.93	28.25	20.76	15.04	15.92	11.73	4.23	0.87	0	0	0
19	0.47	0.53	0.5	3.38	4.35	10.35	16.37	24.13	22.69	27.91	26.78	26.87	33.29	31.58	33.41	29.21	27.82	29.11	20.76	18.76	16.19	12.02	4.35	0.96	0.04	0	0
20	0.63	0.54	0.59	3.66	4.8	11.26	16.63	24.46	24.65	28.97	26.82	27.78	34.35	31.63	34.82	29.44	27.85	29.36	21.97	19.22	16.59	12.31	6.48	1.71	0.14	0	0
21	0.76	0.61	0.76	3.89	5.59	12.29	16.67	24.8	24.77	30.17	27.14	29.25	37.12	32.74	34.94	30.48	28.78	29.53	22.03	20.07	16.65	12.59	6.68	2.3	0.15	0	0
22	0.8	0.84	1.08	4.08	5.75	12.61	17.75	25.58	25.84	31.05	28.97	29.5	37.29	32.84	35.16	31.68	29.16	29.53	22.94	20.57	17.84	13.06	7.16	3.71	0.22	0	0
23	0.9	0.84	1.31	5.11	6.05	12.72	18.13	26.9	25.89	31.67	29.19	29.86	37.61	34.04	35.28	31.89	30.96	30.32	23.02	20.85	17.9	13.14	7.46	4.2	0.29	0	0
24	0.91	0.86	1.66	5.34	7.24	13	18.78	28.12	27.61	32.66	30.38	30	38.18	34.87	35.39	32.82	32.87	32.88	23.86	21.32	18.12	13.58	7.49	4.52	0.29	0	0
25	1.02	1.57	2.04	5.42	7.71	13.65	19.19	28.54	28.47	34.78	32.81	32.34	39.91	35.46	36.94	33.34	33.12	33.5	24.42	21.47	18.22	13.64	8.46	5.59	0.53	0	0
26	1.22	2.7	2.35	6.13	8.35	14.13	19.24	28.59	28.62	35.31	32.9	32.91	40.87	36.83	39.1	34.21	33.74	34.28	25.23	22.45	18.92	14.25	8.55	6.36	0.54	0	0
27	1.25	3.89	3.04	6.16	9.58	14.18	19.57	28.65	29.17	35.37	33.75	34.46	41.24	37.06	39.62	34.23	33.94	35.25	25.54	22.61	19.64	14.92	9.74	6.4	0.64	0	0
28	1.36	4.21	3.59	6.77	10.21	15.37	20.69	29.74	30.54	38.54	33.76	34.9	42.04	37.43	41.47	34.63	34.45	35.42	26.35	23.25	20.31	14.98	10.22	6.6	0.74	0	0
29	1.93	4.25	4.47	6.87	10.41	15.78	21.99	31.06	30.57	39.49	36.87	35.65	42.52	38.62	42.14	35.95	34.94	35.52	27.14	23.31	24.3	15.6	11.04	7.17	0.92	0	0
30	1.94	4.63	6.38	7.65	10.86	16.25	22.35	33.23	31.24	40.01	37.17	38.81	43.57	39.08	42.51	36.74	35.3	38.51	27.3	24.14	25.19	15.67	11.42	7.23	1.02	0	0
31	2.44	4.66	6.54	7.96	11.39	16.57	23.78	33.9	32.32	40.09	37.39	38.91	44.14	39.81	43.35	39.56	35.61	38.64	27.65	24.48	25.56	16.45	11.73	7.59	1.1	0	0
32	2.53	5.27	6.99	8.91	11.87	17.65	23.8	34.35	32.86	40.11	37.71	39.05	45.47	39.88	43.91	39.73	36.79	39.06	28.8	24.76	27.27	17.77	12.52	7.99	1.31	0	0
33	2.69	6.3	7.42	9.3	12.67	18.09	23.93	35.38	32.91	40.18	39.31	39.38	47.7	41.52	44.85	39.81	38.54	40.08	29.4	25.46	27.68	18.61	13.13	8.34	1.69	0	0
34	3.02	6.88	7.85	9.7	12.88	19.22	23.99	36.78	33.74	40.34	39.37	39.46	48.22	42.64	44.95	40.22	39.44	40.18	31.13	25.88	28.44	18.66	13.38	8.36	1.99	0	0
35	3.05	7.08	8.02	10.06	13.42	19.96	25.45	38.2	34.31	41.71	39.76	39.79	48.36	44.18	45.46	41.96	40.2	40.38	31.2	26.31	28.6	18.8	13.42	8.5	2.04	0	0

36 (70%)	3.26	7.38	8.47	10.21	13.47	20.21	26	38.38	34.34	43.31	40.25	40.01	49.46	44.24	45.81	42.5	40.28	42.37	33.8	26.56	28.89	19.51	13.42	8.77	2.16	0	0
37	4.5	7.45	8.79	10.57	13.78	20.26	26.04	39.08	34.39	44.12	40.88	43.24	49.7	45.89	45.9	43.16	41.23	42.5	35.42	26.79	29.01	19.73	14.07	8.83	2.29	0	0
38	5.78	8.02	8.98	12.19	15.37	21.46	27.2	39.18	34.66	45.04	41.12	43.55	50.18	48.21	46.28	43.25	41.83	42.9	35.47	27.09	29.16	20.18	14.18	9.02	2.38	0	0
39	5.89	8.76	9.02	12.29	15.55	21.53	28.96	39.97	35.34	45.04	42.7	43.96	52.7	48.88	46.66	44.13	41.86	43.03	35.62	27.15	29.85	20.99	14.31	9.29	2.47	0	0
40	6.34	8.89	9.29	13.03	15.73	22.27	29.05	40.21	35.59	46.29	43.53	44.08	53.17	50.24	47.65	44.48	42.69	43.12	35.7	28.29	30.47	21.94	15.04	9.3	3.3	0	0
41	6.73	9.71	9.55	13.38	16.48	22.46	29.76	40.33	36.87	46.41	44.43	44.63	53.19	50.99	47.8	46.7	42.82	43.19	37.23	28.55	31.42	21.97	15.17	9.7	4.04	0	0
42	8.36	11.28	9.78	14.03	16.83	22.51	30.01	40.81	37.23	47.44	45.64	46.45	53.2	52.34	48	47.17	43.52	43.2	37.76	30.46	31.55	22.37	16.28	9.84	4.16	0	0
43	8.4	11.76	10.41	14.36	18.22	23.13	32.86	43.86	38.96	47.77	45.67	46.88	55	52.71	48.07	50.29	44.55	43.4	38.38	31.86	32.12	23.28	20.44	10.53	4.31	0	0
44	8.67	11.76	10.45	14.77	18.48	25.55	35.14	44.86	39.6	48.3	45.71	48.25	55.9	53.28	48.66	50.83	46.07	44.04	38.87	33.3	32.83	23.28	20.88	10.85	4.47	0.06	0
45	8.87	11.95	10.56	15.7	20.14	26.99	38.47	44.89	40.8	48.83	46.6	49.23	55.99	53.44	48.91	51.7	46.27	44.9	40.03	33.37	34.03	23.63	21.19	11.71	4.68	0.4	0
46	10.13	12.36	10.8	16.07	20.26	27.07	38.67	45.31	40.94	49.7	48.22	49.41	56.51	53.97	50.25	51.83	46.31	45.84	40.48	33.69	34.47	25.13	21.83	12.1	5.31	0.56	0
47	10.2	12.72	11.11	16.22	20.57	27.25	38.8	46.5	41.21	50.19	48.96	49.54	61.41	54.44	52.28	52.14	46.56	46.07	41.52	33.94	35.34	27.42	21.99	12.14	5.53	0.77	0
48 (60%)	10.46	13.21	11.46	16.7	21.13	28.66	38.99	46.81	41.26	55.2	50.05	50.45	61.41	54.84	53.93	52.23	47.8	46.34	41.76	35.47	36.34	27.54	22.16	12.23	5.91	0.97	0
49	10.48	13.78	11.6	17.45	21.31	29.21	39.19	48.61	42.38	55.51	50.42	52.09	61.5	55.03	54.11	52.84	48.32	46.95	42.05	36.4	37.25	27.88	22.76	12.59	5.92	1.06	0
50	10.74	15.34	11.96	18.97	23.14	29.34	40.46	49.06	42.44	55.64	50.63	52.75	61.73	56.56	54.83	53.24	49.52	48.15	44.21	38.22	37.9	29.47	23.31	13	6.42	1.11	0
51	11.05	16.37	12.44	19.16	23.55	30.2	41.28	49.1	43.36	56.12	53.05	53.5	63.8	57.31	56.04	53.32	49.66	49.04	44.87	38.58	38.4	30.28	24.65	14.19	6.75	1.54	0
52	11.47	16.63	13	19.25	23.89	30.97	42.11	50.55	45.83	56.6	54.49	53.79	65.34	57.84	56.4	53.44	50.93	50.92	45.5	38.62	38.9	30.41	24.8	14.87	6.9	1.68	0
53	11.96	17.14	13.42	19.71	23.95	31.61	42.15	51.59	46	57.41	55.5	54.82	65.44	57.93	58.65	53.65	51.28	51.58	45.86	38.76	39.15	30.45	24.99	15.28	6.97	1.85	0
54	13.43	17.39	14.11	20.44	24.73	31.84	42.74	51.86	46.49	57.51	56.08	55.84	67.99	58.41	60.06	55.13	52.08	53.68	45.94	40.25	39.42	31.21	25.55	15.9	7.12	1.9	0
55	13.93	17.6	15.21	20.49	25.28	33.15	45.56	52.3	47.3	58.28	56.27	55.93	69.11	58.9	60.6	55.92	53.61	53.69	46.03	40.27	39.47	31.35	26.6	16.66	7.45	2.3	0
56	14.03	18.32	15.48	20.59	25.79	33.74	45.7	52.93	51.29	59.59	56.77	57.42	69.73	59.51	62.02	56	55.17	53.81	46.44	41.57	39.66	31.85	27.33	16.74	7.58	2.34	0
57	14.07	19.06	15.87	21.79	25.86	34.07	46.22	54.27	54.24	60.48	56.95	57.62	69.79	60.99	62.12	56.7	56.22	55.4	46.64	42.25	41.62	33.06	27.55	16.81	7.6	2.36	0
58	15.83	19.71	16.5	21.88	27.24	34.75	46.33	54.38	56.33	60.97	57.26	57.97	70.95	61.79	64.12	57.14	56.64	55.77	48.57	42.32	41.93	34.05	27.81	17.29	8.14	2.61	0
59	16.42	20.2	16.54	22.8	27.63	35.54	47.51	56.25	56.78	61.36	57.65	60.42	71.74	61.86	64.4	57.17	57.68	55.81	48.76	43.2	44.08	34.64	28.48	17.76	8.58	2.65	0
60 (50%)	17.17	20.7	17.3	23	27.8	35.96	49.57	57.88	57.24	61.5	58.14	61.62	73.9	62.59	64.76	57.58	59	57.6	50.73	45.66	46.25	37.09	29.19	18.07	10.54	2.65	0
61	17.88	22.8	17.8	23.04	28.59	36.45	54.88	59.36	58.15	61.68	60.02	63.36	74.7	63.66	65.01	57.6	59.8	57.61	50.91	46.19	46.32	37.12	30.31	19.02	10.72	3.02	0
62	18.11	23.31	17.82	23.5	28.64	36.83	55.1	59.92	58.26	61.79	60.42	63.71	74.92	63.73	66.77	57.71	60.55	57.69	51.88	46.51	47.49	37.56	30.51	19.02	11.27	3.28	0
63	18.18	23.75	18.15	24.31	28.69	36.85	55.8	60.71	59.39	61.93	61.22	63.86	76.05	65.62	67.09	58.04	60.99	58.01	53.66	46.93	47.91	38.6	31.01	19.25	13.92	3.36	0
64	18.59	24.87	19.01	26.37	28.76	38.62	55.99	61.46	60.24	62.02	65.65	67.59	76.75	67.6	68.93	58.53	61.32	58.05	54.61	47.7	48.18	39.03	32.82	19.65	15.16	3.39	0
65	18.61	26.07	19.86	26.52	29.05	38.95	56.14	62.43	60.29	62.83	66.03	69.39	77.54	68.18	69.14	58.56	62.06	59.16	54.79	48.35	48.19	40.01	33.39	20	15.9	3.64	0
66	20.49	28.27	19.89	27.68	29.5	39.93	56.93	64.5	61.59	63.32	66.22	70.26	78.08	68.87	69.17	59.28	62.07	60.53	54.97	48.82	48.74	41.07	34.39	20.62	16.11	3.84	0
67	20.54	28.54	20.6	27.87	30.68	40.33	59.38	65.29	62.14	65.18	68.47	71.05	78.55	73.4	69.53	60.19	63.35	63.27	55.5	49.73	48.82	41.4	36.47	23.89	17.28	3.91	0
68	20.68	29.06	21.05	30.07	30.98	40.41	59.44	65.3	62.34	69.11	69.15	72.06	78.97	74.9	73.38	63.72	64.8	63.3	56.97	49.77	49.69	44.02	37.27	25.69	17.88	4.2	0.14
69	20.96	29.3	21.42	30.21	31.59	41.72	59.64	65.67	62.9	69.77	69.53	74.07	79.24	74.93	75.95	69.7	65.08	64.14	57.21	52.33	50.46	44.15	37.68	26.45	19.38	4.71	0.15
70	22.57	29.57	22.63	30.85	32.14	42.64	60.89	65.69	63.83	70.06	69.75	77.51	79.67	76.04	77.23	70.88	67.16	65.09	58.03	52.67	50.75	44.37	37.74	28.12	20.27	4.75	0.2
71	23.36	29.81	23.65	31.89	32.97	43.69	61.36	66.16	64.1	70.07	69.78	77.65	81.62	76.66	78.2	71.28	67.26	65.66	58.97	53.35	50.83	45.97	40.13	29.25	20.54	5.23	0.24
72	23.37	31.8	23.72	32.63	34.12	45.66	62.19	66.26	65.14	71.71	71.04	78.07	81.66	77.56	78.95	72.34	67.9	68.05	59.07	53.82	51.19	49.55	40.47	29.7	23.08	5.96	0.26
73	23.87	34.07	23.87	34.45	34.33	45.83	62.32	66.7	65.3	72.17	71.53	78.12	82.35	78.09	79.19	74.62	67.98	69.18	59.13	54.4	51.61	50.13	41.8	30.88	23.28	7.31	0.49
74	24.78	34.12	24.5	36.14	34.33	45.97	63.08	67.91	68.14	72.9	73.79	79.25	83.22	79.14	79.58	76.77	68.03	70.07	59.45	55.51	52.16	50.25	43.62	30.97	23.43	7.99	0.67
75	25.81	34.69	24.98	36.66	35.03	46.29	63.62	68.1	69.89	74.3	74.86	79.76	83.58	82.35	80.2	77.09	69.98	72.34	60.03	56.4	53.51	50.71	45.08	31.39	23.6	8.07	0.75
76	25.96	35.44	25.15	36.88	35.59	46.95	67.23	68.17	71.79	75.57	75.16	80.18	84.06	82.41	80.96	77.66	70.54	72.36	61.57	56.74	53.79	52.32	45.49	31.73	23.87	8.15	0.81
77	26.23	35.92	25.64	37.07	36.22	47.2	67.69	68.54	73.77	75.98	75.42	80.41	84.76	83.18	81.27	80.6	70.84	72.54	62.05	60.25	54.4	52.42	46.84	32.27	24.22	8.16	2.05
78	26.39	37.15	26.47	37.21	37.7	48.48	67.94	68.78	73.78	78.41	77.47	81.49	85.33	85.07	81.61	81.94	71.21	72.69	62.4	63.53	56.6	52.8	50.5	33.22	26.7	8.6	2.07
79	26.52	37.85	29.66	38.15	37.77	48.91	69.01	69.98	73.84	79.16	77.7	83.08	85.61	85.53	81.63	82.12	72.81	72.72	63.32	65.69	60.42	53.26	52.4	34.34	26.85	8.78	2.34
80	26.74	38.46	29.85	40.14	38.39	50.23	69.88	70.07	76.06	79.45	78.5	83.26	86.07	86.01	83.36	82.71	74.38	73.29	63.6	67.8	61.5	53.28	52.56	35.02	27.27	9.59	3.2

81	27.34	38.97	29.89	40.2	38.53	50.34	71.55	76.2	79.94	79.71	79.86	83.79	86.97	87.92	83.77	83.43	75.91	73.64	63.62	67.89	62.66	53.66	54.79	35.43	32.15	9.61	3.75
82	27.64	39.4	29.94	41.07	38.66	51.05	76.79	79.89	80.43	84.34	80.31	83.89	87.13	89.49	86.01	84.6	76.7	73.69	64.05	68.17	64.62	54.42	55	35.58	32.38	10.18	3.88
83	27.83	40.64	31.11	43.14	39.2	51.66	77.22	82.81	80.54	85	88.72	84.11	87.37	89.77	88.35	85.35	77.87	74.58	68.09	68.81	65.11	54.83	56.45	36.34	32.5	10.6	4.64
84	28.15	40.97	31.95	43.29	40.06	59.13	77.37	82.84	83	87.12	93.26	85.03	87.79	90.28	88.88	88.62	79.66	76.37	71.39	69.01	65.55	60.17	56.46	38.71	32.53	11.11	4.66
85	29.89	41.43	32.69	43.51	40.94	60.31	78.98	85.55	84.65	87.97	94.46	85.91	87.79	91.59	89.27	88.86	79.72	76.56	71.82	69.63	66.38	63.51	58.09	39.15	35.2	11.94	5.37
86	30.48	42.05	32.81	44.71	43.51	62.12	80.23	86.57	86.43	91.77	95.47	85.94	88.57	95.56	91.86	94.62	79.79	79.91	72.89	70.29	66.4	63.96	60.39	42.44	35.76	13.09	5.79
87	30.79	42.58	33.03	45.23	44.37	63.07	80.95	90.02	90.21	92.62	95.96	85.96	92.07	96.9	94.21	96.96	80.52	80.1	74.81	70.71	67.16	64.66	60.46	43.43	36.43	13.6	6.36
88	31.11	42.67	33.48	45.45	47.1	63.81	81.54	93.34	94.22	93.25	97.14	87.91	94.09	97.25	94.31	98.33	82.43	81.03	79.16	70.78	67.34	64.97	62.78	44.56	37.67	13.72	7.26
89	31.97	43.63	33.54	46.97	47.32	64.65	82.04	94.59	95.99	94.32	97.17	88.4	95.59	97.35	94.51	98.54	82.6	81.13	80.36	71.36	68.95	65.37	63.57	45.93	45.26	14.63	8.33
90	33.1	43.72	33.6	48.07	47.34	65.83	82.4	95.55	98.24	95.92	97.51	93.39	96.74	103.2	94.74	99.04	84.85	82.06	81.08	73.6	70.51	66.23	65.15	45.98	45.48	15.09	9.17
91	33.14	44.68	34.38	48.47	47.59	67.91	85.19	97.47	98.47	100.83	97.54	96.01	98.52	104.39	96.88	99.52	84.87	82.23	82.2	75.11	71.01	66.44	67.15	46	45.86	15.47	10.04
92	33.4	46.58	34.51	48.81	47.64	68.91	86.63	102.87	102.2	101.83	99.27	101.08	99.62	105.57	97.86	101.35	87.01	83.91	83.38	79.69	72.09	72	68.25	46.71	48.44	15.85	11.26
93	33.98	47.24	35.34	48.96	50.36	71.25	87.62	104.4	104.25	102.7	99.55	101.22	101.96	105.99	98.69	101.94	88.78	89.02	83.85	79.78	72.34	72.83	69.25	47.79	48.76	16.95	11.72
94	33.99	47.39	35.92	49.36	50.64	71.95	87.91	105.79	109.25	102.71	99.86	102.25	102.15	108.88	102.03	102.64	89.8	89.39	84.68	80.55	72.95	78.43	69.61	48.26	50.29	19.01	13.04
95	36.07	51.61	36.11	51.14	50.78	73.01	92.53	109.73	110.31	106.54	103.41	102.68	102.9	117.49	103.09	104.19	90.24	92.88	86.34	82.01	74.23	78.69	70.79	48.56	50.83	23.13	13.97
96	37.64	51.76	38.76	51.86	56.04	73.82	99.65	112.28	111.99	107.06	104.21	103.14	103.01	121.98	104.04	104.77	90.34	93.65	87.85	82.39	77.92	81.02	70.99	48.94	52.8	24.56	15.13
97	38.74	51.81	45.53	51.86	57.83	77.21	101.46	113.54	119.05	111.16	105.72	104.71	107.31	123.08	104.59	105.07	91.33	94.52	91.71	83.5	81.84	82.85	71.55	49.17	56.75	24.97	15.49
98	40.25	52.34	46.63	53.32	57.9	80	102.96	115.4	126.16	114.8	107.09	106.98	108.42	126.11	107.04	105.11	92.02	97.87	92.87	85.13	82.74	87.59	72.6	49.26	58.37	33.09	16.4
99	40.97	54.17	48.23	53.71	58.14	80.08	104.27	121.43	129.25	115.69	109	109.5	108.6	126.8	112.52	105.13	94.66	98.12	95.63	85.48	83.11	89.98	73.66	49.94	59.13	34.82	17.03
100	42.31	54.94	48.32	55.49	59.94	80.96	104.78	121.66	130.3	118.51	111.79	113.02	108.76	128.93	119.03	107.27	96.35	100.36	95.72	86.54	88.57	92.63	73.69	52.88	62.74	35.72	18.01
101	43.75	55.89	51.16	55.63	60.28	81.08	106.28	122.12	131.83	120.86	111.84	116.16	110.13	132.28	119.7	108.68	97.2	102.96	96.18	86.59	90.57	95.2	75.93	53.58	62.83	37.07	18.43
102	44.77	58.87	51.2	55.92	70.77	84.13	106.95	124.54	131.92	121.74	112.67	119.8	115.82	132.43	120.36	109.01	98.57	105.74	97.12	88.3	91.88	97.84	79.49	53.64	63.3	38.42	21.22
103	44.92	61.08	51.3	56.58	75.1	92.19	107.34	125.52	132.28	132.34	112.75	122.91	122.48	133.72	122	112.72	101.06	108.12	100.14	92.13	92.92	101.39	79.78	57.54	64.37	39.67	24.01
104	45.63	62.02	55.01	56.94	76.7	94.99	109.44	126.52	132.78	134.3	115.21	126.23	132.7	134.09	122.88	121.85	101.41	108.96	102.74	93.54	96.06	102.31	80.62	60.33	68	40.7	25.94
105	46.03	63.46	55.41	64.36	77.47	96.81	111	131.31	140.76	144.15	115.56	130.83	133.55	138	126.32	125.6	101.54	111.16	110.85	94.36	99.33	106.33	84.63	60.69	68.36	43.1	31.02
106	46.17	64.45	55.75	72.14	78.26	97.43	116.41	131.32	143.67	157.25	115.78	132.26	134.33	147.04	132.4	133.32	105.03	114.09	113.38	97.57	100.16	107.15	84.67	61.11	73.79	55.77	31.52
107	47.24	65.07	56.07	79.14	78.38	106.68	123.52	133.29	144.75	159.8	130.46	134.42	136.26	150.22	136.52	133.38	109.97	122.64	115.74	99.07	100.34	118.93	87.03	62.89	75.41	62.09	32.47
108	50.62	66.81	56.93	80.73	78.84	110.36	137.69	134.82	146.93	160.69	130.65	138.93	140.64	157.05	136.68	138.01	115.64	132.63	119.04	104.39	100.64	120.32	94.98	62.91	78.88	70.44	33.59
109	51.89	70.52	57.72	84.03	79.22	110.41	138.2	134.82	149.39	162.31	135.01	149.14	141.09	160.46	137.74	141.89	117.41	138.36	123.15	104.96	103.94	121.15	96.21	65.16	85.69	70.74	49.83
110	55.3	71.91	58.25	84.1	83.91	118.08	140.23	147.09	149.82	165.6	135.14	152.64	141.79	163.31	139.43	144.2	120.57	144.18	124.88	105.29	107.61	122.36	105.74	74.75	91.04	71.34	53.69
111	56.55	76.9	59.32	93.53	88.49	126.12	141.72	152.4	150.82	167.95	137.06	155.29	147.43	164.3	141.75	153.31	122.81	146.04	128.29	132.44	112.85	124.82	105.85	75.13	94.37	80.41	58.22
112	60.35	82.79	62.01	95.32	93.39	136.37	149.66	165.53	155.58	177.47	138.06	155.51	154.44	165.23	144.34	159.07	123.16	152.33	128.45	137.78	115.43	127.91	109.99	77.68	94.37	82.92	59.5
113	63.37	83.41	65.44	104.81	93.88	138.42	157.55	167.44	167.22	177.77	142.21	156.63	160.13	172.01	144.53	164.54	134.78	165.77	139.01	144.05	123.71	155.64	116.13	82.14	102.97	94.35	75.86
114	73.14	83.5	70.46	105.57	101.59	145.91	167.01	198.62	178.53	178.22	144.21	157.83	161.49	175.35	147.9	165.27	144	171.69	141.54	144.48	133.2	170.99	117.1	96.07	115.55	98.93	77.02
115	74.13	85.05	72.51	107.57	102.88	151.43	175.98	219.51	184.59	179.55	146.33	161.98	204.01	186.69	157.31	167.49	147.39	179.67	143.96	162.39	133.32	181.73	117.18	100.72	116.67	100.58	78.95
116	74.43	85.93	78.57	108.48	103.56	157.13	194.53	222.06	189.4	190.33	146.46	165.41	226.49	206.92	172.87	192.88	166.36	187.45	153.66	163.26	136.05	190.19	121.56	109.19	132.89	115.17	90.31
117	75.27	87.51	85.86	117.89	107.7	216.49	226.4	249.95	201.14	219.91	153.3	175.04	232.61	229.9	179.34	195.01	192.05	196.03	200.17	183.72	136.24	257.24	121.66	158.06	133.79	138.39	103.06
118	77.52	98.98	90.81	123.34	121.12	259.08	263.35	282.16	244.4	269.91	159.04	203.17	241.53	251.25	183.82	202.36	199.19	199.89	235.67	187.53	178.79	313.33	158.23	176.07	187.48	141.92	105.32
119	80.73	157.44	104.72	197.53	186.22	291.67	300.1	345.2	253.19	286.32	298.39	252.47	307.32	266.13	185.99	215.19	219.2	202.34	329.28	217.25	182.88	559.66	202.2	202.26	195.12	153.29	105.93
120	83.97	320.8	169.07	236.39	350.36	534.68	323.07	385.13	328.63	439.84	317.54	287.59	342.59	423.29	292.35	221.93	339.91	212.2	365.9	381.12	205.72	604.02	251.13	222.32	198.8	190.04	134.35
Mean Rainfall	**21.68**	**31.17**	**24.64**	**34.32**	**36.86**	**53.26**	**64.06**	**74.43**	**71.82**	**77.76**	**70.39**	**72.90**	**80.24**	**80.62**	**74.51**	**72.12**	**66.28**	**67.54**	**63.07**	**57.14**	**52.63**	**59.36**	**42.63**	**31.43**	**29.65**	**18.63**	**11.87**

Table 2: Calculation of monthly assured rainfall (50%, 60% and 70%) and mean rainfall over 120 years of monthly rainfall

Number of Years	Monthly Rainfall (mm) in ascending order											
	January	February	March	April	May	June	July	August	September	October	November	December
1	0.00	0.00	0.00	0.00	17.13	54.79	86.00	22.10	13.83	0.00	0.00	0.00
2	0.00	0.00	0.00	0.20	20.40	66.81	106.18	122.28	85.09	0.37	0.00	0.00
3	0.00	0.00	0.00	0.31	22.24	67.12	122.98	131.95	93.86	2.38	0.00	0.00
4	0.00	0.00	0.00	0.70	24.18	79.91	141.22	137.46	95.91	7.71	0.00	0.00
5	0.00	0.00	0.00	0.91	24.94	83.35	162.18	140.53	103.62	11.27	0.00	0.00
6	0.00	0.00	0.00	0.99	30.02	94.08	163.11	147.94	114.92	12.59	0.00	0.00
7	0.00	0.00	0.00	2.16	37.33	101.66	168.12	163.68	118.69	13.73	0.00	0.00
8	0.00	0.00	0.00	3.77	41.04	104.51	171.70	165.68	119.80	13.79	0.00	0.00
9	0.00	0.00	0.00	3.81	41.10	112.79	172.59	167.88	124.50	14.01	0.00	0.00
10	0.00	0.00	0.20	5.19	41.11	119.50	180.58	173.06	132.96	14.70	0.00	0.00
11	0.00	0.00	0.37	5.58	42.72	120.07	185.40	193.09	133.91	15.88	0.00	0.00
12	0.00	0.10	0.37	5.79	43.81	124.59	185.90	193.16	134.03	23.15	0.00	0.00
13	0.00	0.13	0.43	5.79	46.32	124.67	188.94	211.50	137.49	24.55	0.00	0.00
14	0.00	0.14	0.64	8.09	46.38	126.50	196.53	212.50	141.75	24.97	0.00	0.00
15	0.00	0.17	0.75	9.63	49.88	131.40	199.75	214.49	142.72	25.95	0.00	0.00
16	0.00	0.37	1.17	11.65	52.31	134.27	200.47	216.77	143.92	29.03	0.00	0.00
17	0.00	0.41	1.27	12.33	53.47	134.95	200.58	220.08	144.85	31.20	0.00	0.00
18	0.00	0.46	1.78	13.42	54.20	137.18	208.29	224.17	153.24	33.51	0.00	0.00
19	0.00	0.47	2.32	14.66	62.45	141.23	209.76	226.45	153.31	35.91	0.00	0.00
20	0.00	0.50	2.53	15.69	66.51	145.24	210.23	229.46	155.68	36.00	0.00	0.00
21	0.00	0.70	2.57	16.56	67.15	149.21	210.32	234.46	157.47	36.08	0.00	0.00
22	0.00	0.75	2.83	16.84	67.41	149.67	219.38	234.96	158.66	36.74	0.00	0.00
23	0.00	1.05	3.14	17.80	69.52	153.91	221.80	235.72	160.04	41.95	0.00	0.00
24	0.00	1.15	3.15	18.04	70.63	154.60	223.71	236.32	163.21	42.23	0.00	0.00
25	0.00	1.17	3.21	18.25	72.36	155.48	225.91	236.64	163.49	42.40	0.00	0.00
26	0.00	1.90	3.26	18.27	73.37	158.87	227.29	238.99	164.85	46.53	0.00	0.00
27	0.00	2.07	3.33	18.49	75.60	161.50	232.05	239.86	166.96	54.39	0.00	0.00
28	0.00	2.23	3.68	18.75	75.77	162.62	233.05	246.03	168.80	55.95	0.00	0.00
29	0.00	2.28	3.80	19.49	79.71	164.44	235.26	247.19	171.29	59.04	0.00	0.00
30	0.00	2.95	4.14	20.57	80.49	169.55	237.50	250.45	175.17	59.88	0.00	0.00
31	0.10	3.00	4.39	22.26	82.73	172.22	240.53	250.82	176.79	63.87	0.00	0.00
32	0.10	3.92	5.26	22.76	84.44	172.60	240.62	251.15	178.23	67.17	0.00	0.00
33	0.14	4.00	5.52	24.75	85.47	173.26	243.36	251.27	180.01	69.12	0.00	0.00
34	0.17	4.14	5.90	24.75	86.44	175.55	243.89	251.91	180.28	69.30	0.06	0.00
35	0.19	4.30	5.95	24.98	87.67	176.50	244.40	253.29	180.95	70.94	0.14	0.00
36 (70 %)	**0.20**	4.41	6.32	25.88	87.81	180.93	249.69	256.05	181.25	73.89	0.26	0.00
37	0.24	5.38	6.34	26.32	87.91	183.69	253.80	256.20	183.53	75.11	0.36	0.00
38	0.35	6.11	6.79	27.18	90.27	193.26	253.84	257.93	188.47	76.74	0.46	0.00
39	0.37	6.53	6.81	27.53	90.98	198.88	255.60	258.31	193.09	76.99	0.46	0.00

40	0.47	6.73	6.88	27.67	92.37	201.43	255.81	261.79	194.49	78.72	0.54	0.00
41	0.49	7.50	7.02	27.79	92.89	202.55	257.30	266.93	195.00	78.94	1.04	0.00
42	0.50	7.69	8.21	28.28	93.61	205.56	261.52	267.11	196.31	79.74	1.08	0.00
43	0.53	7.99	9.68	29.13	93.88	211.85	263.85	271.73	196.32	82.70	1.14	0.00
44	0.74	8.08	10.64	32.29	98.29	212.48	264.40	271.74	198.47	85.75	1.19	0.00
45	0.75	8.19	10.81	34.37	100.31	213.02	265.95	273.37	198.87	87.35	2.00	0.00
46	0.76	8.70	11.59	34.94	100.31	213.90	268.19	274.43	199.98	89.47	2.09	0.00
47	0.89	8.88	12.61	36.08	100.40	215.68	268.89	277.14	201.10	89.63	2.27	0.00
48 (60%)	**0.89**	9.06	13.07	36.77	105.37	216.16	273.41	278.23	202.35	92.76	2.34	0.00
49	0.90	9.20	13.22	37.47	106.54	221.66	274.38	279.75	203.21	95.63	2.74	0.00
50	0.92	9.41	13.52	37.48	107.06	222.77	274.61	281.26	203.73	98.50	2.83	0.00
51	0.92	9.77	13.84	37.58	110.61	226.67	280.52	282.27	204.60	100.43	2.92	0.00
52	1.09	10.18	14.21	37.85	111.58	230.43	282.71	283.92	207.53	101.49	2.98	0.00
53	1.40	10.79	14.29	39.30	111.83	231.03	283.14	284.02	210.32	101.64	3.05	0.00
54	1.42	11.07	14.92	39.37	113.04	233.62	283.87	284.02	212.13	102.54	3.58	0.00
55	1.86	11.14	15.47	40.18	113.21	235.47	288.44	285.14	217.69	107.63	3.61	0.00
56	2.01	11.44	15.70	40.67	114.36	235.83	293.99	286.90	218.78	108.31	3.76	0.00
57	2.33	12.00	15.89	40.81	116.57	240.41	295.94	286.96	219.81	109.42	4.01	0.00
58	2.45	12.40	16.98	40.99	117.19	245.49	300.45	291.90	220.60	109.48	4.02	0.00
59	2.99	13.69	17.08	41.49	118.21	245.91	309.73	296.24	221.11	110.44	4.21	0.00
60 (50 %)	**3.01**	17.01	17.41	41.59	119.26	249.40	312.12	297.90	222.65	110.51	6.63	0.00
61	3.07	17.09	19.83	45.15	119.45	249.92	313.46	299.20	224.80	110.77	7.26	0.00
62	5.41	17.61	20.15	46.08	119.99	250.74	314.26	300.45	226.86	111.94	7.31	0.00
63	5.79	17.78	21.98	46.20	120.68	251.30	314.33	301.97	228.04	116.27	7.43	0.00
64	6.22	17.87	21.98	46.36	121.19	251.41	315.27	304.10	228.29	117.14	7.88	0.00
65	6.62	17.92	22.54	46.74	124.17	251.60	317.14	304.20	229.54	117.90	8.11	0.00
66	6.66	18.33	22.69	47.83	125.73	252.24	318.98	307.32	233.77	119.24	8.44	0.00
67	6.83	18.51	24.91	47.96	126.32	252.33	320.57	315.55	238.33	120.56	9.93	0.00
68	7.06	19.49	26.01	48.02	130.11	259.58	322.51	319.01	240.36	123.25	10.49	0.00
69	8.15	20.03	27.00	48.18	130.95	266.58	323.93	320.04	244.51	123.98	10.50	0.00
70	8.40	22.11	27.67	48.31	131.30	271.43	324.79	320.27	246.31	125.36	10.71	0.00
71	8.93	22.99	27.76	48.62	131.57	273.81	328.04	320.79	249.44	125.95	11.31	0.00
72	9.42	23.34	28.21	50.12	133.83	274.47	332.69	326.27	250.90	126.58	12.72	0.00
73	9.99	23.61	29.64	50.40	134.00	277.67	333.41	326.87	250.97	128.41	13.23	0.00
74	10.37	24.40	30.36	52.13	134.74	278.63	334.60	327.13	256.71	129.44	14.46	0.00
75	10.43	25.31	31.10	54.75	134.79	281.61	343.91	327.93	258.35	129.63	14.73	0.12
76	11.24	25.90	31.87	56.39	135.94	282.23	344.98	328.90	259.12	132.89	15.11	0.14
77	12.07	25.97	32.31	57.81	137.93	283.01	347.93	329.77	260.78	134.35	15.86	0.28
78	12.08	26.48	33.11	58.49	138.58	285.39	352.39	342.57	260.94	135.74	17.24	0.42
79	14.02	27.08	33.63	58.91	139.09	288.78	363.02	344.47	262.48	136.93	18.19	0.66
80	14.52	27.16	35.51	59.72	141.86	294.70	365.96	349.46	262.93	142.51	18.19	0.83
81	14.78	27.47	39.24	65.95	142.76	297.24	369.82	350.39	266.86	144.59	18.57	1.11
82	14.80	28.64	41.71	66.09	145.50	301.04	374.12	351.05	277.96	147.19	19.30	1.17

83	16.70	30.59	42.55	67.17	149.10	301.66	377.17	354.69	278.07	152.05	19.45	1.22
84	16.82	30.84	43.43	67.33	150.31	303.65	378.93	355.76	280.72	152.70	20.76	1.82
85	17.11	31.88	43.82	67.72	153.33	306.67	381.09	358.76	284.03	156.02	21.23	1.89
86	17.20	32.58	43.99	68.73	157.34	308.01	385.71	373.42	286.95	160.10	21.88	1.96
87	17.24	32.80	44.81	69.25	160.98	314.50	389.37	373.73	288.47	165.68	21.91	2.06
88	18.71	34.77	46.19	69.80	165.72	322.30	391.11	373.98	290.75	168.63	22.92	2.10
89	20.05	34.99	47.13	72.37	165.96	328.03	391.22	374.09	296.44	174.51	23.56	2.15
90	21.66	35.32	47.62	72.92	166.70	328.50	391.61	376.50	298.10	176.30	27.49	2.20
91	22.02	35.65	49.91	73.38	168.11	338.05	394.60	392.97	298.82	181.75	27.94	2.22
92	22.43	38.99	50.52	74.61	172.07	342.39	398.03	394.98	300.84	183.83	28.06	2.67
93	23.31	39.46	50.65	78.24	174.76	355.40	399.22	397.18	300.91	184.92	28.50	2.69
94	23.56	40.82	53.98	79.85	175.81	358.52	403.06	397.42	301.77	191.00	30.28	4.34
95	23.74	42.49	54.94	82.04	177.28	362.48	405.89	401.45	301.88	193.87	31.42	4.39
96	23.91	43.89	56.41	84.83	181.57	368.79	407.67	406.69	303.08	196.18	32.58	4.91
97	24.17	44.66	64.14	85.75	183.60	370.84	410.17	411.29	314.07	205.92	35.26	6.73
98	24.39	45.66	66.32	87.18	188.07	374.59	410.81	414.61	319.76	208.98	37.50	10.03
99	25.01	45.98	66.97	90.82	192.99	386.27	411.99	420.59	324.01	210.63	38.97	10.34
100	25.20	46.52	68.26	94.46	197.75	386.38	413.06	422.73	328.51	212.60	39.19	11.36
101	25.52	49.41	70.10	94.73	201.17	392.16	450.28	440.08	338.41	229.47	40.06	11.50
102	25.71	49.60	71.12	95.66	206.35	392.52	453.00	448.06	348.55	230.44	44.47	11.93
103	26.84	52.23	72.29	97.36	207.68	401.17	456.36	449.64	352.78	234.24	46.50	13.98
104	29.06	53.88	72.84	102.60	208.36	409.25	463.06	450.39	354.93	234.85	47.59	14.08
105	30.79	56.83	72.97	103.08	209.28	415.24	465.32	450.43	355.09	236.46	50.35	14.60
106	31.67	61.14	73.47	103.15	209.83	429.76	466.62	460.39	360.02	242.29	56.88	14.92
107	31.86	63.70	77.00	107.97	213.15	452.28	473.06	461.71	365.43	243.55	68.31	16.17
108	32.98	63.84	85.73	122.62	214.16	456.16	481.19	464.28	368.68	246.97	71.01	17.64
109	38.20	65.33	91.66	122.79	218.87	474.84	493.18	466.72	372.91	251.61	72.82	20.84
110	40.86	67.28	92.79	124.12	233.73	480.81	495.37	507.94	379.09	255.90	72.93	22.58
111	41.47	69.59	95.75	125.12	239.58	492.04	528.20	511.30	384.22	284.59	92.39	25.02
112	41.51	72.08	96.14	133.92	240.84	527.45	542.54	516.05	397.60	301.78	101.58	25.87
113	41.73	73.50	107.04	134.71	244.43	530.77	546.95	518.32	412.08	310.04	124.00	26.66
114	42.24	74.59	107.39	139.29	258.06	545.69	549.17	521.79	421.18	313.52	128.15	26.70
115	44.55	75.88	120.64	141.18	260.44	551.79	556.82	544.73	453.98	321.96	131.33	28.70
116	48.76	102.80	128.69	152.42	265.60	559.84	567.50	562.48	540.32	378.40	155.20	43.27
117	53.03	117.81	132.68	164.91	290.52	576.37	572.49	579.63	571.33	391.54	158.75	47.18
118	56.27	157.24	134.26	176.01	357.76	621.51	673.80	588.66	609.11	407.25	196.19	55.17
119	99.10	161.79	152.88	182.95	392.70	660.21	694.04	647.83	632.95	417.00	236.24	62.08
120	118.43	171.80	229.95	199.71	416.99	898.01	782.61	681.37	787.39	418.16	240.67	132.19
Mean	**12.67**	**25.96**	**33.56**	**53.78**	**130.35**	**271.03**	**325.33**	**320.62**	**247.86**	**129.47**	**24.84**	**5.92**

Id Number: **Date:**

Questionnaire

for

People's Perception about problems and prospects to implement the Roof-top Rainwater Harvesting Structure

1. Respondent’s Information:

Name of the respondents: ____

Address:

____

Age: ________ Sex: _______

City: _____________________ Ward no.__________ Occupation: ______________________

2. Household Status and Housing Condition:

I. Number of persons living in your property ____

II. Highest level of qualification of the respondent___________________________________

III. Type of Building: House / Flat

IV. Roof top Materials: ________________ V. Total roof-top area (sq. feet): _____________

C. Water Supply Scenario and people’s perception on Implementation of Roof top Rainwater Harvesting structure:

1. Source of water_________________ 2. Average Supply Hour ________________________

3. Do you get sufficient water from the municipality for the purpose of the following?

    I. Drinking: Enough/ not sure/ not at all enough/ not enough/ don’t know.

    II. Cooking: Enough/ not sure/ not at all enough/ not enough/ don’t know.

    III. Washing: Enough/ not sure/ not at all enough/ not enough/ don’t know.

    IV. Toilet: Enough/ not sure/ not at all enough/ not enough/ don’t know.

    V. Others: Car wash / Gardening

4. Do you fill up the tank with municipal water whenever you want?

    1 Yes, often 2 Yes, sometimes 3. No, never

6. Would you like to establish the rainwater harvesting structure on your roof-top?

1 Yes 2 No 3 Maybe/Unsure

7. Would you think that the government need to provide initial fund for establishment?

1 Yes 2 No 3 Maybe/Unsure

8. Would you think that the implementation of roof top rainwater harvesting structure need to become compulsory for each household, which have a sufficient roof top area?

1 Yes 2 No 3 Maybe/Unsure

9. If government provide fund for one-time establishment, then are you interested for this structure?

1 Yes 2 No 3 Maybe/Unsure

10. Would you be willing to pay for establish the rainwater harvesting structure on roof-top?

1 Yes 2 No 3 Maybe/Unsure

5. Willingness to pay for water (on the basis of Water meter):

1 Yes 2 No 3 Maybe/Unsure

I. If not interested, then specify the causes: Old Buildings / Lack of space / maintenance problems/ Others (If any) ____

6. Ability to pay: 1 Yes 2 No 3 Maybe/Unsure

I. If yes, then how much can afford (one time and maintenance)? ------------------------

7. Do you have any comments or suggestions we should consider? ____
____
____

8. Are there any further details you would like to share with me regarding the topics we discussed?

Id Number: **Date:**

Questionnaire

on

Existing Roof-top Rainwater Harvesting System in Large hotels and shopping mall

A. Name of the Hotel/Shopping Mall:

Address: ____

Ward no.__________

B. Present Status and Condition:

I. Number of floors ___________

IV. Roof top Materials: __________________ V. Total roof-top area (sq. metre/Sq. feet): _______________

1. Source of water___________________ 2. Average Supply Hour ___________________________

2. Is there Rainwater harvesting Structure from roof top?

Yes / No

I. If yes, then for what purpose this water has been used?

II. Any problems faces to harvest roof-top rainwater?

III. Other Information (if any):

IV. Willingness to implement Rainwater Harvesting Structure:

1 Yes 2 No 3 Maybe/Unsure

Others (Alternate): ____

I. If not, then why (any problems)? ---

6. If not, would you like to establish the rainwater harvesting system?

1 Yes 2 No 3 Maybe/Unsure

8. Are there any further details you would like to share with me regarding the topics we discussed?

Id Number: **Date:**

Questionnaire
on
Existing Water Treatment Plant of KMC

A. Name of the Water treatment Plant: ____

Year of Establishment:

Location: ____

Ward no.__________

B. **Present Status and Condition:**

I. Production Capacity per day: ________________

II. Present Production per day: ________________

III. Source of water__________________________

IV. Average Supply Hour ____________________

V. Discharge Capacity: ____

VI. Area of Influence: ____

VII. Are there any plans for additional improvements to the plant? ______________________

VIII. Have there been any modifications of the plant in recent years? ____

IX. Primary Treatment Processes: ____

X. Secondary Treatment Processes: ____

XI. Tertiary Treatment Processes: ____

XII. Advanced Treatment Processes (if any): ____

XIII. Any problems regarding the water treatment plant?

____

____

XIV. Any scope for improvement: ____

2. Estimated Cost to purify per unit of raw water_______________________________________

3. What are the various impurities present in untreated or natural water?

____

8. Are there any further details you would like to share with me regarding the topics we discussed?

____

9.Remarks:

____

____