Planning and Design of a Sustainable Urban Water Management System Using GIS and BIM: An Integrated Approach

THESIS

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By

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CERTIFICATE

This is to certify that the thesis entitled "**Planning and Design of a Sustainable Urban Water Management System Using GIS and BIM: An Integrated Approach**" and submitted by **Mr. Patil Deshbhushan Savindra**, ID No. **2020PHXF0061P** for the award of Ph.D. of the Institute embodies original work done by him under my supervision.

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ABSTRACT

Infrastructure plays a vital role in supporting a country's economic growth by providing essential necessities such as food, water facilities, and transportation networks. However, the management of infrastructure assets is a complex process that involves long-term asset operations and maintenance, resource allocation, budgeting, risk assessment, policy creation, asset evaluation, performance tracking, and asset planning. Modern infrastructure management tools help to maintain the optimal performance, efficiency, and sustainability of infrastructure assets, resulting in an increase in the probability of project success. Successful infrastructure projects offer competitive opportunities and value-for-money for governments but can strain natural resources and decrease environmental sustainability. Therefore, for sustainable infrastructure development, a study has proposed a generic methodology that enhances longevity, resilience, and adaptability to local environmental conditions of infrastructure asset.

The first-stage methodology incorporates geographic, economic, and social aspects, along with stakeholder behaviour to meet the specific needs of communities. By offering comprehensive information and facilitating adaptation to local conditions, microscale planning further improves sustainability, and eventually increases longevity and resilience. Finally, the adoption of modern modeling techniques facilitates informed decision making, risk assessment, and proactive mitigation strategies, resulting in the enhancement of the overall performance of infrastructure assets. To validate the proposed methodology, modern tools, such as Geographical Information Systems (GIS) and Building Information Modeling (BIM) were integrated. This integration brings spatial and asset data together, allowing for stronger collaboration and enhanced project visualization.

Nowadays, uncontrolled development and rapid urbanization exacerbate water-related issues such as flooding and supply-demand disparities. In such a cases Rainwater harvesting (RwH) is an efficient method for conserving freshwater resources, mitigating stormwater impacts, preserving groundwater, and reducing reliance on government resources. Adopting RwH as an integral part of a sustainable water infrastructure signifies environmental stewardship and equitable access to water resources. Therefore, the integration of GIS and BIM was implemented to plan and design a community Rainwater harvesting system (RwHs) in the Jaipur (India) municipal area. Implementing community RwHs requires the consideration of various economic, demographic, social, and environmental factors. Thus, before commencing the study, an array of remotely sensed data from reliable sources, such as the Indian

Meteorological Department (IMD), National Remote Sensing Center (NRSC), United States Geological Survey (USGS), and Food and Agriculture Organization (FAO), were obtained along with ground survey data covering topography, socioeconomic status, water quality, soil, and meteorological parameters.

Initially, the planning and design of community RwHs necessitate the precise evaluation of multiple aspects and design considerations. Understanding the historical development patterns and classification of the study area serves as a foundational study. Through Land Use Land Cover (LULC) analysis and prediction, study quantified that built-up land has increased by 46.55 % over the past three decades and is expected to increase by 12.68% in the coming decade, facilitating decision-making through area categorization and efficient land use planning. In addition to area categorization and prediction, gaining insight into hydrological characteristics is crucial for the development of water infrastructure. Therefore, a hydro-spatial analysis in a GIS environment was performed to establish the relationship between topography and hydrology, resulting in the formation of basins by clustering the area based on topographic features. These results will assist in the comprehensive planning of RwHs.

For comprehensive planning and design, a single municipality ward with a medium built-up land density was chosen. By performing hydro-spatial analysis over a small area, the maximum flow accumulation (FA) points and paths were identified to serve as RwH site alternatives and drainage networks. Consequently, to select the most suitable RwH site alternative, Multi-Criteria Decision-Making (MCDM) was applied by extracting the geometrical and hydrological characteristics of the identified sites. In addition, the viability of the design alternatives was evaluated using the Analytic Hierarchy Process (AHP)-MCDM technique through expert knowledge, which revealed that the underground storage tank (URwH) and underground storage tank with an infiltration well (URwH+IW) were the optimum design alternatives. To ensure water sustainability and flood mitigation, a stormwater drainage network was incorporated by assessing physiographic characteristics to classify the drains into submain, main, lateral, and outfall categories.

Effective on-ground implementation of RwHs demands intense and iterative asset modeling. The emerging characteristics of BIM allow for the design, development, and analysis of infrastructure asset dimensions by incorporating GIS analysis results. Primarily, the development of BIM starts with 2-dimension (D) to determine the optimized RwH component characteristics, which facilitates real-time visualization for stakeholders as 3D aids in conceptual understanding. The developed 3D model serves as essential input data for scheduling and cost estimation, which were considered as 4D and 5D BIM, respectively. The developed 4D and 5D revealed that the planned expected duration for the implantation of RwHs was 204 days with an estimated planned cost of 56248754.66 INR (i.e., 674442.82 USD) which is 3.28 INR per litre. Generally, infrastructure project sustainability is assessed as environmental, financial, or social. To assess the environmental sustainability of RwHs, Life Cycle Analysis (LCA) was performed using the Tally plugin in the Revit tool. The total estimated emission of Greenhouse Gases (GHG) from the implementation of RwHs was 3609.747 tCO2eq. Furthermore, to sustain social sustainability, 7D performed multiple attempts, including optimizing Liters Per Capita per Day (LPCD), water quality assessment, and resource database creation, which shared among the stakeholders through the Autodesk Collaborate Pro platform. Finally, Prevention through Design (PtD) was performed by identifying on-site risks in construction activities to perform risk assessment and formulate safety rules as 8D. Out of 35 assessed activities, 11% activities fell within the unacceptable, 23% were adorable, 34 % were adequate, and 32% were in acceptable classification.

The proposed methodology offers a comprehensive approach to enhance the longevity, resilience, and adaptability of infrastructure by integrating geographic, economic, and social aspects. The implementation of the proposed methodology facilitated the intense and iterative BIM of assets by integrating GIS analysis results to optimize the RwH component characteristics. The development of novel BIM dimensions for RwHs fosters water efficiency and paves the way for assessing environmental, financial, and social sustainability.

Keywords - Infrastructure Planning and Management, Geographical Information System (GIS), Building Information Modeling (BIM), Sustainable Urban Water Management System (SUWM), Water Infrastructure, Rainwater Harvesting System (RwHs), Multi-Criteria Decision Making (MCDM).

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LIST OF ABBREVIATIONS

AAS	Atomic Absorption Spectrophotometer
ADD	Average Daily Dose
AHP	Analytic Hierarchy Process
A_i	Area of each land use soil group
AI	Artificial Intelligence
ANP	Analytic network process
AP	Acidification Potential
BA	Built-up land area extracted from satellite
BCM	Billion Cubic Meters
BD	Built-up land area density
BIM	Building Information Modeling
BMP	Best Management Practices
BSR	Basic Schedule Rates
CA	Cellular Automata
CAD	Computer-Aided Drafting
CDE	Common Data Environment
CH_4	Methane
Cl^-	Chloride
CM	CRITIC Method
CN	Curve Number
CN_{aw}	Area-weighted curve number for the drainage basin
CN_i	Curve number concerning land use soil group polygon
COG	Centre of Gravity
CPM	Critical Path Method
CPWD	Central Public Works Department
CRITIC	Criteria Importance Through Intercriteria Correlation
Cu	Copper
CWMI	Composite Water Management Index
D	Dimension
DEM	Digital Elevation Model
DGPS	Differential Global Positioning System
DO	Dissolved Oxygen

DSS	Decision Support Systems
DT	Direction Tunnels
EN	European Standard
EP	Eutrophication Potential
EPA	Environmental Pollution Agency
ESRI	Environmental Systems Research Institute
EV	Earned Value
EWM	Entropy Weight Method
F^-	Fluoride
FA	Flow Accumulation
FAO	Food and Agricultural Organization
FCC	False Colour Composite
Fe	Iron
FF	Fitness Function
FIS	Fuzzy Inference System
FL	Fuzzy Logic
FM	Facility Management
GA	Genetic Algorithm
GHG	Greenhouse Gases
GIS	Geographic Information System
GML	Generalized Markup Language
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
GWAMP	Geographic Water Management Potential
GWP	Global Warming Potential
HI	Hazard Index
HQ_i	Health hazard Quotient
HQiW	Weighted hazard quotient
ICMR	Indian Council of Medical Research
IDW	Inverse Distance Weighted
IFC	Industry Foundation Classes
IMD	Indian Meteorological Department
IoT	Internet of Things

IRS	Indian Remote Sensing
ISO	International Organization for Standardization
ISR	Integrated Schedule Rates
IW	Infiltration Wells
JMC	Jaipur Municipal Corporation
K_{em}	Unique constant value
LCA	Life Cycle Assessment
LCC	Life Cycle Costing
LEED	Leadership in Energy and Environmental Design
LEI	Landscape Expansion Index
LID	Low-Impact Development
LoD	Levels-of-Detail
LPCD	Liters Per Capita per Day
LPS	Last Planner System
LULC	Land Use Land Classification
MCDM	Multi-Criteria Decision Making
MCE	Minimum Classification Error
MEP	Mechanical, Electrical and Plumbing
MGNM	Multi-purpose Geometric Network Model
MLC	Maximum Likelihood Classification
MLD	Millions of Liters per Day
MLP	Multi-Layer Perceptron
MOLUSCE	Modules for Land Use Change Evaluation
MoUD	Ministry of Urban Development
N	Number of land use - soil polygons in each drainage basin
NDVI	Normalized Difference Vegetation Index
NetCDF	Network Common Data Form
NI	Number of Inputs
NIR	Near-infrared
NO	Output
NO_2	Nitrogen dioxide
NRSC	National Remote Sensing Centre
O&M	Operation and Maintenance

OF	Objective Function
ORWH	Overground Rainwater Harvesting tank
OSHA	Occupational Safety and Health Administration
OSM	Open Street Map
P	Phosphorus
Pe	Precipitation
PAPRIKA	Potentially All Pairwise RanKings of all possible Alternatives
PED	Primary Energy Demand
PERT	Program Evaluation Review Technique
PHED	Public Health Engineering Department
PROMETHEE	Preference Ranking Organization Method for Enrichment Evaluation
PtD	Prevention through Design
Q	Direct surface runoff
Q-GIS	Quantum Geographic Information System
Q_n	Discharge
r	Correlation coefficient
R^2	Coefficient of determination
RDBMS	Relational Database Management System
Rfd	Reference dosage
RHS	Rooftop Harvesting System
RS	Remote Sensing
RMSE	Root Mean Square Error
RwH	Rainwater harvesting
RwHs	Rainwater harvesting system
S	Potential soil retention
SCS-CN	Soil Conservation Service-Curve Number
SDG	Sustainable Development Goals
SFP	Smog Formation Potential
SHM	Structural health monitoring
S_o	Bed slope
SQL	Structured Query Language
SRTM	Shuttle Radar Topographic Mission
SUDS	Sustainable urban drainage systems

SUWM	Sustainable Urban Water Management
SWIR	Shortwave infrared
TDS	Total Dissolved Solids
t_e	Expected time
TIRS	Thermal Infra-Red Sensor
t_m	Most likely time
t_o	Optimistic duration
TOPSIS	Technique for the Order of Prioritisation by Similarity to Ideal Solution
t_p	Pessimistic duration
TRACI	Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts
TRI	Terrain Roughness Index
TWI	Topographic wetness index
UA	Urban Area
UCR	Urban Compactness Ratio
URWH	Underground Rainwater Harvesting
USGS	United States Geological Survey
UTM	Universal Transverse Mercator
VDC	Virtual Design and Construction
VIKOR	VIekriterijumsko KOmpromisno Rangiranje
WASPAS	Weighted Aggregated Sum Product Assessment
WBS	Work Breakdown Structure
WGC	World Geodetic System
WHO	World Health Organization
Wi	Water quality
WoE	Weight of Evidence
WPM	Weighted Product Model
WQI	Water Quality Index
WSC	Water-sensitive city
WSM	Weighted Sum Model
WSUD	Water-sensitive urban design
Y_e	Depth of flow for the most efficient section.
λ	Surface depression storage (Initial abstraction ratio)

1. Introduction

1.1 Overview

This chapter provides an in-depth description of infrastructure, encompassing its development, management tools, and societal consequences. Furthermore, emphasis on water infrastructure illustrates the effects of infrastructure development on maintaining the reliability and sustainability of water resources. Finally, the necessity of water infrastructure and the concept of a sustainable water management system are elaborated, along with an outline of the thesis. Figure 1.1 represents the chapter overview, which is elaborated in a subsequent section.

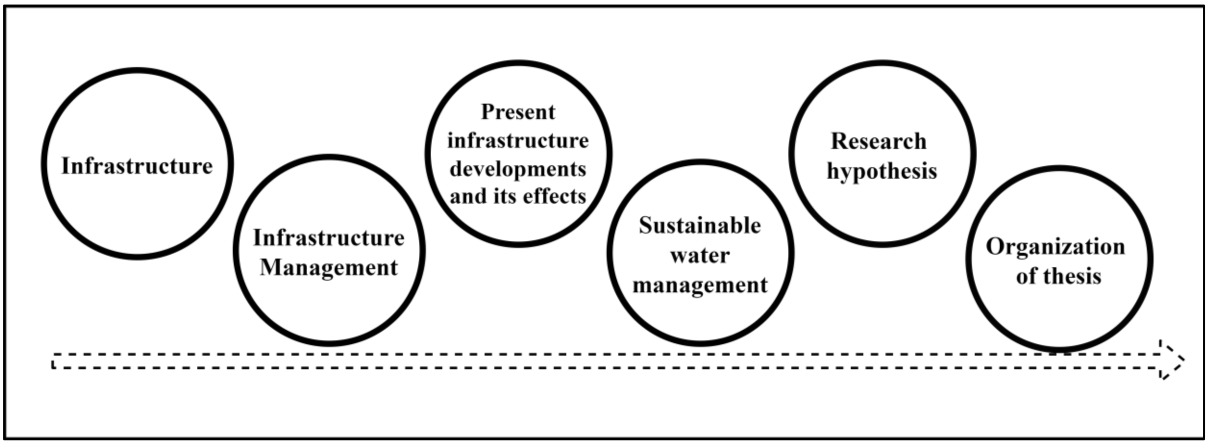


Figure 1.1 Introduction chapter overview

1.2 Infrastructure

In the late 1880s, the French borrowed the word infrastructure with infra meaning below and structure meaning building. "Infrastructure" refers to various systems and structures required for physical existence. It provides essential needs like food - water facilities, equipment, or equivalent physical assets like bridges, ports, terminals, and highways crucial to the country's economic growth (Adbi, 2020). The two fundamental types of infrastructure are soft and hard infrastructure.

1.2.1 Soft infrastructure

Soft infrastructure refers to the human capital and institutions required to sustain an economy that provides specific services to the public, such as healthcare, financial institutions, government offices, law enforcement, and education (Pearce & Wu, 2015).

1.2.2 Hard infrastructure

Hard infrastructure refers to the physical components that sustain daily life, such as electrical grids, roads, bridges, and highway systems, along with the commodities that enable them to function, such as mass transit, buses, and trains (Ambashi et al., 2022). The types of hard infrastructure are shown in Figure 1.2 and explained below.

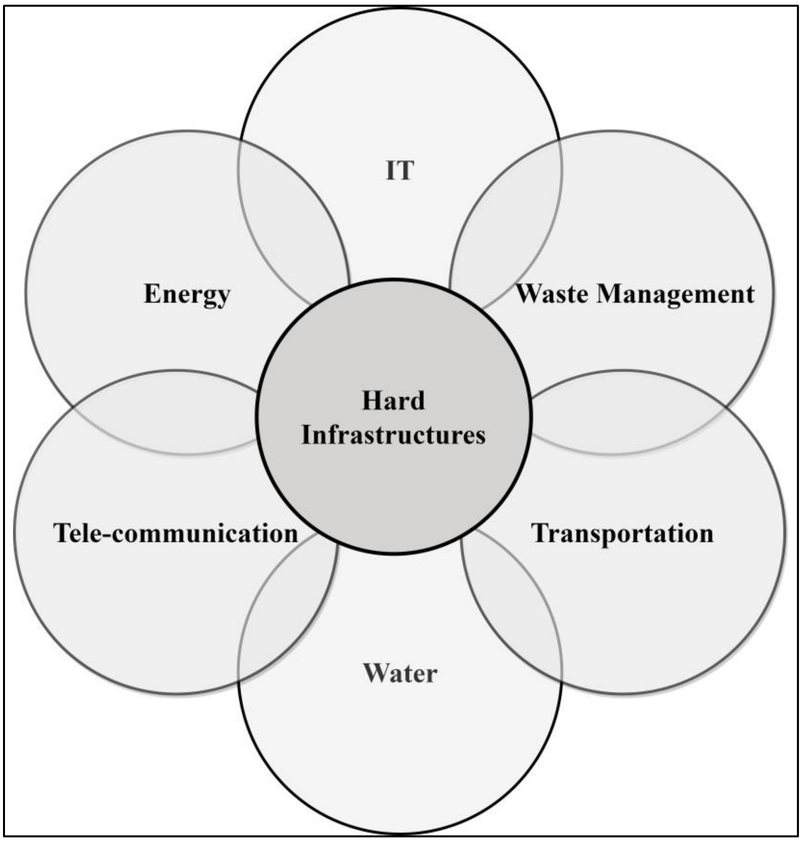


Figure 1.2 Types of hard infrastructure

Infrastructure encompasses various components that are essential for the development and functioning of societies. In such cases, infrastructure management principles, tools, and techniques are crucial for maintaining the functional characteristics of the components that foster sustainable development and stimulate economic progress (Thacker et al., 2019). It mainly concerns infrastructure projects, including activities intended to preserve and extend the infrastructure.

1.3 Infrastructure management

Infrastructure management is a broad and expanding process for designing, implementing, operating, and maintaining infrastructure assets. The fundamental concept underlying strategic infrastructure management is to prolong anticipated service life and sustain performance

(Uddin et al., 2013). Infrastructure with a long-life cycle typically requires much more action, including maintenance, restoration services, and rehabilitation (Suprayitno et al., 2018; Suraji, 2003). It entails strategically managing infrastructure systems to maintain optimal performance, efficiency, and sustainability. Infrastructure management involves long-term asset operations and maintenance, resource allocation, budgeting, risk assessment, policy creation, asset evaluation, performance tracking, and infrastructure asset management planning (Too & Tay, 2008). As a substitute, infrastructure project management is a component of infrastructure management that concentrates on planning, implementing, and delivering individual infrastructure projects.

Infrastructure project management is concerned with managing infrastructures across their lifecycle by referring to a comprehensive, multidisciplinary set of strategies. Infrastructure project management typically targets a larger segment of society and includes various groups of people as key stakeholders. It encompasses various project phases, including design, construction, legal, financial, and operational aspects (Grigg, 2010). The following are some essential procedures and actions performed in infrastructure project management (Piryonesi, 2019; Piryonesi & El-Diraby, 2019; Suraji, 2003; The Institute of Asset Management, 2015).

a) Preservation of a detailed inventory of individual assets, including acquisition cost, initial service life, remaining usable life, physical condition, and repair and maintenance consistency.

b) Creating a defined program for sustaining an asset portfolio through degradation forecasting, planned maintenance, repair, and replacement.

c) Developing and managing information systems to support infrastructure operations.

d) Summarising the present and anticipated service levels and connecting them to capital for planning maintenance.

e) Estimate the lifecycle cost of an asset and potential funding sources for maintenance actions.

An infrastructure project consists of the interconnected systems and networks necessary to provide services and support for social and economic activities, comprising transportation systems (e.g., highways, roads, rail systems, ports), utilities (e.g., water, power, communications), and public facilities (e.g., schools, recreation, prisons, postal facilities) that require continuous monitoring and maintenance (Rioja, 2012). Adopting infrastructure project management involves utilising various techniques and tools aimed at empowering local and national governments to promote inclusive and sustainable development while ensuring economic sustainability (Bushuiev & Kozyr, 2020). Previously, a range of tools and techniques for project planning, scheduling, resource allocation, budgeting, risk management, procurement, and stakeholder coordination had been embraced (Harold, 2017; Project Management Institute, 2008). These techniques streamline infrastructure management by enhancing communication, fostering collaboration, and enabling the planning of associated operations.

Numerous modern tools streamline the entire infrastructure management process. Process modeling and management tools offer a holistic understanding of workflow, thereby enhancing sequential work execution. Soft computing tools further refine workflow modeling, ensuring optimization. Project planning tools play a pivotal role in defining objectives, allocating resources, and scheduling activities, leveraging techniques such as CPM and PERT for optimal scheduling strategies. Risk analysis tools categorize and mitigate infrastructure development risks efficiently. Project management tools, exemplified by Gantt charts and WBS charts, proficiently track progress and allocate resources effectively. Metrics and management tools ensure stringent quality control by meticulously measuring performance against predetermined goals. Quality assurance tools diligently uphold work quality standards, employing techniques such as Pareto diagrams for meticulous oversight. Database management tools efficiently organize project data, fostering seamless information sharing and minimizing conflicts, thereby collectively contributing to the triumph of the project (Georgakopoulos et al., 1995; Harris et al., 2021; Sözüer & Spang, 2014).

1.3.1 Techniques

1.3.1.1 Classic technique

The classic technique includes all activities that must be fulfilled in a predetermined order. Additionally, it involves allocating resources to each activity based on its importance and maintaining track of the work quality by considering deadlines. A small team can manage projects using this approach.

1.3.1.2 Waterfall technique

The waterfall technique is also considered a traditional technique as it builds on the classical approach and is upgraded to a new level. As the name suggests, it is based on performing the activities sequentially, where the next task is only performed when the previous task has been completed. In this approach, a project can be monitored very carefully, and every stage is held accountable and examined to ensure that everything goes according to plan (Bogdan-Alexandru et al., 2019; Thesing et al., 2021). Complex projects can be handled using this method.

1.3.1.3 Agile project management technique

The agile project management technique organizes large projects into multiple sprints, allowing for an extensive review of the entire process throughout development. This in-depth study improves the successful and adaptive planning of projects in response to their needs and changes as they emerge. These actions result in a strong continuous improvement during the developmental stage, and the teams grow more organized and collaborative, aiming to produce the best possible outcome. The Agile project management approach is utilized for projects whose development unfolds in brief but precise steps by small but highly collaborative teams (Highsmith, 2009).

1.3.1.4 Program Evaluation and Review Technique

The Program Evaluation and Review Technique (PERT) is an excellent management technique widely used in various fields, developed during the Cold War. This technique provides the project with extremely complicated and tremendously comprehensive planned scenarios that aid the development team by visualizing the entire process and their ultimate results on PERT charts. The primary advantage of this approach is that it effectively analyses the tasks carried out throughout the project. It allows a team to track all developmental activities and identify and address any flaws. This probabilistic method best suits large, long-term projects involving untraditional activities (Malcolm et al., 1959).

1.3.1.5 Critical Path Method

The Critical Path Method (CPM) is a deterministic method used to schedule and plan work activities as per the specifications provided in the detailed project. This method identifies and confirms the longest path for completing the activities. It entails emphasizing the crucial relevance of the activities that must occur along a specific path so that they can be carried out individually rather than sequentially. The CPM is more frequently applied to complicated projects with many tasks (Kelley & Walker, 1959).

Implementing the infrastructure project management techniques increases the success probabilities by analysing and minimizing the risk involved. The successful implementation of infrastructure projects provides various options, ensuring that they are competitive, result in value-for-money for governments, and are ultimately acceptable and affordable for end-users, laying the path for revolutionary new infrastructure initiatives that promote economic and societal progress (Helby, 2019). The uniqueness of the infrastructure project and its successful implementation encourage the development of new infrastructure projects.

1.3.2 Advances in infrastructure management

1.3.2.1 GIS

Geographical Information System (GIS) is "an automated tool for capturing, storing, retrieving, manipulating, analysing, querying, and displaying spatial and non-spatial data to generate multiple planning alternatives for decision-making." A GIS is a database system with capabilities for geographically referenced data and a collection of operations for enhancing information (Demers, 2008). GIS collects information by digitalizing various maps and satellite imagery acquired from space, market research, physical features, aerial photography, satellite imagery, and even data from a spreadsheet containing values relating to spatial information (Laurini & Thompson, 1992). All acquired data can be loaded into a GIS and then visualized based on the user's needs and the capabilities of GIS, as shown in Figure 1.3.

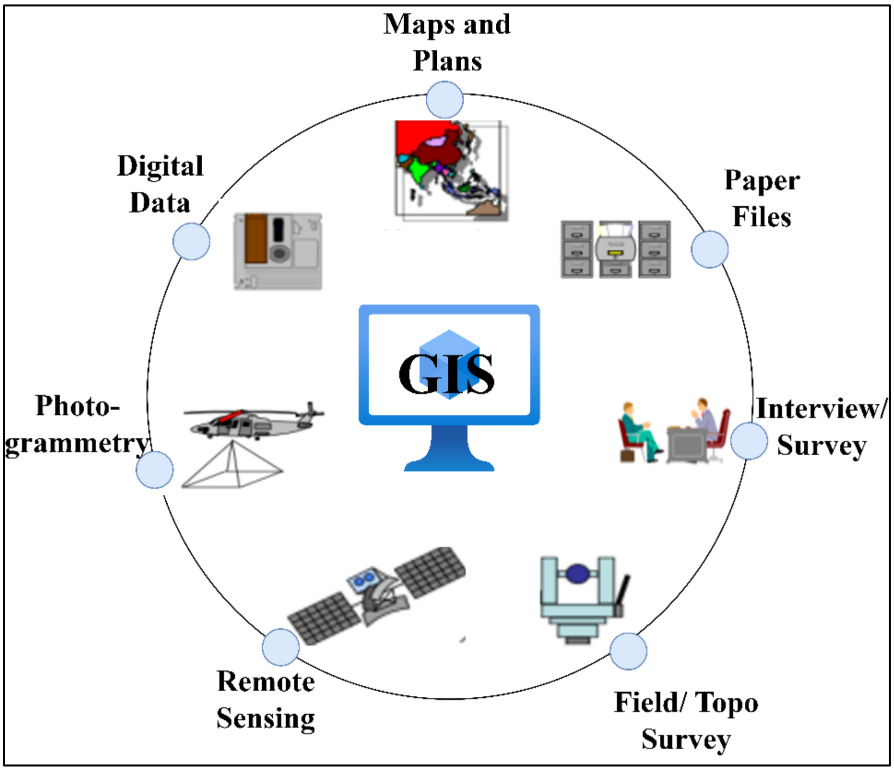


Figure 1.3 Concept of GIS

A GIS stores information in different layers, such as streets defined by one layer, buildings, structures, or other physical features defined by another, and people or other entities are specified as a third layer. Basically, GIS stores information in two formats:

a) Spatial Data: It refers to a characteristic or phenomenon with a specific geographic position, such as a playground, road, river, or school. Each feature has a latitude and longitude in the space, making it visually evident. Two spatial data models allow users to store and analyse the information.

i) Vector: The term "vector" describes the storing of data as objects in space. Vector models are typically used to represent characteristics such as retail stores and telephone pole locations, lines for features such as streets, pipelines, contour lines, polygons for land uses, counties, census tracts, etc.

ii) Raster: It is a method of storing data where information is set out in a regular grid, typically with square-shaped cells, over an area in a predetermined order. Rows and columns with unique values were used to classify the data. The raster data format allows for quicker spatial analysis while dealing with massive amount of data.

b) Non-Spatial Data: It involves information in the form of features. The details are kept in tabular format, commonly referred to as attribute data, and are typically stored in the backend.

1.3.2.2 BIM

Building Information Modeling (BIM) is a method for creating, updating, exchanging, and managing geometric and semantic information about physical facilities throughout their lifecycle (Zhu et al., 2018). BIM represents existing facilities, such as buildings or infrastructure elements, and the built environment in a multidimensional perspective (Cheng et al., 2016). The emergence of BIM, characterized by information management throughout the life cycle of construction projects, offers a cutting-edge digital tool and information-sharing platform for the overall management of infrastructure projects and a new approach for implementing integrated project management principles. The definitions mentioned in Table 1.1 were identified in the literature indicate that BIM was not only utilized as a product but also as a process to contribute towards the design process, which most of the time is iterative among the stakeholders (Architects, 2007; Associated General Contractors of America, 2008; Gabrielli, 2016; ISO 19650-1:2018, 2018; Ku & Taiebat, 2011).

Table 1.1 Definitions of BIM

Source	Definition of BIM
Associated General Contractors of America (AGC (2007)).	A data-rich, object-oriented, intelligent, and parametric digital representation of the facility, from which views and data appropriate to various users' needs can be extracted and analysed to generate information that can be used to make decisions and improve the process of delivering the facility.
American Institute of Architects (AIA (2007)).	A digital three-dimensional model linked to a database of project information, combining all information from the design inception to the facility management.
Autodesk (2009).	An integrated process built on coordinated reliable information about a project from the design through construction and operations.
National Institute of Building Sciences (NIBS (2007)) and Whole Building Design Guide (WBDG (2012a)).	A digital representation of physical and functional characteristics of a facility which serves as a shared knowledge resource for information about a facility forming a reliable basis for decisions during its life cycle from inception onward.
ISO 19650-1:2018.	Use of a shared digital representation of a built asset to facilitate design, construction, and operation processes to form a reliable basis for decisions.

Furthermore, BIM allows for the superimposition of multidimensional data onto the model during the design process, providing a realistic database and fostering better collaboration among project stakeholders (Kensek, 2015). The different aspects of BIM are as follows.

a) A combination of tools and technologies to create multidimensional models with improved visualization and rich project-related data.

b) An integrated process that allows information sharing among stakeholders involved in the FM and operations.

c) A strategy and product combination that assists stakeholders in making decisions about a building throughout its life cycle.

1.4 Present infrastructure developments and its effects

The concept of infrastructure development is linked with industrialization concerning economic development. It is difficult to envisage an economically developed country without a substantial infrastructure. According to the World Bank, a country's ability to industrialize, diversify its production, expand trade, manage population growth, or improve environmental conditions will depend on how well its infrastructure is developed (Ubi & Eke, 2019). On the other hand, the infrastructure sector stimulates the expansion of related industries, including townships, housing, built-up infrastructure, and construction development projects, contributing to economic growth (IBEF, 2022).

The infrastructure industry and its development are the primary concern for India. Notwithstanding the difficulties that countries are experiencing due to the pandemic, India's infrastructure sector has shown exceptional growth, broken records, and contributed to the expansion of the country's economy. India planned to invest $ 1.4 trillion in infrastructure to ensure sustained national development between 2019 and 2023, which resulted in the growth of several road infrastructures, gas pipelines, and industrial developments. The government has suggested spending $750 billion on railway infrastructure between 2018 and 2030 (Ministry of Urban Development, 2015; Tripathi, 2001).

In October 2021, the Indian Union Cabinet adopted the PM Gati Shakti National Master Plan, which contains procedures for implementation, monitoring, and support to revolutionize infrastructure. The government introduced a geospatial platform like remote sensing (RS) as part of this plan to facilitate projects like telecom networks and gas pipes in highways and railroads. Infrastructure for roads and railroads are the most important public resources as they foster economic interaction between large cities and towns. This connectedness allows for more economic activity, which aids the development of underdeveloped areas and promotes equitable and proportional growth. It also promotes industrialization and infrastructure development, improving job prospects by allowing individuals to work in contemporary occupations and contributing to economic progress. Due to better job possibilities, more individuals have been drawn to relocate from rural to urban regions since the industrial revolution (Government of India, 2021).

Many industries and infrastructure developments are concentrated in cities and offer prospects for high urban earnings. Work opportunities are one of the primary elements that attract individuals to urban areas. These factors collectively cause both temporary and long-term migration to metropolitan regions. People are emigrating from rural areas due to poor health care, minimum educational and employment possibilities, environmental changes such as droughts and floods, and a shortage of land with sufficient agricultural potential. The migration of people from rural to urban areas also provides multiple benefits, such as better living standards, better market potential, and advanced urban services, such as transport mobility and healthcare. Over the past 50 years, India's urban population has grown significantly. The Ministry of Urban Development (MoUD) estimates that by 2031, there will be close to 600 million people living in urban areas (Ministry of Housing and Urban Affairs, Government of India 2023). Rapid urbanization frequently causes deforestation, habitat loss, and the withdrawal of fresh water from the environment, which can reduce biodiversity and alter the ranges and interactions of species.

Overcrowding exacerbates these issues, causing social unrest and increased crime rates. Unemployment rates rise as urban growth exceeds job creation, sustaining cycles of poverty. Slum development degrades living conditions and depletes urban resources. Sanitation issues cause health risks, as insufficient infrastructure contributes to environmental contamination and waterborne diseases. Poor health outcomes are common in densely populated areas due to air pollution and limited healthcare access. Traffic congestion reduces mobility, lengthens travel times, and poses safety risks. These challenges highlight the urgent need for comprehensive urban planning and sustainability.

The increase in population and urbanization demands fast withdrawal of fresh water from streams, lakes, aquifers, and artificial reservoirs, resulting in water stress and scarcity. Furthermore, fast shrinking, polluting water bodies in urban areas due to the encroachment of catchment areas, disregarded watersheds, and poor management of waste and water resources have worsened the situation in urban areas (Centre for Science and Environment, 2005). Water stress arises when the demand exceeds the available supply. In past decades, the percentage rise in worldwide water demand has more than doubled that of population growth. It also reveals the strain that population has on water resources by relating the total freshwater resources to the total population in a country. A nation is under water stress if the amount of renewable water per person is less than 1,700 cubic meters. It is deemed to have a water scarcity if the volume drops below 1,000 cubic meters. It is stated as absolute water scarcity when the amount of renewable water per person falls below 500 cubic meters (Falkenmark et al., 1989; UNESCO, 2022).

1.4.1 Water scarcity

In India, annual utilizable water resources are 690 billion cubic meters (BCM) from surface sources and 447 BCM from groundwater (Nagar, 2021). Despite having surface water supplies, the country relies heavily on groundwater. In June 2018, NITI Aayog released a report titled "Composite Water Management Index (CWMI)," which stated that India was experiencing the worst water crisis in its history. The report reveals that nearly 600 million people were experiencing high to extreme water stress, and 200,000 people died annually because of insufficient access to safe water. India ranked 120 out of 122 nations for water quality, with roughly 70% of the country's water being contaminated. The average per capita water availability in India, already considered stressed, is expected to fall further to 1,341 cubic meters by 2025 and 1,140 cubic meters by 2050, reaching the water scarcity threshold. Currently, 163 million people live without access to clean water, and almost 50% of rural families don't have individual piped water supplies. If things continue, 6% of GDP will be lost by 2050 because of the impending water crisis. India has a per-person water storage capacity of roughly 209 cubic meters, which is insignificant compared to countries like Australia (3,223 cubic meters), Brazil (2,632 cubic meters), the United States (2,193 cubic meters), and China (416 cubic meters) (NITI Aayog, 2019).

In such conditions, adopting sustainable water management strategies is the only way to minimize the severity of the scenario. Planning and managing water resources for optimal economic utilization have become critical for preserving and maintaining ecological balance and economic development. The current technological advancement helps to improve the existing system and implement new management practices by incorporating multiple environmental and social variables. Efficient water conservation strategies and management plans must include a variety of techniques, such as efficient irrigation systems, water recycling and reuse, RwH, and water demand management. These methods aim to reduce water waste, overconsumption and encourage sustainable water usage in various sectors, including agriculture, industry, and household use.

1.5 Sustainable water management

Water management is a broad concern, connecting to the agricultural, industrial, domestic, household, electricity, environmental, fishing, and transportation sectors of the Indian economy. India's water management and policy formulation are the most complex due to the extremely diverse hydrological regimes, geo-hydrological settings, climates, physiographic conditions, and socio-ecological and cultural surroundings. The mean annual rainfall ranges from as little as 100 mm in Jaisalmer, western Rajasthan, to 11,700 mm in Chirapunji, Meghalaya, an example of diverse hydrology in the nation. For many decades, various water management systems in India have been practising addressing water-related concerns in various localities based on available resources.

Traditional water management practices encompass a diverse range of effective techniques tailored to harness and preserve water resources. Talabs or ponds, serving as essential repositories, range from manmade reservoirs to natural bodies of water like bandhis (Panda & Islam, 2023). Jhalaras collect underground seepage for communal and religious water supply, while Baolis or Bawari offer access across social strata. Kunds in Gujarat and Rajasthan store rainwater in saucer-like catchment areas (More & More, 2020; Saxena, 2017). Taankas in the Thar desert capture rainwater in underground pits, while Nadis face siltation challenges. Indigenous bamboo drip systems, Ladakh-specific zings, and Himachal Pradesh kuhls exemplify efficient water management (Norphel & Tashi, 2015). Jack wells in low-lying areas showcase resourcefulness in rainwater preservation (More & More, 2020). These practices, rooted in local wisdom, testify to sustainable water management passed down through generations.

Water conservation strategies in India have changed over time, with traditional approaches being supplemented by modern tools and technologies. Understanding their complimentary nature and integrating their concepts for effective water management bridges the gap between traditional and modern water conservation strategies. In recent years, India has developed new ways to conserve water, using technological advances and scientific knowledge. These techniques include RwHs, drip irrigation, recycling and reuse, and effective water management practices in industries and households. These cutting-edge technologies incorporate creativity, scientific research, and advanced engineering to optimize water utilization and reduce waste.

1.5.1 Sustainable water management practices

Sustainable water management entails effective use, conservation, and protection of water resources to meet current needs without compromising the ability of future generations to meet their own requirements. Adopting strategies that ensure the quantity, quality, and accessibility of water resources while reducing environmental impact is crucial as the demand for water rises. Sustainable water management goes beyond the conventional methods of distributing and extracting water. It includes a comprehensive comprehension of ecosystem dynamics, the water cycle, and the interdependence of human activity. Awareness-raising and community involvement are two more vital components of sustainable water management system. Encouraging individuals and communities to understand the value of water and their role in conservation fosters a sense of responsibility. By balancing the ecological, social, and economic aspects, these practices hope to promote adaptability in the face of adversity (Postel, 2000). A variety of methods, from cutting-edge technologies to neighbourhood-based programs, support sustainable water management. These systems also improve climate resilience, which helps to address the challenges caused by climate change by strategically planning for extreme weather events, water scarcity, and climate adaptation (Richards et al., 2021). These systems support sustainable development by anticipating future water needs, population growth, and climate-related effects through long-term planning. Energy efficiency is also taken care of, with several sustainable practices lowering the energy usage related to traditional methods of water supply and treatment.

Water conservation strategies in India have changed over time, with traditional approaches being supplemented by modern tools and technologies. In recent years, India has developed new ways to conserve water, using technological advances and scientific knowledge. These techniques include RwHs, drip irrigation, recycling and reuse, and effective water management practices in industries and households. These cutting-edge technologies incorporate creativity, scientific research, and advanced engineering to optimize water utilization and reduce waste. Some of these modern techniques are discussed below.

1.5.1.1 Smart water metering

A successful method to reduce water waste and encourage sustainable water management practices is installing smart water meters and monitoring water usage in residential and commercial buildings (Howell et al., 2017). By utilizing smart water meters, the quantity of water consumed by individuals or businesses can be accurately recorded and monitored in real-time. These advanced meters have sensors and connectivity tools that make data collection and transfer automatically with minimum resource consumption. Smart water meters enable the regular recording of water consumption data, which offers important insights into consumption trends and patterns (Nguyen et al., 2018). This data can be analysed by local governing and users to find possible regions for excessive water use and detect leaks or irregularities for implementing appropriate conversation strategy. This technique is crucial for improving water management practices, promoting sustainable development, and reducing the problems caused by water scarcity and increasing demand (Sharvelle et al., 2017).

1.5.1.2 Grey water recycling

Greywater recycling is a cutting-edge and environmentally friendly approach that involves collecting and processing waste and wastewater from several dwelling sources such as showers, washing machines, and kitchen sinks (Al-Jayyousi, 2003). Greywater is collected, cleaned, and reused for non-potable uses such as toilet flushing, landscape irrigation, and plant watering. Greywater recycling systems frequently employ multiple treatment procedures to efficiently remove pollutants, pathogens, and impurities from the collected greywater. These strategies include biological treatments, mechanical filtration, disinfection, and advanced purification techniques. By redirecting greywater from traditional wastewater treatment plants, the recycling process conserves water and decreases the pressure on freshwater resources (Ahmed & Arora, 2012).

1.5.1.3 Pressure-reducing valves

A pressure-reducing valve is key to maintaining the hydraulic system's pressure levels at the desired level. These valves significantly helps to conserve water and ensures the effective operation of downstream water system components through its ability to regulate and control water pressure (Tian et al., 2023). Pressure-reducing valves extend the life of pipes, fixtures, and appliances by retaining a predetermined water level, preventing excessive pressure results in a reduction of the frequency of repairs and replacements. Pressure-reducing valves offer energy-saving advantages in commercial, institutional, residential, and industrial buildings (Latifi et al., 2021). By maintaining proper pressure levels, valves support sustainable practices and encourage environmental responsibility by preserving water resources, reducing water use, and extending the lifespan of water system components.

1.5.1.4 Water-efficient accessories

Water conservation innovations have paved the way for significant reductions in water consumption without affecting consumption patterns (Sheth, 2017). These improvements encompass a variety of techniques, such as modifying shower and tap spray patterns and upgrading toilet flushing systems. Applying these innovative strategies makes it possible to reduce water consumption by maintaining the same level of comfort and convenience. Taps and showers can provide a consistent, pleasing stream using less water by employing aerators or flow restrictors. These adjustments enable an improved and controlled flow while minimizing water consumption and maintaining the quality of the experience. Similarly, toilet technology developments have produced outstanding water-saving achievements (Hashemi et al., 2015). These creative solutions demonstrate that advances in technology and design could significantly modify water conservation by preserving comfort and user expectations using modified spray patterns, improved flushing mechanisms, and water-saving accessories. These advancements are essential in resolving the problems associated with water shortages, promoting sustainable practices, and encouraging more effective and responsible management of limited water resources.

Water conservation techniques are essential for overcoming water stress and ensuring a sustainable future. Implementing diverse water conservation strategies ensures equitable access to water resources, protects the ecosystem, and supports economic development. By pursuing communal endeavours, exchanging knowledge, and promoting awareness initiatives, individuals can actively promote minimizing water usage, adopting RwHs, utilizing efficient irrigation techniques, and giving precedence to water recycling and reuse.

1.5.1.5 Rainwater harvesting (RwH)

Currently, most urban areas face problems with flash floods and inundations due to land alteration and deforestation. In this context, RwHs can be considered a long-term adaptation method capable of addressing urban water scarcity and inundation problems (Abdulla & Al-Shareef, 2009). Rainwater harvesting (RwH) is an efficient method for conserving freshwater resources, mitigating stormwater impacts, preserving groundwater, and reducing reliance on government resources. RwH is a system for collecting, storing, and supplying rainwater with three main components: catchment, storage facility, and target (end-user) (Kaposztasova et al., 2014).

a) Catchment: The area from which rainfall is harvested or stored; this is often referred to as the runoff area. The catchment area may include road surfaces, rooftops, agricultural land, and concrete surfaces.

b) Storage facility: It is a facility where collected runoff water is stored until it may be used for other reasons. The collected water is stored above the ground (in reservoirs or ponds), in soil profiles, or in underground storage tanks.

c) A target (End-user): It is the final stage of the RwHs, where the stored water is distributed and consumed.

1.6 Research hypothesis

With the growing pace of urbanization and industrialization, arid and semi-arid countries face significant water issues. RwH technology has gained popularity as an effective alternative to address water-related issues (Amos et al., 2016; Gilliom et al., 2019; F. Li et al., 2000; Srinivasan et al., 2010; Y. Zhang et al., 2009). This study hypothesis claims that integrating GIS and Building Information Modeling (BIM) helps to improve the effectiveness and efficiency of the design and development of community RwHs in urban areas. The performed integration enables precise modeling, simulation, and spatial analysis for RwHs components, resulting in optimized design, effective water collection, and storage. Figure 1.4 represents the hypothesis of the research.

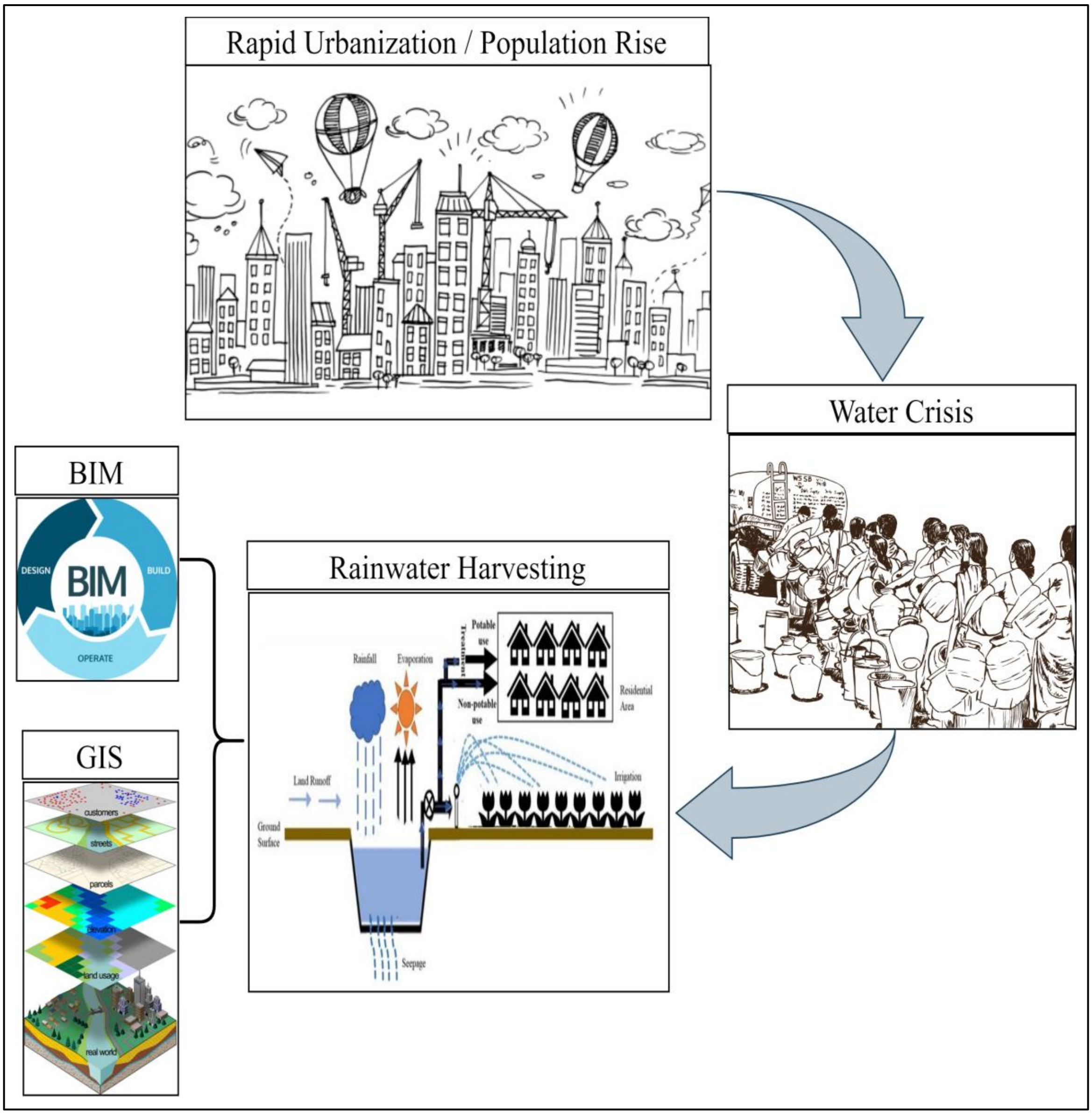


Figure 1.4 Research hypothesis

1.7 Organization of thesis

The thesis is organized into six chapters, each focusing on a specific aspect of the research topic. An overview of the succeeding chapters has been provided below:

Chapter 1: Introduction

This chapter presents an extensive introduction to infrastructure, including its development, management tools, and societal implications. In addition, concentrating on water infrastructure shows how infrastructure development affects the sustainability and dependability of water resources.

Chapter 2: Literature review

This chapter investigates the relevant literature on existing infrastructure development and management research, with particular emphasis on GIS and BIM. In addition, various water management practices prominence on RwH are also explored to establish the theoretical framework and conceptual foundation for conducting research. The section of the chapter has been published in an article under the title *"State of the Art for Integrating Modern Technologies to Develop a Sustainable Water Management Model."*

Chapter 3: Methodology

This chapter describes the proposed research methodology. It includes a detailed overview of the research strategy, data collection methods, and analysis approaches employed for integrating GIS and BIM. The chapter aids in getting a clear understanding of how the research was conducted. This chapter segment has been featured in an article titled as *"A strategic design approach for implementing a rainwater management system using an integration of GIS and BIM tool."*

Chapter 4: GIS analysis

This chapter explains the utilization of GIS to perform multiple spatial and hydro-spatial analyses over the study area. The proposed methodology was applied to the conceptual design of community RwHs over the municipality region of Jaipur (India). Three research articles published the contents of this chapter under the title. *"A systematic basin-wide approach for locating and assessing volumetric potential of rainwater harvesting sites in the urban area," "GIS-based multi-criteria decision-making for ranking potential sites for centralized rainwater harvesting"* and *"Spatiotemporal analysis and prediction of urban evolution patterns using Artificial Neural Network tool."*

Chapter 5: Development of BIM dimensions

In this chapter, the results of GIS analysis were used as input data for developing BIM dimensions. The development of BIM dimensions begins with the creation of 2D as design and planning and progresses to safety analysis as 8D. The dimensions developed in this chapter have been published and incorporated in a research article with the title *"Qualitative and health risk assessment of water using a novel weight-integrated health hazard and fuzzy-derived indices," "A multistage integration of Remote Sensing and BIM tools for conceptualizing and planning a communal rainwater harvesting system,"* and *" An Efficient*

Urban Water Management Practice Based on Optimum LPCD Estimated Using the MLR-GA Optimization Approach- A Case Study for Jaipur, Rajasthan (India).”

Chapter 6: Conclusion

The final chapter summarizes the important findings, establishes conclusions based on the research findings, and explores their consequences. This highlights the study’s aims and contributions to existing systems. Furthermore, based on these findings, this chapter recommends future studies and practical applications.

1.8 Chapter summary

The introduction chapter provides a comprehensive overview of infrastructure, focusing on its development, management tools, and societal implications. It outlines various types of infrastructure, including soft and hard infrastructure, and emphasizes the importance of infrastructure management in ensuring functional efficiency and sustainable development. Furthermore, the chapter discusses infrastructure project management techniques, such as classic, waterfall, agile project management, PERT, and CPM, elucidating their roles in optimizing project outcomes. Advancements in infrastructure management, such as GIS and BIM, are also explored, showcasing their contributions to effective infrastructure planning and implementation. Additionally, the chapter examines present infrastructure developments and their effects, particularly focusing on India’s infrastructure sector and its impact on economic growth and urbanization. It delves into the significance of water infrastructure, highlighting its role in maintaining reliability and sustainability of water resources. The chapter elaborates on the necessity of water infrastructure and introduces the concept of sustainable water management. It also underscores the importance of traditional and modern sustainable water management practices, including greywater recycling, smart water metering, pressure-reducing valves, water-efficient accessories, and rainwater harvesting, in mitigating water stress and promoting sustainable development.

2.1 Chapter overview

This chapter reviews the existing literature used to discover the multiple concepts of infrastructure development in the study field. The opening section of the chapter discusses various infrastructure management tools, techniques, and processes, emphasizing GIS and BIM. In a later section, RwHs were studied as a sustainable water management practice, and a brief overview of how researchers implemented GIS and BIM tools to analyse and implement RwHs was provided. The chapter concludes by identifying the research gaps and objectives of the study. Figure 2.1 illustrates the areas of conducted literature studies.

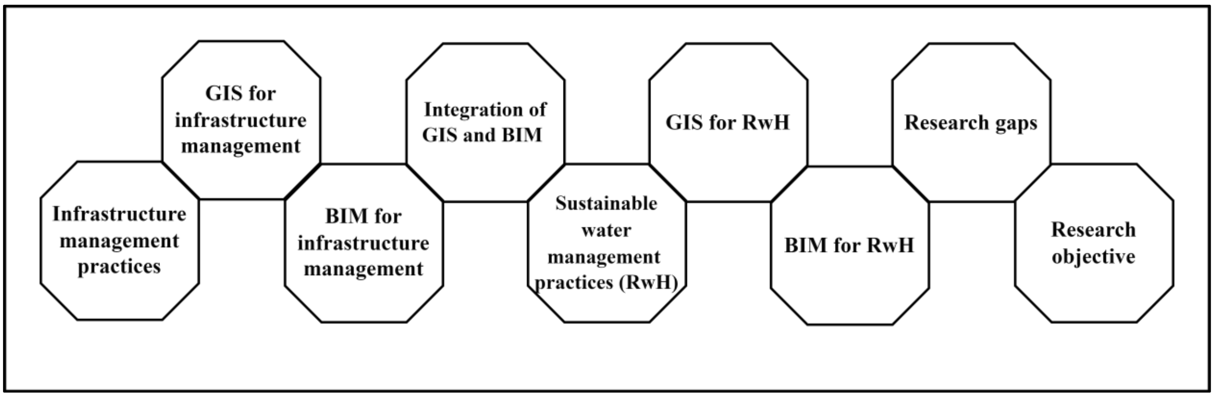


Figure 2.1 Literature review chapter overview

2.2 Infrastructure management practices

Infrastructure management practices are essential for the effective planning, development, operation, and maintenance of infrastructure assets throughout their lifecycle (Sepasgozar et al., 2020). Infrastructure management practices and strategies are constantly altering due to technological advancements, shifting environmental concerns, and the demand for resilient and sustainable systems. By adhering to the principles of management, organizations can improve the performance, longevity, and value of their infrastructure assets while providing services to communities (Hooper et al. 2009). The performed asset management results in predictive maintenance, asset performance optimization, real condition assessment, etc. (Uddin et al., 2013). In addition, multiple asset management software systems are essential for managing infrastructure assets throughout their lifecycle by enhancing asset performance, reducing downtime and maintenance costs, and ensuring regulatory compliance (Kivits et al., 2013). Multiple life cycle and performance-based approaches have been implemented to evaluate the associated risks and benefits (Minsker et al., 2015). Effective planning, resource management, and stakeholder engagement are required at different project stages for successful planning, execution, and delivery (Varsani et al., 2020). Infrastructure management is a complex process that requires the implementation of numerous tools and technologies to effectively manage the life cycle of infrastructure assets, including computer-aided design, 3D printing, the Internet of Things (IoT), advanced analytics, and RS (Howell et al., 2017).

The IoT is a science that employs interconnected devices and sensors to collect and send massive amounts of asset data (Ramamoorthy et al., 2020). IoT was applied to monitor the health of infrastructure assets, spot possible issues, and initiate maintenance procedures as needed. IoT sensors have also been utilized to identify leaks and monitor the conditions of bridges, highways, and water distribution systems (Karimzadeh & Shoghli, 2020). In addition to sensors, machine learning techniques and statistical algorithms must be used to analyse and process the massive amount of collected data. By analysing historical and real-time collected data, several methods have been used to forecast prospective developments or patterns using predictive analytics to identify optimal maintenance schedules, anticipate asset failures, and allocate resources more efficiently (Tao & Yun, 2019).

Along with machine learning techniques, recent years have seen the emergence of 3D printing as a promising technique for producing small replicas of existing infrastructure assets, enabling the comprehensive analysis, and tracking of assets (Shahrubudin et al., 2019). This additive manufacturing technology allows for the creation of objects from digital models by the layered deposition of elements adjusted to individual asset requirements, increasing asset performance, and extending asset life performance (Ali et al., 2022; Lyu et al., 2021). To make maintenance and repair responsibilities easier, mobile devices with augmented reality (AR) deliver real-time information by superimposing digital data onto the physical world, thereby providing users with an enhanced picture of their surroundings to create a digital twin of a physical asset (Hasan et al., 2021). A digital twin also provides a virtual representation of a physical asset that may be utilized for research, testing, and project lifecycle monitoring (Jiang et al., 2021).

In smart city projects, digital twin technology has proven to be an efficient technology by understanding the "urban metabolism" of a city (Bado et al., 2022). Digital twin represent physical assets such as topography, geography, energy and consumption, traffic, infrastructure, public safety, transportation, environmental sanitation, social services, health and hygiene, culture and tourism, parks and entertainment, and water resources (Callcut et al., 2021; Li et al., 2022). In addition, the digital twin enable urban planners and engineers to plan infrastructure by analysing real-time data (Dembski et al., 2020). Infrastructure assets such as roads, bridges, pipelines, and utilities are geographically dispersed and require accurate location-based data for effective management and maintenance (R. Liu & Issa, 2012). In such scenarios, a systematic approach is essential for gathering, analysing, and visualizing infrastructure data across diverse geographic locations. GIS tools and technology play a pivotal role in facilitating geographic data collection, enhancing asset monitoring, optimizing maintenance strategies, and supporting well-informed decision making throughout the entire asset lifecycle (Lee et al., 2018).

2.3 GIS for infrastructure management

GIS maps provide a new perspective for data analysis, aiding the visualization of complicated patterns in real-world planning and policy issues. Because of its superior spatial data processing capabilities, GIS was used to carry out various tasks, including land surveys, cadastral management, and environmental management (Zhang et al., 2009). Moreover, introducing GIS-based simulation models helps planners and environmentalists to resolve real-time issues precisely (Li et al., 2016). The implementation of GIS has been recognized as a key theme in spatial planning over time, particularly in combination with funding organizations, development plans, and infrastructure managers (Jain et al., 2019; Kidd, 2007; Healey, 2006; Todes, 2012; Vigar, 2009).

In practice, strategic spatial planning facilitates the more effective integration of various factors (such as economic, environmental, cultural, and social policies), which leads to efficient decision-making (Albrechts, 2004; Healey, 2006). In spatial decision-making, selecting one or more site alternatives is performed based on multiple variables by an individual or group (Kazemzadeh-Zow et al., 2018; Malczewski & Rinner, 2015). It also quantified the advantage of local competition and measured infrastructure growth and/or deterioration in different towns within a particular municipality to perform the development plan (Baud et al., 2016). By contrast, the concept of GIS includes a) mapping infrastructure regions, b) mapping infrastructure quantities, c) mapping infrastructure densities, d) identifying everything inside the municipality infrastructure, e) identifying everything near the infrastructure, and f) mapping all infrastructure changes (Madela-Mntla et al., 2016). GIS has been adopted in infrastructure projects to identify and illuminate geography-driven problems by developing geographic patterns from mapped data (Mentis et al., 2017). Additionally, GIS has proven efficient in monitoring infrastructure changes and revealing the extent to which infrastructure retreats (Liu et al., 2017).

The visual representation and data processing of GIS allows the integration of multiple multi-criteria analyses to make an important decision (Carver, 2007). Several researchers have also conducted comparative studies between the integration of GIS and different MCDM technique to address various issues related to site selection and design considerations. In some studies, the capabilities of GIS were utilised to select the optimum site for human settlement (Garni & Awasthi, 2017; Merrouni et al., 2018; Dhiman et al., 2018; Villacreses et al., 2017). The integration of GIS and MCDM was performed to analyse and assign weights to multiple topographic factors to provide an integrated environment for road alignment (Aguiar et al., 2021; Pushak et al., 2016; Singh & Singh, 2017). All infrastructure projects are notable for their complexity, political sensitivity, and economic unpredictability. These projects involve public versus private distributional difficulties and environmental concerns seeking modern technology such as digital twins and BIM (Casady et al., 2019). In recent years, BIM has proven to be the most promising tool in infrastructure asset management by enabling the real-time monitoring and controlling of infrastructure assets by providing valuable information on asset performance and conditions (Simpson et al., 2018).

2.4 BIM for infrastructure management

Early BIM technology typically focused on paper documentation underpinning the building and design processes, leading to computer-aided drafting (CAD) solutions that assist users in generating drawings. Currently, BIM is becoming increasingly important in the AEC industry because of its information-rich technique for preserving project details in a realistic model that may include visualizations of the designed real-world asset and extensive data for purchasing, scheduling, and even simulating how assets react in their environment after construction. It also allows for the superimposition of multidimensional data onto the model during the design process, providing a realistic database and fostering better collaboration among project stakeholders (Kensek, 2015). The different aspects of BIM are as follows.

a) A combination of tools and technologies to create multidimensional models with improved visualization and rich project-related data.

b) An integrated process that allows information sharing among stakeholders involved in the FM and operations.

c) A strategy and product combination that assists stakeholders in making decisions about a building throughout its life cycle.

Currently, BIM is becoming a common language for the construction and infrastructure sectors worldwide, providing opportunities for more efficient collaboration among stakeholders. The effective implementation of BIM by experienced engineers or designers generates huge profits and reduces the time of large-scale infrastructure projects (Czmoch & Pękala, 2014). The global BIM market will increase to $15,06 billion by 2027 and has been accepted in numerous nations, including the United States, Canada, Germany, the United Kingdom, China, Japan, India, South Korea, and Singapore, which applied over the entire life cycle of the project (Vikas, 2020). Initially, BIM was utilized in vertical construction projects; however, it has now been widely applied in various fields, including civil infrastructure. Several terminologies, including horizontal BIM, heavy BIM, virtual design and construction (VDC), civil information modeling, BIM on its side, and BIM for infrastructure, are used to characterize model-based technologies and processes for infrastructure projects (Zhang et al., 2020). The adoption of BIM for infrastructure projects is divided into three stages: planning, design, management, and maintenance.

In the planning phase, BIM facilitates efficient and rapid selection of optimal solutions from multiple design alternatives (Li et al., 2012). The use of BIM from the beginning of infrastructure projects streamlines communication by fostering collaboration among stakeholders. In the design stage, BIM decreases design flaws, improves quality, checks for quality, and clashes. To preserve the consistency of the representation across the different Levels-of-Detail (LoDs), an Industry Foundation Classes (IFC)-based multi-scale BIM shield tunnel model was developed using a transformation methodology in the city Generalized Markup Language (GML) format (Borrmann et al., 2015). Lean construction principles were incorporated into the design using a BIM-based reinforced workflow of precast shop drawings (Nath et al., 2015). Further, a BIM-based parametric modeling approach has been applied to enhance design efficiency and interoperability (Girardet & Boton, 2021).

A well-developed BIM throughout the planning and design phases is beneficial for minimizing construction errors and improving construction quality and processes during the construction phase. During the construction stage, incorporating the time and cost "resource management model" was proposed and developed by integrating BIM with the earned value (EV) concept to determine the status of a project on a specific date (Marzouk & Hisham, 2014).

To minimize the likelihood of stochastic spatiotemporal conflicts, 4D BIM has been proposed for successive construction and reconstruction of highways (Mawlana et al., 2015). In the case of rail transit development, the multidimensional (nD) modeling technique was developed by integrating a WBS and other construction code structures (Ding et al., 2012). The adoption of BIM has been validated through seven construction projects at railway construction sites (Shin et al., 2018). At the maintenance stage of the infrastructure, the BIM philosophy was implemented to develop the port maintenance system and perform utilities in tunnel construction (Lee et al., 2018; Valdepeñas et al., 2020). The BIM bridge model was developed as a case study to combine the design and construction processes for a precast box girder bridge (Shin et al., 2018). At the same time, BIM has also proven effective for maintaining the underground utility management system (Sharafat et al., 2021). Later, structural health monitoring BIM (SHM-BIM) was developed for the automatic health monitoring of infrastructure, which facilitates periodic maintenance and risk management (Boddupalli et al., 2019).

Environmental sustainability has become a major concern because of massive infrastructure development. With BIM, it is possible to undertake sustainability in the environmental, economic, and social aspects. The 6D BIM was developed by considering sustainability parameter (Olawumi et al., 2018). The developed 6D BIM model allows the analysis of the carbon footprint across the lifecycle, which helps in decision-making by scrutinizing various design substitutes (Kaewunruen et al., 2020). In addition, it improved the performance of the infrastructure by comparing design alternatives (orientation, aspect ratio, window-to-wall ratio, glass type) and simulating multiple orientations, window-to-wall ratio, window glass type, water usage, and ventilation alternatives (Santos et al., 2020). BIM allows the performance of Life Cycle Costing (LCC) and Life Cycle Assessment (LCA) to make the project resource-efficient (Marzouk & Othman, 2020; Sun et al., 2016).

GIS creates a geographical context for infrastructure planning and design by collecting and interpreting geospatial data, such as land use, topography, and environmental factors, which are essential for infrastructure planning and design. Conversely, BIM produces detailed digital representations of physical assets, such as buildings, utilities, and transportation systems, allowing for precise modeling and analysis of their components and characteristics. By integrating GIS with BIM, infrastructure projects can leverage the potential of both technologies to improve decision-making, project outcomes, and operational efficiency. The performed integration enables data sharing and information in real-time, allowing stakeholders to access accurate and up-to-date geographical and asset data throughout the project lifecycle (Faisal and Khan 2017; Ramachandra et al. 2018).

2.5 Integration of GIS and BIM

Integrating GIS and BIM brings spatial and asset data together, allowing for better decision making, enhanced project visualization, stronger collaboration, and efficient asset management in infrastructure projects at the micro and macro levels. GIS and BIM interpret 3D modeling from two perspectives: GIS focuses more on real-world modeling, whereas BIM focuses more on the design process. GIS often focuses on geographical information and the shape of buildings and building components from a geographical perspective. In contrast, BIM often focuses on detailed building components and project information, such as cost and schedule, from architectural and construction perspectives (Cheng et al., 2016).

To perform a climatic assessment of buildings, an integrated BIM model with climate data allows designers to make decisions on reducing climate-related damage (Hjelseth & Thiis, 2008). In some studies, GIS and BIM have been integrated into infrastructure projects to perform earthwork simulation, schedule management, construction equipment management, walkability assessment, and facility management (FM). The integrated model enables visualization of buildings at a city scale, incorporating essential geometric and attribute data (Kari et al., 2012). The connected BIM model with the building mechanical, electrical, and plumbing (MEP) system and the GIS-based pipeline network for underground utility operation and maintenance (O&M) provides a 3D holistic utility model (Liu & Issa, 2012). For highway construction, the integrated system of BIM and topographic data from GIS provides cut-and-fill operation details from topographic analysis to reduce total earthwork (Kim et al., 2015). In addition, the platform was developed using the BIM merged Digital Elevation Model (DEM), real-time photographs, and scheduling information to perform highway schedule management by applying multiple queries and analyses. In metro construction, to identify the risks involved in underground activities, an early risk warning and management system was developed using a Global Positioning System (GPS) receiver and building-related information models (Du et al., 2015). For the maintenance phase, the developed BIM model was used to audit and evaluate road workability conditions for a specific location (Kim et al., 2016).

For interior acoustic design, integrating BIM and GIS on a single platform aids in better decision-making by evaluating outdoor traffic noise and mapping the indoor environment (Deng et al., 2016). While performing indoor-to-outdoor route planning, a multipurpose geometric network model (MGNM) was developed to incorporate IFC data into a GIS system (Teo & Cho, 2016). Subsequently, a concept was developed to integrate BIM and GIS to assess safe routes to schools (Kim et al., 2016). The integrated tool for geometric visualization and coordinate transformation helps resolve the project's complexity, accuracy, and operational speed (Ng et al., 2017). The integration methodology incorporates several forms, such as ontology building, semantic integration via compatible data formats and standards, and querying different data sources (Santos et al., 2019). In another study, three hypotheses were created for integration: technological, scientific, and data sources. The model developed from these hypotheses provides an exact solution for quantitative analysis, decision making, and management, and its application in infrastructure development. The criteria for assessing the integration were identified and termed EEEF: Effectiveness, Effort, Extensibility, and Flexibility (Liu et al., 2017).

In addition, spatiotemporal statistics lent to the evolution process of integrating BIM and GIS applications and forecasting possible future integration development (Liu et al., 2017). Some studies have used integration for robot positioning and navigation (Herslund & Mguni, 2019). The integration also facilitated the quantification of waste generated during construction and estimated the related costs (Santos et al., 2019). The utilization of a converted BIM model, representing an as-built building in the form of an LOD model, greatly enhances the process of gaining building design authorization. However, the interoperability problem between BIM and GIS has been identified as the absence of standard formats, public motivations for adopting BIM, and the lack of libraries with rich semantic objects (Alexopoulos et al., 2019). To overcome the interoperability problem and perform integration, different combinations were created, such as "BIM leads and GIS supports," "GIS leads and BIM supports," and "BIM and GIS are equally involved," which were tested for real-time projects (Yang et al., 2021).

The adoption of modern tools and technologies plays a pivotal role in accelerating infrastructure development through early identification of potential risks. These infrastructure developments and technological advancements are critical to sustain the country's economy. Although it provides numerous benefits, it also has some side effects that must be properly addressed. Since the 1990s, New Zealand and the United States have adopted the Low-Impact Development (LID) policy to reduce the adverse effects of infrastructure development (Chui et al., 2016; Fletcher et al., 2014; Mao et al., 2017; Ni et al., 2017; Ren et al., 2017; Z. Zhang et al., 2013). The transformation of the landscape due to infrastructure development encourages human migration, with the hope of upgrading work opportunities and living standards. The processes of urbanization and migration have resulted in significant strain on existing systems and natural resources. In such cases, increasing water demand with limited water resources poses a significant challenge to society, specifically in urban areas (Salzman et al., 2019; Wang & Zimmerman, 2015). To ensure a safe and sustainable water management system, adopting integrated sustainable water management practices is required in urban areas (Willuweit & O'Sullivan, 2013).

2.6 Sustainable water management practices

The concept of sustainability originated in forestry, stating the practice of never extracting more resources than what naturally regenerates (Wiersum, 1995). The German word for sustainability, Nachhaltigkeit, was first used in this sense in 1713 (Wilderer, 2007). The World Commission on Environment and Development (WCED), led by Norwegian Prime Minister Gro Harlem Brundtland, formulated the most widely accepted concept of sustainable development in 1983. It says that "development that meets present needs without compromising the ability of future generations to meet their own needs" is what is meant by "sustainable development" (Chaharbaghi & Willis, 1999; Khalfan, 2011). Sustainable development involves three major components: social fairness, environmental conservation, and economic growth, also known as the 'triple bottom line' (Heinberg, 2010; Parkin et al., 2015).

With rising population and climate change, framing sustainable water management strategies are becoming extremely important. Adopting sustainable water management practices ensures the long-term availability of water resources and minimizes the effects of infrastructure development, such as urbanization, on water quality and quantity. Water conservation is an effective approach that lowers water usage by adopting water-efficient technologies and behavioural modifications, ensuring access to clean and safe water sources (Environmental Protection Agency, 2007). Several sustainable water management techniques have been used worldwide based on severity and available resources.

For urban water planning and management, researchers and industry experts have put forwarded an array of concepts and theories, including Best Management Practices (BMPs), which were established in the United States, and Sustainable urban drainage systems (SUDS) in the UK in the 1970s (Fletcher et al., 2014; Scholz, 2009). In the 21st century, Australia launched Water-sensitive city (WSC) or water-sensitive urban design (WSUD), which experienced six development stages of urban water management to deliver a range of benefits that not only safeguard the degradation of urban water sources but also manage and recycle rainwater so that cities become sustainable, liveable, and resilient (Brown et al., 2009; Fletcher et al., 2014). To achieve sustainable urban water management (SUWM), municipalities prioritized water in urban development by integrating the urban design process with other disciplines responsible for water service provision and establishing social-political capital for engaging with water (Edmondson et al., 2018).

Recently, integrated urban water management has gained traction. Under this paradigm, sewage, stormwater runoff, and the water supply operate as a single integrated system (Mitchell, 2006). However, integrated urban water management permits demand-side strategies and decentralized management. In practice, traditional and more recent approaches to urban water management take a largely "utility-centric" perspective on urban water supply, where the urban water utility is the primary entity that constitutes, manages, and distributes water. Most of the urban regions in emerging nations have experienced high densities of population development, the rapid propagation of impermeable highways and rooftops, and pressures from water flood disasters due to climate change. Using sustainable water practices enhances access to hygienic services, lowers health issues, and fosters economic growth (Srinivasan et al., 2010).

In addition, developing countries are facing problems with water-borne diseases and epidemics due to increased urbanization, intensive irrigation, and industrial progression. Moreover, decreased water infiltration in urban areas reduces groundwater recharge, increases the risk of flooding, and accelerates pollution transfer (Behzadian et al., 2018). Adopting RwH in urban areas involves transitioning from a reactive approach to water management to a proactive approach. However, many studies have demonstrated that RwH systems are effective in semi-arid regions and can serve as alternate water sources after being stored properly (Ammar et al., 2016). RwHs are classified into two types: roof harvesting systems (RHS) and pond harvesting systems (PHS). The RHS is more widely used in countries such as Jordan, Spain, Italy, Australia, Ireland, and Malaysia (Cook et al., 2013; Farreny et al., 2011; Liuzzo et al., 2016). Rainwater collected from the RHS is commonly used to meet both non-potable and potable water demands. There are two types of storage tanks for an RHS: aboveground and underground.

2.6.1 Rainwater harvesting

Rainwater harvesting (RwH) has proven to be one of the most cost-effective and environmentally friendly water conservation methods that simultaneously addresses water scarcity issues and alleviates groundwater over-extraction (Doulabian et al., 2021; Khorrami et al., 2019; Musayev et al., 2018). Implementing RwHs enhances the community's quality of life by conserving rainwater, making it available to living beings, and replacing it with an unsafe water source (Campisano et al. 2017; Kumar and Jhariya 2016). Historically, archaeological evidence in Southwest Asia revealed that RwH had been practised since the Neolithic Age (around 10,000 BC to 4500 BC) (Pandey et al., 2003).

The adoption of RwHs contributes to increased water resource sustainability by reducing the rising social demands on the existing system (Daily, 1997; Grooten et al., 2012; Postel, 2000; Thomas, 1994). In developing countries with low domestic water utilization, RwH meets much water demand (Kahinda et al., 2008; Senay & Verdin, 2004). Harvested water was managed and diverted for other purposes, such as groundwater recharge, downstream flood mitigation, soil moisture improvement, irrigation, and livestock purposes (Goyal 2014; Lani et al., 2018; Tiwari et al., 2018). RwHs are divided into two broad classes based on design considerations: passive and active systems (Accetturo, 2015; Psillas, 2015). Passive RwHs generally use gravitational flow to collect water at a designated place without temporarily storing it. These systems operate without auxiliary infrastructure, such as pipelines, meters, pumps, etc. (Accetturo, 2015). In active RwHs, water is stored in storage tanks and is subsequently used. Depending on the site's size, condition, weather circumstances, etc., these systems might not only rely on gravitational flow but might also require pumps (Xu et al., 2018).

While designing RwHs, most previous studies have evaluated the hydrological feasibility and economic viability (Kumar et al., 2006; Pacheco & Campos, 2017). The main parameters that affect the viability and feasibility of these systems in an urban area include the per-person roof area, space available for storage, rainfall volume, pattern of rainfall in connection with the pattern of water demand, and cost/price of water supplied by the utilities (Kanno et al., 2021; Snir & Friedler, 2021; Traboulsi & Traboulsi, 2017; Villar-Navascués et al., 2020). Along with these socioeconomic and hydrological parameters, multiple ancillary data are required in the form of water supply-demand data, precipitation records, and soil data over the study area to influence the characteristics of the RwHs (Aladenola & Adeboye, 2010;

Silva & Ghisi, 2016). The potential rainwater volume was estimated using quantifiable variables such as local precipitation, catchment area, and tank size. With these variables, several approaches have been implemented for estimating the RwH potential from available roof catchments, considering building data and demographic statistics (Adugna et al., 2018; Aladenola & Adeboye, 2010; Gwenzi & Nyamadzawo, 2014; Roman et al., 2017). In addition to estimating the potential of RwHs, several other benefits of implementing RwHs, such as runoff control and flood mitigation, have been identified using the stormwater management models (Huang et al., 2015; Jamali et al., 2020; Petrucci et al., 2012; Steffen et al., 2013).

Concurrently, the efficiency and sustainability of RwHs may be influenced by the geographic suitability of the study region and the technical feasibility of the proposed structure (Jothiprakash & Sathe, 2009). In many developing countries, implementing individual RwHs is hindered by economic and technological constraints; in this situation, implementing community based RwHs is an alternate method. Inducting RwHs at the community level demands multiple economic, demographic, social, and environmental factors, making the process more complex and time consuming (Chakhar & Mousseau, 2010; Dhakate et al., 2013; Gurung & Sharma, 2014; Hashim et al., 2013). In such cases, GIS tools provide geographic data collection, geospatial analysis, topographic calculations, contextual simulation, and monitoring, which characterize real-world planning and design problems (Ban et al., 2015). The advancement of GIS technologies allows the incorporation of multiple biophysical (rainfall, runoff, slope, soil type, soil depth, land use/cover, drainage network, and watershed size) and socio-economic (cost, distance to settlements, stream flow, borders, roads, agricultural area, population density, and infrastructures) factors for conducting spatial or hydro-spatial analysis on a large volume of spatial data, thereby aiding the implementation of efficient RwH (Campisano et al. 2017; Edossa et al. 2013).

2.7 GIS for RwHs

The adoption of GIS technology is widespread in many industries, including water resource management and RwH implementation, due to its ability to perform spatial analyses on multiple datasets representing ecological and environmental factors (Mbilinyi et al., 2007). The remotely sensed data enables instant and relevant preliminary data on parameters such as soil type, land use/land cover, lineaments, and geomorphology, and integrates all parameters as thematic layers to perform multiple analyses at the design phase of RwHs (Khamis Naba Sayl et al., 2017). In dry climates, the site selection process for implementing RwHs relies on the precise design of catchment basins. Precise design and effective management plans necessitate a significant amount of readily available multi-disciplinary data, such as morphological data (watershed size and shape, topography, drainage parameters, etc.) and information on land use, land cover, soil, and its properties that influence catchment characteristics (Nooka Ratnam et al., 2005). While in practice for large catchment areas, evaluating multiple thematic maps makes the process complex and resource-consuming, in such a case, the GIS tool manages, analyse and assists site selection processes (Bonacci et al., 2010; Chowdary et al., 2008; Jamali et al., 2014; Kadam et al., 2012; Krois & Schulte, 2014; Sayl et al., 2016).

In several arid and semi-arid regions, GIS has saved money in the site selection process for implementing RwHs by considering soil and topographic suitability, land cover and land use, and surface runoff generating potential factors (Al-Adamat et al., 2010; Deelstra et al., 1997). In general, the adoption of GIS in site selection is mostly based on decision rules that specify how to combine a set of criterion maps so that alternative decisions (locations) can be ranked concerning evaluation criteria (Malczewski, 2004). In addition, the Geographic Water Management Potential (GWAMP) spatial analysis model was developed by calculating the Normalized Difference Vegetation Index (NDVI) for estimating the soil moisture conservation and rainwater potential for the dam site. Past studies revealed that adopting GIS for designing and developing RwHs helps to perform optimum design, monitor, and assess RwHs performance, identify potential RwH sites, and estimate the amount of water harvested by consuming minimum effort and resources (L. K. Singh et al., 2017).

Implementing RwHs at the community level requires an intense, iterative, sophisticated process seeking modern tools and techniques to reduce complexity and processing time (Horman et al., 2006; Kashyap et al., 2003; Magent et al., 2005; Reed & Gordon, 2010). To manage the complexity of projects, stakeholders have adopted BIM to visualize the systems and materials, regulate geometry, which aid in site safety and cost analysis, and promote sustainability for implementing RwHs (Azhar et al., 2008; Ku et al., 2008; Ku & Mills, 2010). The sustainability and efficiency of the RwHs depend on site selection and design considerations incorporated during the design phase of the project (Gabrielli 2016; Ku and Mills 2010).

2.8 BIM for RwHs

Implementing BIM for RwHs allows the modeling and analysis of multiple design aspects throughout the lifecycle of the project. During the planning and design phase of RwHs, creating a 2D model provides the optimal geometrical characteristics of the components of RwHs and identifies the potential issues and challenges involved (Costin et al., 2018). The generated optimal design and analysis aid in identifying cost-saving opportunities for the installation and operation of the system. Adopting BIM effectively ensures system integration to maximize sustainability (Z. Liu et al., 2019). To maintain sustainability, BIM allows the integration of multiple tools for plumbing design, life cycle analysis, and safety management, ensuring that the systems work together efficiently and effectively (Olawumi & Chan, 2018). Therefore, numerous researchers in the past attempted to implement BIM for designing and analysing RwHs by following BIM guidance for the water industry report.

In large buildings and infrastructure projects, developing a rainwater distribution network becomes challenging, which is minimized by creating a network-wide code and developing software tools integrated with BIM (Martins & Monteiro, 2013). During the building design phase, a rainwater and water circulation simulation was performed for the entire building analysis to store a large amount of rainwater from the roof, and a tent-shaped roof was designed (Bonenberg & Wei, 2015). In Shanghai Tower China, the adopted BIM aided in designing a specific curtain wall construction to lower high-rise wind loads and increase RwH by supporting the water consumption analysis and assisting in optimizing the water distribution system for the building (Lu et al., 2017). The identified location and design alternatives generated through BIM for RwHs improved sustainability by lowering the building water requirements (Olawumi & Chan, 2018). Open BIM data standards facilitated the smart sewerage asset information model to streamline data exchange during the RwH operation phase (Edmondson et al., 2018). Adopting BIM during the operation phase assists in managing and controlling resource consumption (Motawa & Carter, 2013). In addition, BIM allows the integration of smart appliances, intelligent sensing, and cybernetics, which helped to reduce installation and maintenance costs throughout its lifecycle (Howell et al., 2017). Integrating BIM with the Leadership in Energy and Environmental Design (LEED) rating system for green buildings has assisted in achieving a water-efficient design process by enforcing the implementation of RwHs (Ni et al., 2017).

2.9 Research gaps

After conducting a literature study, several gaps were identified in the existing studies, highlighting the areas that require additional research and development. The identified gaps are listed below.

a) Limited research initiatives have delved into establishing the relationship between rapid urbanization and urban water management systems.
b) Minimal efforts have been made to understand the potential of communal RwHs as sustainable urban water resource.
c) The integration of GIS and BIM has predominantly concentrated on individual RwHs, prioritizing technological progression and initial expenses, which limiting its applicability to developing nations.
d) Relatively limited research has been done on the tactics and techniques for creating and improving BIM tailored specifically for RwHs, with the potential to maximize benefits and water efficiency.

2.10 Research objectives

To address the identified research gaps, the following research objectives were established to explore and advance the integration of GIS and BIM:

a) Conducting a comparative study to establish the relationship between the urbanization, infrastructure developments and urban water management systems.
b) Developing a framework methodology for conceptualizing, analysing, and designing an infrastructure to maximize its benefits and efficiency.
c) Validating the proposed methodology, by integration of GIS - BIM tool to plan, analyse, and design a sustainable infrastructure.
d) Implementing an integrated GIS-BIM framework for conceptualizing, analysing, and designing community RwHs as an integral part of sustainable water infrastructure.

2.11 Chapter summary

This chapter explored past studies on infrastructure management, BIM for infrastructure management, and GIS for infrastructure management. While exploring these fields, emphasis was placed on the application of GIS and BIM to real-time infrastructure projects. Additionally, the study explored sustainable water management practices with a focus on RwHs as a viable solution to counter water scarcity challenges arising from rapid urbanization and infrastructure development. Despite the growing importance of integrating GIS and BIM for sustainable water management, there is still a significant gap in existing research, particularly on their application to RwHs. This emphasizes the need for extensive research and innovation for the RwHs as an integral part of sustainable urban water management system field. Finally, four research objectives are framed based on the identified research gaps. These objectives include conducting a comparative study to elucidate the relationship between urbanization, infrastructure development, and urban water management systems, developing a comprehensive framework methodology for optimizing infrastructure benefits and efficiency, validating the proposed methodology through the integration of GIS-BIM tools for sustainable infrastructure planning, and implementing an integrated GIS-BIM framework for community RwHs to enhance water infrastructure sustainability. To accomplish these objectives, a framework methodology was developed and proposed for the integration of GIS and BIM, which is discussed in the upcoming chapter titled methodology.

3. Methodology

3.1 Chapter overview

This chapter describes the development of the methodology and its validation based on a literature study. The primary goal of this chapter is to formulate a methodological framework for conceptualizing, analysing, and designing infrastructure to optimize its benefits and efficiency. The proposed methodology is divided into three key steps: study area analysis, microscale planning, and infrastructure component modeling. To validate this methodology, cutting-edge tools, and technologies such as GIS and BIM were integrated, and the detailed explanations of the steps involved in this integration were provided.

3.2 Infrastructure planning and design

For efficient planning and design of infrastructure, analysing the study area is a prerequisite that serves as a foundation for informed decisions, and to ensure the project feasibility, and sustainability. Understanding the local context, including the geographic, economic, and social aspects, paves the way for tailoring infrastructure to meet the unique requirements of the community that is intended to serve. In addition, the consideration of stakeholder behaviour and the characteristic of the area provides the valuable insights to align the infrastructure project with the interest of priority, enhancing efficiency and maximizing the overall utility of the infrastructure. The study area assessment also represents the drawbacks and capabilities that allow for the assessment of the risk associated with environmental, social, and economic parameters which allows to formulate context specific infrastructure asset that prove self-efficient to fulfil it intend.

In addition to analysing and estimating the potential of the study area, performing microscale planning of the infrastructure asset results in maintaining the overall sustainability of the project by specifying detailed information of the asset. While performing micro-level planning, a thorough assessment of specific requirements and surroundings is necessary to enable the adaptation of solutions and asset characteristics. The assessed comprehensive aspects provide technical design aspects, structural integrity, and material properties that improve longevity and resilience. In addition, microscale planning helps to improve infrastructure adaptability to local environmental conditions, energy efficiency, and the integration of innovative technologies.

Modeling infrastructure assets is critical for improving sustainability from both environmental and economic perspectives. The adoption of modern modeling techniques allows for the comprehensive evaluation and visualization of assets prior to their actual implementation. This pre-implementation insight enables decision makers to make informed and long-term decisions. Furthermore, modeling is a valuable tool in risk assessment, allowing for the identification of potential challenges, as well as the development of effective mitigation strategies throughout the asset's entire lifecycle. By integrating modeling into asset management practices, decision-makers can proactively address sustainability concerns and optimize the overall performance and resilience of infrastructure assets. The proposed methodology is illustrated in Figure 3.1.

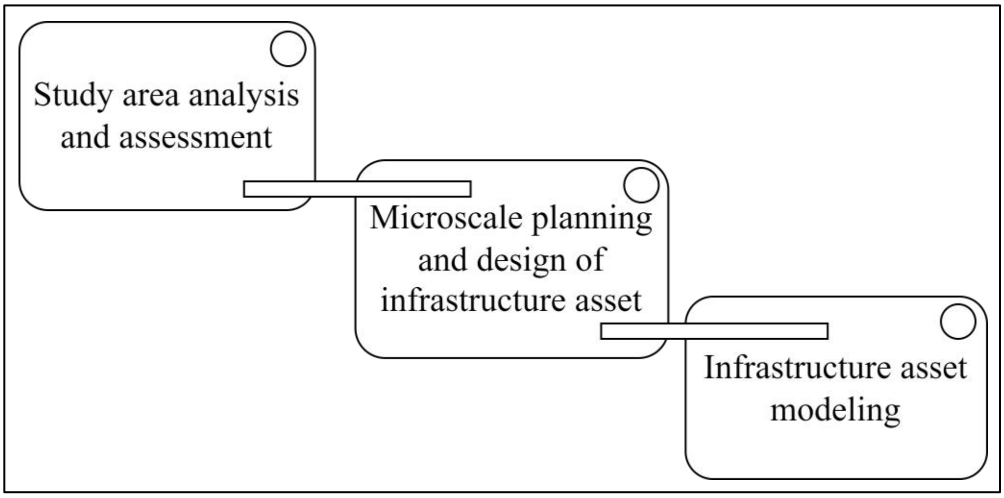


Figure 3.1 Universal study methodology

To validate the proposed methodology, the advanced tool such as GIS and BIM were integrated to plan, design, and analyse the infrastructure. The integration commences with the utilization of GIS tools for spatial analysis, leading to the development of BIM using spatial analysis outcomes. Multiple GIS analyses were applied to analyse spatial and surveyed data to establish relationships among features, which aided in performing site selection, evaluating design alternatives, and designing the infrastructure components. The results of the spatial analysis serve as essential input components for BIM development. The developed BIM has become a vital data source, allowing for effective data management and efficient decision-making. Figure 3.2 illustrates the proposed methodology.

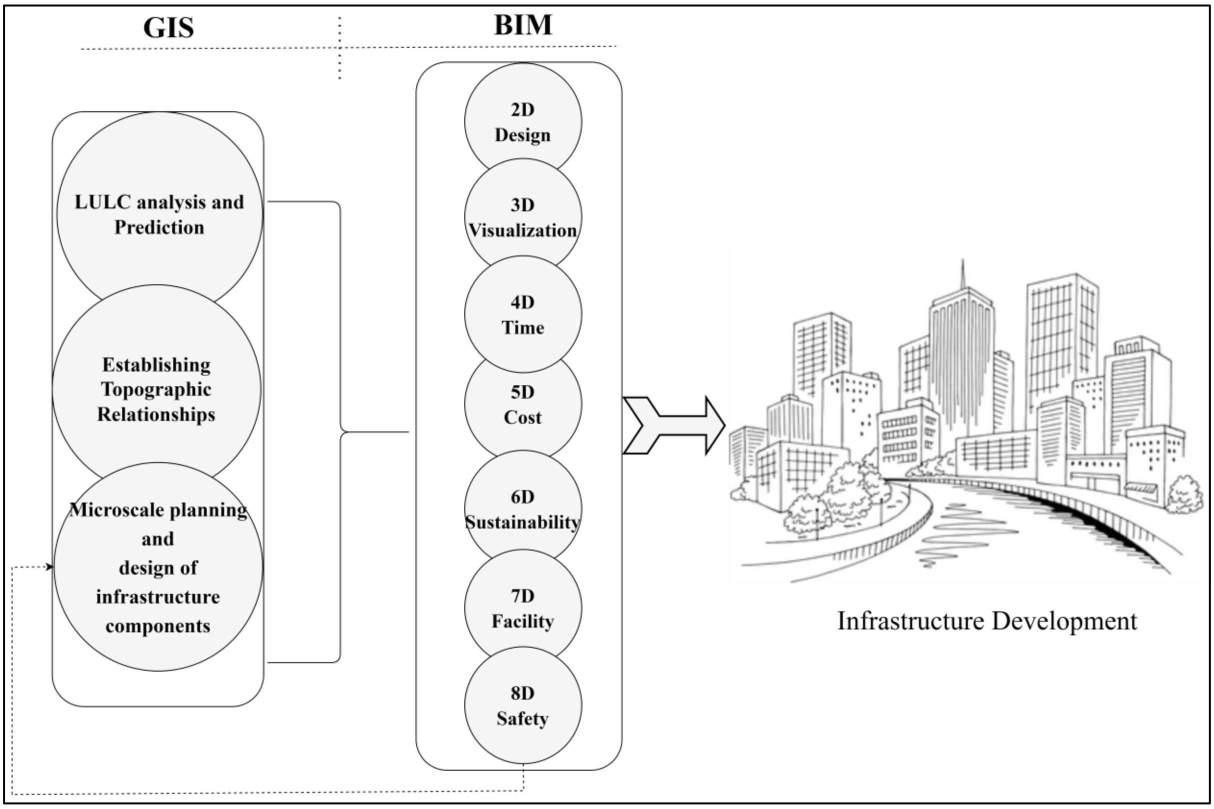


Figure 3.2 Detailed methodology for study

The detailed methodology applied during the study is further extended in subsequent sections, providing a comprehensive explanation of the sequential approach used to integrate GIS and BIM for the conceptual design and planning of the infrastructure projects.

3.3 GIS analysis

The design and development of infrastructure necessitate the integration of numerous economic, demographic, social, and environmental aspects, making the process more complex and time-consuming (Gurung and Sharma 2014; Hashim et al., 2013). Advancements in RS and GIS technologies have enabled the incorporation of multiple biophysical factors (rainfall, runoff, slope, soil type, soil depth, land use/cover, drainage network, and watershed size) and socio-economic factors (cost, distance to settlements, stream flow, borders, roads, agricultural area, population density, and infrastructure) to conduct extensive spatial analyses on a large dataset. This facilitates the identification of suitable sites and the generation and analysis of multiple alternatives, and ultimately contributes to efficient infrastructure development (Campisano et al. 2017; Edossa et al. 2013; Wang and Maduako, 2018). To plan, design, and analyse infrastructure development, multiple spatial analyses were performed, beginning with a wide study area, and narrowing down to a small area for conducting extensive analysis.

During the initial stages of infrastructure design and planning, understanding the historical development patterns and classification of the study area serves as a foundational study. The performed Land Use Land Cover (LULC) analysis quantified the unrestrained development and ecological characteristics of the area that used to predict probable development in coming years, strengthening decision-making power through area categorization, and allowing them to allocate resources and efficient land use planning. Following area categorization, relationships among geographic and other features, including hydrological, social, and economic aspects, were established to determine infrastructure characteristics. These established relationships helped to understand the characteristics of the study area and identify suitable sites for infrastructure development.

To further identify site alternatives and assess the suitability of the identified sites, multi-criteria decision-making (MCDM) in conjunction with GIS was employed. The utilization of MCDM allows the integration of data processing and visual geographic data representations, which results in suitable site identification. Once a suitable site was identified, the selection and analysis of design alternatives, along with their optimal geometric characteristics, were performed by comparing design alternatives using MCDM and applying standard guidelines to ensure the economic and operational sustainability of the infrastructure. Subsequently, multiple infrastructure-specific GIS tools, including ArcGIS, Quantum Geographic Information System (QGIS), were utilized to achieve the optimal design of infrastructure components. The GIS analysis performed in the proposed study is shown in Figure 3.3 and elaborated in the following section.

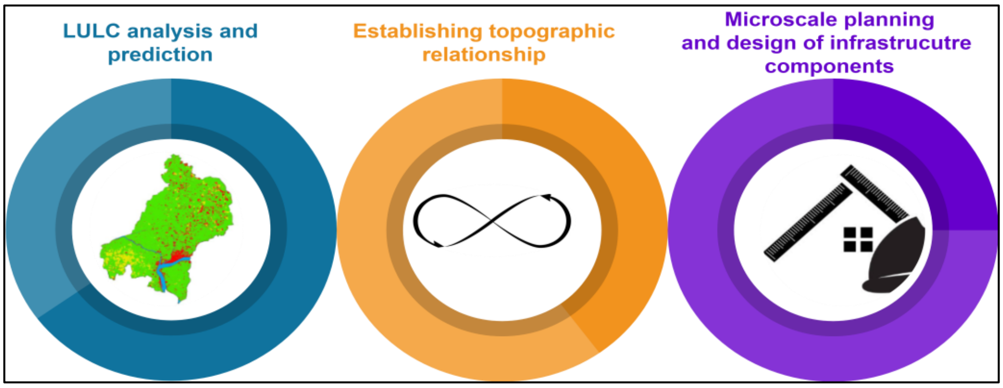


Figure 3.3 Methodology for GIS analysis

3.3.1 Land Use Land Cover analysis and prediction

Rapid urbanization and land alternation result of multiple parameters such as natural, proximity and socioeconomic factors which includes existing transportation infrastructure, availability of natural resources, GDP, population density that can be linked with the LULC projection based on availability of data. In most urban areas, LULC changes have been influenced by various dynamic natural, geological, topographic, and socio-economic factors that need to be analysed to attain sustainable infrastructure development goals (Sahana et al., 2016). RS technologies have proven effective for conducting various spatiotemporal analyses of land and other natural resources (Aboelnour et al., 2018; Wang & Maduako, 2018). Implementing these technologies has made it possible to quantify LULC by utilizing multi-temporal and multispectral satellite images over larger areas with precise and consistent datasets (Chang et al., 2019; Fu et al., 2019; Pandey and Joshi, 2015). In LULC maps, land use refers to the land that humans utilize, whereas land cover refers to the available natural terrestrial surfaces (Lei et al., 2021; Nong et al., 2018). LULC analysis deals with the transformation of land-use patterns, and area change statistics are used to forecast probable land changes. Further forecasted map was utilized to categorize the area for infrastructure development. In this study, LULC analysis was divided into five stages, commencing with data acquisition, and culminating with the validation and analysis of the simulated map, as shown in Figure 3.4 and explained below.

Figure 3.4 Methodology for Land Use Land Cover analysis and prediction

3.3.1.1 Data acquisition

To facilitate LULC analysis using a GIS tool, historical satellite images or remotely sensed data from reliable sources were acquired. In addition to satellite data, supporting data such as building shape files and open street map (OSM) data were obtained to forecast potential development based on historical development patterns.

3.3.1.2 Pre-processing of images

Initially, the acquired data were clipped for the study extent to reduce unnecessary image processing time, and preprocessing was performed to reduce any errors caused by the sensor and atmospheric attenuation. The band composite operation was performed on clipped pictures, and a false colour composite (FCC) was created by combining various bands of satellite images. Different colour combinations create false colour visuals (schemes), which display the very-near infrared as red, red as green, and green as blue. Further, the smoothing convolution

(Low Pass filter) function was applied to reduce local variation and remove noise. The Convolution function filters the pixel values in an image by eliminating spurious data or by enhancing the features in the data. The applied function calculates the average (mean) value for each neighbourhood pixel, reducing the FCC values.

3.3.1.3 Image classification

Image classification is a technique for assigning land-cover classifications to pixels. The three main image classification techniques in RS are unsupervised, supervised, and object based. Unsupervised classification utilizes computer algorithms to provide pixel-based classification without human intervention. This method clusters pixels into different land-cover classes based on spectral characteristics. In contrast, supervised classification utilizes training samples created by humans to direct the classification process. By providing algorithm-labelled samples of various land cover classes, it can learn to categorize the pixels reliably. Object-based image classification adopts a slightly different technique: creating cohesive objects with geometric bounds rather than identifying individual pixels. In general, some of the classifications are water, urban, forest, agricultural, and grassland. The performed image classification allowed the extraction of valuable LULC data from satellite or aerial imagery to better understand the earth's surface and support various applications, such as land cover mapping, vegetation monitoring, urban planning, and natural resource management.

3.3.1.4 LULC change analysis and modeling

Utilizing LULC maps is essential for understanding and organizing massive amounts of data as it allows for quantifying, analysing, and monitoring land changes over time (Sheikhi et al., 2015). The classified LULC maps were used to understand and quantify the changes in land cover types for change analysis. In this change analysis, the change in land area for each pixel transition was derived from the computed statistics of pixel count. These alterations helped to provide important insights into the geographical and temporal patterns of land-use changes. Finally, the identified transitions of pixels were used as inputs to perform change analysis modeling, which resulted in a simulated map.

3.3.1.5 Model validation, prediction, and analysis

After obtaining the simulated map, validating it is an important step in geospatial modeling, as it ensures reliability. The kappa coefficient was estimated to validate the simulated map. The kappa coefficient values ranged from 0 to 1, representing the accuracy of the simulated map in comparison to the reference map. After assessing the reliability of the simulated map, a prediction map was created using the potential model developed to create probabilistic scenarios. The developed maps were utilized to plan infrastructure development by incorporating probable transformations.

Along with the prediction and classification of land, understanding the topographic relationships of an area is crucial for enhancing the efficiency of a project by incorporating natural features and attributes of the land. The developed relationship minimizes adverse effects, promotes sustainability, and ensures long-term functionality of the built environment.

3.3.2 Establishing topographic relationships

Infrastructure development seeks to evaluate, plan, and manage multiple criteria to minimize adverse effects and enhance sustainability (Musayev et al., 2018; Sayl et al., 2020). Therefore, understanding the topographic characteristics of the area plays a vital role in enhancing the efficiency of infrastructure projects. Developing topographic relationships involves the evaluation of physical resources (elevation, slope, aspect, and climate), natural resources (soils, geology, hydrology, flora and fauna habitat, and ecologically sensitive areas), and current land use patterns and developments (manmade facilities such as transportation systems, existing urban areas, and utility networks). Each of these characteristics was considered to determine the potential of the site (regions suitable for land use) and limitations (areas unsuitable for land use) (Laurin & Ongaro, 2006). Multiple spatial analysis tools and sequential operations were performed to establish a relationship between topography and other factors across the study area, such as physical, hydrological, and social parameters. The established relationship aided in comprehending the characteristics of the study area, facilitating the identification of its potential for infrastructure development. In addition, the efficiency of an infrastructure project is significantly influenced by design considerations and the site selection process. Selecting the most suitable site involves assessing various factors, including geographical and geological characteristics, environmental considerations, accessibility, proximity to resources, and potential impacts on the surrounding areas.

3.3.3 Microscale planning and design of infrastructure components

3.3.3.1 Site identification and providing rank order using MCDM

Recently, MCDM analysis has proven to be an effective methodology that involves identifying, ranking, and assessing the best alternative sites by incorporating predetermined criteria (Salvatore et al., 2016). MCDM allows the integration of data processing and visual geographic data representations, which promotes decision-makers in making critical decisions (Kumari et al., 2021; Sayl et al., 2016). Numerous environmental and socioeconomic factors influence decision-making and are prone to challenges at different project stages (Sayl et al., 2020). GIS is vital in facilitating decision-making for selecting the most suitable site among multiple alternatives. Therefore, to assess site suitability, MCDM with GIS was implemented. Implementing the GIS tool enabled the execution of the overall MCDM process, involving collecting and storing mapping data and analyzing the attribute and spatial data, which assisted decision-making. Comprehensive planning aims to narrow the study area. The selected small area allowed us to incorporate and visualize multiple considerations more deeply. Figure 3.5 depicts the workflow methodology; the subsequent sections provide a detailed process.

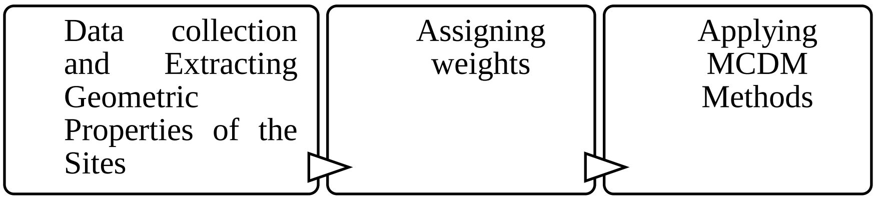


Figure 3.5 Methodology for the site selection and planning

a) Data collection and extracting geometric properties of the sites: To conduct site suitability analysis, accurate ground data were collected by gathering relevant information through on-ground surveys or remotely sensed data. The GIS tool enables the extraction, identification, and analysis of multiple site alternatives by providing a platform for importing and integrating the collected data. The characteristics obtained from these alternatives were then utilized in the MCDM analysis, facilitating the evaluation and comparison of site suitability based on several criteria.

b) Assigning weights: Assigning weights to an attribute is an important step in MCDM. The assigned weight indicates the potential of the criteria to influence the results compared with the other weighted criteria. Generally, there are two ways to assign weights to criteria: subjective and objective weight methods. In subjective weight methods, criteria weights are determined by the decision maker’s preference to obtain subjective judgments. In contrast, objective weight criteria assign weights to different criteria by considering the amount of information within them and their influence on overall decision-making (Vujicic et al., 2017). The weights assigned to the criteria reflected the influential power over the site suitability results and were used further to perform the MCDM analysis.

c) Applying MCDM: MCDM methods produce a set of solutions that are optimal in the solution using multiple criteria (Abdulla et al., 2002; Jayasooriya et al., 2018; Krois & Schulte, 2014). The accuracy of MCDM depends on the degree of uncertainty in the data, the weights assigned to the criterion, and the degree of agreement among stakeholders (Vassoney et al., 2021). Nowadays, technological advances have resulted in the development of multiple MCDM techniques such as Analytic Hierarchy Process (AHP), Analytic network process (ANP), Weighted product model (WPM), (VIekriterijumsko KOmpromisno Rangiranje (VIKOR), Preference Ranking Organization Method for Enrichment Evaluation (PROMETHEE), Potentially All Pairwise RanKings of all possible Alternatives (PAPRIKA), Technique for the Order of Prioritisation by Similarity to Ideal Solution (TOPSIS) etc,. The applied MCDM methods facilitated the identification of suitable sites by considering geospatial data and providing rank order for identified sites based on predefined criteria.

Along with site selection, the effectiveness of an infrastructure project is influenced by design considerations and alternatives. The design phase must incorporate significant factors to optimize the plan, size, materials, and methods, ensuring the sustainability and efficiency of the project by reducing its operational and maintenance costs. Therefore, after selecting the most suitable site, the optimal design alternative was determined. While determining the optimum design alternative, the viability of the proposed system was evaluated considering on-the-ground conditions. So, to better understand practical situations, the expert's opinions were incorporated through the AHP- MCDM technique to obtain the best design alternative.

3.3.3.2 Determining infrastructure design alternatives

Analytic Hierarchy Process (AHP) is one of the most commonly applied decision-making methods (Han et al., 2020). The utilization of a hierarchical structure facilitates the representation of intricate problems, which offers decision-makers a comprehensive understanding of on-ground situations (Tanyimboh & Kalungi, 2009). The AHP employs a multi-objective decision-making strategy and offers a systematic technique for combining all variables. It also integrates qualitative and quantitative methods and structures the decisions into a multi-level hierarchical framework that includes the aim, criteria, sub-criteria, and alternatives (El-Abbasy et al., 2015). This process allows decision makers, including engineers, stakeholders, managers, experts, and non-experts, to choose a preferable alternative option subject to a finite number of criteria. (Zyoud et al., 2016). AHP analysis provides suitability values for the design alternatives considering the specified evaluation criteria. The determined design alternative insisted on determining optimum geometric characteristics for maintaining its effectiveness and economic sustainability.

3.3.3.3 Designing infrastructure components

Geographical Information System (GIS) capabilities have greatly aided in facilitating the execution of infrastructure development at both the micro and macro levels by allowing infrastructure project-specific analysis. The spatial analysis resulted in the estimation of the potential of the study area, which facilitated the optimum design. It is well acknowledged that the development of different components within the infrastructure system impacts the efficiency of infrastructure projects in addition to their overall design. To determine the geometric characteristics of infrastructure components, standard rules and guidelines were followed by analyzing spatial data, evaluating numerous possibilities, and making informed choices using a GIS tool.

The application of GIS in the processing, analysis, and design of infrastructure improves productivity, encourages efficient decision making, and contributes to the project's overall success. At the same time, BIM is an essential process component to plan, visualize and control the infrastructure project. The iterative nature of the BIM process encourages collaboration and coordination among project participants, resulting in efficient management of design modifications, updates, and maintenance activities over the project lifecycle. Integrating GIS with BIM enhances project results and streamlines processes, and makes it possible to create infrastructure holistically. In the proposed study, the unique dimensions of BIM were developed using the results of the LULC analysis, established relationships, site identification, and determined the characteristics of infrastructure components. The following sections elaborate on the methodology applied to develop the dimensions of BIM.

3.4 Development of BIM dimensions

Building Information Modeling (BIM) contributes from planning to the (O&M) process, which is frequently iterative among project stakeholders (Ku & Taiebat, 2011). Additionally, it permits the superimposition of multidimensional data onto the model during the design phase, offering a realistic database that promotes improved collaboration among project stakeholders (Kensek, 2015). Depending on the level of information, the development of BIM dimensions begins with a 2D model and progresses to an nD model. The term "BIM dimensions" describes the type and level of digitized building data required for a specific BIM model of a construction project.

By integrating additional data into its models, BIM dimensions can improve the knowledge of infrastructure projects.

Initially, creating a plan using a CAD tool came under the 2D model, whereas developing a visualization model was termed as a 3D model. The addition of parameters increased the information content of the model. The involvement of the project extent in terms of time and cost was considered as the 4D and 5D BIM, respectively. Additionally, considering sustainability parameters as the 6D BIM allowed us to estimate the carbon footprints and the effects of activities on the environment. FM, as the 7D, endorsed stakeholders to provide additional supporting documents and perform the analysis, which eased the operation and modification of planned construction activities. Finally, the 8D was Prevention through Design (PtD), which was achieved through the proper design of optimized safety principles through the identification of on-site risks in construction (Kamardeen, 2010). The multiple BIM dimensions, encompassing 2D, 3D, 4D, 5D, 6D, 7D, 8D, 9D and 10D BIM dimensions, have been illustrated in Figure 3.6 and discussed in detail below.

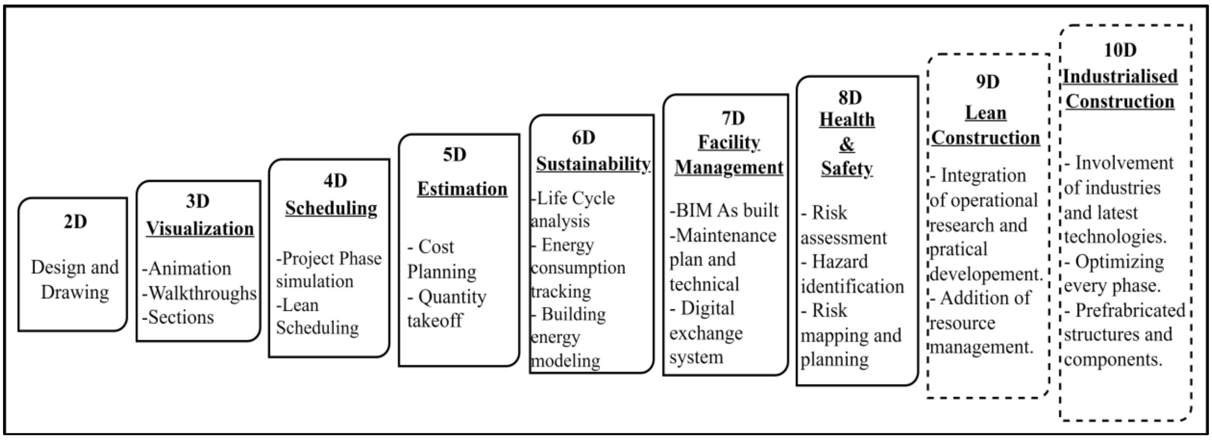


Figure 3.6 BIM dimensions

3.4.1 2D BIM

In the initial stages of BIM, the 2D is focused on design and planning. This dimension provides graphical information along the x- and y-axes, indicating that the drawings were flat without depth. Typically, these models are manually created or drawn using CAD methods. These drawings are essential communication tools among project stakeholders that facilitate effective coordination and collaboration. For 2D design, CAD software such as AutoCAD and AutoCAD LT are commonly used today. The tool utilized for 2D design allowed the creation of technical drawings, which included plans, permit drawings, landscaping reviews, and inspection plans.

The developed 2D BIM serves as the foundation for technical design drawings and communication.

3.4.2 3D BIM

A shared informational model, or “Z-axis,” is the third dimension of BIM, which is added to the X- and Y-axes. 3D BIM models were created by drawing 2D with elevation data. To share building information in a Common Data Environment (CDE), 3D BIM generates both graphical and non-graphical architectural information, which assists project stakeholders working in interprofessional collaboration in developing and analyzing complicated model elements. It also facilitates stakeholders to effectively manage their multidisciplinary collaboration in modeling and evaluating complex structural problems. Multiple 3D modeling tools, such as Autodesk Revit, Revizto, BIMcollab, and Graphisoft ArchiCAD, are available for the development of 3D BIM models. Developed 3D model provides the clear vislauzation of infrastrucutre components and facilitate to resources assignment.

3.4.3 4D BIM

Building Information Modeling (BIM) integrated with schedule information (4D) enables communication, collaboration, and coordination among stakeholders by tracking, coordinating, and managing various activities involved in infrastructure projects (Mahalingam et al., 2015). Currently, multiple methods such as line-of-balance, quantitative scheduling, resource-oriented scheduling, Gantt charts, the Last Planner System (LPS), the CPM, and PERT are employed for infrastructure projects. The added time or scheduling information helped to estimate how long it would take to complete the project and how it would evolve. It enabled efficient scheduling throughout all design and construction stages, irrespective of the project size. The information included details regarding the time needed for installation or construction, the time required to complete the project, the order in which different components should be placed, and additional scheduling data. It also helps in early conflict detection by seamlessly managing information related to site status and visualizing the impact of changes undertaken during the entire life cycle. Integrating BIM with schedule information strengthens effective collaboration, communication, and coordination among stakeholders and directly impacts a project’s cost performance, which is an essential measure of its success. So, incorporating cost as 5D BIM visualizes and estimates the cost implications of design changes or project delays.

3.4.4 5D BIM

The cost performance of a project is one of the most significant indicators of success (Rahman et al., 2013). The accuracy of the quantity take-off, bills of quantities, cash flow projection, and overall cost management are significant factors influencing the cost performance of the project. The 5D BIM concept relies on the "Quantity Take Off" process, which involves extracting measurements from a project to determine the required resources. It assists in accurately estimating budgetary requirements, including any changes in scope, materials, labour, or equipment, from the beginning of the project (Cheng, 2014; Doloi, 2012; Memon et al., 2014). In this development, cost estimation was performed using the developed 3D model and assigned resources. 5D BIM allowed us to accelerate this process by providing precise and transparent budget information. Additionally, it enables the examination of multiple variables within the project's parameters, such as cost, appearance, constructability, and timeframe. The resource assessment capabilities of 5D BIM allowed us to perform the LCA, which helps to reduce the adverse effects of the infrastructure project.

3.4.5 6D BIM

In infrastructure projects, the concept of sustainability is investigated from three perspectives:

a) Environmental: The ability to sustain and replenish natural resources.

b) Financial: The ability to produce money and employment.

c) Social: As a source of well-being for people.

From an environmental sustainability standpoint, 6D BIM is associated with the sustainable development of new or existing building components and energy efficiency. The 6D of BIM development provided valuable information for performing assessments such as energy consumption and cost estimates, commencing at the earliest design phases. This information empowers us to choose the most suitable and efficient solutions, promote sustainable practices, and ensure a balance between the environmental, financial, and social aspects. Multiple tools, such as building energy modeling (BEM, energy plus, eQuest) and LCA software (Umberto, Simapro, Gabi, Tally) have been implemented by considering the available resources and levels of sustainable goals. The LCA analysis performed in this study with the provided information enabled the selection of suitable technology, solutions, materials, and design alternatives to reduce energy consumption while improving quality and comfort. This analysis also contributed to the overall sustainability and more resilient and responsible built environment of the project. While implementing the project, healthy collaboration among stakeholders is essential to mitigate the risks involved. Therefore, FM plays an important role in increasing the transparency and understanding among stakeholders. FM optimizes complex processes by providing a comprehensive and accessible platform that stores precise information about the infrastructure components.

3.4.6 7D BIM

7D concerns FM, an important asset for managers and owners. It specifies asset data, including technical details and status, to facilitate project operations, implementation, and maintenance. This dimension tracks key asset data such as its status, maintenance/operation manuals, warranty information, and technical specifications for future use. BIM can provide significant benefits throughout the O&M phase by serving as a repository for precise information on built assets (Motamedi et al., 2014). The operational management of a building asset is optimized using this technology throughout its lifetime. Through its construction phase, the updated drawing becomes an 'as-built' model for turning over to the owner. Therefore, to update the drawings and maintain the records, an online cloud-based platform, such as Autodesk Collaborate Pro, was utilized. The added dimension aids decision-making by increasing safety and productivity.

3.4.7 8D BIM

The 8D BIM is a dimension that adds safety information to the geometric model, allowing for the prediction of risks throughout the construction process and identifying activities to improve workplace safety and prevent accidents. By visualizing the construction site before the start of work, 8D BIM makes it possible to effectively analyse all possible consequences to avoid dangers and other problems. In this way, possible risks were identified before execution to make the workplace safer. Multiple national and international safety guidelines are available and are effective for assessing construction activities.

3.5 Chapter summary

This chapter comprehensively explained the proposed methodology for panning, analysing, and designing the infrastructure projects. The proposed framework is classified into three major components: study area analysis, microscale planning, and modeling. To validate the proposed methodology, GIS and BIM were integrated to plan, analyse, and design the infrastructure. This chapter also provides an in-depth description of the procedures used to integrate these technologies, including the data preparation, analysis, validation, and integration strategies. Initially, spatial analysis was performed on the acquired remotely sensed and ground survey data to analyse the study area and assess its potential. The spatial analysis paves the way to further carry out micro-level planning for the infrastructure components in terms of selecting the most suitable site and determining the optimum design alternative and geometric characteristics. The results generated from GIS analysis serve as an essential input for developing BIM dimensions. The development of comprehensive BIM starts with 2D design and culminates in 8D safety analysis and management of infrastructure projects. This methodology attempts to improve spatial data management and analysis within the built environment by integrating GIS and BIM, eventually contributing to more efficient decision-making for infrastructure development.

4.1 Chapter overview

In this chapter, the GIS analysis is performed over the Jaipur Municipality area as a case study to plan and analyse community RwHs. The implementation of the proposed methodology begins with the same chapter to satisfy the last objective. By selecting Jaipur as a study area, it is intended to evaluate the feasibility and effectiveness of implementation in an urban area with specific geographical and demographic characteristics to overcome water scarcity.

4.2 Selection of study area

Jaipur is located in the state of Rajasthan (India), was founded in 1727. It is currently the capital of Rajasthan state and is the centre of the economic and demographic life, recognized as the pink city and a famous tourist destination. The Nahargarh hills, which are part of the Aravalli hills, surround the city to the north and Jhalana hills to the east. Jaipur City is located at 26° 55’ north, 75° 49’ east. Table 4.1 provides the physiographic characteristics of Jaipur City.

Table 4.1 Physiographic characteristics of Jaipur City

Physiographic type	Value
Latitude	26° 46’ N to 27° 01’ N
Longitude	75° 37’ E to 76°57’ E
Area (km^2)	467
Perimeter (km)	126.54
Max - Elevation (m)	645
Min - Elevation (m)	329
Mean elevation (m)	408

Jaipur falls in India’s semi-arid zone and is distinguished by high temperatures, low rainfall, and mild winters. Jaipur has experienced rapid physical and demographic growth, with an expected population of 50.5 lakhs by 2030 at an annual growth rate of 5.3 % (Anamika & Sharma, 2023; Dadhich & Hanaoka, 2011). Owing to its topographical constraints, the city is experiencing growth in the southern and western directions and is expanding in a distorted linear geometry. The city is conveniently located, with the capital of India, Delhi, at 258 km and Agra at 232 km, forming a part of the well-known Golden Triangle. The Jaipur Municipal Corporation (JMC) oversees the city administration, which covers 467 sq.km and is divided into two municipal corporations, the "Greater Jaipur Municipal Corporation." and the "Jaipur Heritage Municipal Corporation," each with 150 and 100 wards as shown in Figure 4.1.

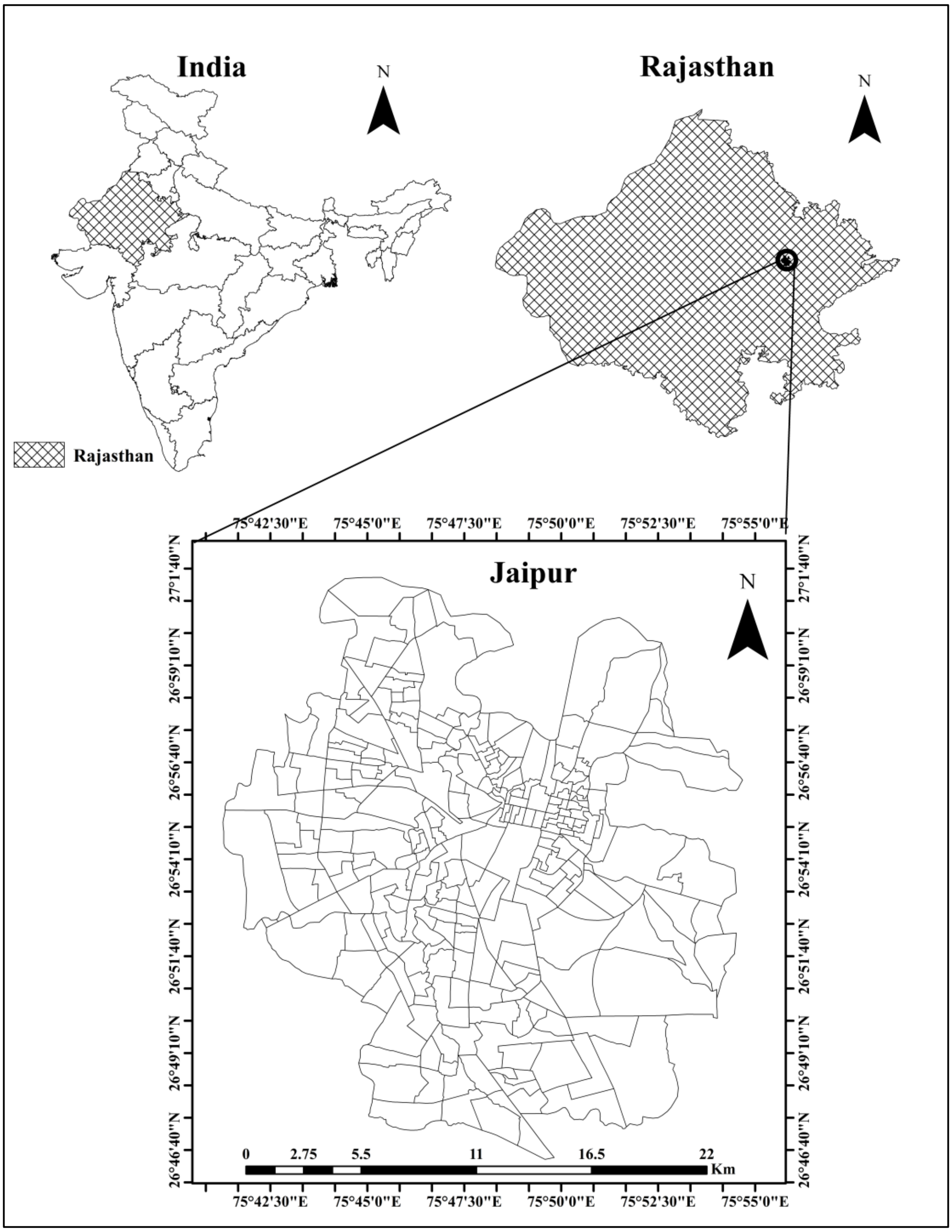


Figure 4.1 Study area map

4.2.1 Challenges in the study area

Although Rajasthan state has lower levels of urbanization than the national average, the capital city of Jaipur has witnessed the opposite trend due to net urban-rural migration (Dadhich & Hanaoka, 2011). High population growth coupled with increasing urban housing demand arising from in-migration and other factors has led to unplanned city expansion, encroachment of water bodies, catchment areas, etc. (Jawaid et al., 2017).

The unusual growth of the urban population resulted in significant pressure and demand for urban land in the periphery, culminating in the exploitation of a wide stretch of fertile agricultural land for urban and residential developments (Jawaid et al., 2014). On the other hand, the migration of people to the city from rural areas and other parts of the country for better prospects of employment and better quality of life has resulted in the formation and propagation of slums in the absence of affordable housing provisions, which has resulted in issues such as depletion of water resources, and climate change has resulted in the degradation of the urban environment. City authorities have found it difficult to harmonize the development intensity of the urban area with time, which has an adverse impact on its resource management.

Despite having a higher annual rainfall of 676 mm (24 inches), Jaipur faces water scarcity due to its increased population and adverse climatic conditions. The water supply infrastructure in Jaipur is over a century old. Maharaja Jai Singh II established Jaipur's water supply system in 1726 by constructing hilltop broad water channels and three water tanks at Jaigarh Fort that held 6 million gallons of rainwater. At the same time, to the Jal Mahal Palace (Man Sagar Lake) was built on the Dravyavati River in 1728 to meet the water demand of Jaipur as a new capital. In addition to the lake, Tal Katora Tank and Raja Mal ka Talav were built to meet the needs of 150000 people. The first planned water supply system for the city began with the construction of canals from 100 open wells to accommodate the rising population.

The first planned water supply system for the city began with the construction of canals from 100 open wells to accommodate the rising population. However, from 1896 to 1912, an increase in water scarcity stimulated the construction of the massive Ramgrah Dam reservoir on the Banganga River.Initially in 1963 reservoir was used to supply 27 MLD (million liters per day) which was further increased to 234 MLD in 1980 to 1984. Unfortunately, excessive extraction and unrestrained development caused the reservoir's water levels to drop, which in turn depleted the water table in the area. To overcome the water scarcity the new water source Bisalpur dam on Banas-river was explored and commissioned in year 1990, and the transmission of the water from Bisalpur to Jaipur was commissioned in year 2009. At present, Jaipur City needs 462 million of litres per day (MLD) of water, out of which 275 MLD comes from the Bisalpur dam, 97 MLD comes from the tube well (1900 Nos.) and 2 MLD water came from single-point tube wells (117 Nos.). Jaipur is estimated to have a 125 MLD water deficit (Vyas & Goyal, 2021).

The most significant problems among these are the inadequate quantity and quality of water and rapidly growing demand. While overcoming scarcity and enhancing water infrastructure sustainability, the implementation of measures such as increasing open areas, creating artificial recharge zones, educating the public on water issues and conservation, reclamation, and reuse of wastewater, RwH, and investment in updating the water distribution and metering system must be adopted at the individual and community levels. In many developing countries, economic and technological constraints hinder the implementation of individual RwHs. In such cases, implementing community RwHs plays an important role by serving as an alternate water resource and reducing the risk of flooding. So, for implementing community RwHs, spatial and hydro-spatial analysis must be performed over the study area to assess its topographical and hydrological characteristics. The ArcGIS 10.8.2 tool was used for the spatial and hydro-spatial analyses. In the proposed study, the JMC area was initially considered a case study area, which was further narrowed to a single municipality ward to perform the micro-level conceptual design, plan, and analyse the community RwHs. The subsequent section elaborates on the steps performed in spatial and hydro-spatial analysis.

4.3 Land Use Land Cover analysis and prediction

According to the United Nations report on world urbanization, 50% of India's population lives in cities or urban areas due to infrastructure development and industrialization (Aboelnour et al., 2018). From 1991 to 2017, urbanization increased by 23% in 47 major cities in India due to the migration of people from rural areas (Dinda et al., 2019; Mishra and Rai, 2016). Rapid urbanization has caused decreases in sustainability due to significant land transformation and deforestation over time (Busho et al., 2021; Dutta and Das, 2019). To overcome the problems caused by rapid urbanization, it is necessary to understand a city's growth pattern and stimulate future growth, which will aid in administrative planning. In quantifying unrestrained development and ecological characteristics of the city spatiotemporal analysis plays a vital role (Kafy et al., 2021; Gao et al. 2020; Osumanu and Akomgbangre 2020). The outcome of the spatiotemporal analysis in the form of LULC maps helps to build sustainable land use control policies by considering past development patterns and present circumstances (Faisal et al., 2018).

In past urban studies, integrating multi-layer perceptron (MLP) and Markov chain analysis was carried out to enrich the LULC modeling and restore the dimensional LULC changes in GIS to carry out large-scale spatial simulation and projection with high precision (Faisal & Khan, 2017; Ramachandra et al., 2018). The created models allow the development of possible future scenarios by incorporating factors such as population, topology, development, and distance from the road, which are responsible for the land transformation (Faisal et al., 2018). Along with this, various tools such as logistic regression, decision support, and cellular automata (CA) models have been implemented through various software packages such as DINAMICA and Modules for Land Use Change Evaluation (MOLUSCE) by incorporating multiple social and economic parameters (Gao et al. 2020; Xia et al. 2019; Falah et al., 2020). Artificial neural networks (ANN) have been utilized to perform various spatial simulations and LULC analyses (Moghaddam et al., 2022; Das and Angadi, 2021). For understanding and analysing the land use pattern and transformation, the extended JMC area (5 km buffer) is considered a study area shown in Figure 4.2, with the past 30 years as a study period. The extended study area allowed us to visualize the intensity of land transformation along the periphery of the city boundary.

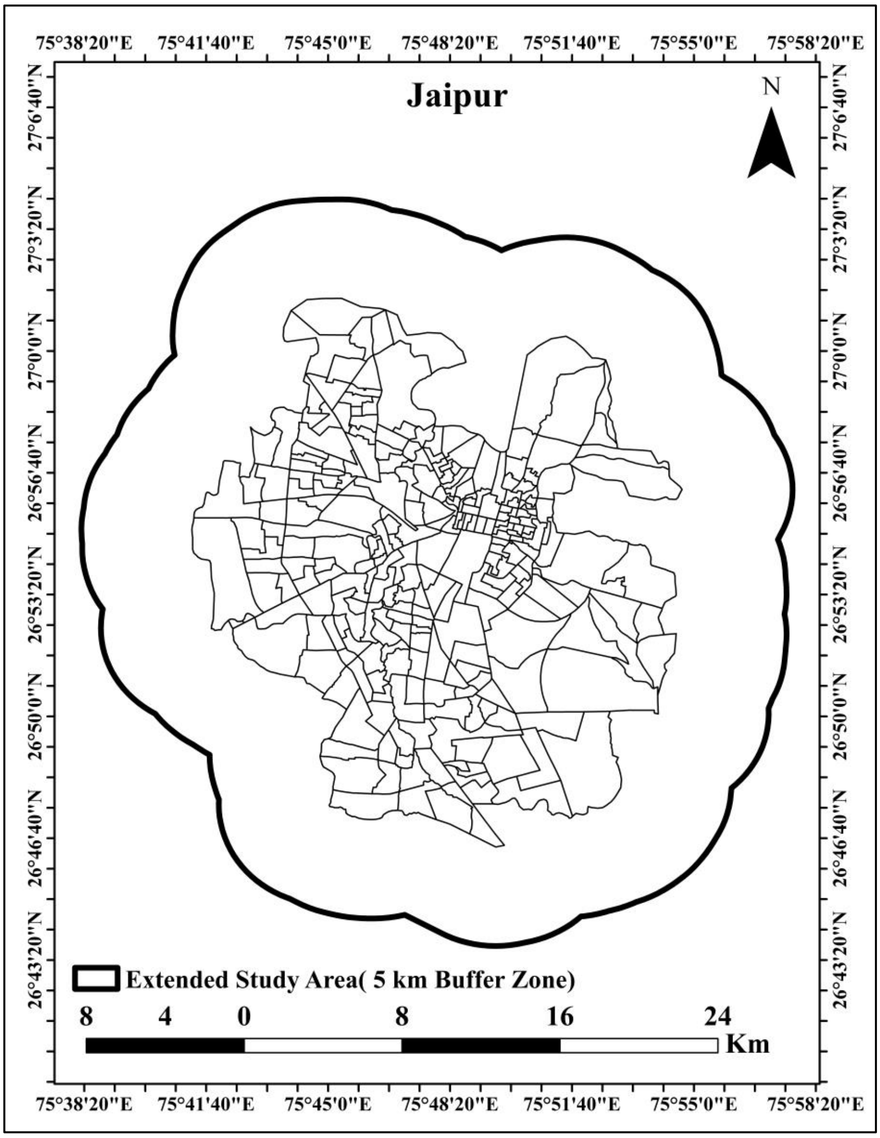


Figure 4.2 Extended study area map for LULC analysis

4.3.1 Data acquisition

To perform the LULC analysis, the study entails processing Landsat series satellite images for the extended study area. Satellite images were acquired from the United States Geological Survey (USGS) Earth Explorer over the past three decades (1990, 2000, 2010, 2015, and 2020) to perform LULC analysis. For conducting change analysis, Landsat 5 (Path/Row 147/41) for the date 21st May 1990, Landsat 7 (Path/Row 147/41) for the years 2000 and 2010 (on 5th March 2000 & 17th March 2010), and Landsat 8 (Path/Row 147/41) for the year 2015 and 2020 (on 12th April 2015, 1st December 2020) were acquired and analysed. Detailed properties of the satellite images are listed in Table 4.2. Along with the satellite data, the ancillary data included the road shapefile and the DEM data. The DEM data were obtained from the USGS Earth Explorer at 30m grid spacing (with the same resolution as Landsat images) from the

Shuttle Radar Topographic Mission (SRTM), which includes a terrain roughness index (TRI), topographic wetness index (TWI), slope length, and ground steepness. The required road shapefile was downloaded from OSM for calculating the distance from road maps using the Euclidian distance method in the GIS tool.

Table 4.2 Satellite image properties

Satellite/Sensor Path/Row Date Acquired	**Spatial Resolution(m)**	**Spectral Resolution**
Landsat 5 (Thematic Mapper)	30	0.45-0.52 (Visible Blue)
147/41	30	0.52-0.60 (Visible Green)
21st May 1990	30	0.63-0.69 (Visible Red)
	30	0.76-0.90 (NIR)
	30	1.65-1.75 (SWIR)
	120	10.40-12.50 (Thermal)
	30	2.08-2.35 (SWIR-2)
Landsat 7 (Enhanced Thematic	30	0.45-0.52 (Visible Blue)
Mapper Plus +) 147/41	30	0.52-0.60 (Visible Green)
5th March 2000, 17th March	30	0.63-0.69 (Visible Red)
2010	30	0.77-0.90 (NIR)
	30	1.55-1.75 (SWIR)
	60	10.40-12.50 (Thermal)
	30	2.08-2.35 (Mid Infrared)
Landsat 8 ((Enhanced	30	0.45–0.51 (Blue)
Thematic Mapper Plus +)	30	0.53–0.59 (Green)
147/41 12th April 2015, 1st	30	0.64–0.67 (Red)
December 2020	30	0.85–0.88 (NIR)
	30	1.57–1.65 (SWIR-1)
	30	2.11–2.29 (SWIR-2)
	100	10.60–11.19 (TIRS-1)

4.3.2 Pre-processing of images

The multiple sensors from the Landsat satellite reflect and record the electromagnetic spectrum, including gamma and X-rays, and all digitally recorded ground data are transmitted to ground stations (Hua et al., 2014). Therefore, preprocessing of the images was performed to remove sensor and atmospheric attenuation errors. Initially, all images were geographically referenced in the Universal Transverse Mercator (UTM) projection and the World Geodetic System (WGS) 1984. A band composite (data management) tool was used to develop false-colour composite (FCC) images for all images, and each processed composite image was clipped with a confined study area. To reduce the local variation and noise, a convolution function is used to smoothen the raster images by smoothing 5 × 5 pixels. The stepwise hierarchy involved in the pre-processing of satellite images is shown in Figure 4.3.

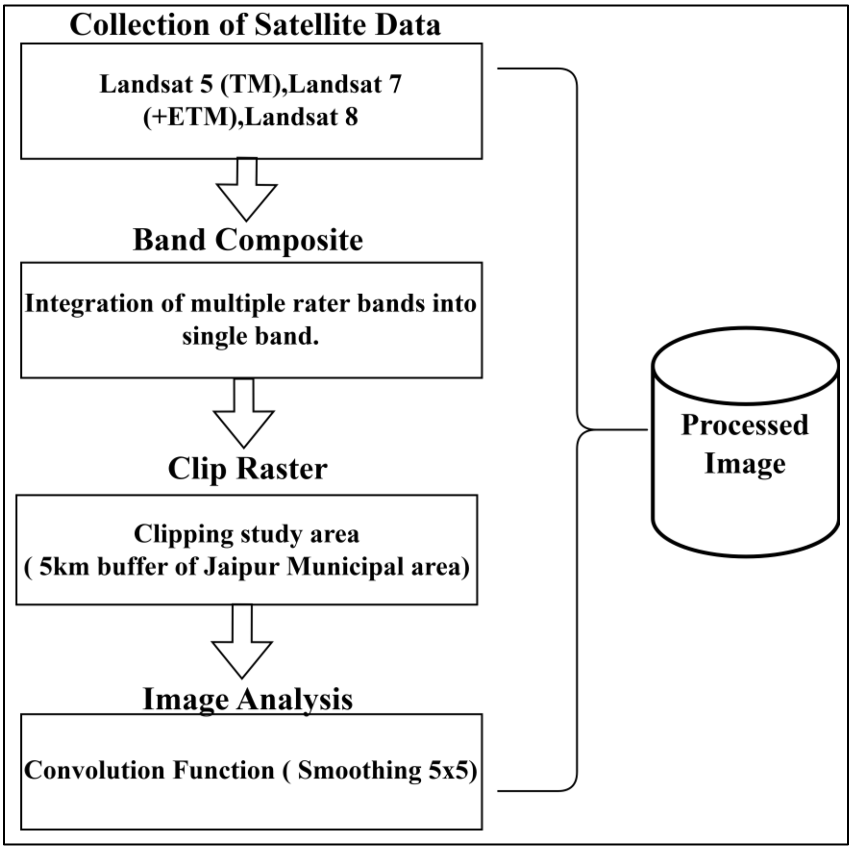


Figure 4.3 Steps in pre-processing of satellite images

4.3.3 Image classification

Unsupervised classification works effectively with coarse-resolution raster data such as Landsat because satellite image clusters consist of spectrally similar cells grouped into classes with similar spectral properties (Pal & Ziaul, 2017). This classification is useful for quickly assigning labels to uncomplicated, broad land cover classes such as water, vegetation/non-vegetation, and forested/non-forested. (Congalton & Green, 2019). In unsupervised classification, the computer determines the pixel category based on the pixel characteristics of the class without requiring a predetermined set of classes or training data, as shown in Figure

4.4. Instead, the classifier examines the data and determines the various statistically significant classes that best match the data. These classifications are reported as generic classes and must be assigned to categories after classification completion.

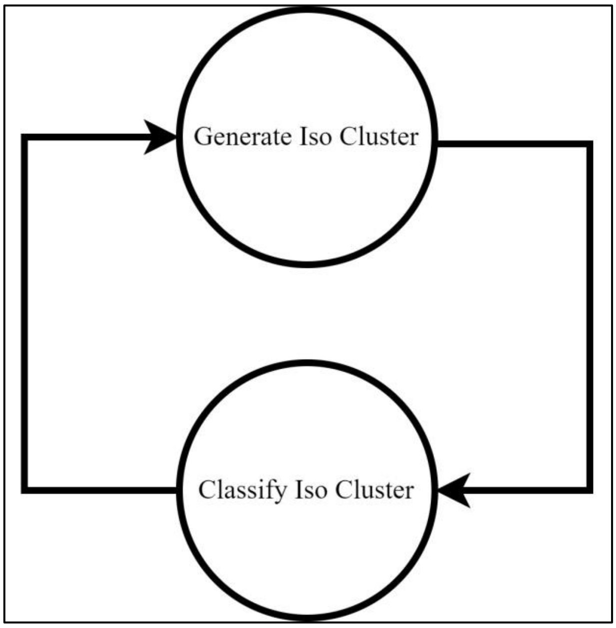


Figure 4.4 Steps in Unsupervised classification

In this study, the pre-processed satellite images were classified into 15 classes based on each pixel value. The classes were reclassified, and all pixels were divided into three new categories: built-up land, barren land, and vegetation. The reclassification images reflect the entire built-up land area, vegetation, and barren land. Figure 4.5 represents the characteristics of unsupervised classification.

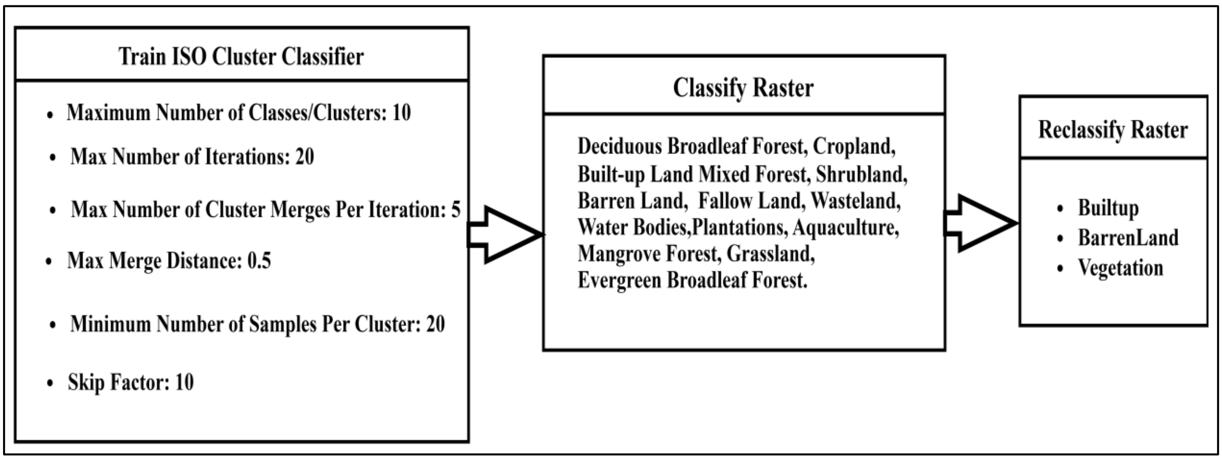


Figure 4.5 Characteristics of Unsupervised classification

The classified maps reveal that major land alteration occurred over the study period around the periphery of the municipality boundary, whereas the land alteration of the walled city (heart of the city) remained constant, as it is an already densely populated area. The urban growth pattern for the extended study area of Jaipur over the past three decades (for years 1990, 2000, 2010, 2015, and 2020) is presented in Figure 4.6.

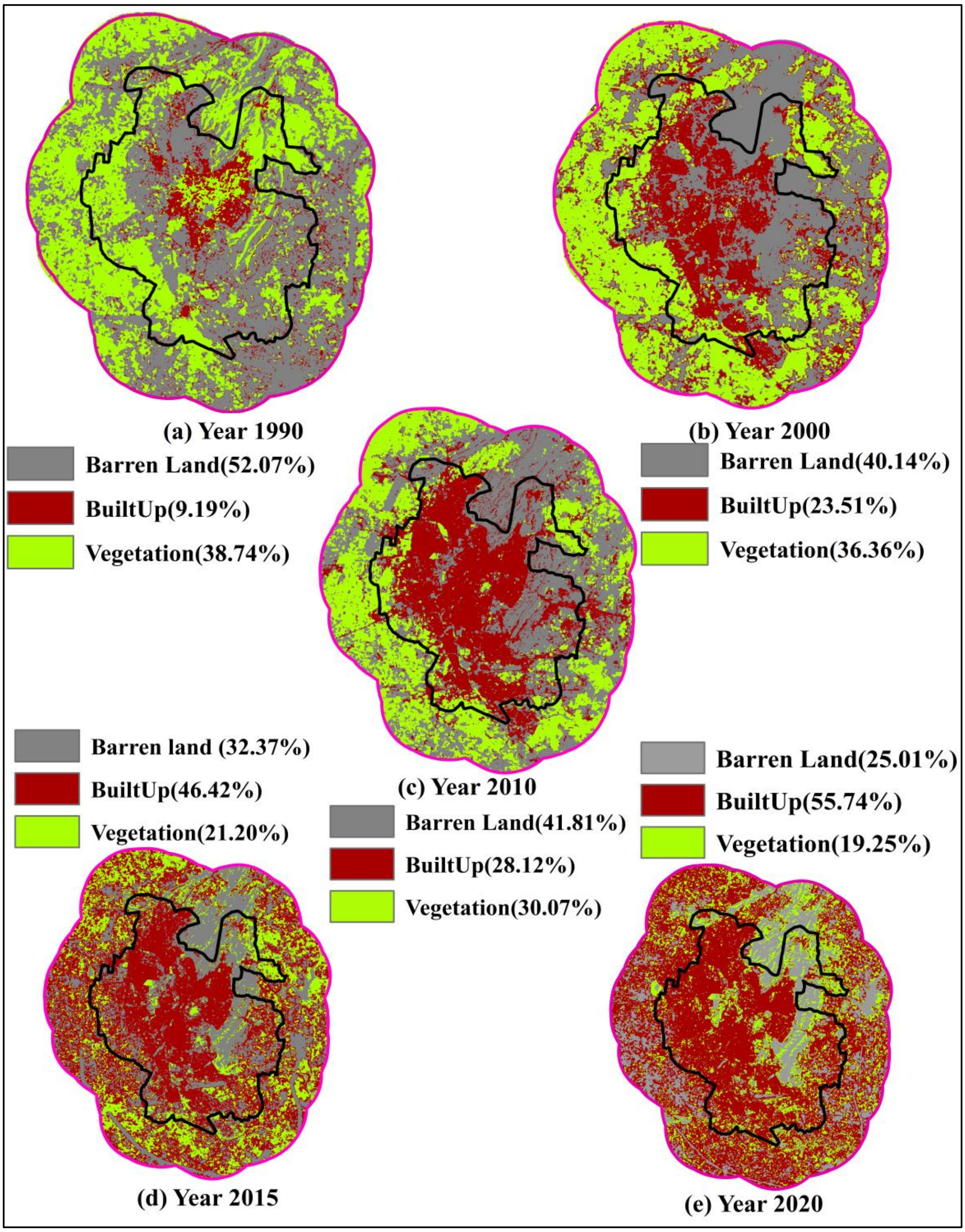


Figure 4.6 Classified image for years a) 1990, b) 2000, c) 2010, d) 2015, e) 2020

4.3.4 LULC Change analysis and prediction

The classified images of the past three decades (for years 1990, 2000, 2010, 2015, and 2020) were selected to perform the change analysis, allowing a better understanding of past growth patterns of Jaipur city, and imported in Q GIS 2.18.16 environment along with existing road network shapefile. The Q GIS tool is a powerful open-source software application that facilitates the creation, analysis, and visualization of spatial data. The MOLUSCE plugin from the Q GIS tool was used to perform the LULC analysis. This plugin contains a set of algorithms, including ANN, Learning Rate (LR), Weight of Evidence (WoE), and Minimum Classification Error (MCE), that were used to analyse and simulate land utilization transformations, as well as the validation of Kappa Statistics. Initially, the area change statistics for each predefined class (barren land, Built-Up, Vegetation) were calculated by multiplying the pixel count by its image resolution from the classified maps. The obtained area change transition matrix was used to quantify the changes that occurred in the LULC. The calculated area-change statistics are presented in Table 4.3.

Table 4.3 Area change statistics

LULC Features	1990	2000	2010	2015	2020	Overall (%)
Barren Land (sq.km)	483.5034	372.6927	389.043	332.15	232.182	-27.06
Built-Up (sq.km)	85.3236	218.2689	261.5976	392.84	517.563	46.55
Vegetation (sq.km)	359.7219	337.5873	277.9929	203.52	178.7625	-19.49

Furthermore, the plugin provides a transition map and matrix considering area change statistics to identify class transitions from one class to another. The quantitative transformation of the areas for this period was determined using a transition map and a matrix. The transition coefficients for classes are listed in Table 4.4.

Table 4.4 Transition matrix

Class	Land	Built-Up	Vegetation
Barren Land	0.5435	0.3750	0.0814
Built-Up	0.1177	0.8240	0.0581
Vegetation	0.4167	0.4170	0.1662

The transition map created was used to train the prediction model using an ANN equipped with an MLP. The MLP is a feed-forward ANN model that converts input datasets into suitable outputs. MLP is the most practical method for classifying and forecasting LULC changes (Islam & Ahmed, 2011). Because of appropriateness and minimum parameter requirements, MLP was used to analyse the LULC changes from the map between 1990 and 2015 (for the training model). The trained transition potential model analyses the area change and the explanatory power of variables.

4.3.5 Model validation, and prediction

This study created a validation map for 2020 with trained transit potential modeling and compared it with a satellite-driven classified map using kappa coefficients (overall kappa and per cent of correctness). Validation of the simulated map is an important stage in all geospatial modeling as it ensures the reliability and acceptance of the simulated map. The performed validation for a simulated model was strongly validated by the kappa values obtained from the MOLUSCE plugin, with a per cent correctness of 85. Further, using transit potential modeling, MLP and CA models were used to forecast the future map for 2030, as shown in Figure 4.7.

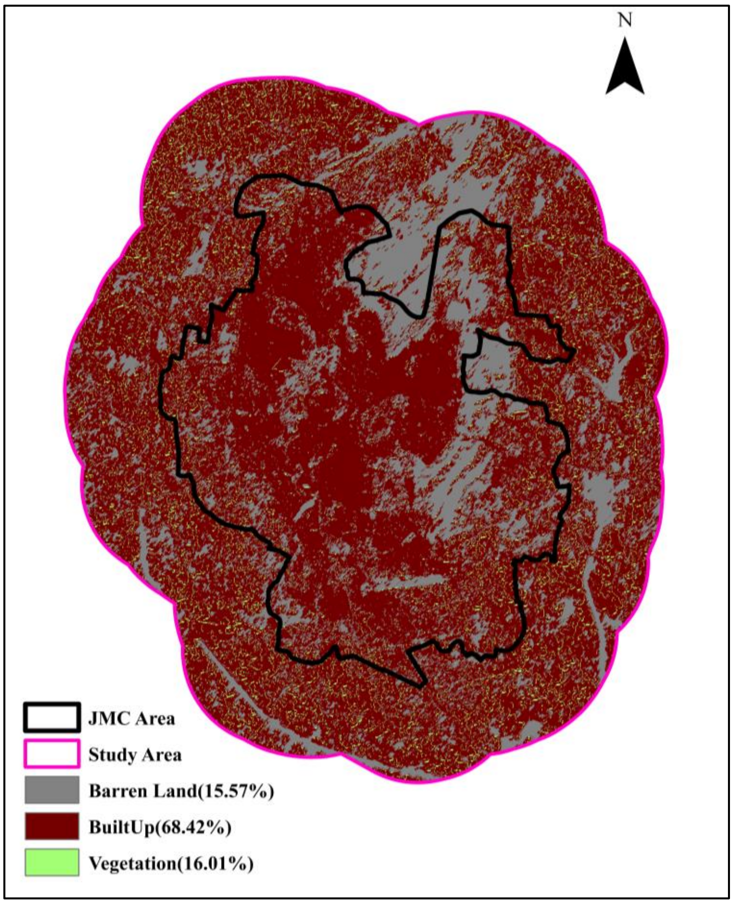


Figure 4.7 Simulated LULC map for the year 2030

According to the change analysis and prediction between 2020 and 2030, the net increase in built-up land area was 12.68%, decreasing barren land and vegetation by 9.44% and 3.24%, respectively. The predicted analysis showed remarkable growth in a built-up land area and a significant decline in vegetation and barren land on the outskirts of the main city area. The analysed and simulated land-use transition illustrates that the urban (built-up) land areas are rapidly expanding by transforming the surrounding agricultural and barren land. Unplanned growth and rapid urbanization pose several issues that diminish a city's overall sustainability. To overcome water scarcity due to rapid urbanization and infrastructure development, the implementation of community RwHs has been proposed. Understanding the relationship between topographic and hydrologic characteristics of the study area plays an important role in the efficient design of community RwHs as water infrastructure.

4.4 Establishing topographic relationships by performing hydro-spatial analysis

Nowadays, the availability of safe water is declining due to increased urbanization, accelerated industrialization, and over-exploitation of water sources (Kumar et al. 2018; Doulabian et al. 2021). In particular, people in developing countries experience severe water scarcity due to unregulated consumption and poor water supply system management (Joshi et al., 2016; Mohammady et al., 2018). Numerous initiatives such as RwH have been undertaken to overcome this scarcity. RwH needs the establishment of a relationship between the hydrology and topography of the area to enhance the community's life quality by conserving rainwater, making it available to living beings, and replacing it with an unsafe water source (Al-Adamat et.al, 2012; Campisano, 2017; Kumar & Jhariya, 2016). The relationship development involves identifying and assessing suitable sites for RwHs, incorporating numerous features (Norman et al. 2019; Ali et al., 2020).

Generally, the sustainability of RwHs is influenced by rainfall intensity, quantity of runoff, governing support, site location, and design criteria applied (Unami et al. 2015; Wurthmann 2019). Runoff is generated by heavy rainfall and significantly affects the hydrological cycle of the area, and the quantification of runoff plays a vital role whenever the watershed or river basin is considered the primary water source (Campisano, 2017; Jamali et al., 2020; Rana & Suryanarayana, 2020). To efficiently collect the generated runoff, a feasible site should be identified where all runoff water will collect automatically or by means of gravity, which helps reduce the operational cost of the RwH system (Wu et al., 2018; Mugo and Odera 2019). In such a case, the remotely sensed data enables instant and accurate preliminary data for parameters such as soil type, land use/land cover, lineaments, and geomorphology, which were integrated as thematic layers to assess the runoff potential (Ammar et al., 2016; Hashim & Sayl, 2021; Rajasekhar et al., 2020; Singh et al., 2017).

4.4.1 Basin formation

To establish topographic relations with the hydrology of the area, the entire Jaipur municipality area was considered as study area and shown in Figure 4.8. Establishing a relationship between the topography and hydrologic parameters resulted in basin formation and quantifying volumetric runoff potential. The detailed procedure used in this study is explained in the following sections.

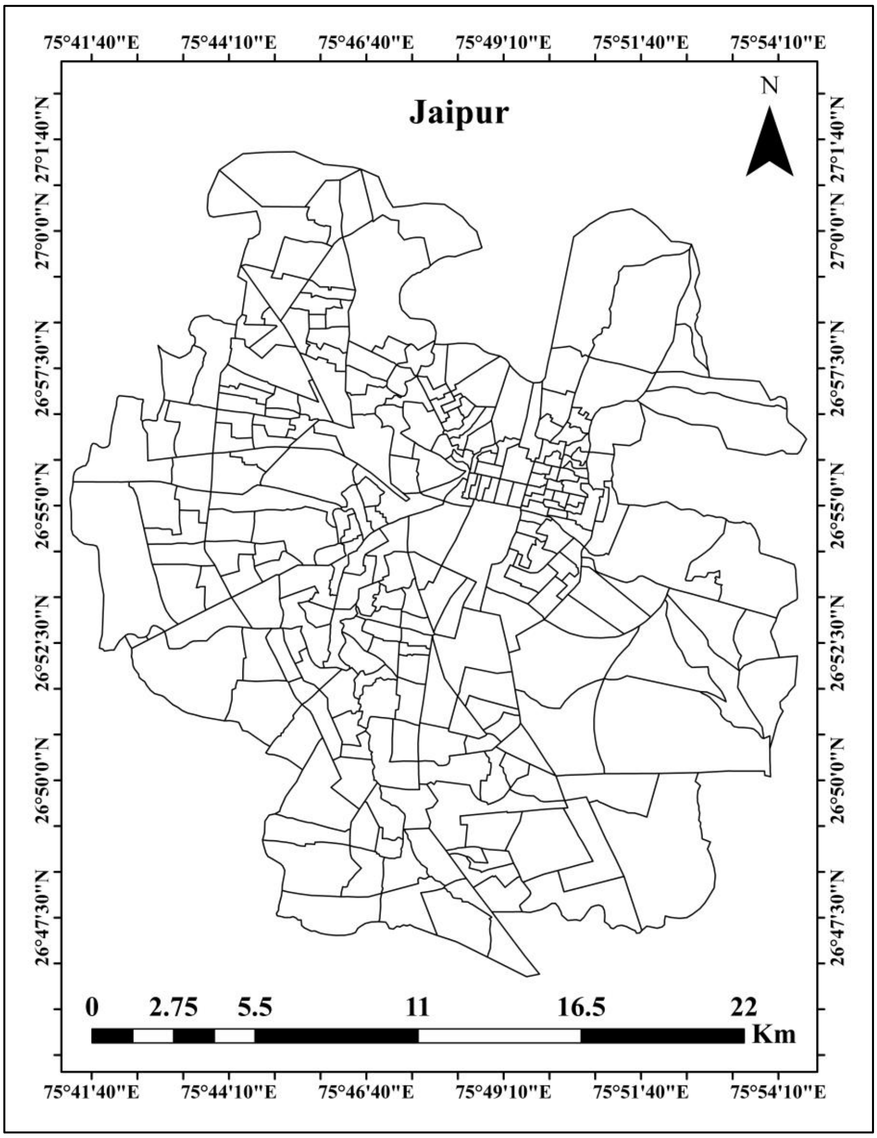


Figure 4.8 Study area map for establishing topographic relationships

4.4.1.1 Data collection and preparation

To conduct the study, multiple spatial and ground data were acquired from reliable sources. The Carto DEM V3 R1 with a spatial resolution of 30 m was acquired from the National Remote Sensing Centre (NRSC) Bhuvan platform, and two DEM tiles (cdng43d v3r1 and cdng43j v3r1) were mosaicked together and clipped inside the study area to perform hydro-spatial analysis. In addition, the IRS (Indian Remote Sensing) LISS-4 satellite images with specifications 95-52-D, 95-52-C, and 95-53-A were obtained for the dates 9/10/2019, 24/04/2019, and 20/12/2019, with a pixel size of 5 m and were radiometrically normalized for performing LULC classification (Indian Geo Platform of ISRO, 2022; Kumar et al., 2022).

Rainfall and a soil map are two more data sets required for hydro-spatial analysis. From 2011 to 2021, daily rainfall data for India were downloaded in Network Common Data Form (NetCDF) format, gridded at 0.250 x 0.250 intervals, from the Climate Data Service Portal of the Indian Meteorological Department (IMD), Pune (Pai et al., 2014). The IMD data was used to create a rainfall map, and the DEM data was used to analyse the contributing area. A world soil map was acquired and clipped from the United States Food and Agricultural Organization (FAO) website for the study area (FAO, 2007). All obtained thematic layers were geo-referenced using the UTM system, WGS 84, and zone 43 N. Figure 4.9 provides the detailed workflow methodology to form and assess the volumetric potential of the basin area.

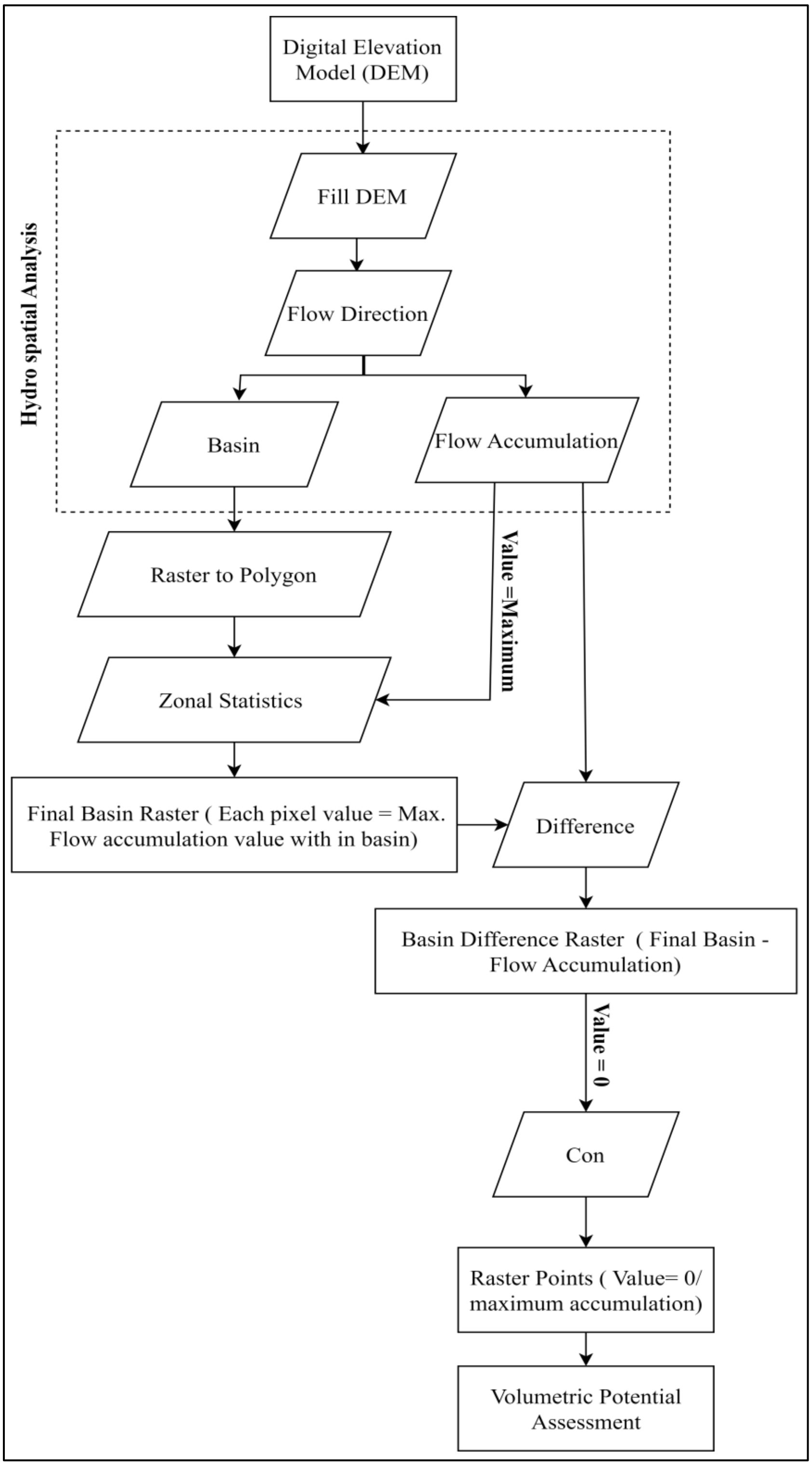


Figure 4.9 Methodology for establishing topographic and hydrologic relationship

4.4.1.2 Hydro-spatial analysis

Hydro-spatial is a branch of applied science that deals with the analysis, understanding, and access to static and dynamic geospatial digital and analogue data and information, digital signals, measurement, and description of the physical, biological, and chemical features of oceans, seas, coastal areas, lakes, and rivers from all possible available data sources in near-real time and in real time. In this study, hydro-spatial analysis was performed to form a basin and pinpoint its maximum accumulation points. The hydro-spatial analysis needs to perform multiple operations hierarchically to achieve the basin formation goal explained below and is represented in Figure 4.10.

a) Fill DEM: In the generated DEM, sink errors frequently occur because of the data resolution or elevation rounding to the closest integer value. So, this error should be filled in properly to ensure the delineation of the streams and basin. From the spatial analyst toolbox in the ArcGIS environment, the fill tool was used to remove the small imperfections available in the data. The operation helps to remove the false cells with greater elevation values than the expected pattern of the surrounding pattern (ESRI_a, 2022).

b) Flow direction: The flow direction tool was utilized to detect the direction of flow from each pixel in the DEM, which is an important step in establishing the hydrological characteristics of the surface (Adham et al., 2019). This tool is commonly worked on the D8 approach in which the eight applicable output directions relating to eight adjacent cells into which the flow might travel are considered, and the direction of the flow is determined by the direction of the steepest descent or by maximum drop from each cell (ESRI_b, 2022). The output raster generated from this analysis helped to understand the direction of flow within the study area as shown in Figure 4.10 (b).

c) Basin: In the analysis, the basin tool was used to identify the ridgeline along the basin by consuming the flow direction raster, where all the groups of connected cells from a similar basin were analysed. The created basin identified the contributing area for each pour point by locating the pour points at the edges. The output raster generated by the tool provides a raster that delineates the drainage basin (ESRI_c, 2022). The output raster represents multiple basins formed within the study area, as shown in Figure 4.10 (c).

d) Flow accumulation (FA): The FA tool estimates the accumulated flow of each cell flowing into each downslope cell using flow direction as the input raster. The available cells with high FA are the concentrated flow areas used to identify the stream channels along the basin (Hydrologic Interpretation of a Digital Elevation Model (DEM) 2022). The resulting FA raster identifies cells with high FA values corresponding to the contributing area. For example, the FA value of a cell corresponding to a 1 sq.km region across a DEM with a spatial resolution of 30 m is 1111 (1000000/ (30 × 30)). With the help of the FA map, it is possible to determine the amount of water that would flow from each pixel (Alwan et al., 2020). The output generated by the FA tool creates a stream network by applying the required threshold value to select an accumulated flow, as shown in Figure 4.10 (d).

e) Raster to Polygon: The output generated from the basin analysis is a raster in which each pixel value has an assigned value. So, to quantify the feature class from the raster, it is required to cluster all the pixels from the same category as a single feature (Zahra et al. 2017; Pala et al. 2020). The conversion of the pixels in the form of points, polygons, and lines was performed using a raster-to-polygon tool.

f) Zonal statistics: A zonal statistics operation computes statistics on the cell values (a value raster) within zones defined by other datasets, and output is generated by calculating one statistic at a time. A value raster is a raster whose cell values are used to perform operations in the zonal statistics tool. The zonal Statistics tool provides an output table by calculating one or more statistics using predefined mathematical operations like means, sum, median, standard deviation, maximum, etc.(ESRI_d, 2022). By performing the Sum in the zonal statistic tool, the maximum amount of water accumulation was estimated, and the value was assigned to each pixel within the basin (Olson et al., 2006; Mbilinyi et al., 2007).

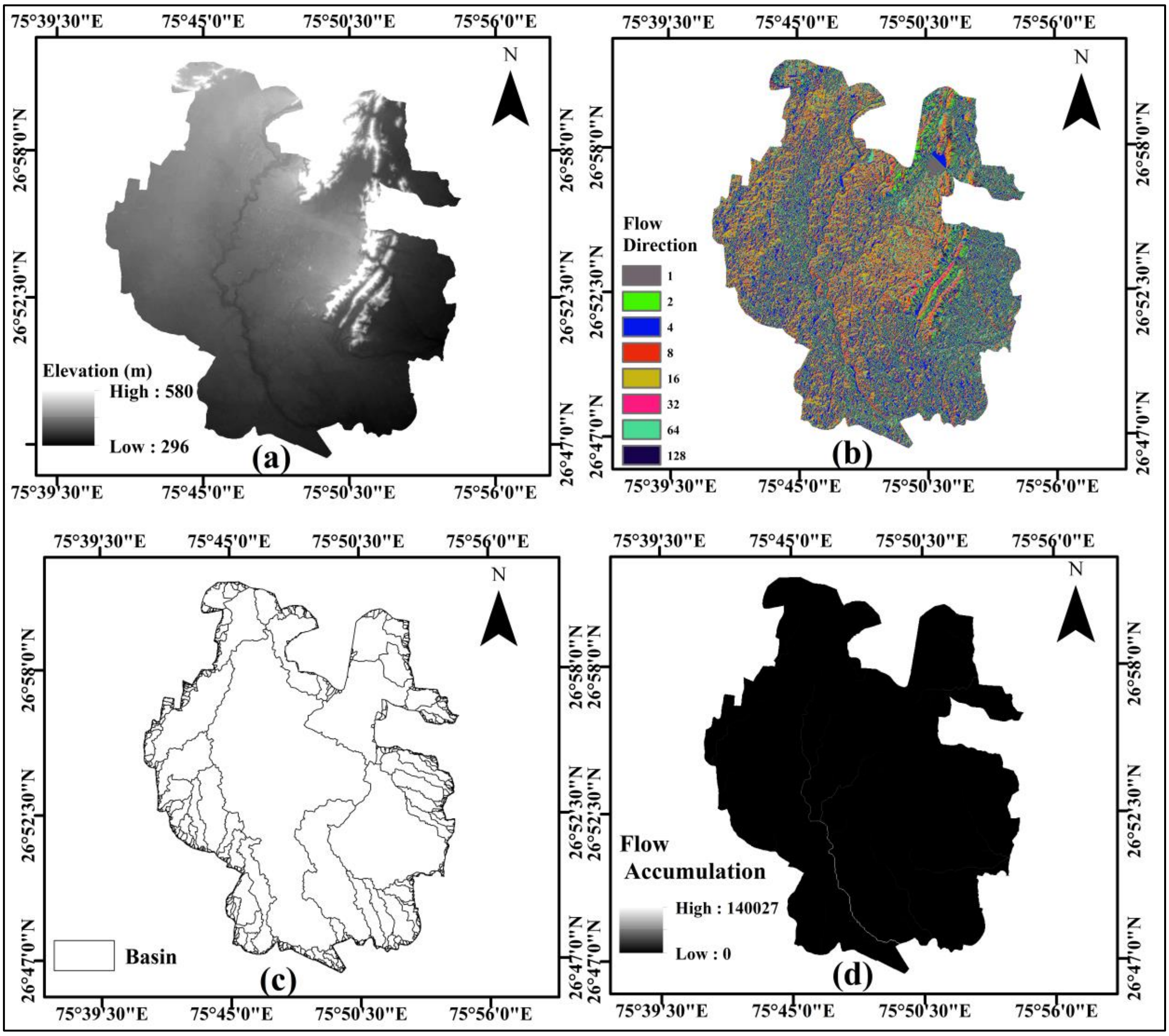


Figure 4.10 a) Elevation, b) Flow direction, c) Basin, d) Flow accumulation

g) Pinpointing maximum accumulation points: The raster generated from the zonal statistics tool and the FA raster were used to determine the exact location of the points of maximum accumulation. The features created by differencing the FA and output raster from the zonal statics provided the exact point where the FA was maximum within the basin. The identified locations were represented by the point where the difference between the two cell values was equal to zero, showing the location of the maximum FA within the basin. Equation 4.1 was used to pinpoint the exact location of maximum runoff accumulation points, as illustrated in Figure 4.11.

$$\text{Max. Flow accumulation points} = \text{Output raster from zonal statistics} - \text{FA} \qquad \text{Eq. 4.1}$$

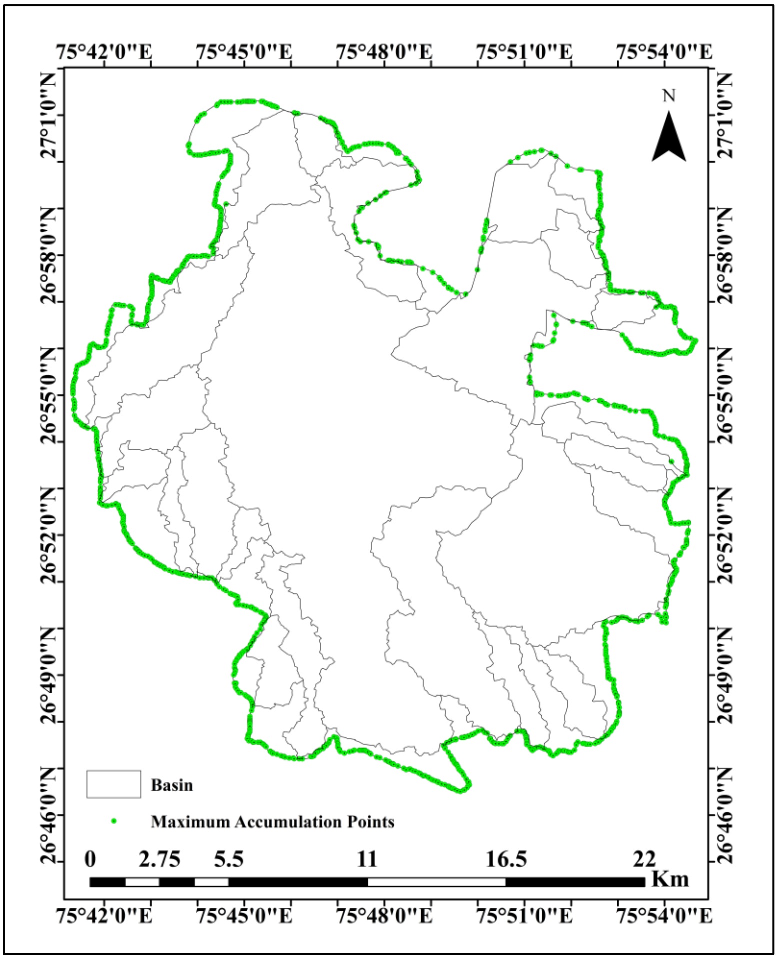


Figure 4.11 Maximum flow accumulation points

After basin formation, estimating the runoff potential is an important step in understanding the hydrologic potential of the area. Assessment of runoff volume potential requires multiple maps that reflect the physical and hydrological properties of the site. The following section explains the thematic maps involved while assessing the volumetric potential for the identified basin.

4.4.2 Volumetric potential assessment

Assessing the volumetric potential of the developed basins is a multidimensional work that involves multiple thematic layers such as soil, land use, slope, rainfall, and DEM. After initial abstraction by ground surface/soil, rainfall within a basin contributes to the runoff and flow towards the distributed accumulation points. The runoff has been calculated using the Soil Conservation Service-Curve Number (SCS-CN) method (SCS Engineering Division, 1986) (USDA-NRCS, 2014). To cope with the SCS-CN method, the following thematic maps (land use land cover, rainfall map, runoff map, and hydrological soil group map) were developed and illustrated in Figure 4.12 and explained below.

4.4.2.1 Land Use Land Cover map

Land use is the most significant factor influencing surface runoff generation (Mishra & Rai, 2016). The Maximum Likelihood Classification (MLC) was performed to determine various land use classifications across the study area. The radiometrically normalized LISS-4 satellite images were used to perform the classification. The study area was classified into four categories: built-up land, green land, water bodies, and fellow land. The created LULC map generates the curve number (CN) map in terms of the related runoff coefficient for each class.

4.4.2.2 Soil hydrologic group

A soil map from the Food and Agriculture Organization of the United Nations has been downloaded and clipped within the study area (FAO, 2007). The study area comprises only two soil groups, C and D (Neitsch et al., 2011).

4.4.2.3 Generation of runoff potential map / CN map

The CN is a hydrological parameter representing the area's stormwater potential as a function of land use and soil type (Ibrahim et al., 2019). The CN was prepared by compiling soil and land use maps to predict the runoff amount. A raster calculator tool was used to perform the mathematical operation involved in the calculation of CN. Equation 4.2 was used to create the CN map.

$$CN_{aw} = \frac{\sum_{i=1}^{x}(CN_i * A_i)}{\sum_{i=1}^{x} A_i} \quad \text{Eq. 4.2}$$

Where,

CN_{aw}= Area-weighted curve number for the drainage basin.

CN_i = Curve number concerning land use soil group polygon

A_i= Area of each land use soil group.

N= number of land use - soil polygons in each drainage basin

4.4.2.4 Rainfall map

To create the rainfall map, rainfall data obtained in the NetCDF format were utilized (Pai et al.,2014). The NetCDF data for each year were exported as a multiband raster with 365 bands using the NetCDF to Raster tool, and a single raster for each year's annual rainfall was constructed using the Cell Statistics tool. The wettest four months (June, July, August, and September) from the rainy season was considered to estimate the 10 days of rainfall to estimate the volumetric potential. The considered 10-day period reduced the chance of contamination from water without showing a drastic change in physicochemical properties (Struk-Sokołowska et al., 2020).

4.4.2.5 Preparation of potential maximum retention S curve/ Initial soil abstraction

The potential retention map represents the amount of infiltration that occurred after the start of runoff (Khudhair et al., 2020). The amount of infiltration governs the runoff at the soil surface, the rate of transmission in the soil profile, and the water storage capacity of the soil. The greatest potential retention is proportional to the CN, calculated using Equation 4.3.

$$S = 25.4\left(\frac{1000}{CN} - 10\right) \qquad \text{Eq. 4.3}$$

Where,

S=potential soil retention

CN= Curve Number

4.4.2.6 Runoff map

A potential retention and rainfall map were used to create potential runoff maps. The map created with the Natural Resource Conservation Service Curve Number (NRCS-CN) has proven to be the most reliable conceptual technique (Winnaar et al., 2007). The created map helps estimate the value of the surface runoff, and Equation 4.4 was used to create the runoff map.

$$Q = \frac{(Pe - \lambda S)^2}{Pe + (1 - \lambda)S} \text{ for } Pe \geq \lambda S \qquad \text{Eq. 4.4}$$

Where,

Q= Direct surface runoff

Pe = Precipitation

S= Potential soil retention

λ = Surface depression storage (Initial abstraction ratio) (0.2 as per standard value by the soil Conservation Service)

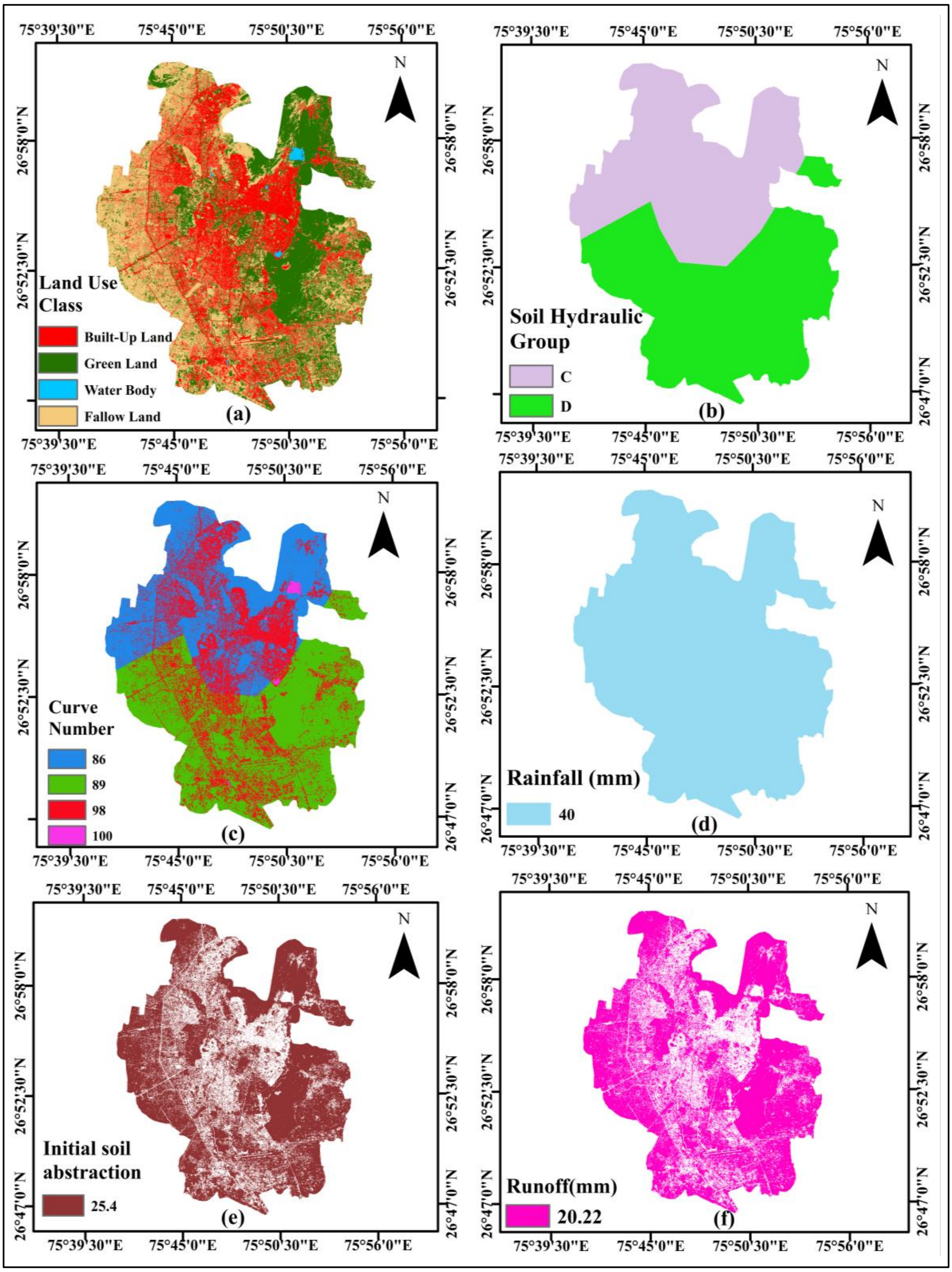


Figure 4.12 Thematic maps a) Land use class, b) Soil hydraulic group, c) CN, d) Rainfall, e) Initial soil abstraction, f) Runoff

4.5 Microscale planning and design of RwH site and alternatives

For an efficient sustainable water management, microscale planning and design of RwHs plays and pivotal role. The microscale study involves analysis conducted at a highly detailed level. In this study, the micro scale study refers to the three aspects as: the utilization of high-resolution satellite images, incorporation of household survey data and consideration single municipality ward. The utilization of high-resolution satellite images (5m x 5m) for comprehensive hydro spatial analysis, which is categorized as microscale. Conversely, the application of coarse resolution satellite images (30m x 30m) across the entirety of the Jaipur municipality area is considered macroscopic. The incorporation of the household survey data facilitates micro-level analysis, while gathering soil and water samples from various sources lays the path for macroscopic analysis. Furthermore, the analysis conducted over the entire Jaipur municipal corporation area is considered as a macroscale study, while the study conducted over a single municipality ward is deemed a microscale study. As Jaipur, situated in the semi-arid zone, is characterized by its high temperatures, limited rainfall, and mild winters. In recent times, the Jaipur Municipal area has contended with numerous water-related challenges, including flash floods. Understanding the root causes of these incidents necessitates micro scale analysis. Therefore, to assess the factors contributing to such occurrences and put forward an efficient solution, the single administrative area of the Jaipur Municipal Corporation (JMC) is considered for micro scale planning of communal RwH. The considered municipality ward serves as a pilot study area which can be applicable over the other areas in study region. The micro scale design and planning of RwHs comprises of three crucial stages: Site identification and providing rank order using MCDM, Analytic Hierarchy Process (AHP) for ranking RwH design alternatives and Development of stormwater drainage network as shown in Figure 4.13. For performing the micro scale study, the high-resolution satellite imagery along with the household data were incorporated. Initially the process begins with the identification of suitable sites and providing rank orders using MCDM techniques. Subsequently the AHP is employed to identify the suitable RwH design alternative for the sites. Finally, development of stormwater drainage network was performed to efficiently collect the stormwater by incorporating the hydrological characteristic of the study area. Following subsection elaborates the three stages involved in Microscale planning and design of RwH site and alternatives.

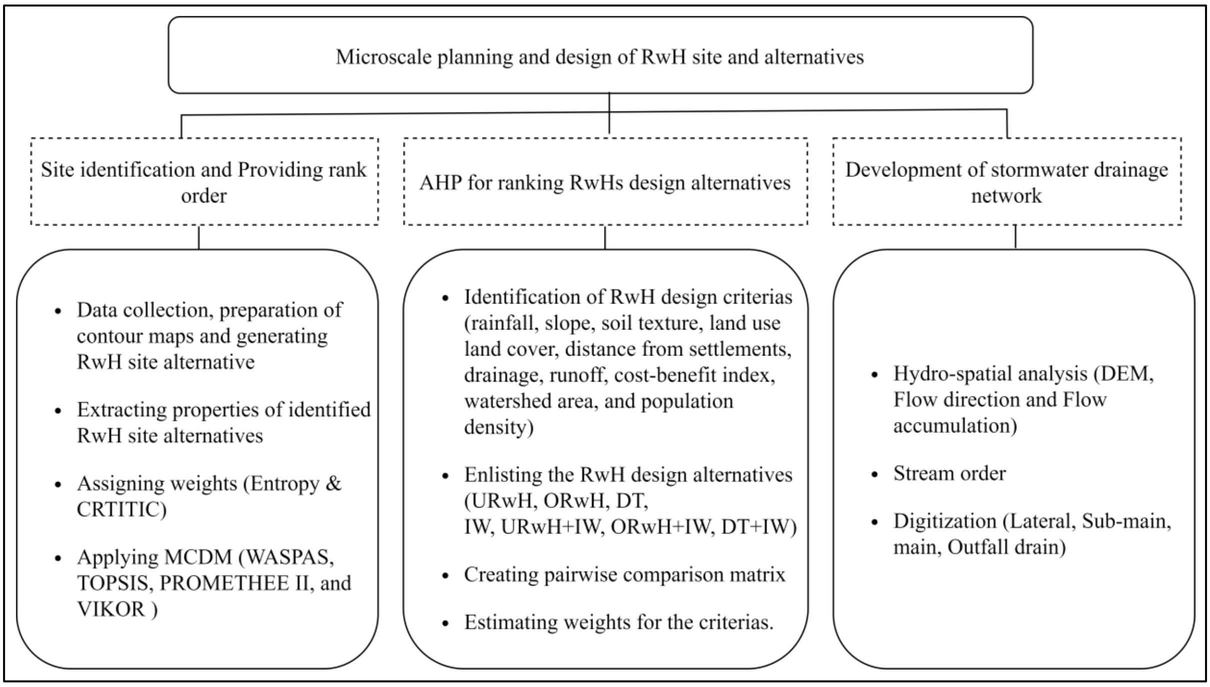


Figure 4.13 Microscale planning and design of RwH site and alternatives

4.5.1 Site identification and providing rank order using MCDM

The efficiency and sustainability of RwHs depend on the selected site and technical design details of the systems created by considering various natural and manmade parameters (Al-Adamat et al., 2012; Ghani et al., 2013; Winnaar et at., 2007). For identifying suitable RwH sites, the adoption of GIS tools and techniques provide the hydrological potential of the area and facilitate decision-making (Saraf and Choudhury, 2010). Nowadays, the effectiveness of GIS in location analysis and decision-making has significantly improved by enabling the integration of Decision Support Systems (DSS) and MCDM (Rikalovic et al., 2014). The MCDM analysis has proven to be an effective methodology that involves identifying, ranking, and assessing the best alternative sites by incorporating predetermined criteria (Salvatore et al., 2016). The applied MCDM methods assist in determining the suitable RwH sites by considering geospatial data and providing rank order for identified sites based on predefined criteria (Abdulla et al., 2002; Jayasooriya et al., 2018; Krois & Schulte, 2014). In addition, the MCDM also allows the integration of data processing and visual geographic data representations, which promote decision-makers for making critical decisions (Köhler et al., 2019; Kumari et al., 2021). It can also improve the auditability, transparency, and accuracy of decisions (Šantl & Steinman, 2015).

To perform the site selection process, the study area was narrowed to a single municipality ward of the JMC. The selection of study area influenced by the consideration of current and predicted built land area density. The municipality ward is located on the north side of the city at latitude 26°59’09.88” N to 26°59’53.37” N and Longitude 75°45’11.54” E to 75°44’11.02” E and has an area of about 1.6462 sq. km was selected as a study area. The selected ward area shows medium built-up land density (78 to 93%) which will be convert to high density (94 to 100%) in coming year and reduces the chance of land availability. Figure 4.14 represents the study area map for site identification and providing rank order.

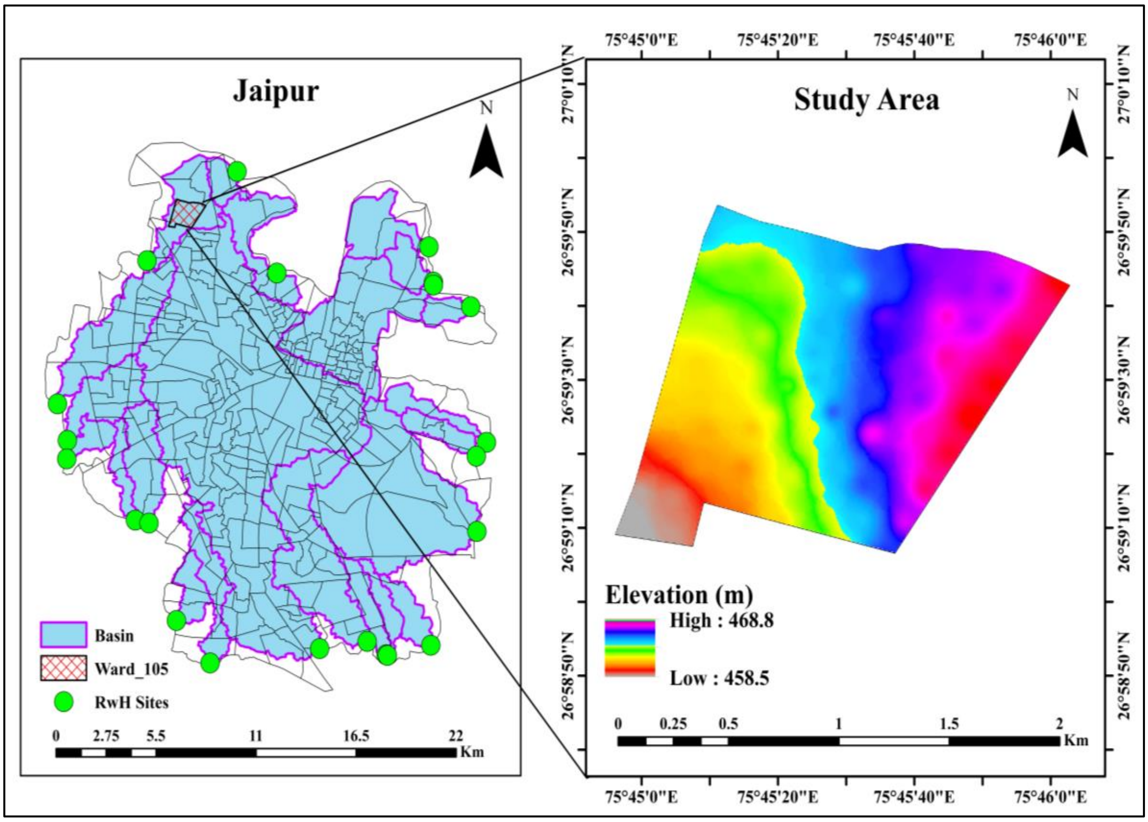


Figure 4.14 Study area map for MCDM analysis

4.5.1.1 Data collection and generating RwH site alternatives

Elevation is a key factor to consider while creating a community RwH, as it helps to lower operational costs by minimizing extra resources. A Differential Global Positioning System (DGPS) survey was conducted over the study area to collect three-dimensional coordinates in the WGS-84 coordinate system. The raw data was pre-processed with Global Navigation Satellite System (GNSS) software to remove inaccuracies and calibrate the readings to centimetre precision. The processed ground data (after removing outliers and wrong entries) were imported into the GIS environment and plotted as a shape file. The sample DGPS survey location is appended in Appendix A. The z-coordinate values from the DGPS data were incorporated for creating a DEM using an Inverse Distance Weighted (IDW) interpolation method. A DEM is a three-dimensional (3D) computer graphics representation of the earth’s topographic surface elevation, excluding trees, buildings, or other surface features (Suresh Babu et al., 2015).

So, identifying the low-lying area within the study area where maximum rainwater is supposed to be collected by gravitational force initiates the site selection process. The DEM generated from the DGPS survey data was clipped using the extended study area. The satellite images of IRS Resourcesat LISS-4 with scene specifications 95-52-D, captured on 9/10/2019, having a spatial resolution of 5 m, were procured from the National Remote Sensing Center, India. A previously acquired soil and rainfall map for the Jaipur municipality area was incorporated to determine the soil type and estimate the volumetric potential.

The clipped DEM with a resolution of 30m was resampled with a pixel resolution of 5 m (same as LISS-4) and used to create a contour map for identifying low-lying areas for RwH locations. Figure 4.15 (a) shows the resampled generated contour map. The study area has a maximum elevation of 468.89 m and a lowest elevation of 458.44 m. Due to the constrained (small ward area) study area, rather than performing LULC classification, the identification and selection of sites were made manually based on land-use patterns (available land/free space) by importing base maps and contour maps. Figure 4.15 (b) shows the identified RwH site alternatives. In contrast, the site areas in large areas can be identified by performing LULC classification, which helps reduce time and complexity. Sites such as open spaces, recreational centers, and grounds were identified and considered as RwH site alternatives for creating community RwHs.

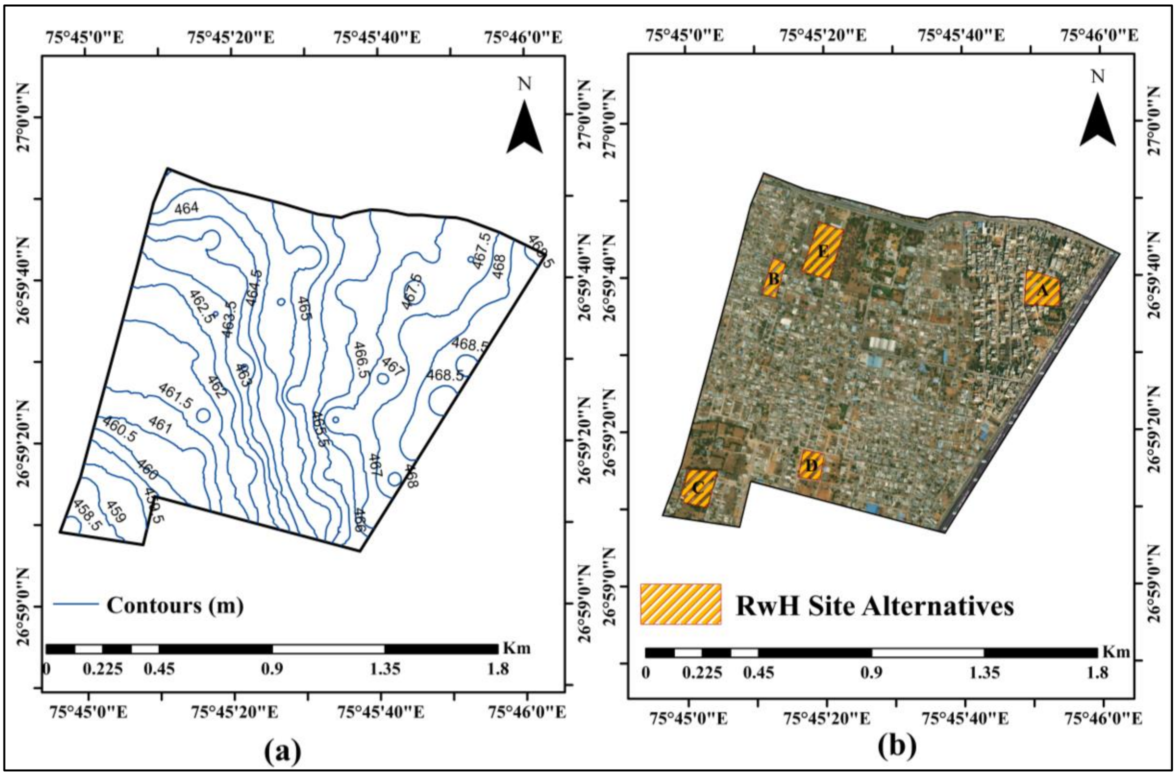


Figure 4.15 a) Contour map, b) Identified RwH site alternatives

4.5.1.2 Extracting site properties

After identifying the site, the extraction site properties were used to perform MCDM analysis. The extraction of site properties includes physical and hydrological parameters such as runoff volume, elevation, available area, perimeter, and distance from the centre. The interpretation for the considered criteria's is provided in Table 4.5.

Table 4.5 Interpretation for MCDM criteria's

Criteria	Interpretation
Volume (Runoff)	Runoff takes into consideration the rainfall intensity and reflects hydrological potential of area along with the infiltration rate of the soil.
Elevation (Site altitude)	Provides relative site altitude with study region altitude for maintaining gravity flow.
Site Area & Perimeter	Represents available site area to generate RwH design alternatives and site potential for future expansion.
Distance from centre	Establishes the relationship between the centre of the area and site with price of water supply and collection.

So, to estimate the runoff volume accumulated over sites, hydro-spatial analysis was performed over the area using thematic maps. The procedure used to estimate the runoff volume was the same as that described in Section 4.4.2, using the CN method. Along with the hydro-spatial analysis, extensive capabilities of GIS analysis were used to extract the site properties from imported satellite imagery as a base map. Table 4.6 provides the extracted site properties.

Table 4.6 Extracted site properties

Sites/ criteria	**Volume (cub.m)**	**Elevation (m)**	**Area (sq.m)**	**Perimeter (m)**	**Distance from Center (m)**
A	1392.5	467.51	16759.66	523.23	714.27
B	9763.08	461.62	9216.11	387.07	516.23
C	16898.18	458.83	15481.08	508.14	936.26
D	7535.19	462.47	7992.78	402.79	486.19
E	1093.57	463.75	22421.92	629.6	507.47

4.5.1.3 Assigning weights

To perform MCDM analysis, the objective weight methods have been used to assign weights to the extracted criteria by considering the amount of information within them and their influencing power over overall decision-making (Vujicic et al., 2017). In the objective weight method, the amount of information in each criterion is proportional to its strength, which is reflected by the weights assigned to it (Zavadskas & Podvezko, 2016). The proposed study applied two objective weight methods: one is based on the amount of information, and the other is based on a statistical approach were applied and compared.

a) Entropy Weight Method (EWM): The EWM is a weighting method commonly used in decision-making to measure the value of dispersion. The greater the degree of dispersion, the greater the degree of differentiation, and the greater the amount of data derived. The amount of undefined information in the decision matrix affects the criteria weights, which generate a set of weights for specific criteria by comparing the values of a single criterion to the values of all criteria simultaneously. The following steps and Equations 4.5 to 4.8 were used to calculate the Entropy objective weights (wij):

Step 1: Normalization of criteria values (r_{ij}) of x_{ij} variants from the decision matrix.

$$r_{ij} = \frac{x_{ij}}{\sum_{i=1}^{m} x_{ij}} \qquad \text{Eq. 4.5}$$

Step 2: The Entropy value (e_j)for each criterion is calculated by

$$e_j = -k \sum_{i=1}^{m} r_{ij} \ln r_{ij} \qquad \text{Eq. 4.6}$$

where k = constant, ($k = 1/\ln n$)

Step 3: The degree of divergence (d_j) can be calculated as

$$d_j = 1 - e_j \qquad \text{Eq. 4.7}$$

Where dj (j=1, 2,..., n) represents the actual intensity of the criteria contrast Cj.

Step 4: Final relative weight of the criteria (w_j)

$$W_j = \frac{d_j}{\sum_{j=1}^{n} d_j} \qquad \text{Eq. 4.8}$$

The above-performed steps provide the objective criteria weights for each extracted site property.

b) CRITIC Method (CM): Criteria Importance Through Intercriteria Correlation (CRITIC) method is a type of correlation method that deals with the analytical validation of the decision matrix to find out the amount of information enclosed in the criteria and its variants. For each x_{ij} criterion, the r_{ij} membership function is described, which interprets all values of criterion fj into the interval [0, 1]. The following steps and Equations 4.9 to 4.11 were used to calculate the CRITIC objective weights.

Step 1: Conversion of an initial matrix in the generic element (r_{ij})

$$r_{ij} = \frac{x_{ij} - {x_j}^{min}}{{x_j}^{max} - {x_j}^{min}} \qquad \text{Eq. 4.9}$$

Step 2: Each vector is assigned a standard deviation, indicating the degree of uncertainty of variant values for a set of criteria for an average value. The following formula was used to determine the total of information Cj contained in the criteria j:

$$C_j = \sigma_{j \sum_{i=1}^{m}(1-r_{ij})} \qquad \text{Eq. 4.10}$$

Step 3: Normalization of the Cj to get the objective weights:

$$W_j = \frac{C_j}{\sum_{i=1}^{m} C_i} \qquad \text{Eq. 4.11}$$

Table 4.7 provides the criteria weight calculated by the Entropy and CRITIC methods. These objective weight methods derive weights considering the amount of information, eliminating subjectivity, irresponsibility, and a lack of decision-makers.

Table 4.7 Objective weights of criteria

Method	**Volume**	**Elevation**	**Area**	**Perimeter**	**Distance from Centre**
CRITIC	0.2129	0.1650	0.1833	0.1816	0.2571
Entropy	0.2231	0.1915	0.1977	0.1929	0.1947

4.5.1.4 Applying MCDM

The estimated objective criteria weights are utilized for multi-criteria decision-making, directly influencing the decision. To conduct the analysis, multiple MCDM methods were used depending on the accessibility of data and the amount of information. In this study, the MCDM methods WASPAS, TOPSIS, PROMETHEE II, and VIKOR were applied to identify and rank suitable sites for community RwHs. The incorporation of these four MCDM allows for a thorough examination of various criteria and factors, reducing the subjective judgement and enabling a more robust assessment of consistency in ranking.

a) Weighted Aggregated Sum Product Assessment (WASPAS): This method combines the weighted product model (WPM) and Weighted Sum Model (WSM) (Hwang & Masud, 2012). The integration of these two MCDM methods increases accuracy and reliability. Table 4.8 shows the rank values for various site alternatives obtained using the WASPAS method and weighted using the Entropy and CRTIC methods.

Table 4.8 WASPAS method

Site	**CRITIC**		**Entropy**	
	Joint Generalized Criteria	**Ranking**	**Joint Generalized Criteria**	**Ranking**
Site A	0.58955	5	0.56479	5
Site B	0.71803	2	0.68478	2

Site C	0.78743	1	0.796434	1
Site D	0.69057	3	0.650988	4
Site E	0.68905	4	0.659224	3

b) Technique for order of preference by similarity to an ideal solution (TOPSIS): In 1981, Hwang and Yoon introduced the TOPSIS method, based on the principle that "the optimal decision should have the closest distance from the positive ideal solution and the greatest distance from the negative ideal solution" (Hwang & Masud, 1981). Based on this approach, alternatives are rated based on the distance between their optimal solutions. The TOPSIS approach was used to assess the appropriateness of the various alternatives, combining the advantages of rough precision theory and prospect theory and has many applications for identifying suitable areas. Table 4.9 displays the performance score and rankings for the alternative sites by TOPSIS method.

Table 4.9 TOPSIS method

Site	CRITIC		Entropy	
	Performance Score	**Ranking**	**Performance Score**	**Ranking**
Site A	0.13297	5	0.26920	5
Site B	0.52748	2	0.48304	2
Site C	0.77552	1	0.69960	1
Site D	0.39127	3	0.40143	3
Site E	0.33933	4	0.39429	4

c) VIseKriterijumska Optimizacija I Kompromisno Resenje (VIKOR): In 1998, Serafim Opricovic developed the VIKOR (Multi-Criteria Optimization and Compromise Solution) method to solve conflicting and incommensurable criteria. The method ranks the alternatives by designating it as a "Compromize" to obtain the ideal solution for decision-making (Huang et al., 2009). The linguistic variable is used to rank the alternative decision-makers in this method. This method is widely applied to decision-making in the economic field. Table 4.10 presents the Compramize Ranking Value and rankings for the alternative sites.

Table 4.10 VIKOR method

Site	CRITIC		Entropy	
	Compramize Ranking Value	Ranking	Compramize Ranking Value	Ranking
Site A	0.68015	5	0.92998	5
Site B	0.29234	2	0.31527	2
Site C	0.67452	4	0.09806	1
Site D	0.35212	3	0.45691	3
Site E	0.20682	1	0.5	4

d) Preference Ranking Organization Method for Enrichment Evaluations (PROMETHEE II): In 1985, Brans and Vincke developed the PROMETHEE method, which provides the best alternative by considering the objective and understanding problems by providing a comprehensive and rational framework (Brans & Vincke, 1985). Using this method, it is possible to quantify and identify conflicting criteria of actions and highlight them as the main alternative. PROMETHEE- I give a partial order for the alternatives, whereas PROMETHEE-II provides the unique ordering values for an individual alternative. This method is widely used to analyse the transportation industry, healthcare, and education decisions. Table 4.11 presents the Outranking Flow Value and ranking of the alternative sites.

Table 4.11 PROMETHEE-II method

Site	CRITIC		Entropy	
	Outranking Flow Value	Ranking	Outranking Flow Value	Ranking
Site A	-0.201	5	-0.2045	5
Site B	-0.0259	3	-0.0519	3
Site C	0.07338	2	0.15153	2
Site D	-0.0669	4	-0.1037	4
Site E	0.22051	1	0.20855	1

4.5.2 Analytic Hierarchy Process for ranking RwH design alternatives

Analytic Hierarchy Process (AHP) is one of the most applied decision-making methods with significant application in the field of water infrastructure (Han et al., 2020). It enables modeling of a complex problem in a hierarchical structure, giving a general overview of the problem for decision-making since the hierarchical criteria system follows the structure of several well-known analogies, and the weighting by pairwise comparisons is equally reasonable (Tanyimboh & Kalungi, 2009). AHP employs a multi-objective decision-making strategy and offers a systematic technique for combining all variables. It also integrates qualitative and quantitative methods and structures the decision into a multi-level hierarchical framework that includes the aim, criteria, sub-criteria, and alternatives (El-Abbasy et al., 2015). This process allows decision-makers, including engineers, stakeholders, managers, experts, and non-experts, to choose a preferable alternative option subject to a finite number of criteria. Therefore, a principal advantage of using AHP is that the end-users (decision-makers) do not go into the mathematical details of the calculations, thereby increasing participation (Zyoud et al., 2016). In this study consideration of the AHP analysis brings the subjective knowledge of experts through their responses to rank the suitable RwH design alternatives by considering corresponding criteria's. For this analysis, remotely sensed and survey data were used to extract the characteristics of the study area. The AHP broadly depends on three principles: decomposition, comparative judgment, and synthesis. The steps followed in the AHP analysis are as follows:

a) The primary goal of this research was to identify the best RwHs based on predetermined criteria. The criteria such as rainfall, slope, soil texture, land use land cover, distance from settlements, drainage, runoff, cost-benefit index, watershed area, and population density were extracted from the previously developed and acquired maps. The interpretation for the considered criteria's is provided in Table 4.12.

Table 4.12 Interpretation for AHP criteria

Criteria	Interpretation
Rainfall	The measurement of how much water falls as rain in a certain period of time, for example, a week or a month. Rainfall is measured by collecting rainwater across different areas and times, as the amounts may differ between locations and times.
Slope	Slope refers to the extent that a soil surface has an incline relative to the horizontal. In percentage terms, slope represents the elevation that occurs between two different points.
Soil texture	Soil texture is important because it influences water retention, erosion potential, nutrient leaching, drainage capability and agricultural productivity. Texture indicates the relative content of particles of various sizes, such as sand, silt, and clay in the soil. Texture influences the ease with which soil can be worked, the amount of water and air it holds, and the rate at which water can enter and move through soil.
Land use and land cover	Land cover refers to the surface cover on the ground like vegetation, urban infrastructure, water, bare soil etc. Land use refers to the purpose that the land serves, for example, recreation, wildlife habitat, or agriculture. When used together with the phrase Land Use / Land Cover (LULC) generally refers to the categorization or classification of human activities and natural elements on the landscape within a specific time frame based on established scientific and statistical methods of analysis of appropriate source materials.
Distance from settlements	Our hypothesis is that the distance between a city and its water supply is positively correlated with the price of water city residents pay, and that both of these variables have a negative relationship with the population of the city. For example, we expect that a large city would have a lower water rate compared to a smaller city. Our rationale for this idea is that in order to sustain a large urban population into the millions, there needs to be a reliable water source nearby that provided enough water of adequate quality. A safe distance from rivers is always advisable; otherwise, the water harvesting structure created may be disturbed due to sliding of the soil of the boundary.

Drainage	The most important principle that can be considered in natural drainage systems is in providing a corridor for natural streams to flow through areas without interruption or construction. Providing this corridor for the flow of streams provides certain advantages in terms of the drainage patterns for the area. These include the abatement of flooding, less erosion of the banks of streams, less sedimentation, better groundwater recharge, greater moisture content in soil, filtration of pollutants and excess nutrients and better soil fertility with better habitats for animals.
Runoff	Surface runoff water harvesting is the collection, accumulation, treatment or purification, and storing of stormwater for its eventual reuse. It can also include other catchment areas from manmade surfaces, such as roads, or other urban environments such as parks, gardens and playing fields. Runoff takes into consideration the rainfall intensity and infiltration rate of the soil.
Cost-benefit index	The cost–benefit index defines the ratio of the potential volume of storage to the volume of the RWH structure. Water storage represents the benefit, while the cost of the RWH system is a function of the volume of the embankment.
Watershed size	A Watershed is a land area whose runoff drains into any stream, river, lake, and ocean. Watershed has hydrologic and ecological functions. When buildings and other impervious areas such as parking lots cover the ground, infiltration decreases and most of the water runs off into collection ditches where stream channel erosion may occur. Protecting healthy watersheds can reduce capital costs for water treatment plants and reduce damages to property and infrastructure due to flooding, thereby avoiding future costs. Additionally, protecting healthy watersheds an generate revenue through property value premiums, recreation and tourism.
Population density	Population growth particularly will limit the amount of water available per person, because an increase in per capita water consumption driven by development will intensify water demand, straining the local water supply.

The seven RwHs alternatives enlisted are Underground RwH tank (URwH), Overground RwH tank (ORwH), Direction Tunnels (DT), Infiltration Wells (IW), URwH + IW, ORwH + IW, DT+IW and are illustrated in Figure 4.16. The advantage and disadvantages of these RwH design alternatives is provided in Table 4.13.

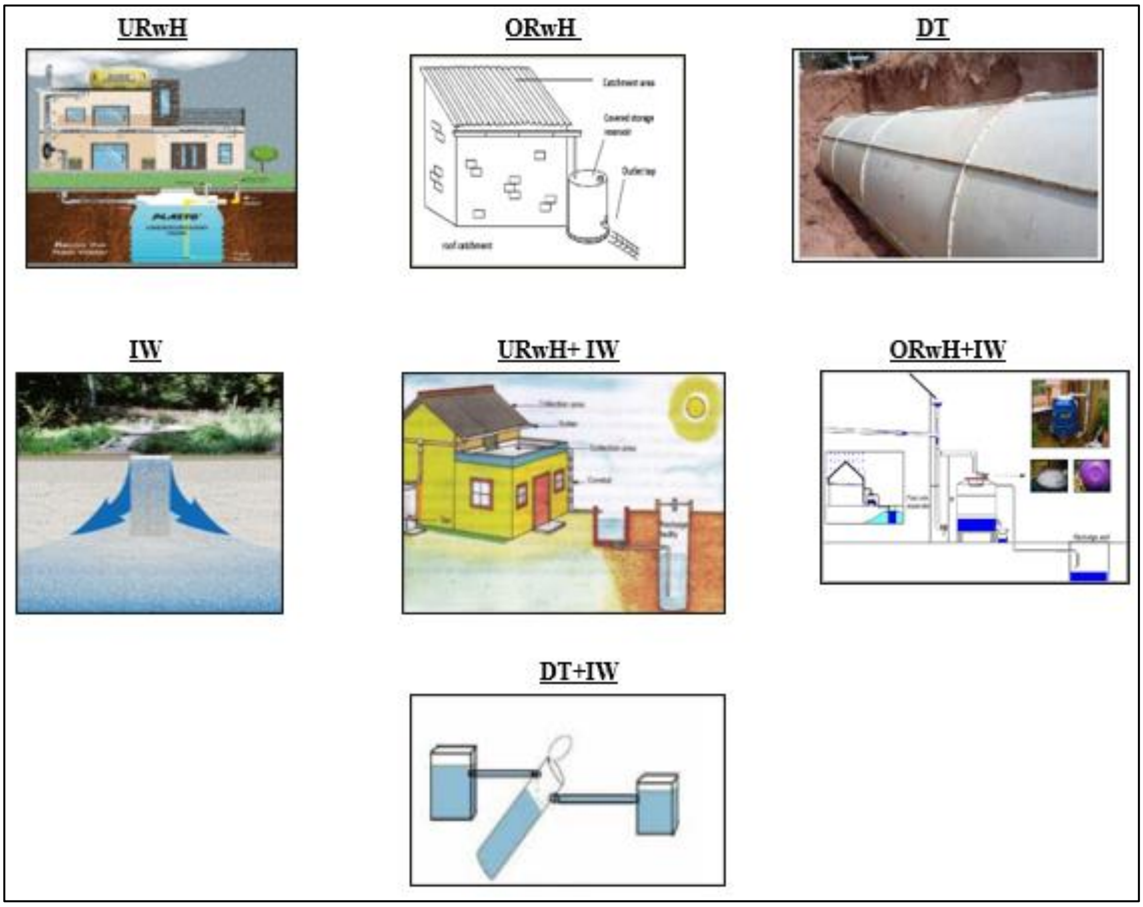


Figure 4.16 RwHs design alternatives

Table 4.13 Advantages and disadvantages of RwH design alternatives

RwH alternative	Advantage	Disadvantages
Underground RwH tank URwH	• Reduction in evaporation and contamination. • Space saving on the surface	• Higher installation costs due to excavation and construction. • Limited accessibility for maintenance and inspection. • Possibility of contamination if not properly sealed or maintained.
Overground RwH tank (ORwH)	• Ease of installation Accessibility for maintenance and inspection, facilitating easier monitoring	• Consumes more surface space. • Susceptible to weather elements, increasing evaporation and risk of contamination. • Shorter lifespan due to external exposure.

Direction Tunnels (DT)	• Ease for extracting stored water. • Suitable for small communities.	• High initial construction costs. • Requires expertise in design and construction. • Consumes more underground space.
Infiltration Wells (IW)	• Effective in recharging groundwater resources. • Less space and easy installation.	• Limited capacity compared to larger storage tanks • Not suitable for areas with impermeable soils. • Potential for contamination
URwH + IW	• Maximizes rainwater harvesting potential. • Flexibility in system design to suit site-specific conditions.	• Higher upfront costs due to the combination of technologies. • Maintenance requirements for both tank and well components.
ORwH + IW	• Maximize rainwater harvesting potential. • Simpler installation compared to underground tank and infiltration well combination.	• Regular maintenance is needed for both tank and well components.
DT+IW	• Effective for small communities.	• Limited capacity • Large underground space required. • Not suitable in metro region.

For performing AHP analysis over the identified RwH alternative, the hierarchical structure demonstrating the goal, criteria, and alternatives is prepared and represented in Figure 4.17.

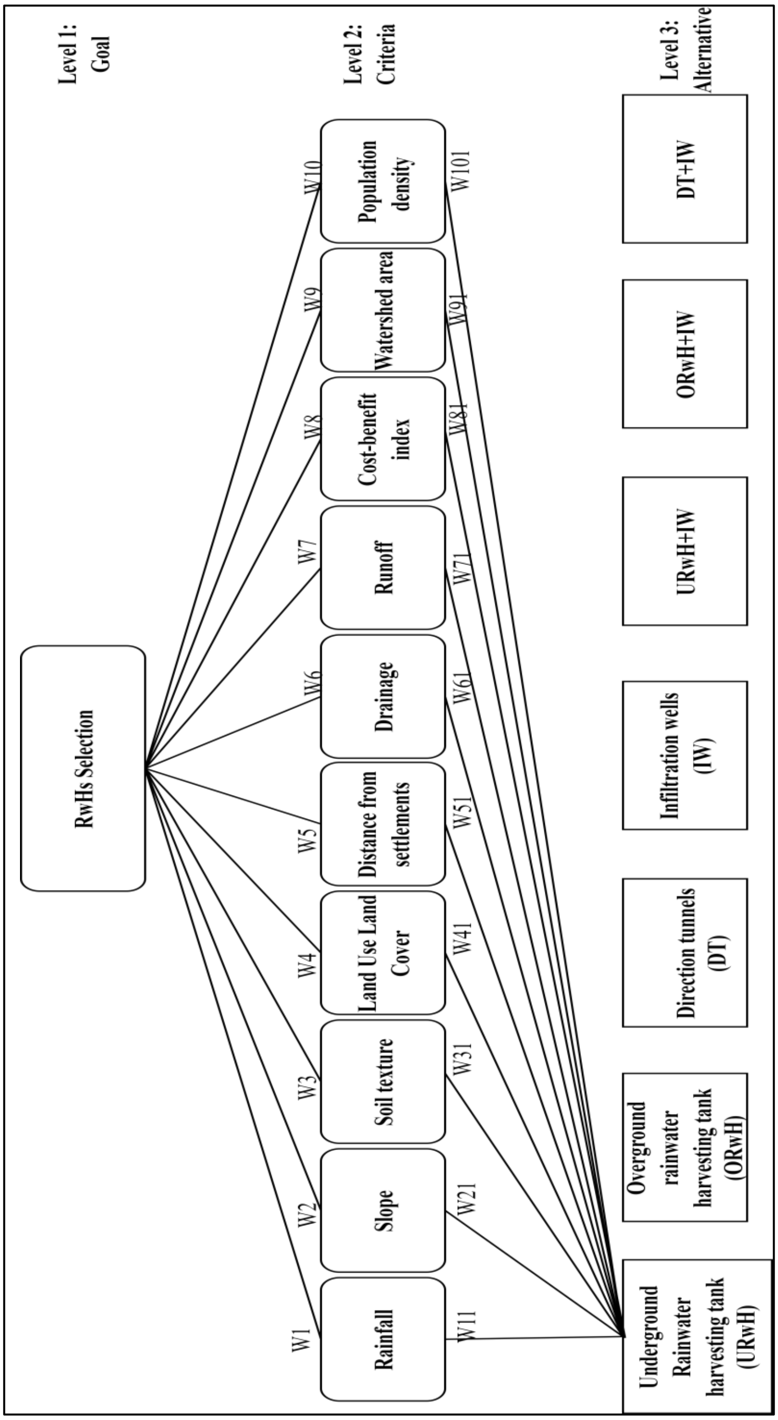


Figure 4.17 AHP hierarchy network for the RwHs alternatives

b) The second step is to create the “pairwise comparison matrix” which compares how criteria and alternatives relate to one another using the Saaty scale in Table 4.14 (Saaty, 2004). Based on the decision-maker’s preferences, convictions, and experiences, the importance of criteria and alternatives varies from 1 (i.e., “Criterion i is equally important as criterion j”) to 9 (i.e., “Criterion i is extremely more important than criterion j”). The matrix is completed by setting reciprocal values to reverse the direction of the preference. The consistency index for the pairwise matrix was checked. In some of responses adjustments were made to ensure consistency by refilling responses along with statistical methods such as eigen values and geometric mean which results in a consistency index (CI) of less than 0.2.

c) The modeling process, considering n criteria, requires $n(n-1)/2$ pairwise comparisons, i.e., the definition of the upper triangular elements of the matrix. A normalized form of the pairwise comparison matrix is then obtained and used for computing the 'criteria weight vector' (Pagano et al., 2021).

Table 4.14 Saaty scale

Numerical rating	Verbal judgments of preferences
9	Extremely preferred
8	Very strongly to extremely
7	Very strongly preferred
6	Strongly to very strongly
5	Strongly preferred
4	Moderately to strongly
3	Moderately preferred
2	Equally to moderately
1	Equally preferred

The final step combines the obtained weights for the criteria and alternatives for each expert and derives the rank for each alternative. The applied AHP method provided the suitability weightage to each alternative. Table 4.15 provides the ranking and suitability of the RwH system calculated by the AHP method.

Table 4.15 Alternative weightage and ranking

RwH Alternatives	Alternative weightage	Rank
URwH	0.1899	1
ORwH	0.1230	4
DT	0.0827	7
IW	0.1384	3
URwH+IW	0.1842	2

ORwH+IW	0.1196	5
DT+IW	0.0860	6

After identifying a suitable design alternative for the storage tank, mapping the optimum drainage network is important to efficiently collect stormwater over the study area. The hydro-spatial analysis tools in the GIS environment were applied over the same study area to design the stormwater drainage network.

4.5.3 Development of stormwater drainage network

In RwHs, a stormwater drainage network is important in maintaining water sustainability and flood mitigation by efficiently collecting stormwater over the region. While designing the drainage network, establishing a relationship between the geometrical and hydrological characteristics of the basin area helps to reduce unnecessary resource consumption and expenses (An et al., 2015). In the study, the extracted hydrological parameters from the developed DEM were utilized to establish the relationship between the hydrological trends and physiographic characteristics of the drain, such as size and shape. The peak runoff values for designing the drains were obtained from the peak rainfall value and initial soil abstraction raster by performing hydro-spatial analysis. The performed hydro-spatial analysis provides the flow path, which was further used to classify as a stream, as shown in Figure 4.18.

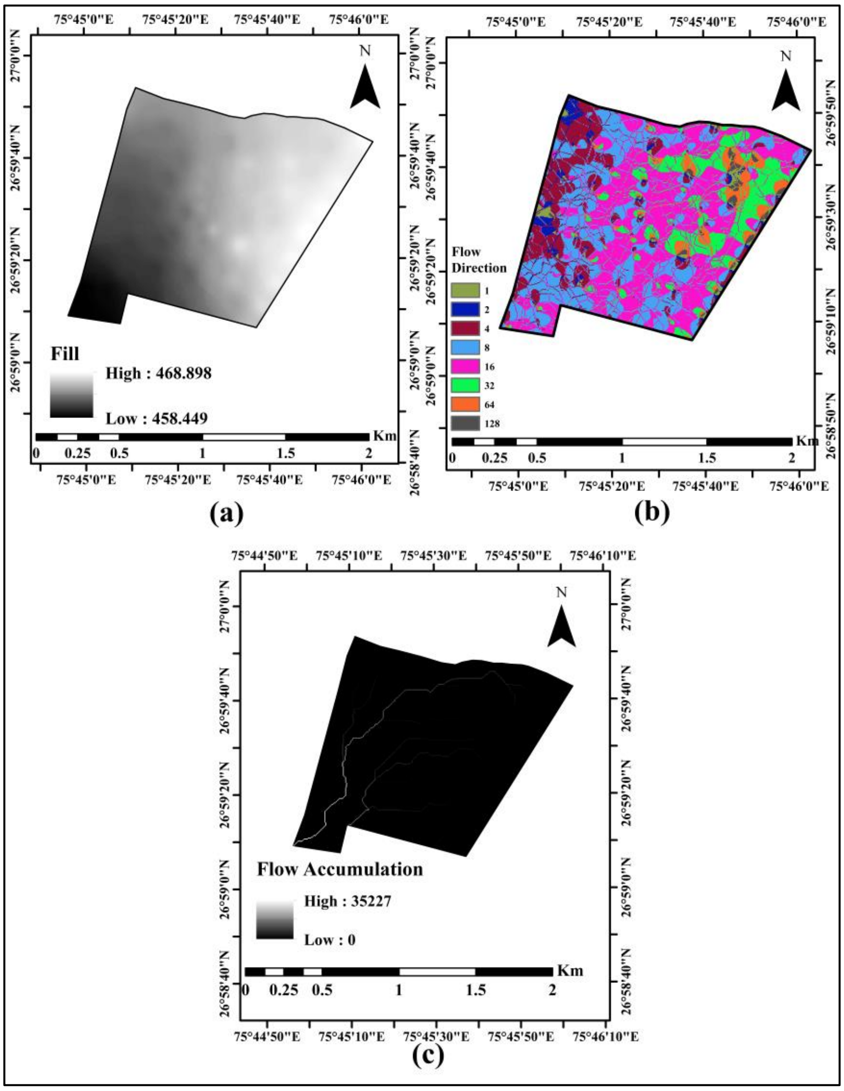


Figure 4.18 a) Fill raster, b) Flow direction, c) Flow accumulation

4.5.3.1 Stream order

Stream order is an approach for assigning a numerical order to the links in a stream network. This order can identify and categorize different stream types based on the number of tributaries in a stream. The provided stream orders help to understand the characteristics of the streams. The generated FA map was utilized to classify the flow path as a stream using the stream order tool in ArcGIS. All generated streams were divided into four classes: lateral, sub-main, main, and outfall drains, using a FA map, as shown in Figure 4.19 (a).

4.5.3.2 Digitization of streams

Digitizing in GIS turns geographic data into vector data by tracing the feature class. The generated shapefile was used to digitize and align the drain over the area. The generated FA map did not contain any information about buildings and other objects on the surface, which overlapped the flow line over the building and other objects. So, to align the flow lines per the land availability, the satellite image was imported as a base map and a shape file for each classified stream was created as a drain, as shown in Figure 4.19 (b).

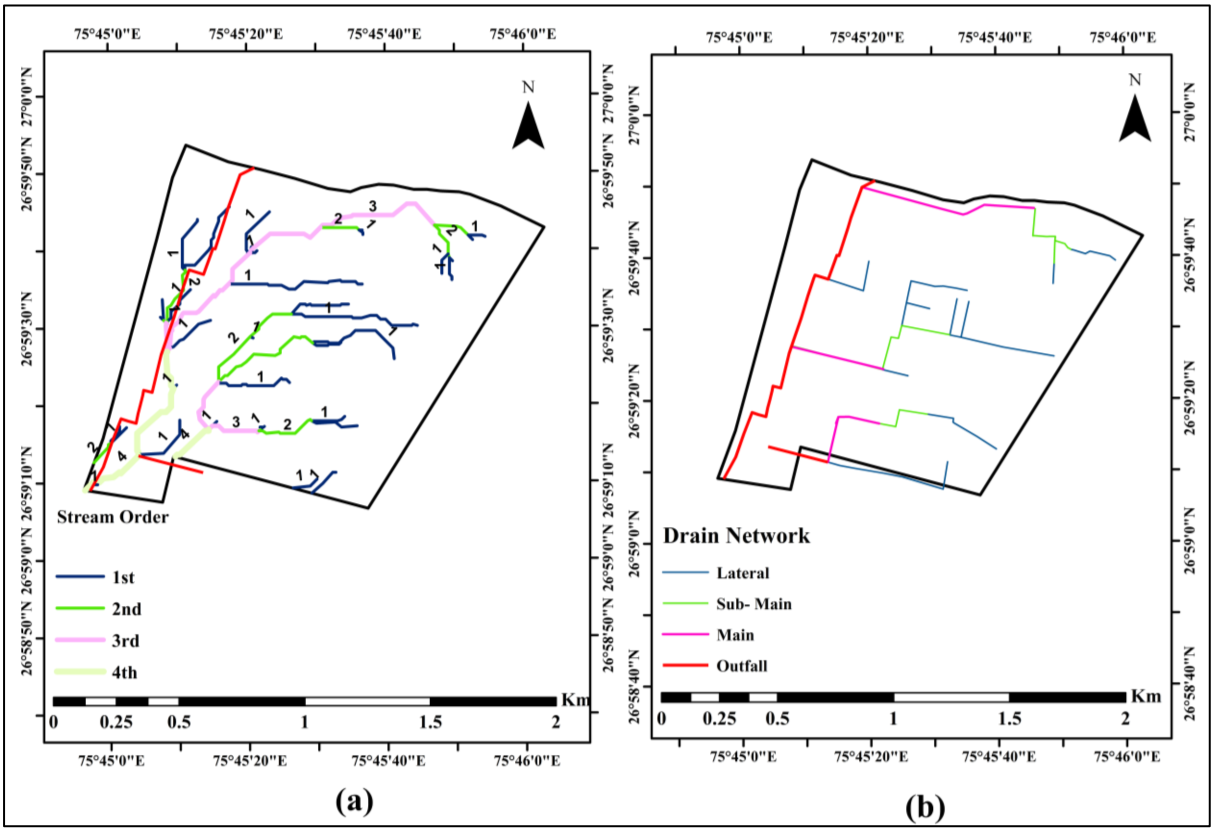


Figure 4.19 a) Stream order, b) Digitized drain network

The adoption of GIS encompasses many advantages in water infrastructure development by facilitating various infrastructure-related activities, including site selection, volumetric potential evaluation, ranking prospective RwH alternatives, and developing stormwater drainage networks. To effectively design and plan the implementation of the analysed components of community RwHs, the unique dimensions of the BIM were developed. The outcomes generated from the GIS analysis were consumed as input data to develop the BIM. This integration allows for a comprehensive and data-driven approach to designing sustainable RwHs. The development of the dimension of BIM has been elaborated on in the forthcoming chapter.

4.6 Results and Discussion

4.6.1 Land Use Land Cover analysis and prediction

In previous studies, urban design has been redefined as the understanding and design of urban environments by considering the sustainability of placemaking (Abusaada & Elshater, 2020; Harding, 2019). Urban design has been conducted by analysing the historic evolution relationship, attitude towards urban evolution, and multiple social and economic factors involved (Romice et al., 2022). In certain situations, case-specific urban design is performed by defining boundaries for different areas using the public service facility index method (Yang et al., 2019). In addition, to assess dynamic urban growth, the landscape expansion index (LEI) has been used in emerging theories of urban growth and the diffusion coalescence model. The developed landscape matrix, in terms of the LEI, quantifies dynamic urban growth modes (Sethi et al., 2021). While quantifying urban growth and performing urban design, the adoption of land-use regulations has been examined using land-use surveys, community surveys, and longitudinal employer household dynamics origin–destination employment statistics (Durst, 2021).

In this study, LULC analysis and prediction were performed using MLP and CA models from the MOLUSCE plugin. Furthermore, a transition study was conducted between 2020 and 2030 to analyse urban expansion and density patterns, which revealed that the built-up land density in 1990 was 9.1%, and by 2020, it had risen to 57.42 %. The analysis indicates that the compactness ratio of Jaipur City will be 70% by 2030. In urban areas, the built-up land areas are proportional to the urban compactness ratio. The built-up land area per square meter of urban area is known as the Urban Compactness Ratio (UCR). The UCR is directly affected by sustainable development through the energy consumption and utilization of natural resources, posing stress to the existing system, which was calculated using Equation 4.12 (Shahfahad et al., 2021). The compactness ratio for the 250 municipal wards was individually calculated using the simulated map, as shown in Figure 4.20.

$$\mathrm{BD} = \frac{\mathrm{BA}}{\mathrm{UA}} \qquad \text{Eq. 4.12}$$

where,

BD = Built-up land area density

UA = Urban Area

BA = Built-up land area extracted from satellite

LULC analysis also helps to understand and control unexpected developments in the municipality area by governing new administrative rules and regulations. In addition, the developed ward-wise map assists in categorizing city areas to understand the transition pattern, which is significant for carrying out area and sustainable infrastructure development plans.

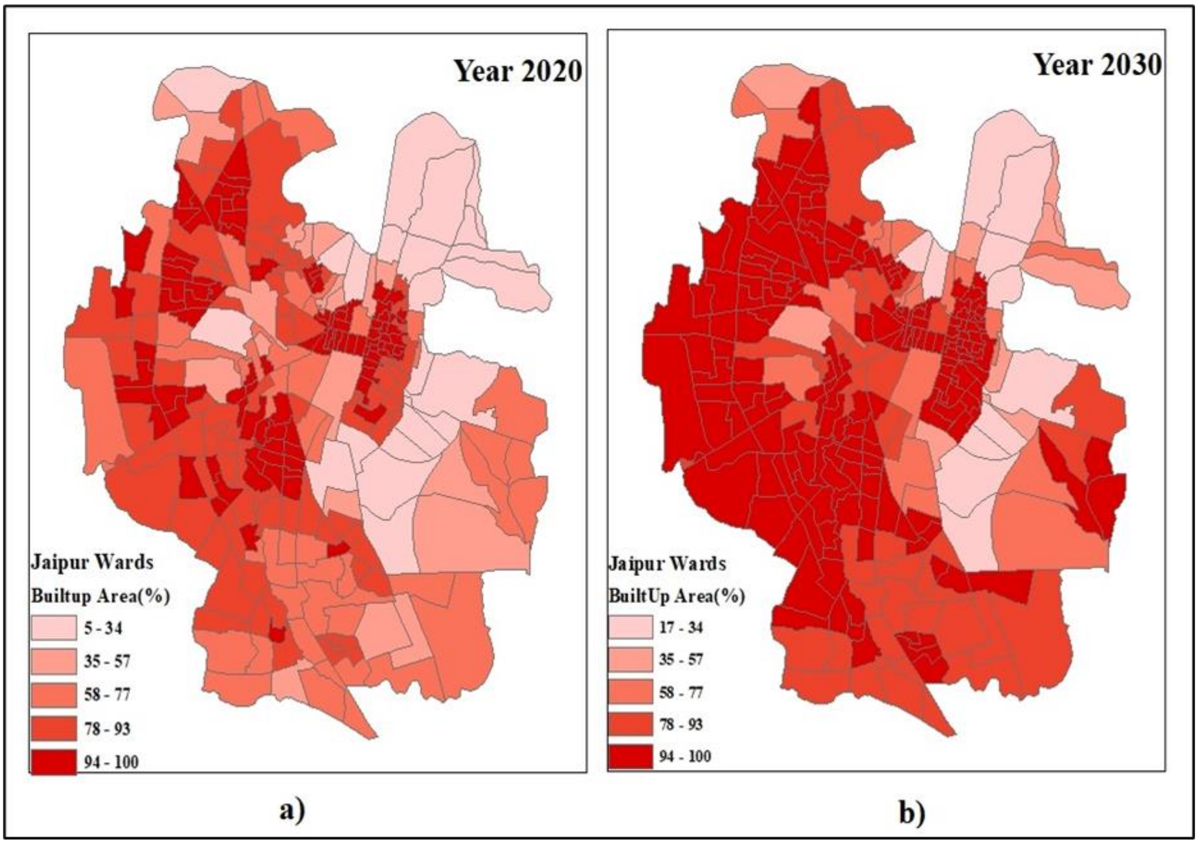


Figure 4.20 Built-up land area density map for the year (a) 2020 and (b) 2030

From the built-up land area density map, all the wards were categorized into three classes based on their urban compactness ratios. The wards with a BD between 5% and 34% were considered low-density. In contrast, wards with BD of more than 78 % were considered high-density wards, and the remaining areas were considered medium-density wards. The calculated built-up land area density is presented in Appendix B. The transitions of wards that may occur in these classes are provided in Table 4.16.

Table 4.16 Ward transformation for the year 2020-2030

Density	Year 2020		Year 2030	
	Heritage (Ward No)	Greater (Ward No)	Heritage (Ward No)	Greater (Ward No)
Low Density	1,96,8,2,3,95,99,11,7, 4,76,13,10,97,38,12,8 3,22,6,9,18,39,28.	107,111,138,1,137,56,1 12,131,35,97,120,150,1 5,2,22,116.	96,1,2,8,95,11,7,76,99,3, 97,4,13,10,3,83.	107,111,138,1.
Medium Density	47,35,78,17,100,48,41 ,40,26,49,55	125,53,114,96,109,118, 119,136,90,95,63,104,9 9,87,91,98,121,123,5,10 3,124,25,41,117,113,51, 102,122,142,4,84,43.	18,6,5,12,22,9,28,78.	137,56,2,131,150,22,35,112, 120.
High Density	50,86,14,34,88,53,36, 52,94,90,27,98,54,31, 92,37,77,46,82,20,32, 93,42,57,89,24,19,67, 51,15,62,43,29,91,65, 44,23,33,16,21,25,30, 45,56,58,59,60,61,63, 64,66,68,69.70,71,72, 73,74,75,79,80,81,84, 85,87.	86,76,94,82,106,71,66,4 4,9,85,8,148,101,133,23 ,67,3,88,31,29,108,65,4 8,128,47,147,105,93,12, 100,130,20,83,110,80,7 5,59,21,49,74,6,37,89,6 4,127,24,62,54,10,30,11 ,26,13,46,68,144,78,3,7, 27,149,126,55,60,70,61, 17,45,72,50,52,38,40,32 ,58,143,77,39,81,36,140 ,139,92,42,28,12,134,16 ,14,9,15,18,19,33,34,57, 79,132,135,141,145,146	48,100,47,17,39,41,26,50 ,4,35,34,40,14,53,88,87,3 2,36,46,54,55,52,94,98,3 1,90,37,92,82,93,29,27,4 2,62,24,20,19,89,77,15,6 7,51,64,33,16,44,43,91,2 1,23,25,30,45,56,57,58,5 9,60,61,63,65,66,68,69,7 0,71,72,73,74,75,79,80,8 1,84,85,86.	125,97,53,115,116,136,109,5 ,95,96,114,104,87,90,103,4,1 23,102,99,106,118,63,91,98, 119,8,142,121,43,86,3,41,76, 25,117,84,133,113,44,31,85, 122,108,105,71,129,29,66,48 ,51,128,94,124,82,148,101,6 9,67,80,88,75,23,65,6,93,147 ,20,30,59,26,21,72,83,110,60 ,127,62,47,24,49,50,61,100,7 ,27,130,54,89,126,13,37,10,6 8,70,7,38,46,144,73,55,78,32 ,17,149,134,52,81,77,45,11,1 43,36,139,58,40,92,9,39,12,1 5,42,14,16,18,19,28,33,34,57 ,64,79,132,135,140,141,145, 146.

4.6.2 Establishing topographic relationships by performing hydro-spatial analysis

The success of RwHs depends on the selection of suitable sites and their technological designs (Al-Adamat et.al, 2012). Several design tools and composite materials have been developed to enhance the sustainability of RwHs. Research in the 1990s concentrated on bio-physical criteria; later, socioeconomic elements were included in the economic development and management of RwH sites (Gregersen et al., 2007; Sayl et al., 2017). Furthermore, MCA and GIS have been integrated to obtain a reasonable, objective, and unbiased strategy to identify suitable regions for creating RwHs (Al-Adamat et al., 2010; Alwan et al., 2020). In the proposed regionalization of RwH site was performed using novel approach that pinpoint the exact location of the RwH sites where maximum FA (runoff) occurs with respect to the basin.

Incorporating hydrological features during the preliminary stage of hydro-spatial analysis is adequate for estimating the runoff potential of the area. Initially, while performing the hydro-spatial analysis over the study area, the basin tool was used to classify the area along the ridgeline. The output from the basin tool provided many basins that were available within the area. Depending on the prospective basin area, the number of basins formed was more than 1500, increasing the complexity of the analysis and decision-making. To minimize the complexity, five scenarios were developed by considering the basin area as a parameter. Therefore, to specify the area and classify the generated basin for a specific threshold value, the conditional tool was run individually for areas of 1, 2.5, 5, 7.5, and 10 sq.km, as shown in Figure 4.21. The developed scenarios were further analysed and verified for the number of locations and the probable volume of water collected.

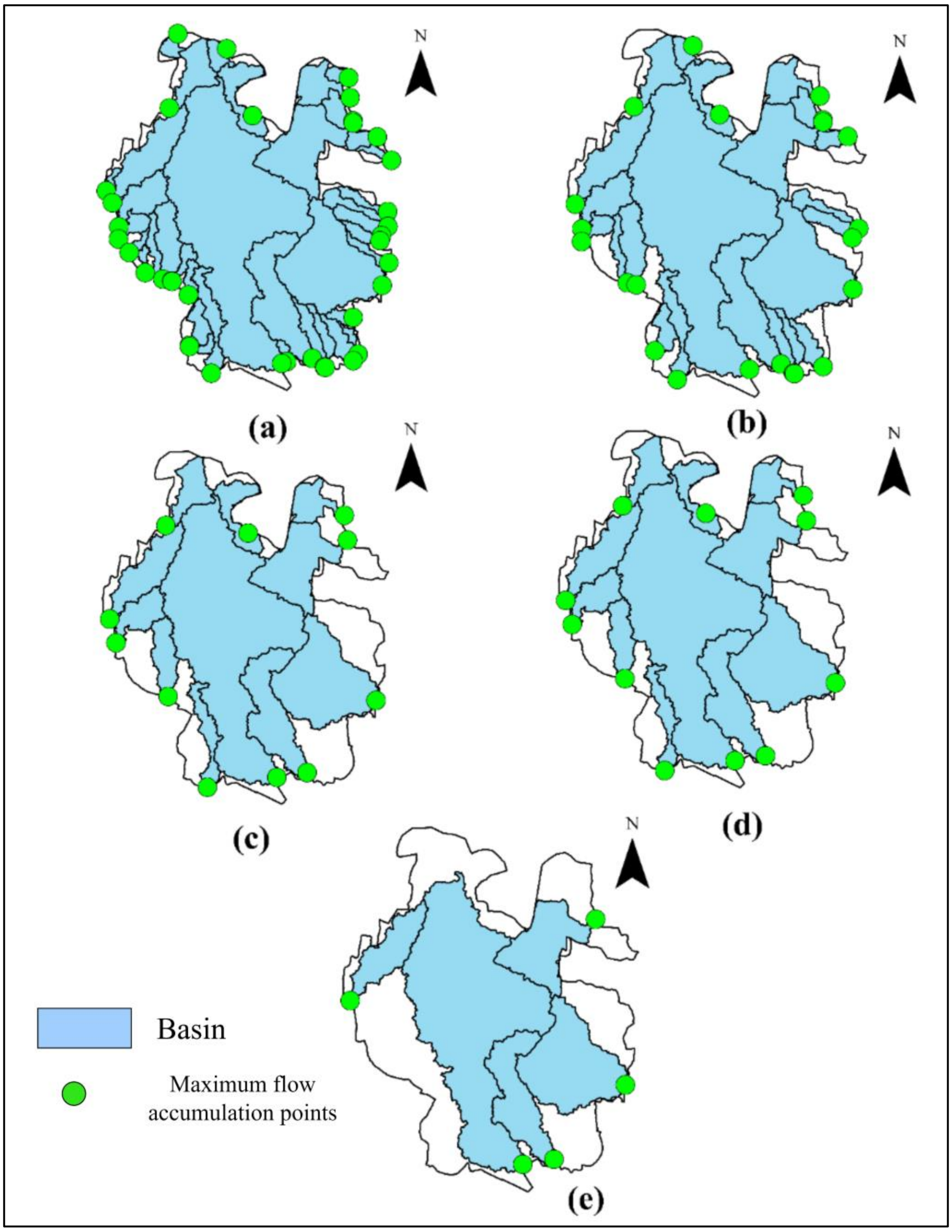


Figure 4.21 Identified basin and maximum accumulation points for considered scenarios of a) 1 sq.km, b) 2.5 sq.km, c) 5 sq.km, d) 7.5 sq.km, e) 10 sq.km

Basin area and runoff quantity are the two parameters responsible for collecting stormwater (Naseef & Thomas, 2016). To calculate the runoff in each basin for the respective scenario, multiplication of the resolution of the raster (30m) with runoff raster (values) was performed, and the zonal statistics tool was used to calculate the summation of all runoff cells within the basin. Equation 4.13 represents the formula applied to estimate the volumetric potential of the individual basins.

$$\text{Volume} = \text{Raster value (Runoff raster)} * \text{Cell area (spatial resolution)} \qquad \text{Eq. 4.13}$$

The analysis provides the basin formation along with the volumetric potential based on topographic and hydrologic parameters. The study area contains natural and man-made water bodies that store considerable amounts of runoff water. This was overlooked in an analysis that compensated for the extra volume of runoff water generated owing to the exponential growth of impervious surfaces or any flood situation that may cause further damage. The estimated runoff volumes for each identified RwHs are presented in Appendix C.

4.6.3 Microscale planning and design of RwH site and alternatives

Nowadays, evaluating, planning, and managing the multiple criteria for creating efficient RwHs has become an important concern (Musayev et al., 2018). In the past, most researchers have been practicing methods such as water balance, agricultural nonpoint sources, and soil conservation service CN to evaluate the hydrological potential of an area to determine the ideal design criteria for RwHs (Carver, 2007). Another study attempted to integrate GIS with AHP to determine forest road networks (Laschi et al., 2016; Baghdadi et al., 2011).

In this study, the extensive capabilities of GIS in integration with MCDM were utilised to provide site suitability values. To assess the site alternatives, criteria such as runoff potential, area, perimeter, distance from the centre, and elevation were considered. Furthermore, CRITIC and Entropy object-based methods were used to assign relative weights to the criteria. To assess the suitability of the identified site alternatives, four MCDM methods were used: WASPAS, TOPSIS, VIKOR, and PROMETHEE-II. The analysis revealed that sites C and B were the most suitable, with consistency values of 63 and 75%, respectively. According to the analysis, Site D was the third most appropriate site with a significant consistency of 63%, whereas Site E was the fourth most suitable site with 50% consistency. Finally, site A was ranked last (least suitable) for community RwHs with 100% consistency values based on the incorporated parameters. Table 4.17 shows each alternative's overall rank order values with different MCDM methods.

Table 4.17 Overall rank order for RwH site alternatives

Alternative	WASPAS		TOPSIS		VIKOR		PROMETHEE-II	
	CRITIC	Entropy	CRITIC	Entropy	CRITIC	Entropy	CRITIC	Entropy
Site A	5	5	5	5	5	5	5	5
Site B	2	2	2	2	2	2	3	3
Site C	1	1	1	1	4	1	2	2
Site D	3	4	3	3	3	3	4	4
Site E	4	3	4	4	1	4	1	1

The analysis shows that all MCDM methods affect the ranking and incorporate all the sensitive criteria that influence the decision at various levels of the process. The suitability of the sites was as follows and listed in Table 4.18.

"Site C > Site B > Site D > Site E > Site A"

Table 4.18 Landmarks for the identified sites

Site	Latitude	Longitude	Landmark
Site A	26.9927	75.7547	Near Cambridge Indian Secondary School.
Site B	26.9875	75.7549	Near Tagore PVT. ITI college (Ganga Path)
Site C	26.9868	75.7504	Near Sri Devdarshan Temple Macheda
Site D	26.9943	75.7534	Opposite to Sant Rampal Ji Maharaj Ashram
Site E	26.9953	75.7554	Behind hotel Apano Goan and Resort

The obtained rank order values for site suitability help decision makers select the most suitable site while implementing RwHs. Along with the site selection, the efficiency of RwHs is influenced by the design considerations of the system. Therefore, an assessment of multiple design alternatives is required in the conceptual phase to assess the feasibility of RwHs.

The AHP offers a systematic and structured methodology for the integration of various variables by employing a multi-objective decision-making approach. In the proposed study, to identify the most optimal design alternatives for RwHs, a comprehensive analysis was conducted based on ten distinct criteria, which were applied to assess seven different design alternatives using AHP. A Google questionnaire was prepared and distributed to industry professionals to collect expert insights and opinions on these design alternatives. The responses acquired from the experts are appended in Appendix D. The obtained responses from the survey were then subjected to decomposition, comparison, and synthesis. This method allows for the calculation of rank values for each design alternative, thereby providing a clear and data-driven means of evaluating and selecting the most suitable RwH design alternatives. The analysis revealed that URwH and URwH+IW are appropriate design alternatives considering the RwH-related parameters. The mathematical analysis performed for these alternatives shows that the alternative weightage values for URwH and URwH+IW are almost equal, indicating that both are suitable for implementation. The study also found that a directional tunnel with an infiltration well is the least suitable.

A stormwater drainage network in RwHs can contribute to flood mitigation and water sustainability by effectively collecting stormwater from across the region. Mapping the drainage network by understanding the on-ground situation aids in reducing extra resource consumption and enhances the efficiency of the system by collecting maximum rainstorm water. The hydro-spatial analysis provided stream paths that were considered as drains. Based on the amount of peak runoff, the generated drains were classified as lateral, sub-main, main, and outfall drains. The estimated length of drain for the classified drain is listed Table 4.19.

Table 4.19 Classified drains and their properties

Drain Type	**Total Length (m)**	**Peak Runoff (m^3/hr)**
Lateral drain	3114.767	1.702
Sub main drain	1535.113	31.86
Main drain	975.5422	68.68
Outfall drain	3681.807	148.74

4.7 Chapter summary

In this chapter, the GIS analysis as a first stage of proposed GIS - BIM integration was performed to plan and design community RwHs over the Jaipur municipality region as a case study. The GIS analysis commenced with the analysis and understanding of the past growth pattern of the study area and simulation of the probable growth. The analysis provided clear visualization and allowed categorization of the entire study area. The efficiency of RwHs is highly influenced by topography and runoff potential. So, to establish the relationship between the topography and hydrologic characteristics of the study area, the hydro-spatial analysis was performed along with SCS-CN method. The established relationships paved a path to perform further microscale planning and design of RwHs by providing the runoff potential and maximum accumulation points. The microscale planning and design involved identifying the most suitable site, determining an efficient design alternative, and mapping the stormwater drainage network. To accomplish microscale planning, multiple MCDM methods such as WASPAS, PROMETHEE-II, VIKOR, TOPSIS, and AHP have been applied in addition to GIS tools. As a result, this chapter analyses the study area, identifies suitable sites, provides rank orders to RwH site alternatives, and provides the most suitable design alternative for RwHs components. The findings and insights from this analysis could be a significant resource for developing BIM dimensions for RwHs.

5. Development of BIM dimensions

5.1 Chapter overview

This chapter provides the detailed process of developing BIM dimensions for the community RwHs. The spatial and hydro-spatial analysis results were used as primary input data to design and develop BIM dimensions. This integration of GIS with BIM eases the implementation of the proposed system by allowing to model, visualize, plan, and analyze the entire system on a single platform.

5.2 Development of BIM dimensions

Building Information Modeling (BIM) development has transformed the approaches employed in the planning, design, and management of construction projects. These dimensions enabled stakeholders to design and collaborate in a virtual environment by considering multiple aspects of the project. Integrating characteristics, such as time, cost, and sustainability information, into BIM has strengthened project coordination and facilitated better decision-making throughout the project lifecycle. In the proposed study, the development of BIM for community RwHs was initiated using 2D BIM. This step involves formulating plans and designs for community RwHs and drawing insights from the results of the GIS analysis. Furthermore, creating 3D models from different perspectives facilitates clash detection and improves visualization in real-world situations considered as 3D BIM. The addition of parameters increases the information level of the model. The involvement of project extent in terms of time and cost in implementing RwHs has been considered as the 4D and 5D BIM, respectively. Considering sustainability as the 6D, the carbon footprint estimation for the implementation of RwHs was assessed. This performed LCA analysis helps stakeholders adopt sustainable design alternatives to reduce environmental footprints.

Facility Management (FM) was performed as the 7D BIM to ease system (O&M) by providing additional supporting documents and performing analysis utilizing the Autodesk Collaborate Pro platform. Utilizing a cloud-based platform allows stakeholders to easily operate and modify asset data, technical specifications, and scheduled activities during the implementation of RwHs. Finally, the 8D, Prevention through Design (PtD), was conducted by designing optimized safety principles by identifying on-site risks in construction activities through a questionnaire survey shared among project stakeholders (Kamardeen 2010). The developed BIM dimensions for community RwHs allow efficient design, accurate cost estimation, optimized scheduling, and sustainable decision making, ultimately leading to the successful implementation of RwHs. The following sub-sections elaborate on the development of the dimensions of BIM in-depth, and the detailed sequence adopted for developing the dimensions of BIM for RwHs and is illustrated in Figure 5.1.

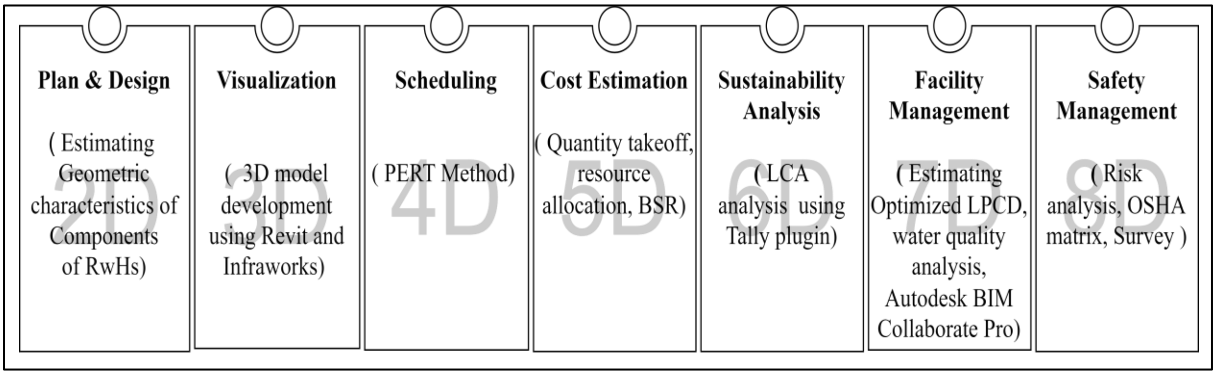


Figure 5.1 BIM dimensions for RwHs

5.2.1 2D BIM: Plan and Design

The efficiency of RwHs depends on the site selection and design considerations incorporated at the pre-conceptual stage. In the proposed study, the design and determination of the geometric characteristics of the RwH storage tank, sedimentation tank, and stormwater drainage network were considered in 2D BIM. To determine the geometric characteristics of the RwHs components, the outcomes from the GIS analysis, such as volumetric potential, suitable location, and peak flow in drainages, were utilized as input data. The detailed process involved in designing RwHs components is provided below.

5.2.1.1 Design and consideration of rainwater storage tank

To design the rainwater storage tank, site suitability values and the amount of runoff generated were considered using GIS analysis. In addition, the AHP analysis revealed that the underground storage tank and underground storage tank with infiltration well were suitable RwH structures for the study area based on the predefined criteria. The obtained two suitable sites falling on highest stream order were considered for designing RwHs (i.e. site C and site B). The ideal trapezoidal tank shape for the underground storage tank with infiltration well is considered with adequate side slopes of 1.5 H:1V as the study area comprises type C soil (i.e., sandy loam) for both sides. For the obtained design volume and design consideration, the geometric characteristics of the tank were determined and provided in Table 5.1.

Table 5.1 Geometrical characteristics of RwHs storage tank

Site B		Site C	
Volume (m^3)	Dimensions ($\mathbf{l * b(a, b) * h}$)	Volume (m^3)	Dimensions ($\mathbf{l * b(a, b) * h}$)
7535.19	$45 * (23.9 * 31.9) * 6$	9585.91	$50 * (27.9 * 35.9) * 6$

a= bottom with, b= top width

5.2.1.2 Design of sedimentation tank

Sedimentation is a natural process in which solids have a higher density than the fluid in which they are suspended sinks owing to gravity. Sedimentation removes larger suspended particles from the water, allowing them to sink to the bottom of the tank. The structure used to lower the flow velocity to settle the suspended particles is known as a sedimentation or settling tank. The generated runoff raster was consumed to design the sedimentation tank and calculate the settling velocity by applying Stoke's law. Some common terminology used while designing the sedimentation tank has been explained below.

a) Overflow rate: The volume of water applied per unit time per unit horizontal surface area is called overflow rate surface, or loading rate, or overflow velocity. The overflow rate can be calculated using Equation 5.1.

b) Detention period: The time taken by water to travel from the inlet to the outlet is termed as detention period or detention time.

In this study, a rectangular sedimentation tank was considered, which is the most preferred and widely used because of its low maintenance cost and large inflow capacity. The flow occurs in the horizontal direction, which is length-wise in rectangular tanks. The effective depth of the rectangular section was calculated using Equation 5.2. The following considerations and equations were incorporated while designing a rectangular sedimentation tank.

a) Detention period = 3 hours for plain sedimentation.

b) Specific gravity of particle = 2.68.

c) Kinematic viscosity of water = 0.7528 mm^2/sec.

d) Particle size = 0.075mm (Fine sand) to achieve the required efficiency.

e) Overflow rate = 30 to 40 m^3/m^2/day for horizontal flow.

f) Length of tank = 4 * Width of tank.

$$\text{Volume} = \frac{\text{Inflow} * \text{Detention Period}}{24\ \text{hrs}} \qquad \text{Eq. 5.1}$$

$$\text{Effective depth} = \frac{\text{Volume}}{\text{Surface Area}} \qquad \text{Eq. 5.2}$$

The calculation results in optimal geometric characteristics of the rectangular sedimentation tank, as provided in Table 5.2 for both identified locations.

Table 5.2 Geometrical characteristics of sedimentation tank

Site B		**Site C**	
Volume (m^3)	**Dimensions ($l * b * h$)**	**Volume (m^3)**	**Dimensions ($l * b * h$)**
735.518	$3 * 13 * 5$	958.591	$3 * 14 * 5$

5.2.1.3 Designing a stormwater drainage network

In RwHs, a stormwater drainage network is important for maintaining water sustainability and flood mitigation by efficiently collecting stormwater throughout the region. In this study, hydrological parameters extracted from the developed DEM were utilized to establish the relationship between hydrological trends and the physiographic characteristics of drains, such as size and shape. Therefore, to design the geometric characteristics of the drains, the generated and classified streams with peak flow values in section 4.5.3 were considered. The streams generated from the stream order were considered, along with the peak flow value, and Manning's equation was used to determine the geometrical characteristics of the drain.

The Irish Engineer Robert Manning introduced Manning's equation in 1889, which was the most commonly used equation for governing open-channel flow. Due to its simplicity and acceptable accuracy in practical application, the equation was used to design stormwater pipe drains and channels (Schmitt et al., 2004). An rectangular channel was considered for collecting the stormwater, and the design was performed using Equation 5.3. Drains must be designed as the most efficient sections to ensure their economic viability.

$$K_{em} = \frac{Q_n}{y_{em}^{\frac{8}{3}} S_0^{\frac{1}{2}}} \quad \text{Eq. 5.3}$$

Where,

em subscript denotes the most efficient.

Y_e = Depth of flow for the most efficient section.

Q_n = Discharge (i.e., flow accumulation).

S_o = Bed slope.

K_{em}= Unique constant value (1.260 for rectangular drains).

A section is most efficient if the runoff carrying capacity is maximum for a cross-section area. After getting the flow depth from Equation 5.3, the other dimensions of the drain, such as area, wetted perimeter, width, and the hydraulic radius of the most efficient section, were calculated using Equation 5.4, 5.5, 5.6,5.7 respectively.

$$\text{Area} = 2y_e^2 \quad \text{Eq. 5.4}$$

$$\text{Wetted Perimeter} = 4y_e \quad \text{Eq. 5.5}$$

$$\text{Width} = 2y_e \quad \text{Eq. 5.6}$$

$$\text{Hydraulic Radius} = \frac{y_e}{2} \quad \text{Eq. 5.7}$$

Using the above equations, the geometrical characteristics of the economical rectangular drains were calculated for the lateral, sub-main, main, and outfall drains. Table 5.3 represents the calculated geometric characteristics of the drains.

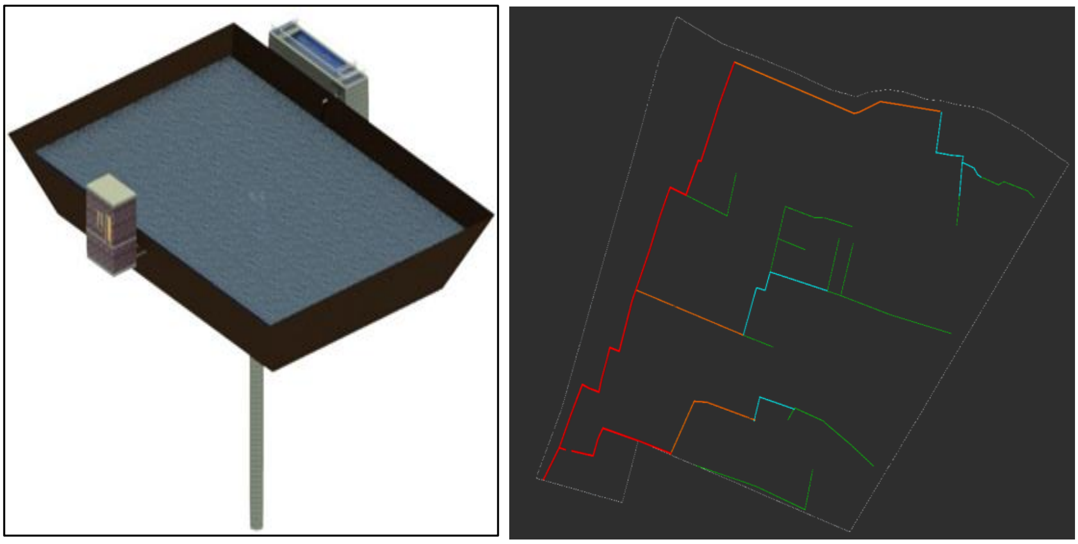
Table 5.3 Geometric characteristics of drainage network

Drain Type	**Drain depth (m)**	**Drain Width (m)**	**Perimeter (m)**	**Area (m^2)**	**Total Length (m)**	**Peak Runoff (m^3/hr)**
Lateral Drain	0.5	1	2	0.5	3114.76	1.702
Sub Main Drain	1.5	3	6	4.5	1535.11	31.86

Main Drain	2	4	8	8	975.54	68.68
Outfall Drain	2.72	5.44	10.88	14.8	2072.24	148.74

5.2.2 3D BIM: Visualization

The principle of BIM encourages real-time visualizations to express ideas and share information among the stakeholders. The obtained properties and the geometric characteristics of the RwHs components from 2D BIM were used to create the visualization. Models created by architects, designers, and engineers have progressed from traditional 2D drawings, sketches, and textual requirements to parametric, object-oriented 3D models embedded with information to describe the structure in detail. The results of strategic planning in developing 2D were used to develop 3D visualization models. For developing the 3D model, the Autodesk Revit tool was utilized by incorporating the data for the storage tank, sedimentation tank, and recharge well, along with the material properties. Figure 5.2 provides the 3D models for sedimentation tank, storage tank and drainage network.



a) b)

Figure 5.2 Visualization for a) Proposed storage and sedimentation tank, b) Drainage network

The generated models were imported into the Autodesk Infraworks tool for visualization with real ground features. The infraworks tools also allow visualisation of the existing surface and building information using the model builder tool. The model builder tool creates a 3D model with the UTM system, WGS 84, and zone 43 N to geo-reference all acquired thematic layers, such as roads, existing buildings, and infrastructure. It allows importing additional supporting files of different formats, such as *.shp, *.rvt, *.cad, *.png, *.jpg, etc., to create a comprehensive visualization. The created 3D model for the storage tank and sedimentation tank and different drain sizes were imported along with the developed model builder model.

The developed visualization of RwHs provides a clear idea and infographic view of the proposed system, which aids stakeholders in understanding the project at the conceptualization stage. On the other hand, the developed visualization will serve as input data to schedule and estimate the cost involved in the project.

5.2.3 4D BIM: Scheduling

The PERT method was applied to schedule the activities involved in implementing the RwHs. In 1959, Malcomb developed PERT to aid the US Navy in developing the Polaris submarine/ballistic missile system (Malcolm et al., 1959). This was first intended as a project management strategy to ensure that an extremely difficult and crucial project would be completed on schedule. PERT has remained the dominant planning and control method in the United States, particularly for major aerospace and military projects. Subsequently, PERT was effectively utilized for planning and controlling construction projects. This study considered the activities involved in implementing RwHs from the conception to accomplishment of the project phase for scheduling. Based on the events involved in implementation, 84 activities were identified from the conceptualization to the finishing stage. These activities were based on expert knowledge and experience from the execution of similar projects. The identified activities were categorized as Initiation, Planning, Execution, Finishing work, and Closure. Initial letters, such as I, P, E, F, and C, were used in the network diagram to simplify the representation. While implementing PERT, the initial step is to create a network diagram of the project, where each arrow represents a task and each node represents an event (such as the start or end of a task). represents the developed network diagram for the activities involved in the design and development of RwHs.

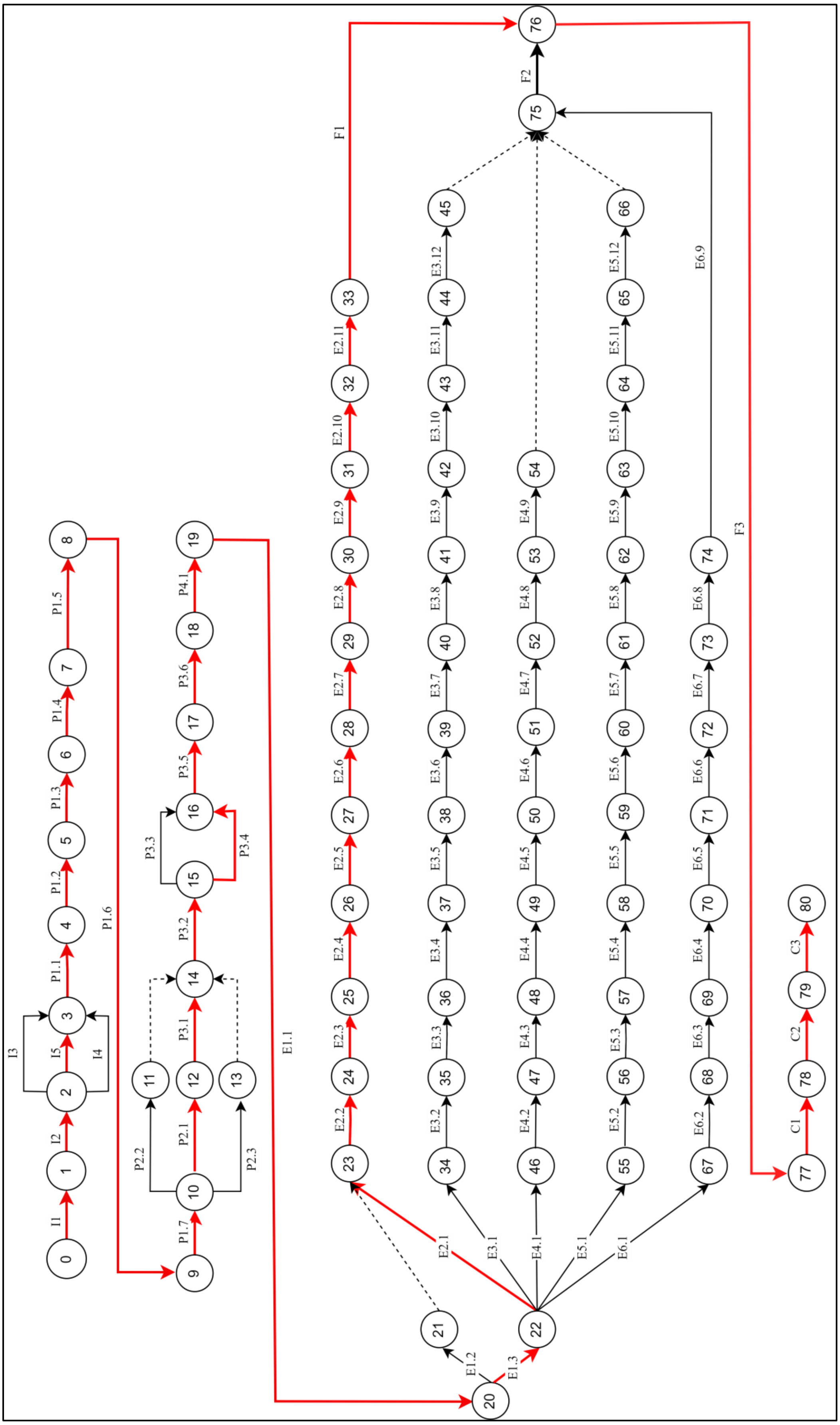


Figure 5.3 PERT network diagram

The second step was to designate three-time estimates for each activity. In PERT, activities and their interdependence are assumed to be well-defined, although uncertainty is recognized in the time estimate. PERT incorporates uncertainties in activity durations in its analysis, requiring three durations for each activity: the most probable, optimistic (shortest), and pessimistic (longest) durations. The frequency distribution of the duration of an activity has the shape of a beta distribution. As the names imply, pessimistic time is the best estimate of the maximum time required to complete the activity, and optimistic time refers to the best estimate of the minimum time required to complete the activity. The probability that the duration would be less than the optimistic duration (t_o) is about 1%, and the probability that the duration would be more than the pessimistic duration (t_p) is also about 1%. The PERT distribution is a smooth variant of the uniform or triangle distribution and is also known as beta-PERT or the three-point estimation technique, as shown in Figure 5.4.

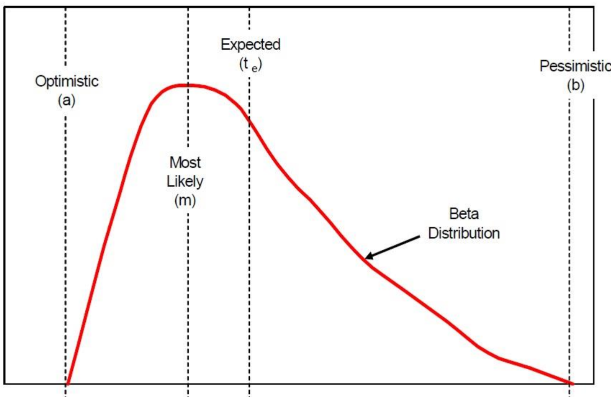


Figure 5.4 Beta distribution for PERT

The average or expected time (te) was calculated as a weighted average of the three estimates, assuming that optimistic and pessimistic times are approximately equally likely to occur and that the most probable activity time is four times more likely to occur than the other two. Mathematically, the average, or expected, time was calculated by Equation 5.8.

$$t_e = \frac{t_o + 4t_m + t_p}{6} \qquad \text{Eq. 5.8}$$

In this analysis, t_o, t_p, and most likely time (t_m) for each activity were determined considering the amount of work and standard working units for the resources as per the Central Public Works Department (CPWD) and the standard specification of the machinery as represented in Table 5.4 (CPWD, 2010). The three estimates were determined and represented in the table below.

Table 5.4 Time estimates for activities.

Code	Activity	Time Estimate (Days)			
		Optimistic	Most Likely	Pessimistic	te (Days)
Initiation (I)					39
I1	Understanding Problem Statement	2	4	6	4
I2	Preliminary Survey	15	20	30	21
I3	Collection of Data	1	2	6	3
I4	Determining Tools and Technology	1	2	4	2
I5	Documentation and Certification	10	14	17	14
Planning (P)					55
GIS Analysis (P1)					16
P1.1	Importing Spatial Reference Data	0.5	1	2	1
P1.2	Developing methodology for identifying locations	4	8	9	7
P1.3	Excluding areas of existing water bodies (Study area analysis)	1	1	1	1
P1.4	Selection of Basin for performing pilot study	1	1	1	1
P1.5	Selection of ward and clipping the extent	1	1	2	1
P1.6	Classification and digitization of drain lines	1	1	1	1
P1.7	Estimation of Runoff (Thematic Map Preparation)	2	3	7	4
Designing (P2)					3
P2.1	Determining Drain size	2	3	4	3

Code	Activity	Time Estimate (Days)			
		Optimistic	Most Likely	Pessimistic	te (Days)
P2.2	Design of Sedimentation Tank	1	2	4	2
P2.3	Design of Storage Tank	1	2	4	2
Modeling (P3)					16
P3.1	Importing data	0.5	1	2	1
P3.2	Performing Visual Modeling	3	5	7	4
P3.3	Scheduling (4D)	1	2	3	2
P3.4	Material Estimation (Quantity Takeoff)	1	2	3	3
P3.5	Resource Allocation	3	4	5	4
P3.6	Cost Estimation (5D)	3	4	5	4
Tendering and Bidding (P4)					20
P4.1	Tendering and Bidding	10	20	30	20
Execution (E)					89
Preparation (E1)					9
E1.1	Allocation of Work	2	3	5	3
E1.2	Purchasing and Ordering	4	6	8	6
E1.3	Land Acquisition	3	4	5	4
Drainage Construction (E2)					89
E2.1	Drainage Layout Marking	2	3	6	3
E2.2	Site Clearing	7	10	14	10
E2.3	Excavation	50	57	68	58
E2.4	Levelling and RCC	22	30	48	32
E2.5	Vertical Reinforcement	20	30	45	31

Code	Activity	Time Estimate (Days)			
		Optimistic	Most Likely	Pessimistic	te (Days)
E2.6	Formwork Placing	10	15	20	15
E2.7	Vertical Concreting	5	6	13	7
E2.9	Curing	12	22	28	21
E2.8	Formwork Removal	3	4	5	4
E 2.910	Drainage cap and curing	9	14	18	14
E2.911	Backfilling and Finishing	2	3	5	3
Sedimentation Tank Construction Site B (E3)					47
E3.1	Site cleaning and Layout marking	0.5	1	2	1
E3.2	Excavation and Levelling	1	2	4	2
E3.3	Foundation and Curing	8	9	13	10
E3.4	PCC Bed concrete and curing	8	8	10	8
E3.5	Installation of Reinforcement	2	3	5	3
E3.6	Base Concreting and curing	5	7	13	8
E3.7	Vertical wall construction	2	4	6	4
E3.8	Plastering	2	3	4	3
E3.9	Curing	3	7	10	7
E3.910	Provision of Inlet and Outlet connection	3	4	5	4
E3.911	Water Proofing	2	4	6	4
E3.912	Backfilling and Finishing	1	2	3	2
Storage Tank Construction Site B (E4)					64
E4.1	Site Clearing and Marking	1	2	3	2
E4.2	Excavation	15	19	30	25

Code	Activity	Time Estimate (Days)			
		Optimistic	Most Likely	Pessimistic	te (Days)
E4.3	Levelling and blinding	2	3	5	3
E4.4	Base Compaction	2	3	4	3
E4.5	Construction of Outlet Structure and percolation well	10	15	20	15
E4.6	Slope stabilization and Tank Lining	3	6	20	8
E4.7	Stone bunds and boundary construction	3	4	7	4
E4.8	Curing and Drying	5	6	12	7
E4.9	Finishing work	2	3	4	3
Sedimentation Tank Construction Site C (E5)					50
E5.1	Site cleaning and Layout marking	1	2	3	2
E5.2	Excavation and Levelling	1	2	4	2
E5.3	Foundation and Curing	8	9	13	10
E5.4	PCC Bed concrete and curing	7	7	12	8
E5.5	Installation of Reinforcement	2	3	6	3
E5.6	Base Concreting and curing	7	7	12	8
E5.7	Vertical wall construction	3	4	11	5
E5.8	Plastering	3	4	7	4
E5.9	Curing	3	7	10	7
E5.910	Provision of Inlet and Outlet connection	4	4	6	4
E5.911	Water Proofing	3	5	9	5
E5.912	Backfilling and Finishing	1	2	3	2

Code	Activity	Time Estimate (Days)			
		Optimistic	Most Likely	Pessimistic	te (Days)
Storage Tank Construction Site C (E6)					71
E6.1	Site Clearing and Marking	2	3	6	3
E6.2	Excavation	20	25	35	26
E6.3	Levelling and blinding	3	4	6	4
E6.4	Base Compaction	3	4	7	4
E6.5	Construction of Outlet Structure and percolation well	10	14	20	15
E6.6	Slope stabilization and Tank Lining	5	8	15	9
E6.7	Stone bunds and boundary construction	4	6	8	6
E6.8	Curing and Drying	3	7	11	7
E6.9	Finishing work	1	3	5	3
Finishing Work (F)					25
F1	Cleaning of Drains	3	7	10	7
F2	Tank Cleaning	1	2	4	2
F3	Fault detection and repair	3	7	10	7
Closure (C)					7
C1	Taking out actual Quantities	1	2	4	2
C2	Completion certificate	2	3	4	3
C3	Handover	1	2	4	2
Total expected duration in days					**204**

To perform scheduling, the Oracle Primavera p6 tool was used. The Oracle Primavera p6 tool is a comprehensive and integrated system that generates and analyzes schedules for infrastructure projects by enabling the construction of international codes and resources and the connection of various schedules, which decreases the time involved and human error (Algedo et al., 2022; Meredith et al., 1986). Utilizing Primavera p6 for scheduling offers increased visibility, communication, early clash detection, real-time updates, and better time and cost management, which are effective for project planning, execution, and stakeholder collaboration. “Primavera p6” consists of a Structured Query Language (SQL), Oracle, and SQL Server Express databases, allowing for the construction of global codes and resources to link various schedules (Meredith and Mantel, 1995). P6 simultaneously manages numerous large-scale projects and uses common windows interfaces to simplify operations.

The expected time frame for completing all identified activities was 204 days, as revealed by the developed scheduling dimension of BIM after assigning the lead and lag. Lead and lag techniques were used to optimize the project timeline. Lead refers to a situation in which the successor activity starts before the completion of its predecessor activity, and lag refers to a situation in which there is a delay between the completion of the predecessor activity and the start of the successor activity. The performed scheduling provides the critical path and project timeline, which aids in assigning resources efficiently. In conjunction with the time dimension, considering cost as a 5D increases project efficiency, reduces costly rework, and ultimately contributes to enhanced cost performance, ensuring that projects are completed within budget while accomplishing infrastructure project goals.

5.2.4 5D BIM: Cost estimation

In most infrastructure projects, cost overruns have become a common issue because of the inaccuracy of the quantity take-off and bills of quantities, and the inaccurate forecasting of the project’s cash flow (Vigneault et al., 2020). The 5D BIM can solve this problem and improve cost management (Mitchell, 2012; Smith, 2014). This BIM dimension connects cost information to an existing 3D model to regulate and analyze project lifecycle expenses, automate cost estimation, and improve accuracy, whereas the manual cost estimation procedure is time-consuming and prone to inaccuracy, as it involves human involvement (Cheng, 2014).

In the proposed study, the implementation of the RwHs would take place in the Jaipur municipality area, India; the schedule rate and material cost required would be considered from the schedule rates book provided by the regional governing authority. Therefore, to estimate the overall cost, the Basic Schedule Rates (BSR) provided by the public works department, city circle Jaipur, and the Integrated Schedule Rates (ISR) provided by the Rajasthan Urban Infrastructure Development Project were considered for the resources involved. Quantity takeoff and resource consumption were estimated using the developed 3D model for cost estimation. To perform resource allocation, Primavera p6 provides the default 3 classes of resources: labour, material, and non-labour. The manpower used in the construction activity was classified as "labour," whereas machinery and equipment were classified as "non-labour," and materials required were considered as the material resource. After allocating the resources and assigning a standard working duration for each resource, the total planned cost for implementing RwHs was obtained in Primavera p6. Table 5.5 provides a description of the item and the standard rates considered.

Table 5.5 Scheduled rates for cost estimation

Item	Cost per Unit	Unit
Mason 1st class	700	Day
Helper	500	Day
Driver (for Road Roller, Concrete Mixer, Truck etc.)	700	Day
Engineer/Surveyor	3500	Day
Plumber	500	Day
Mistry	700	Day
Machinery		
Excavator	8000	Day
Tractor with trolley	1300	Day
Air compressor 250 cfm with two leads for pneumatic cutters/ hammers	1575	Day
Tractor with front leveller	1500	Day
Smooth Wheeled Roller 8-tonne	1730	Day
Dozer D - 50 - A 15	790	Hour
Hire and running charges of vibrating pile driving hammer complete with power unit and accessories	37000	Day

Item	Cost per Unit	Unit
Materials		
Modular bricks class designation 75	11	per item
Providing and laying in position cement concrete including curing, compaction, etc., complete in specified grade excluding the cost of centring and shuttering - All work up to plinth level. M20 grade Nominal Mix 1: 1.5: 3 (1 cement: 1.5 coarse sand: 3 graded stone aggregate 20mm nominal size).	4468	cum
Cement sand Mortar 1: 3 (1 cement: 3 sand) checked the cement-to-sand ratio	4145	cum
Centring and shuttering with plywood or steel sheets, including strutting, propping, bracing both ways and removal of formwork for foundation, footings, strap beam, raft, bases of columns, etc.	64.00	kg
Thermo-mechanically Treated bars (Conforming of relevant IS code)	8000	tone
Providing and laying water proofing treatment to vertical and horizontal surfaces of depressed portions of W.C., kitchen and the like consisting of: a) Ist course of applying cement slurry @ 4.4 Kg/sum mixed with water proofing compound conforming to IS 2645 in recommended proportions including rounding off junction of vertical and horizontal surface. b) IInd course of 20mm cement plaster 1:3 (1 cement: 3 coarse sand) mixed with water. proofing compound in recommended proportion including rounding off junction of vertical and horizontal surface.	513	sqm

c) IIIrd course of applying blown or residual bitumen applied hot at 1.7 Kg per sqm. of area. d) IVth course of 400-micron thick PVC sheet (Overlaps at joints of PVC sheet should be 100 mm wide and pasted to each other with bitumen @ 1.7 Kg/sqm.).		
Stonework (machine cut edges) for Wall cladding/ Veneering work up to 10 m height with 20 to 30 mm thick Red Sand Stone (Karauli) and backing filled with a grout of 12 mm thick cement mortar 1:3 (1 cement : 3 coarse sand) including pointing in white cement mortar 1:2 (1 white cement: 2 stone dust) with an admixture of pigment matching the stone shade :(To be secured to the backing by means of cramps which shall be paid separately).. 6.8.1 Exposed face rough dressed.	1649.00	sqm
Reinforced HDPE Geomembrane 500 Micron Dollar,0.5 mm THK, laminated HDPE woven fabric for waterproof lining, type II with IS:15351:2015	95	sqm

After allocating the standard rates to the resources in Primavera p6, the per-day involved cost can be calculated, which maintains the cash flow throughout the project by assisting financial management, as shown in Figure 5.5. The total planned cost for implementing the proposed RwHs was 56248754.66 INR (i.e., 674442.82 USD). Appendix E provides the costs incurred in each activity.

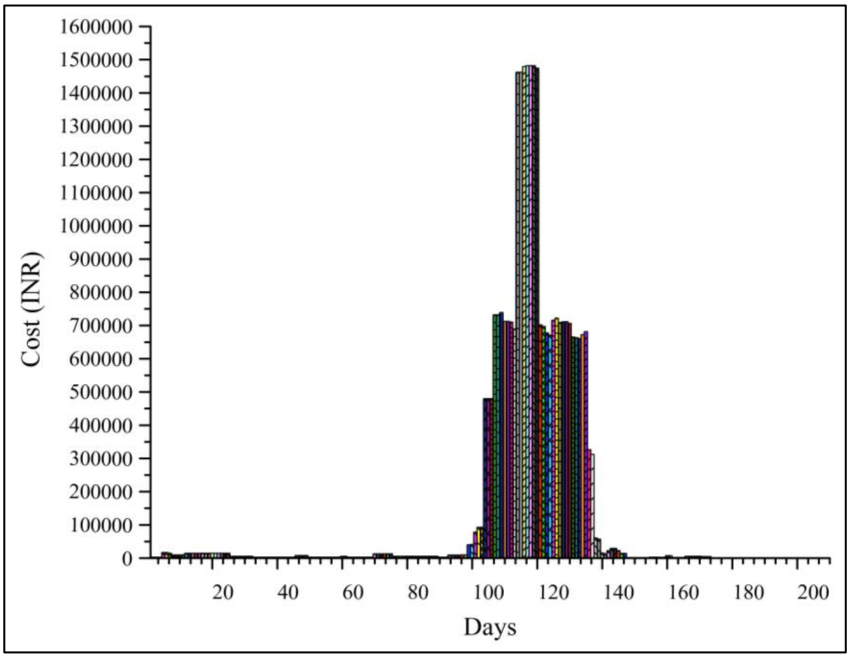


Figure 5.5 Day-wise cost estimation for proposed RwHs

The assigned resource type plays an important role in maintaining environmental sustainability. Consideration of energy-efficient technology, materials, and procedures is critical for optimizing resource use and minimizing environmental consequences, resulting in the fulfilment of the infrastructure project's sustainable development goals (SDG). The materials and resources involved in these activities must be analyzed to minimize their adverse effects on the environment. Incorporating the sustainability dimension provides detailed information about the carbon footprints and energy involved in individual materials, which helps decision-makers increase the sustainability of the proposed system.

5.2.5 6D BIM: Sustainability analysis

Sustainability entails sustaining and replenishing natural resources, minimizing the impact on the ecosystem, and promoting long-term environmental health. A recent study revealed that over 33% of global ozone-depleting GHG releases come from the built environment (Hollberg et al., 2020). The energy used during building, operation, and demolition causes large GHG emissions, adversely affecting the surrounding environment (Peng & Wu, 2015). In such cases, LCA is essential for determining the carbon emissions produced by infrastructural development. LCA evaluates the environmental effect of a product or service by calculating carbon emission (CO_2eq), a composition of GHGs such as Carbon dioxide (CO_2), Methane (CH_4), and Nitrogen dioxide (NO_2) (Chau et al., 2015; Wu et al., 2012). LCA also assessed energy consumption during the operational phase of the project (Jayasinghe et al., 2021; Xu et al., 2022). The International Organization for Standardization (ISO) 14040 series of standards cover quantitative assessment methods for assessing the environmental elements of a product or service throughout its life cycle within system boundaries and functional units (Finkbeiner, 2014).

In addition to LCA advances, BIM innovations have enabled architects and engineers to access technologies that allow them to analyze energy efficiency measures and incorporate them into their designs (Pishdad-Bozorgi et al., 2018). BIM enables graphical, numerical, and qualitative data processing, and efficiently communicates comparative visual and numerical information. In the proposed study Tally Revit plugin was used to assess the environmental impact of the RwHs implementation. The plugin allows the assessment of the environmental impact of construction materials for whole-project analysis and comparative design option studies. The Tally plugin applies a custom-designed LCA database created by employing GaBi databases, complying with the LCA standards ISO 14040-14044, and considers the entire cradle-to-grave lifecycle as per European Standard (EN 15978). The term "cradle-to-grave" refers to the entire life cycle evaluation, including the resource extraction, use, and disposal phases. The information available through Tally's interface includes a data window with a detailed description of (1) the dimensions taken from the Revit model, (2) the quantity take-offs produced by Tally (volume, area, density, default value, or predefined value), (3) the mass of the material, and (4) the service life of the specified material. The incorporated material entries in Tally were validated through its metadata report, which contained an itemized list of each material used in the project, along with the mass of the material (kg) used in each Revit family type, which provided transparency to the custom database and the opportunity to understand the exact procedure.

The dimensions extracted from the Revit model, the quantity take-offs produced by Tally (volume, area, density, default value, or predefined value), and the service life of the material were not incorporated into Tally's metadata report, but instead found in Revit's bill of materials, which was launched in conjunction with Tally's report. Although this information was displayed in Tally's interface during the building analysis assembly and material specification, better integration and transparency between Revit's bill of materials and Tally's metadata would be useful for designers and would reduce any model uncertainties and assumptions. To measure the energy and emissions accumulated during the construction of a building's structural components, Tally estimated the impacts from construction (anticipated or measured energy and water consumed during the construction of the building) and transportation lifecycle stages. While performing the LCA in Tally, the following stages of the building material, from raw material acquisition to final disposal, have been considered.

a) Product: It involves the entire manufacturing process, from the extraction and processing of raw materials through the final production and assembly.

b) Transportation: This includes transportation from the manufacturer to the construction site and is vulnerable to modification by the modeller.

c) Maintenance and Replacement: This includes replacing materials after their estimated service life has passed. This covers the afterlife services for the current products and the cradle-to-gate manufacturing and distribution of the replacement products.

d) End of Life: This covers the rates of appropriate material collection for recycling, the necessary steps in processing recycled materials, incineration, and landfilling rates.

e) Module D: This accounts for reuse potentials that extend beyond the system boundary, such as energy recovery and material recycling.

5.2.5.1 Calculation methodology (Environmental Impact Categories)

All emissions and fuel use were converted into categorized environmental impacts using a characterization scheme for reference. The results are provided as impact potential because the extent of environmental harm caused by emissions depends on the local ecosystem circumstances and the area in which it occurs. In analysis, the potential effects were presented in kilograms of an emission frequently linked to that environmental impact (e.g., kg CO2eq) as an equivalent relative contribution (eq). The types of environmental effects listed below were described in accordance with the "Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts" (TRACI) 2.1 categorization scheme, the environmental impact model created by the US Environmental Pollution Agency (EPA) to calculate the risk of environmental damage associated with emissions to the environment in the US (EPA et al., 2012).

a) Acidification Potential (AP): A measurement of environmental acidification-related emissions. Potential consequences include fish death, forest degradation, and corrosion of building materials.

b) Eutrophication Potential (EP): A measure of the impacts of excessively high levels of macronutrients, the most important of which are Nitrogen (N) and Phosphorus (P).

c) Global Warming Potential (GWP): A measurement of greenhouse gas emissions, including methane and carbon dioxide emissions. The natural greenhouse effect escalates due to these emissions, boosting the earth's natural radiation absorption.

d) Smog Formation Potential (SFP): An indicator for the amount of ground-level ozone that results from different chemical interactions between sunlight's volatile organic compounds (VOCs) and nitrogen oxides (NOx). Effects on human health can cause various kinds of respiratory issues, including worsening bronchitis, asthma, and emphysema symptoms.

e) Primary Energy Demand (PED): The amount of primary energy extracted from the earth. PED is also measured by the amount of energy demanded from renewable and non-renewable sources.

LCA assessment allows the decision maker to select eco-friendly materials and develop design alternatives to reduce the negative impact of construction activities. Developments in LCA and the innovative capabilities of 6D BIM are interconnected, permitting architects and engineers to optimize operations throughout the project phase. During the O&M phase, BIM serves as a central repository for accurate and up-to-date information regarding built assets.

5.2.6 7D BIM: Facility management

In this study, the Autodesk Collaborate Pro platform was used to streamline the FM process and enhance the operational efficiency of the proposed RwHs. This 7D BIM can provide significant benefits throughout the operation, execution, and maintenance phases by optimizing numerous processes and serving as a repository for precise information on the built asset (Motamedi et al., 2014). Static documents (such as CAD and PDF) frequently transmit facility information, underutilizing the potential advantages of digital technology (Simpson et al., 2018). During the conceptual stage, while developing design alternatives, BIM can be utilized to update a facility's operation database with geometry and parameters, consequently supplementing the information technology employed by owner organizations (Pishdad-Bozorgi et al., 2018). BIM enables large-scale economies by supporting the lifecycle of information management. The accuracy and availability of data generated and updated during the design, construction and operation phases are essential for FM, resulting in efficient decision-making (U.S. General Services Administration 2011).

The water management system deals with the quality and quantity of the water source. This study undertakes an analysis of both aspects of the water sources for its efficient utilization. First, an optimum Liters Per Capita per Day (LPCD) estimation was performed by considering zones of the municipality area. The estimation of the LPCD revealed the large variation in supply and demand of the water leading to the water wastage. The estimated optimized LPCD allows to design the user centric supply and demand system with minimum losses. Second, a comprehensive assessment of water quality was conducted. This study analysed the quality of the region's accessible water sources by considering characteristics such as the pH level, presence of contaminants, and overall water purity. This analysis reflects the contaminants in a specific region. The performed water quality analysis guide to select the suitable treatment plant while performing on-ground implementation of RwHs. Finally, the database was created by incorporating site-specific schedule rates of the resources, which could be utilized to assess the particle feasibility of the proposed RwHs at multiple locations. The created database serves as a repository of the standard rates of resources and their detailed specifications, which were used to develop site-specific BIM dimensions.

Estimating the optimized LPCD, water quality assessment, and database creation provide considerable benefits for implementing the proposed methodology at multiple locations. It streamlines the processes required to conceptualize, develop, and maintain RwHs. The optimized LPCD enables the RwHs design to match the region's water demands by lowering the probable waste and resource consumption. The water quality assessment enabled the selection and integration of appropriate treatment facilities at each site, guaranteeing that the captured rainwater fulfils the required criteria and is safe for use. Finally, the created database helped to assess the feasibility of the proposed system by providing accurate site-specific schedules and cost estimates. The creation of the database, assessment of water quality, and estimation of the optimized LPCD offer useful insights and support the life cycle management of the project. The detailed procedure involved in these attempts is described in the subsequent section.

5.2.6.1 Estimation of optimized LPCD

The influence of socio-demographic, climatic, and regional variables on water consumption was incorporated in earlier research that concentrated on water end-use consumption and conservation behaviours (Brown et al., 2009; Kakwani & Kalbar, 2020). The overall findings demonstrated the discrepancy between perceived and estimated demands and real water usage in the Indian setting, the general public's unwillingness to adopt water conservation, the inefficiency of water pricing, and inconsistent water supplies (Kumar et al., 2021). Maintaining an optimal water supply throughout the day is important to alleviate the perception of water scarcity and to prevent excessive water use without compromising hygienic practices. In previous studies, to design and optimize the RwH tank and performance, water balance simulation, hydrological (local rainfall, potable water demand), and probabilistic approaches were developed by considering various constraints and attributes as design input parameters (Aladenola & Adeboye, 2010; Gao et al., 2014; Haque et al., 2016; Khastagir & Jayasuriya, 2010; Kahinda et al., 2009). With the incorporation of multi-input parameters, a multi-objective model for optimizing the construction areas of porous surfaces and green roofs was applied to estimate the stormwater volume and its environmental impacts (Y. Li et al., 2017).

This study divides the estimation of the optimum LPCD into three steps. First, ground survey data or household survey data were collected to understand ground conditions. The data collected from the survey were further used to perform optimization using linear equations. Finally, Genetic Algorithm (GA) optimization was performed to develop equations as the constraint and objective functions. The detailed methodology explanation below and is illustrated in Figure 5.6.

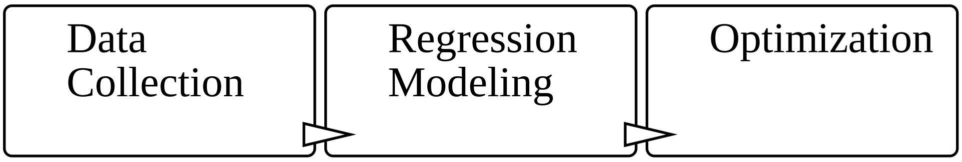


Figure 5.6 Methodology for estimating optimized LPCD

a) Data Collection: Household surveys are a vital source of social and demographic data. These surveys provide extensive and diverse sociodemographic data on people’s welfare, demographic features, cultural elements that influence behavior, and social and economic changes. Household surveys containing nearly any population-based field are a powerful alternative and have become one of the most adaptable data sources for social phenomena in the past few decades. A survey was conducted to track the living standards, demographics, and socioeconomic aspects of each home. The survey enabled us to comprehend the daily requirements and challenges of each household in community experiences. For performing a study, 2200 responses from different houses evenly spread throughout the study area were collected, as shown in Figure 5.7.

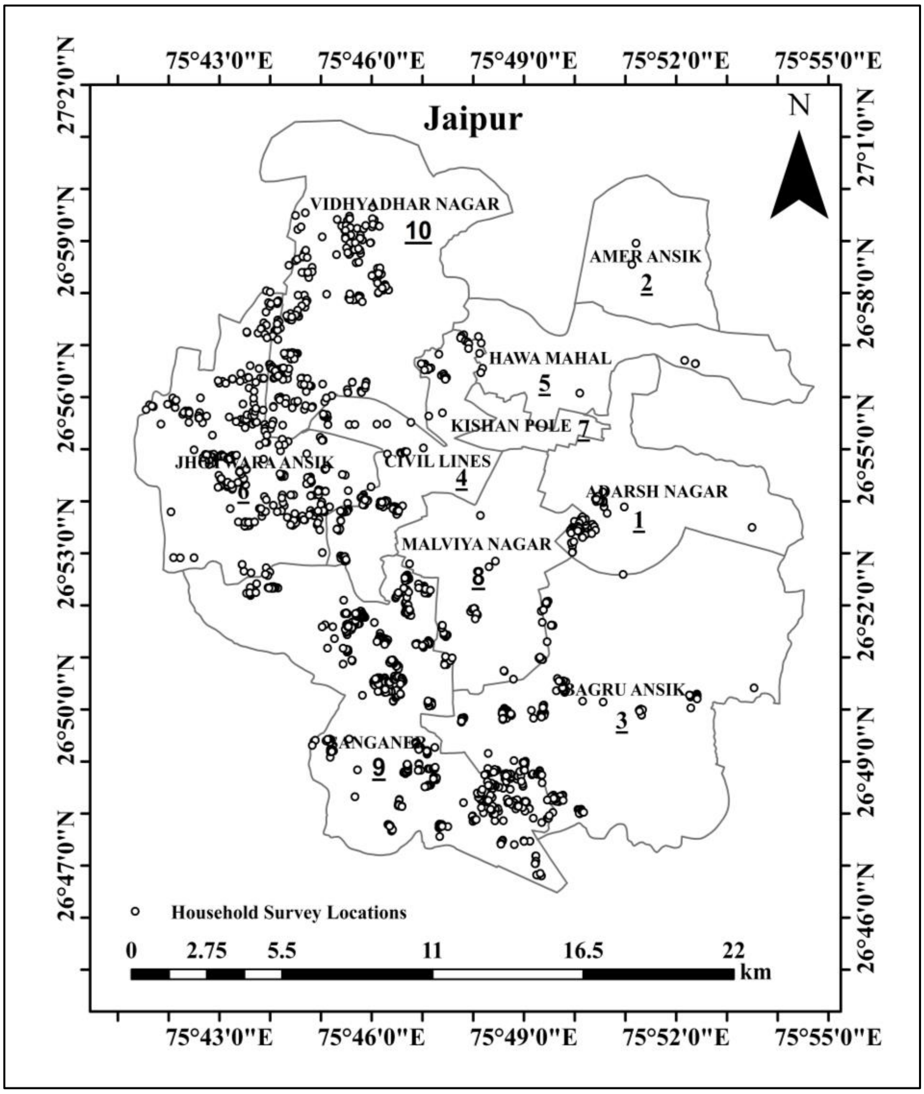


Figure 5.7 Study area map with household survey locations

The questionnaires for the household survey were designed to understand the area's current economic situation and water supply information, including the family's annual income, water demand, house area, and the number of persons living in a house. The latitude and longitude information included in the survey allowed for the visualization and analysis of the survey data in the GIS environment. The statistical distribution of the performed household survey is displayed in Table 5.6.

Table 5.6 Statistical distribution of household survey data

Variables	Mean	Median	Percentiles			
			25	75	90	95
Individuals in households	5.85	6	5	7	8	9
Supply	653.28	500	350	1000	1200	1200
Demand	784.12	804	670	938	1072	1206
Income	174424	150000	100000	250000	300000	300000
Household Area	1019.86	980.49	700	1200	1500	1782.72

b) Multiple Regression Modeling for Optimization: Regression analysis is one of the most extensively used approaches for expressing the dependency of a response variable on numerous independent factors (Abdul-Wahab et al., 2005). The key aspects of the regression analysis are (1) selecting appropriate dependent variables, (2) discovering linear correlations of cause and effect between dependent and independent variables, and (3) including only related independent variables in the model. The ideal combination of independent variables to predict the dependent variables must be determined when dealing with many independent variables (Overmars et al., 2003). Various methods are employed in regression analysis to examine the relationships between different variables. The proposed study used linear multiple regression and its equation form using the SPSS statistical tool. Equation 5.9 represents the general form of linear regression.

$$Y = \beta + \beta_1 X_1 + \beta_2 X_2 + \cdots + \beta_n X_n \qquad \text{Eq. 5.9}$$

Were,

β, β1, β2= Coefficients

X_1, X_2, X_n= Independent variables

Y= Dependent variable

Before optimization, the data for the households obtained from the ground survey were used to create the governing equations for the 10 zones. The potential water demand per household was chosen as the dependent variable (Y), and household water supply (X_1), house area (X_2), and annual household income (X_3) were considered independent variables. Regression models were developed using the SPSS tool, and independent parameters were extracted zonewise using the GIS tool. For the study region of Jaipur, 133.66 LPCD is considered as the daily per capita water demand, which needs to be minimized (Urban Water Supply Policy, 2018). For each identified zone, regression modeling was performed to form the main equation, and subsequent partial estimations were performed to obtain the constraint equations. The R^2 and p-values were used to evaluate the performance of the regression model. Equations 5.10, 5.11, 5.12, and 5.13 show the sample equations created for one zone where the first equation acts as the objective function, and the remaining three were the constraint functions for further optimization.

$$y = 469.40 + 0.539 * (x_1) - 0.026 * (x_2) + 0.301 * (x_3) \quad \text{Eq. 5.10}$$

$$y_1 = -341.122 + 0.551 * (x_1) + 0.027 * (x_2) \quad \text{Eq. 5.11}$$

$$y_2 = 105.99 - 0.027 * (x_2) - 0.357 * (x_3) \quad \text{Eq. 5.12}$$

$$y_3 = -235.132 + 0.551 * (x_1) - 0.357 * (x_3) \quad \text{Eq. 5.13}$$

c) Optimization (GA): In this study, GA was used to perform LPCD optimization. GA is a family of metaheuristic optimization models inspired by natural processes such as evolution (Karr and Gentry 1993). The biological principles of natural evolution and the selection of individuals have inspired the class of heuristic methods known as GAs, which are used to sample the search space and find the best solution. Individuals are the candidate solutions to the optimization problem that differ in appearance (phenotype), that is, the values of the decision variables. The phenotype is coded as a genotype string and then sub-stringed to indicate the binary grey coding of the choice variables. Individual features determine an individual's Fitness Function (FF) value, which is determined by both the objective function (OF) value associated with the phenotype and the degree of satisfaction with the constraints. An initial population of N individuals was randomly formed at the start. Individuals are rated in increasing order based on their fitness and each is assigned a selection probability that decreases with the ranking order. Finally, the individuals are chosen based on their selection probability and gathered in a "mating pool" to create couples that will serve as parents of the individuals in the next generation. These algorithms encode a potential solution to a simple chromosome-like data structure problem and apply recombination operators to these structures to preserve the critical information. GA are often viewed as function optimizers, although the range of problems GA has been applied to is quite broad.

The main parameters of GA are the dimensions of the initial population, number of generations, mutation rate, and crossover rate. The best GA control parameters are determined through successive trials. In this study, the objective function determines the outer water demand by incorporating the water supply, household area, and annual household income. The model equations were used as FF for optimization. The optimization toolbox in MATLAB (ver. R2019b) was used to perform the optimization. After providing the model with the constraint equation and setting the lower and upper bounds, the optimum value of the water demand was obtained for each zone. The zone-wise optimized LPCD values are shown in the following Table 5.7 and sample imput data along with estimated LPCD is appended in Appendix F.

Table 5.7 Zone-wise optimized LPCD values

Zones	**Area (km^2)**	**Optimized LPCD**
1	31.099	131.52
2	18.810	128.745
3	78.164	129.026
4	24.732	106.621
5	25.818	128.745
6	43.988	122.752
7	5.571	128.745
8	29.665	130.111
9	61.25766	108.9336
10	56.879638	128.8136

According to the administrative government, the LPCD for Jaipur City is 133.66, whereas the optimum LPCD value range from 106.52 to 129.58. The computed LPCD values aid in reducing the extra demand on the existing water delivery system. The visualization of the optimized LPCD is shown in Figure 5.8.

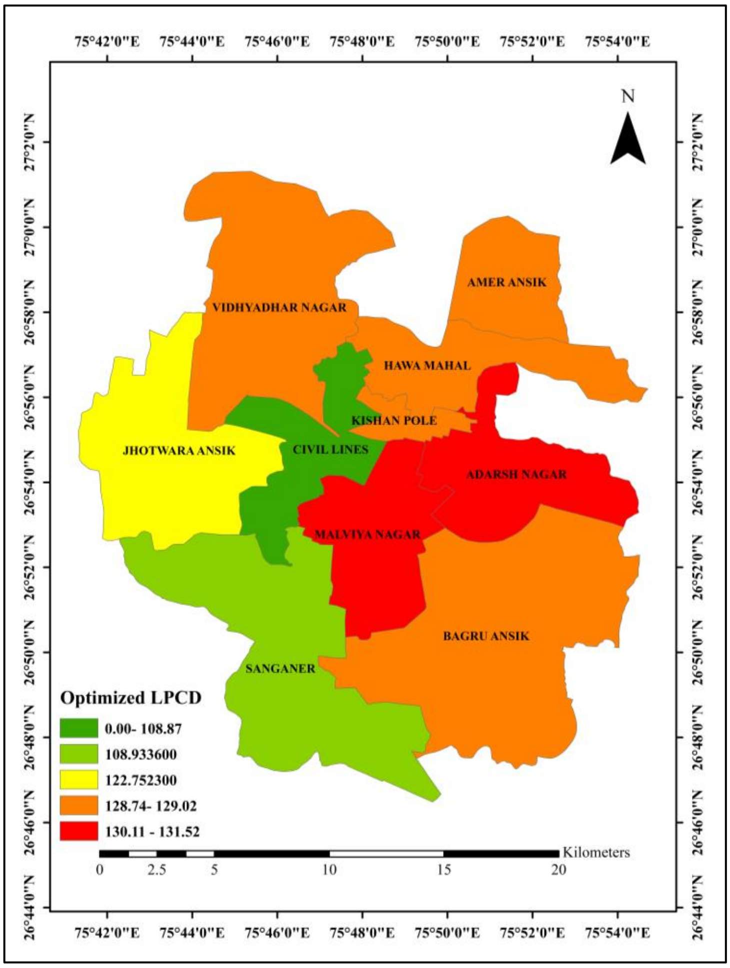


Figure 5.8 Visualization of optimized LPCD for the study area

The estimated LPCD values for each zone play an important role for decision-makers in performing real-time water management and designing RwH components by considering optimized LPCD values. The design and water management enabled informed choices with the primary goal of minimizing losses. The created visualization of the estimated LPCD values make it clearly understandable among the stakeholders, which was shared on the Autodesk Collaborate Pro platform. The shared LPCD values and map enables efficient communication and exchange of data, hence promoting effective collaboration among stakeholders and specialists to improve strategies for managing water resources.

5.2.6.2 Water quality assessment and modeling

Due to increased urbanization, intensive irrigation, and industrial progression, threats of water-borne diseases and epidemics are predominant in most underdeveloped countries and emerging economies (Rahman & Hashem, 2019; Adimalla & Qian, 2019; Soleimani et al., 2018). In these scenarios, individuals are exposed daily to low amounts of anthropogenic and biological chemicals through heterogeneous distribution channels (Jinturkar et al., 2010; Adimalla & Qian, 2019). Therefore, a thorough assessment of health risks is crucial to ensure the qualitative safety of water supplied to end users (Hu et al., 2022b; Fazal-ur-Rehman, 2018; Eggers et al., 2018). Generally, water quality indicators rely on normalizing or standardizing data factor by factor in accordance with anticipated concentrations and interpretations of "good" vs. "bad" readings (Matinpoor, 2018). These indicators were created as the weighted average indices of all pertinent data, with the qualitative parameters receiving weights based on their perceived significance to the overall water quality. A Water Quality Index (WQI) integrates the measurements of various water quality parameters to characterise water quality through a single number ranging from 0 to 100, where 100 indicates excellent water quality, and a value of 0 indicates very poor water quality, unfit for household utilization (Abtahi et al., 2015).

The most notable WQI technique is the Hazard Index (HI) which combines exposures/ Health hazard Quotient (HQ_i) to evaluate the danger of groupings of chemicals with shared mechanisms but varying influences and exposure characteristics (Wilkinson et al., 2000). HQ_i is a method for evaluating non-cancer risks based on the ratio between the estimated dose of a contaminant and the dose level below which there is no significant harm or the reference dose (Khandare et al., 2020). EPA first established two methods for characterizing risk: an HQ_i for a particular chemical and an HI for a grouping of chemicals. HQ_i is the ratio of the suitable reference dosage (Rfd) to the Average Daily Dose (ADD) of the contaminant. Conversely, HI is the summation of the HQ_is of all chemicals and contaminants. The actual element content per exposure scenario, i.e., site and population-specific, was used to calculate the ADD. In contrast, the RfD for elements or pollutants was determined based on standards and the literature (Abtahi et al., 2015; Hu et al., 2022; Javed & Usmani, 2016).

Several advancements in developing WQIs have happened over time, beginning with the initial index developed by Horton in 1965 (Horton, 1965). Zadeh first proposed fuzzy logic (FL), which has since become one of the most widely used techniques in artificial intelligence (AI) (Zadeh et al., 1996). Fuzzy is a reliable technique to communicate assessment results in a simplified manner which comprehensible to the general public, managers, decision-makers, and non-experts (Asgari et al., 2021; Hu et al., 2019). In recent years, the fuzzy technique has proven effective in solving problems with fuzzy boundaries and controlling the effect of monitoring errors on assessment results and has been intensively explored for water quality assessment (Haiyan, 2002; Onkal-Engin et al., 2004).

These advancements are largely attributable to the adoption of soft technology applications, such as data mining algorithms, AI, and fuzzy modeling systems, which address the escalating uncertainties that arise in the assessment of traditional WQI approaches (Babbar & Babbar, 2017; Chau, 2006; Pham et al., 2021). Nowadays, predictive algorithms such as ANN and ANFIS have proven efficient in representing non-linear input-output relationships of complex data by providing substantial model flexibility (Khan & Chai, 2017; Nasiri et al., 2007). ANFIS integrates a Fuzzy Inference System (FIS) into an adaptive network architecture, which provides the combined advantages of ANN and fuzzy approaches by eliminating the core difficulty of specifying the membership function constraints and creating a set of fuzzy if-then rules (Shwetank et al., 2022).

To perform water quality analysis, area-based classification of water samples was performed using a novel weighted hazard quotient (HQ_iW) index, and a fuzzy-based index approach and classified water samples were used to train the ANN and ANFIS prediction models using MATLAB. To begin with, the basic procedures for conducting water sampling and testing were followed according to the norms published by the World Health Organization (WHO). The water quality indexing was carried out using the water testing results as input. Figure 5.9 depicts the thorough procedure used to develop the water quality indexing and prediction.

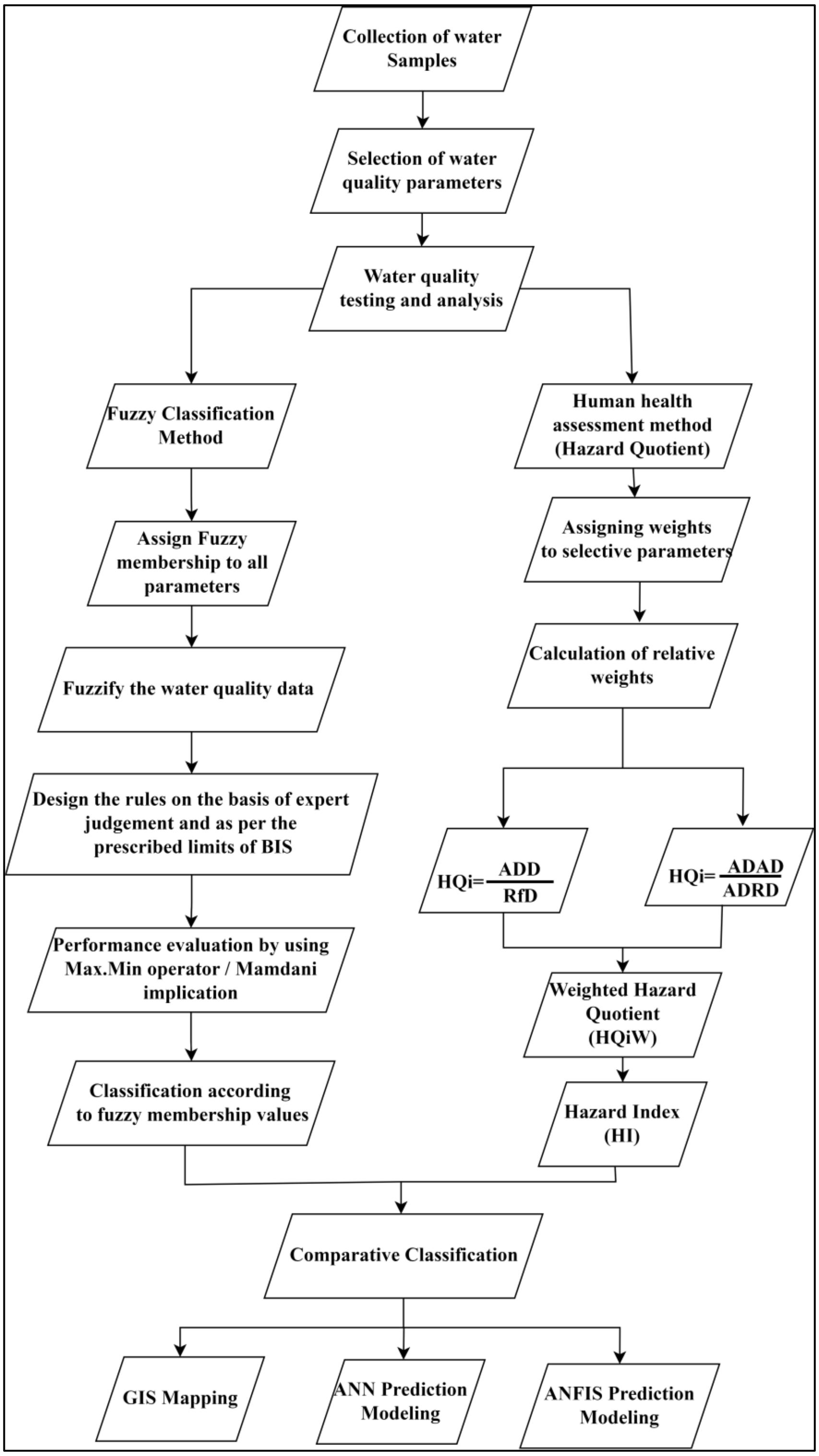


Figure 5.9 Methodology for water quality assessment

a) Data collection: During the initial phase of the study, 350 water samples were collected from multiple locations across the city. Due to the inaccessibility of several places, uniform sampling could not be carried out in some areas of the city. Figure 5.10 provides the visualization of water sample collection over the study area.

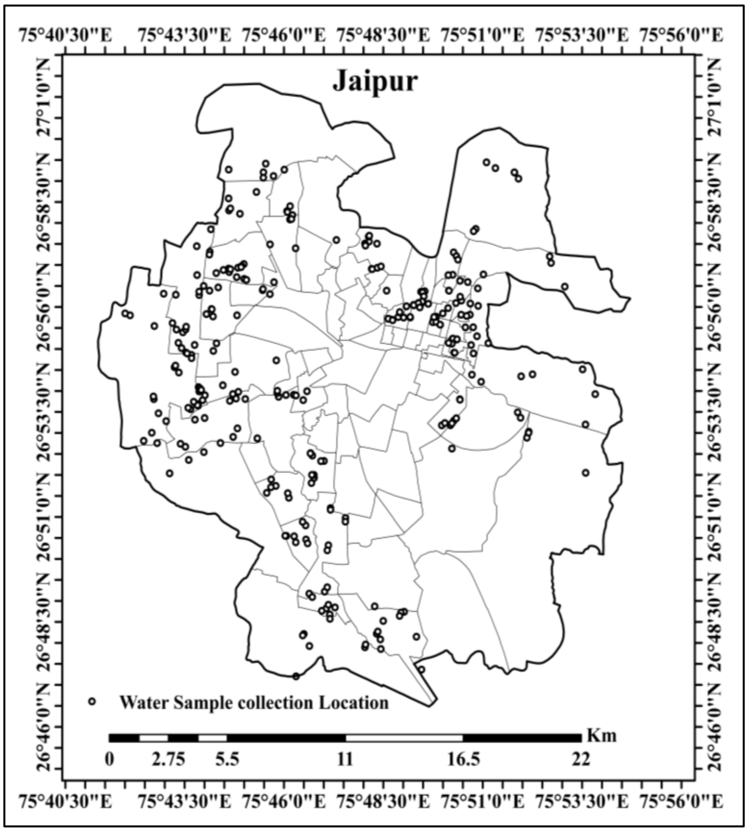


Figure 5.10 Study area with water sample location

The water samples were taken by maintaining standard procedure. For sample collection, 1 L narrow-mouth polypropylene bottles were immersed in 5 % HNO_3 for 24 hrs before being repeatedly rinsed with deionized water. Water samples were collected after the bottles had dried. Figure 5.11 shows the collected water samples for analyzing the water quality index.

Figure 5.11 Collected water samples

Most of the city area receives water from the Public Health Engineering Department (PHED) (Bisalpur project), and the remaining portion of the city receives water from tankers and individual tube wells. Water quality is influenced by physical, inorganic pollutant, and biological parameters induced by various man-made activities (Robinson et al., 2018). Therefore, to determine their health risk probabilities, it is prudent to evaluate the supplied water based on the qualitative characteristics defined by the WHO and the Indian Council of Medical Research (ICMR) (Jinturkar et al., 2010). For this study, the water quality indicators such as pH, Dissolved Oxygen (DO), Total Dissolved Solids (TDS), Chloride (Cl^-), Hardness (as $CaCO_3$), Fluoride (F^-), Nitrates (NO_3^-), Iron (Fe), and Copper (Cu) were analyzed as per the standard guidelines. For estimating concentration, testing methods such as titrimetric, colourimetric, and Atomic Absorption Spectrophotometer (AAS) were performed as per the standard guidelines proposed by the American Public Health Association 2007 (Nelson et al., 2007). The detailed methods used to assess the qualitative parameters of water are represented in Table 5.8.

Table 5.8 Test methods and statical information for qualitative parameters

Qualitative parameter	**Method Used**	**Min.**	**Max.**	**Mean**	**Std. Deviation**	**BIS (Acceptable)**	**WHO (Desirable)**
TDS	Digital meter	143	6840	964.38	853.46	500	1000
Total Hardness	Titrimetric method	30	1840	303.67	250.81	300	500
Fluoride (as F^- in mg/l)	Spectrophotometric method	0.10	3.20	0.61	0.54	1.5	1.5
Nitrate (as NO_3^- in mg/l)	Spectrophotometric method	1	331	73.29	73.27	45	50
Iron	Spectrophotometric method	0.10	1	0.43	0.24	0.3	0.3
Chloride (as Cl^- in mg/l)	Argentometric Titration	23	3100	296.86	417.39	250	250
Copper	Spectrophotometric method	0.10	2	0.57	0.36	1.5	2

pH	pH meter	6.8	8.5	7.77	0.44	6.5-8.5	7-8.5
DO	Titrimetric Method	5	18	10.6	2.52	5	NA

The reported data were compared with the Indian drinking water standards (BIS). To conduct the proposed study water quality parameters were selected based on their harmful effects on individuals. The analysis showed that 100% of the collected samples met the drinking water thresholds established for pH and DO, with recorded values varying between 6.5 to 8.5 and 4 to 6, respectively. Nitrates, notorious for methemoglobinemia, were significantly high, with a maximum observed value of 331 mg/l, and approximately 60% of the water samples exceeded the acceptable limit of 45 mg/l. Fe and Cu were the two heavy metals analyzed in the study area, while the Cu content varied from 0.1 to 2 mg/l, and astounding 75% of the samples exceeded the permissible thresholds. Although the iron values were between 0.1 and 1 mg/l, 51.7% of the samples surpassed the standard limit of 0.3 mg/l. The obtained chloride levels in the collected specimens ranged from 23 to 3100 mg/l, averaging 296.86 mg/l; a significant portion of the samples (72.86 %) affirmed the prescribed standard value of 250 mg/l. With a maximum recorded value of 6840 mg/l, 11.4% of the collected samples had TDS values greater than the permissible threshold of 2000 mg/l, while 60.57% of samples had recorded TDS between 500 to 200 mg/l, around 27.71% had TDS below the acceptable limit of 500 mg/l.

Hardness results were primarily due to Ca, Mg, and various other compounds, with observed readings varying between 30 to 1840 mg/l, averaging 303.67 mg/l; most samples, approximately 62.6%, were classified as very hard. While 20.29% and 15.14% of samples fell under the categories of moderate and hard, respectively, a less number of samples, at 1.71%, were classified as soft. The allowable F range per standard is 0.5 to 1 mg/l. However, most samples at 57.14% had recorded F^- levels below 0.5 mg/l. 21.71% and 15.43% of the samples lay within the range of 0.5 to 1 mg/l and 1 to 1.5 mg/l, respectively. Approximately 5.43% of the observed samples exceeded the threshold value of 1.5 mg/l. Table 5.9 provides the Water quality limits and their effect on human health.

Table 5.9 Water quality limits and their effects on human health

Water Quality Index	**IS 10500:1991**		**Actual sample collected**		**Undesirable effect outside the desirable limit**	**Reference**
	Desirable Limit	**Permissible Limit**	**Min.**	**Max.**		
pH	6.5 to 8.5	No Relaxation	6.5	8.5	Impact on Mucous membrane.	(Avvannavar & Shrihari, 2007)
Total Hardness	300	600	0	1840	The encrustation of water supply structures and detrimental effects on home use.	(Nelson et al., 2007; Ocampo-Duque et al., 2013; Patki et al., 2015)
Cl^- (mg/L)	250	1000	23	3100	It affects taste, corrosion, and palatability.	(Hoque et al., 2018; Rahman & Hashem, 2019)
NO_3- (mg/L)	-	(200 WHO)	1	331	High rates of blood pressure, heart attack, and stroke	(Campisano, 2017)
Fe (mg/L)	0.3	1	0.1	3.2	Taste and appearance are disturbed, which harms household usage and water supply structures.	(Ghosh et al., 2010; Tyagi et al., 2018)
Cu (mg/L)	0.05	No Relaxation	0	1.2	Vomiting, nausea, abdominal pain, and/or diarrhoea.	(Dietrich et al., 2004)
F (mg/L)	1	1.5	0.1	3.2	Very low and high concentrations of fluoride are harmful	(Meenakshi & Maheshwari, 2006)
TDS (mg/L)	500	2000	143	6840	Palatability drops after this threshold	(Nollet, 2000)

		and may cause gastrointestinal discomfort.

Pearson's correlation analysis was conducted with the parameters to understand their correlations among the parameters. The correlation coefficient 'r,' ranging from -1 to +1, is a mathematical term measuring the strength of the statistical relationship between two continuous variables. If the r value is +1, -1, or 0, the relationship is defined as perfectly positive, negative, or no correlation, respectively. A correlation coefficient (r) less than 0.3 indicates a weak association. However, if the R-value is between 0.3 and 0.7, the association is deemed moderate, and if it is larger than 0.7, the relationship is termed strong (Bertinato et al., 2015).

DO had a negligible negative relationship with pH, TH, and NO_3^-. In addition, a negligible weak relationship was observed between Cl^- and NO_3^-. As previously reported, pH and F^- had a similar weak negative correlation (r = -0.177). pH had a weak negative relationship with all parameters except NO3-, where a weak positive correlation was observed (r = 0.256). Similarly, a positive relationship was observed between F- and Cl- (r = 0.396). Fe and Cu were positively correlated, indicating a similar anthropogenic source (Kumari et al., 2013). Figure 5.12 shows Pearson's correlation matrix heat map among the collected water sample's quality. Based on the correlation analysis, the subsurface water source contained higher TDS and chloride than the water supplied by the PHED. In contrast, water from surface sources contains a high level of fluoride and chloride in major areas of the city area.

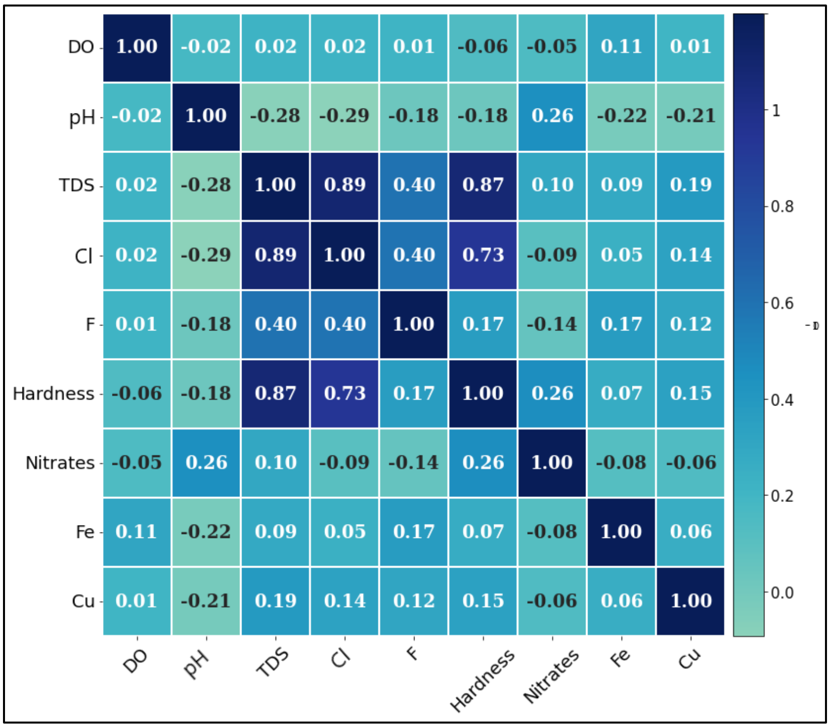


Figure 5.12 Pearson correlation coefficient among water quality parameters

b) Development of a novel Weight Integrated Health Hazard Index: The newly termed HQiW was developed in the proposed study by including weighted relevance and attempts to turn the massive and difficult information of raw water quality data into a simpler and logical form using various categories of water quality reflecting the overall water quality state of the chosen region. In this technique, weights of different magnitudes are employed in the HQi to compute the risks posed by each pollutant. The weighting method prevents erroneous risk estimates, resulting in moderate-to-significant underestimation. Each drinking water quality measure was assigned a specific weight depending on its relative importance to overall water quality (Wi).

To quantify the relative weight of the grouped qualitative variables, the Wi was derived by dividing the allocated weight by the cumulative weights of all parameters. Maximum and minimum weights of 5 and 3 were assigned to each criterion based on their relevance. Depending on the contribution of the contaminant to the overall pollution, the assigned weights may vary based on their concentrations at different locations. Copper is a heavy metal that has severe effects on human health and is assigned a value of 5. In the same vein, nitrates are known to affect babies and were classified into the same weight group. Although not directly involved in affecting human health, Iron was assigned a weightage value of 4. All other parameters, such as TDS, TH, F, and Cl, were present well within their permissible limits and were assigned weightage based on their relative significance in the water quality evaluation.

The second step was to quantify the relative weights of grouped qualitative variables. The relative weight (Wi) was derived by dividing the allocated weight by the cumulative weights of all the parameters. The third step included the relative weights in determining the hazard quotient and deriving HQiW. The HQiW developed in the proposed study attempts to convert the massive and difficult information of raw water quality data into a simpler and logical form by using various categories of water quality that reflect the overall water quality state of the chosen region. The summation of HQiW gives the weighted integrated hazard index. The following subsection provides a detailed procedure for computing the HQiW.

i) Calculation of daily dose (ADAD/ADRD/ADD): In toxicological databases, the minimum necessary or maximum permitted daily doses for Total Hardness, Chloride, and TDS were not defined in terms of human health. Therefore, for these three parameters, the following ADD were proposed to assess the hazard quotient:

I) Average daily required dose (ADRD)
II) Average daily accepted dose (ADAD)

Drinking and bathing are the two primary ways people consume hazardous compounds from groundwater. The threats that bathing poses to human health remain mostly unknown. Therefore, only the impacts of the drinking water route on persons living in the research region were considered in this study. The average daily intake of an essential element from distinct components of the environment is represented by ADAD, and ADRD is equivalent to the numerous nutritional requirements of the RDA (recommended dietary allowances) type (Cabral et al., 2020). As long as the facts allow for the computation of such a dose, both dosages were reduced to exposure from a single environmental compartment (in this case, drinking water). According to the US EPA's Integrated Risk Information System (IRIS) database, the reference dose for fluoride in a specific route is 0.06 mg/kg-day, and for nitrate is 1.6 mg/kg-day (Environmental Protection Agency 2007). The RfD values for Iron and copper are 0.7 mg/kg/day and 0.04 mg/kg/day, respectively (Javed & Usmani, 2016).

ii) Computation of HQiW and HI: For computing the HQiW and HI, the following procedure needs to follow

I) Shortlisting significant parameters for the calculation of the HI. TDS, CL, F, Hardness, Nitrates, Fe, and Cu were selected for their adverse effects on human health and daily activities.

II) Initial weights (wi) were given to each parameter based on their respective significance and contribution to the overall site-specific drinking water quality (via expert opinions).

III) The relative weightage of the considered parameters was evaluated by using the following Equation 5.14 and calculated relative weights shown in Table 5.10.

$$\mathrm{Wi} = \frac{\mathrm{wi}}{\sum_{i=1}^{n} \mathrm{wi}} \qquad \text{Eq. 5.14}$$

Table 5.10 Relative weights of chemical parameters

Qualitative parameter	**wi**	**Wi = wi/Σwi**
TDS	3	0.115
Total Hardness	3	0.115
Fluoride	3	0.115
Nitrate	5	0.192
Iron	4	0.154
Chloride	3	0.115
Copper	5	0.192

IV) The average daily dose (ADD) as the exposure metric for Cu, Fe, F^-, and NO_3^- was calculated using Equation 5.15 (Hu, 2022).

$$\mathrm{ADD} = \frac{\mathrm{C \times IR \times ED}}{\mathrm{ABW \times AT}} \qquad \text{Eq. 5.15}$$

For Chloride, TDS, and Total Hardness, two values of ADAD and ADRD were calculated using Equation 5.16 and 5.17, respectively.

$$\mathrm{ADAD} = \frac{\mathrm{C \times IR \times ED}}{\mathrm{ABW \times AT}} \qquad \text{Eq. 5.16}$$

$$\mathrm{ADRD} = \frac{\mathrm{MRC \times IR \times ED}}{\mathrm{ABW \times AT}} \qquad \text{Eq. 5.17}$$

Where C is the amount of pollutants in a litre of water (mg/L), IR is the amount of water consumed daily (L), and ED is the amount of time exposed (days); The average body weight (kg) is ABW; The minimum necessary concentration, or maximum required concentration (MRC), is the lowest concentration of an element at which there is no known harm to health. AT stands for averaging time (days), which denotes the period over which the dose is averaged (Rapant et al., 2020). This study averages the exposure dose throughout the duration; thus, AT equals ED in value. Table 5.11 shows the input exposure data for human health risk assessment estimation.

Table 5.11 Input exposure data for estimating of human health risk assessment

Parameter	**Value**	**Unit**
ABW – average body weight	76.74	kg
C – concentration of chemical elements in water	Site-specific	mg/l
IR – daily water intake	2.59	L
ED – duration of exposure	1	Year
AT – averaging exposure time	365	Days
EF – exposure frequency	365	Days/year

V) The hazard quotient (HQi), which was determined by comparing the ADD and the RfD (mg/kg/day), was used to quantify the non-cancer risk using Equations 5.18 and 5.19.

$$HQ_i = \frac{ADD}{RfD} \quad \text{Eq. 5.18}$$

$$HQ_i = \frac{ADAD}{ADRD} \quad \text{Eq. 5.19}$$

VI) Individual parametric HQiW was calculated using Equation 5.20.

$$HQ_iW = HQ_i * W_i \quad \text{Eq. 5.20}$$

VII) A HI was calculated as the sum of HQiWs

$$HI = \Sigma HQ_iW \quad \text{Eq. 5.21}$$

The following scale shown in Table 5.12 has been adopted to assess the level of non-carcinogenic health hazards to consumers due to continuous consumption of contaminated water.

Table 5.12 Hazard index classification

Risk Level	HI	Risk classification	Colour
1	≤0.1	Without risk	
2	>0.1	Low risk	
3	>1.0	Medium risk	
4	>4.0	High risk	

However, because various age groups have various vulnerabilities, such as newborns, toddlers, and adults, more precise health risk assessment results may be obtained by categorizing the population into these different representative age groups (Rapant et al., 2020). The performed classification of water based on a human health hazard index reveals that out of 350 water samples, 165, 177, and 7 samples fall in the low, medium, and high-risk zones, revealing that 52% of the city area comes under the medium and high-risk zones, proving detrimental to human health. Most of the study region receives water from the Bisalpur dam after primary treatment, resulting in water quality ranging from good to fair, depending on onsite storage and supply circumstances. The water obtained from the hand pump and tube well (especially from the industrial area) has low and marginal water quality, with medium and high risk of being subject to natural geogenic and anthropogenic pollution. Figure 5.13 represents the percentage of water samples classified using the health hazard index.

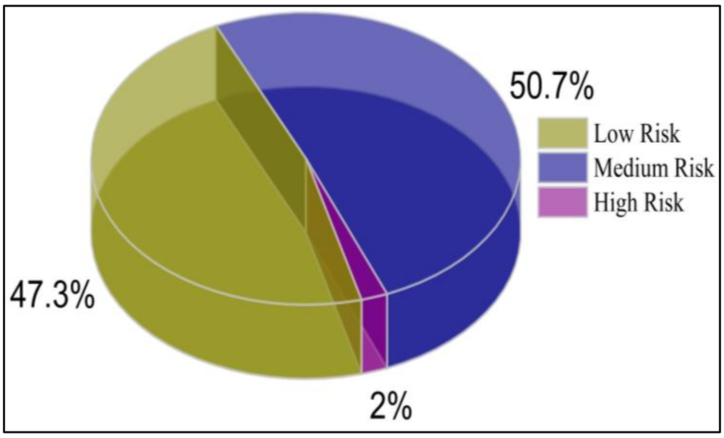


Figure 5.13 Weighted health hazard index-based water classification

c) Development of Fuzzy Logic (FL) based Index: Creating an index based on FL involves considering three key components of the FIS: membership functions, fuzzy set operations, and inference rules. Each chosen input or input set has a subset-based domain known as the universe of discourse articulated using linguistic terms. If-then rules and fuzzy set operators specify the links between the subsets of inputs and outputs (Zadeh et al., 1996). The FIS creates a non-linear mapping of an input data vector into a scalar output using fuzzy rules. Input/output membership functions, FL operators, fuzzy if-then rules, output set aggregation, and defuzzification are all part of the mapping process. A multi-output FIS is comprised of independent multi-input, single-output systems. Figure 5.14 shows a general model of the FIS that turns sharp inputs into crisp outputs.

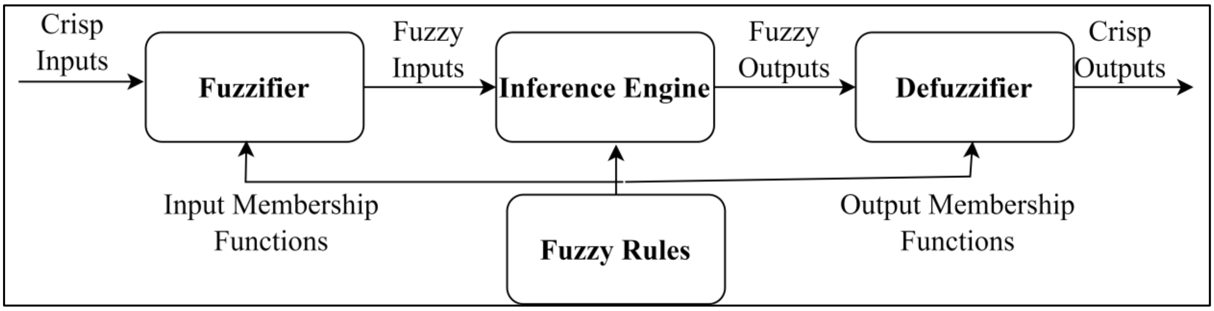


Figure 5.14 Fuzzy interference system

Generally, the FIS comprises four components: fuzzifier, inference engine, rule base, and defuzzifier. In fuzzifier maps, the input data first identifies the extent to which the values belong to each fuzzy set using the established membership function provided in Equation 5.21 (Jang & Sun, 1995; Turksen, 1991; Karr & Gentry, 1993). The interference engine maps the input data into fuzzy output sets and assesses the extent to which the antecedent satisfies the rule. The rule base includes linguistic rules offered by experts, which are extracted from numerical data. Fuzzy operators are used to provide a unique number representing the antecedent's outcome for a given rule when the antecedent has many clauses where one or more rules could activate simultaneously. Once the rules are established, the FIS can be seen as a system that maps an input vector to an output vector (Vyas et al., 2019). The outputs from each rule are then combined. During aggregation, fuzzy sets representing each rule's output are merged into a single fuzzy set. The defuzzifier returns one number after receiving a fuzzy set with various output values, converting the fuzzy set into a crisp number using Equation 5.22 and 5.23 (Gharibi et al., 2012; Ocampo-Duque et al., 2013; Patki et al., 2015).

$$mA_{(x)} = \{(x_1, \mu_A(x)) | x \in X\} \qquad 0 \leq \mu_A(x) = 1 \qquad \text{Eq. 5.22}$$

$$Z = \frac{\int \mu(z) z dz}{\mu(z) dz} \qquad \text{Eq. 5.23}$$

For conducting the water analysis, the pH, Dissolved Oxygen (DO), Total Dissolved Solids (TDS), Chloride (Cl^-), hardness (as $CaCO_3$), Fluoride (F^-), Nitrates (NO_3^-), Iron (Fe), and Copper (Cu) were considered. The analysis shows that values of pH and DO of all water samples lie between the standard limits defined by BIS, which exempts it from developing the fuzzy Index. The triangular membership function was initially defined for each parameter by adopting the experimental value range and Equation 5.24.

$$(x; a, b, c) = \begin{cases} 0, & x < a \text{ or } c < x \\ \dfrac{(a - x)}{(a - b)}, & a \leq x \leq b \\ \dfrac{(c - x)}{(c - b)}, & b \leq x \leq c \end{cases} \qquad \text{Eq. 5.24}$$

Where the parameters {a, b, c} with (a < b < c) specifies the x-axis coordinates of triangular membership function and x represents site-specific experimental value.

The linguistic terms used to define the fuzzy set were very low, low, moderate, high, and very high for Total Dissolved Solids (TDS), Chloride (Cl^-), Hardness (as $CaCO_3$), Fluoride (F^-), whereas Low, medium, and high were used for Nitrates (NO_3^-), and Iron (Fe). For Copper (Cu), Low and high terms were used, and each parameter as an input was assigned to one of the three fuzzy sets in terms of the membership functions. The developed triangular membership function for each parameter is shown in Figure 5.15.

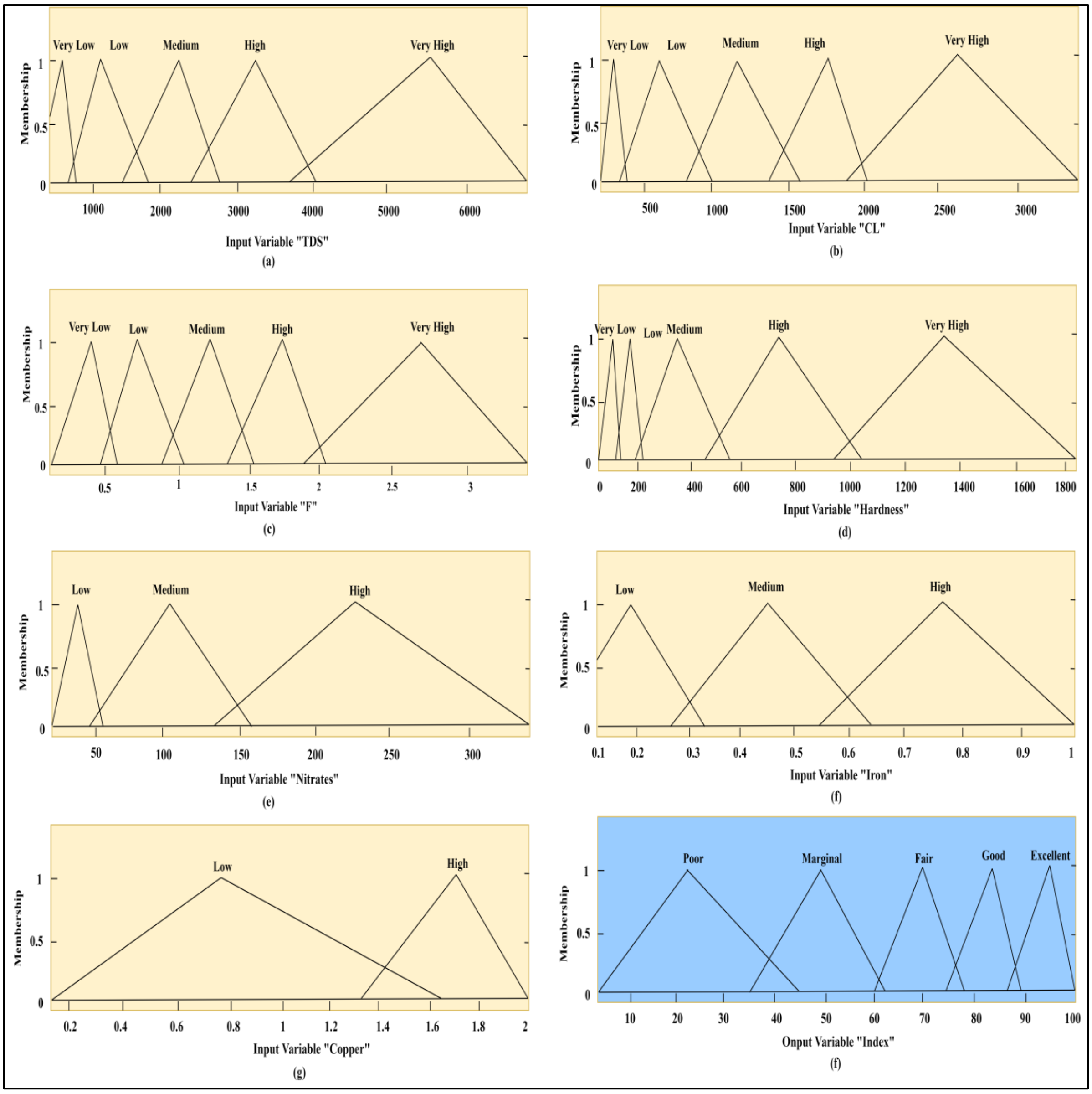


Figure 5.15 Fuzzy membership function for predefined water quality parameters

For selecting the ranges for each variable, the threshold values have been set as the boundary values. Below-standard levels for each parameter are categorised as low, while above-standard values are categorised as high. Further, the rules were formed based on expert knowledge (Le et al., 2019; Zadeh et al., 1996). The normalization in the current work was carried out utilizing the fuzzy inference technique. Further, the Mamdani inference system was employed as part of our attempt to integrate the expert's knowledge and use it to develop a FL based water quality indicator (Ross, 2009; Tiwari et al., 2018). Table 5.13 highlights some fuzzy inference rules developed during the study.

Table 5.13 Examples of fuzzy inference rule

Input								Output
Operators →	**AND**	**AND**	**AND**	**AND**	**AND**	**AND**	**AND**	**THEN**
Criteria►	**TDS**	**CL**	**F**	**Hardness**	**Nitrates**	**Iron**	**Copper**	**Results**
Rule 1	Very High	Low	High	Very High	Low	High	Low	Poor
Rule 2	Low	Very Low	Low	Medium	Low	High	Low	Marginal
Rule 3	Very low	Very Low	Very Low	Low	Low	High	Low	Fair
Rule 4	Medium	Low	Medium	High	Low	High	Low	Good
Rule 5	Low	Low	Low	Low	Low	Low	Low	Excellent

By utilizing the centre of gravity (COG) approach (Equation 5.22), the outputs were defuzzfied. The COG method is the most practical and physically applicable among the numerous defuzzification techniques. After defuzzification, the values obtained from the MATLAB tool were utilized to determine the water quality based on the predefined categories. In terms of output values, the most typical scoring method for assessing water quality is between 1 and 100, with a result near 90 samples indicating good quality water. Table 5.14. shows the water quality categories applied for the proposed study.

Table 5.14 Fuzzy-based water quality classification

Range	Description	Colour
0-44	Poor	
45-64	Marginal	
65-79	Fair	
80-94	Good	
95-100	Excellent	

For performing the fuzzy-based water classification, the FL tool from MATLAB was used. From the parameter qualitative tests, it was evident that the pH and DO values were 6.5 to 8.5 and 4 to 6 mg/l, meeting the standard permissible limits for drinking water, which were excluded from the classification. The remaining parameters, TDS, Cl^-, Fe, N, Cu, F^-, and Hardness were considered for the fuzzy indexing. From the water quality index generated through fuzzy, it is perceived that 67, 154, 41, 84, and 4 samples fell into the poor, marginal, fair, good, and excellent categories, respectively. About 63.7 % of the samples belonged to the marginal and poor category and demanded effective water treatment before consumption at an individual or community level. Figure 5.16 shows the percentage of water samples classified using the fuzzy-based index.

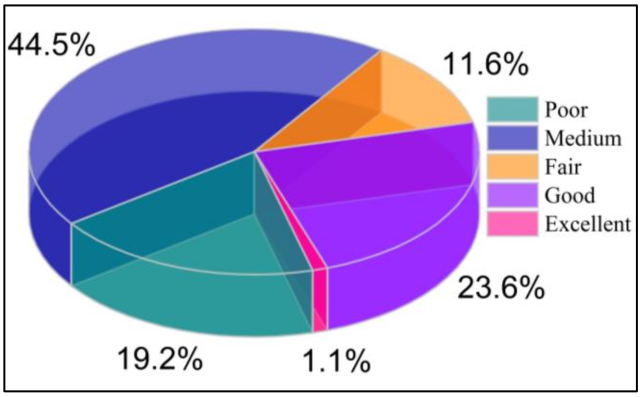


Figure 5.16 Fuzzy based water classification

d) Mapping of water quality index: The extensive capabilities of the GIS tool were used to create a water quality map for the study area by super positioning the indices created by the fuzzy and HQiW. Each sampled point was classified as a discreet source serving a particular area within a radial distance. The city's population density and tentative population served by a source collected during the preliminary survey were used to determine the served area. The radial area in sq. km was then incorporated as input data, and along with derived indices, thematic maps for the city were developed.

The calculated index values and geographical locations of the sampling points were considered input, and the latter were imported as point features in the GIS environment. The total population serviced by each sampled source at a population density of 6500 people per sq. km demarcated the region it served. The obtained area values were then utilized to create buffer zones identifying the area served by a sample point on the GIS interface. Finally, the point feature was classified as per the classification interval for the fuzzy and health hazard indices to distinguish the categorised area. Figure 5.17 shows the classification of the city area based on the qualitative classification. The consumed input data and estimated HI and fuzzy index sample is provided in Appendix G.

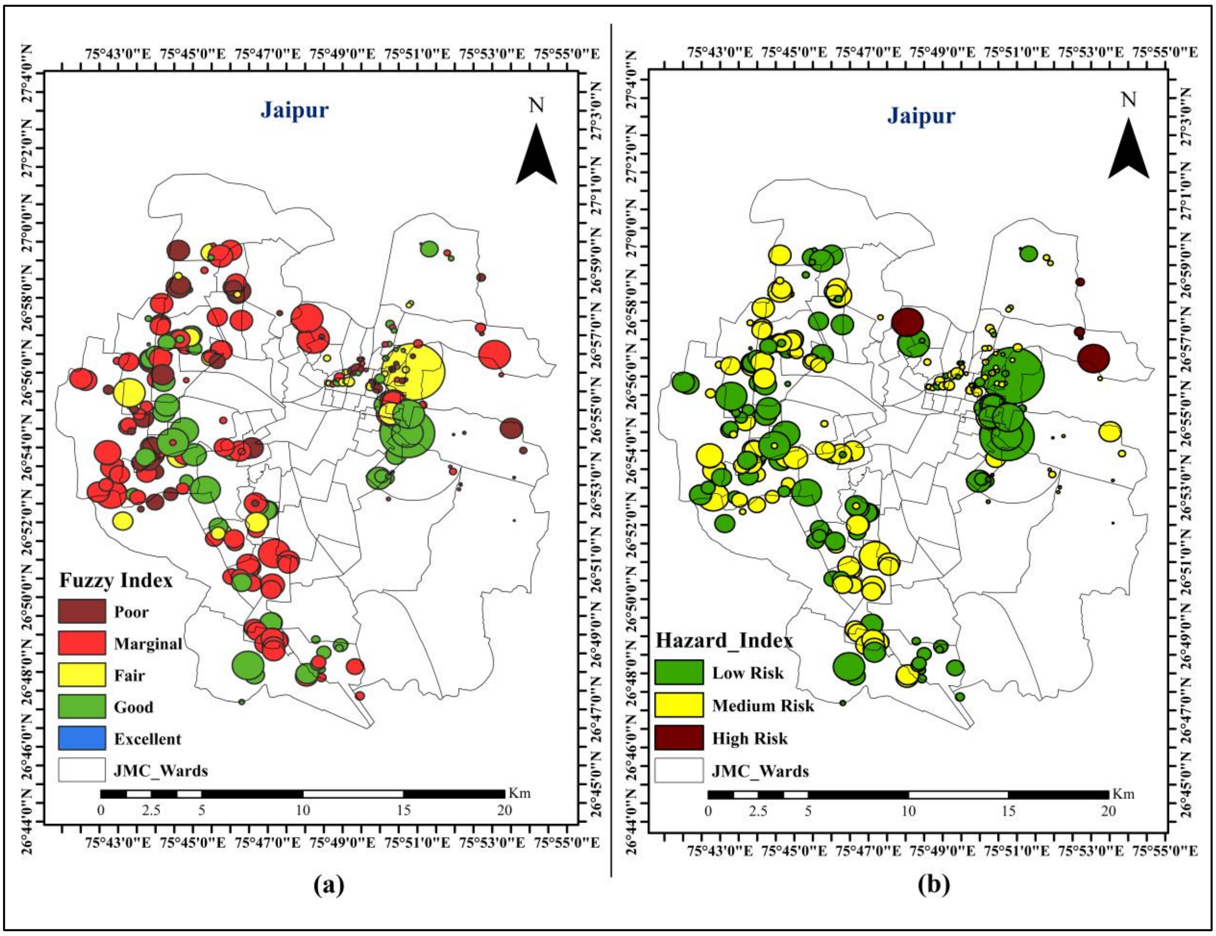


Figure 5.17 City area classification based on a) Fuzzy index (b) Hazard index

The maps show a clear overlapping of locations for both indices. The marginal and poor points shown in Figure 5.17 (a) have a clear synchronism with sample points falling under the high and medium risk category in Figure 5.17 (b). Similarly, the sampled points were classified as excellent, good, and fair and fit harmoniously with locations classified as low risk through the novel health hazard index. These maps efficiently classify the Jaipur municipal area for the new water infrastructure construction while highlighting the critical water treatment systems and the visualization. However, due to physical and time constraints, most of the city area and water resources remain unclassified. So, to classify the remaining water samples, ANFIS and ANN prediction modeling were performed. The developed prediction model eases the classification of the water samples from the remaining area. The following section elaborates on the detailed procedure for performing prediction modeling.

e) Water quality prediction modeling: Water quality modeling leverages advanced analytical and environmental data to forecast the water quality over the study region. Many AI algorithms enhance the efficiency and accuracy of prediction modeling by incorporating real-time sensor data, historical information and physicochemical parameters. In this study, Artificial Neural Network (ANN) and Adaptive Neuro-Fuzzy Inference System (ANFIS) prediction models were trained and compared using the classified water samples over the Jaipur municipality regions.

i) Artificial Neural Networks (ANNs): An ANN, a black-box technique, which models and learns complicated non-linear relationships between the input and output. ANN is a reliable computational tool that maps input and heterogeneous data in many scientific applications (Ighalo et al., 2021). In ANN, neurons are the smallest component of a neural network and are typically organised in a network for prediction. The neurons receive input data from the environment or an internal node, accomplish operations on the data and generate the output. These neurons get fired when their net output exceeds a certain threshold. Generally, ANN is divided into three layers to estimate and forecast a complex function: input, hidden, and output layer, as shown in Figure 5.18 and iterative trials were required to determine the number of hidden layers.

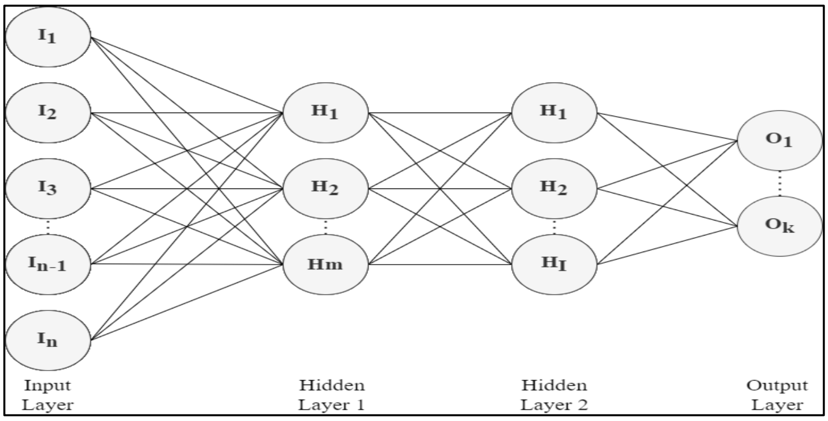


Figure 5.18 ANN architecture

The classified water sample data set is supplied into the input layer (I_1, ... I_n), and the output is estimated using Equation 5.25.

$$n = \sum w_{ij} x_i + b_i \qquad \text{Eq. 5.25}$$

Where w_{ij} is the difference in weight between neurons in two different layers, n is the neuron's output, bi is the bias, and xi is the value of the neuron in the preceding layer. At last, the sigmoid function was employed as the output transfer function. In this study, Out of 350 classified samples, 70%, 20%, and 10% were split and exhausted for training, testing, and validating purposes. For determining the number of neurons, the specific empirical criteria by considering the number of inputs (NI) and the output (NO) is represented in Table 5.15 and model parameters are determined as 7:14:1 architecture, meaning there are seven inputs (WQ parameters), fourteen hidden nodes, and one output (WQI) from the coefficient of determination (R^2) value.

Table 5.15 Determination of the number of neurons

Number of Neurons	**Number of Neurons**	**Overall R^2 value**
2*NI	14	0.9531
NI+ NO	8	0.73579
0.75 * NI	5	0.95099
2* NI +1	15	0.95105
NI	7	0.95236
(NI+NO)/2	4	0.94487

R^2 is typically used to evaluate the trained network's accuracy. The coefficient of determination indicates how well independent variables explain the dependent variable's value. A better predictive relationship is indicated by a higher R^2 score (Chang et al., 2010). With the determined model architecture of 7:14:1 (2*NI), the ANN model was trained and tested for fuzzy and HI indices. Figure 5.19 represents the comparison between calculated and predicted values; a solid line is the best-fit line, indicating the closest approximation between the predicted and calculated values. The reported R^2 value for the HI index is 0.839, which indicates that the input variables included in prediction modeling are sufficient for predicting the HI index. In contrast, the R^2 value for the Fuzzy Index is 0.524, which indicates that the input variables included in prediction modeling are insufficient for predicting.

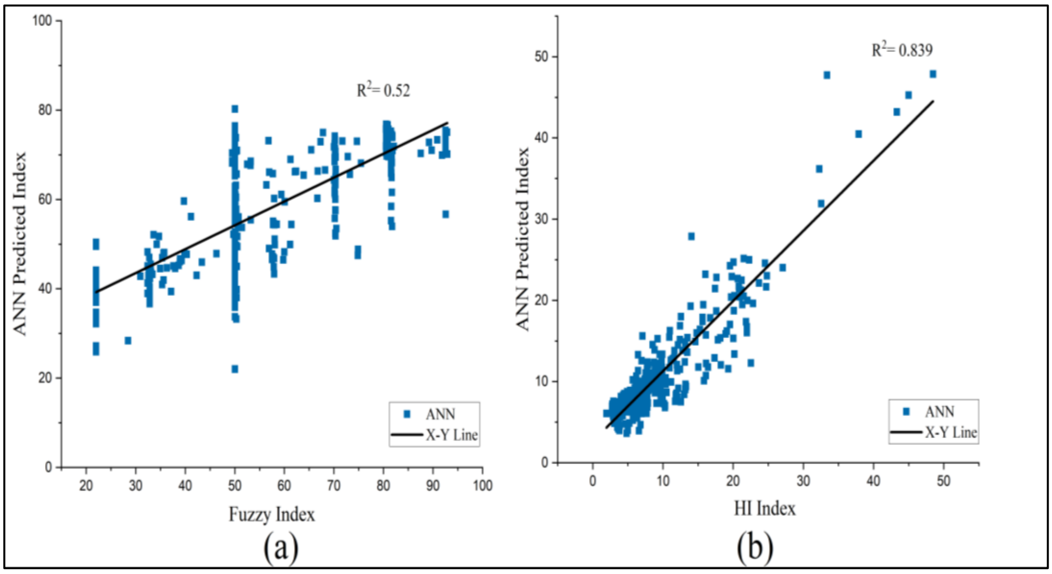


Figure 5.19 ANN predicted output for a) Fuzzy index and b) Hazard index

ii) Adaptive Neuro-Fuzzy Inference System (ANFIS): Jang proposed an ANFIS algorithm, an integration of ANN and FIS, in 1993 to map and simulate input-output interactions (Buragohain & Mahanta, 2008). ANFIS employs both neural network learning techniques and a fuzzy approach as a multi-layer network (Gallo et al., 1999). It uses a Takagi-Sugeno type FIS, with each fuzzy rule output as a linear combination of input variables plus a constant term. ANFIS applies two learning algorithms: backpropagation and hybrid learning (Loganathan & Girija, 2013). The hybrid learning strategy combines backpropagation with the least squares method, whereas backpropagation learning uses the ANN methodology. A basic ANFIS architecture has five layers, shown in Figure 5.20 and explained below. For understanding a FIS, following two fuzzy rules assuming two input variables, x and y, and a single output variable as z are considered, Equations 5.26 and 5.27.

$$R_1.\text{If x is } A_1 \text{ and y is } B_1, \text{then } f_1 = p_1 + q_1 + r_1 \quad \text{Eq. 5.26}$$

$$R_2.\text{If x is } A_2 \text{and y is } B_2, \text{then } f_2 = p_2x + q_2y + r_2 \quad \text{Eq. 5.27}$$

where x and y are inputs for node i, A1, A2 and B1, B2 are membership functions, and p1,p2, q1,q2, and r1,r2 are the consequent parameters and f1 and f2 are the output function variables.

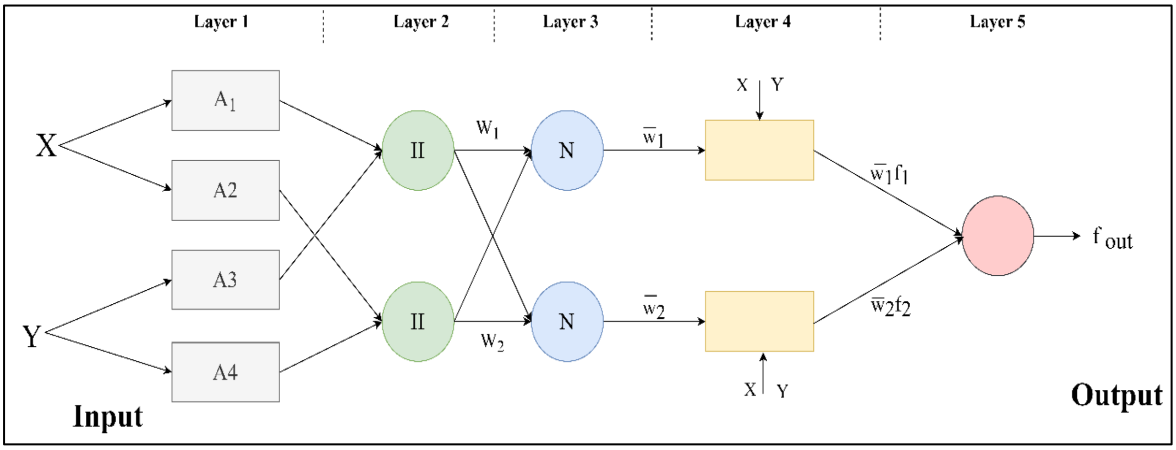


Figure 5.20 ANFIS architecture

Layer 1: In this layer, inputs have been fuzzified using an appropriate membership function. Generally, membership functions exist in various shapes, including general bell, triangular, trapezoidal, and Gaussian. Following Equation 5.28 and 5.29 generally suggests a general bell shape feature. At this layer, the node function is represented as each node.

$$O_{1,i} = \mu_{Ai}(x) \text{ for } i = 1{,}2 \text{ or} \quad \text{Eq. 5.28}$$

$$O_{1,i} = \mu_{Bi-2}(y) \text{ for } I = 3;\ 4 \quad \text{Eq. 5.29}$$

Where x and y represent input nodes, Ai and Bi represent fuzzy sets, and (x) and (y) represent membership functions.

Layer 2: This layer is referred as the firing layer. It is the preceding component of a fuzzy rule. At this point, each node multiplies the input signals and passes the result to the node of the following layer, as an example shown in Equation 5.30.

$$w_i = \mu_{Ai}(x)x * \mu_{Bi}(y)\ for\ i = 1, 2 \quad \text{Eq. 5.30}$$

Where wi denotes the firing strength of a rule at the i^{th} node.

Layer 3: This phase offers normalized firing strengths. At this step, each node computes the firing strength of the i^{th} rule using Equation 5.31.

$$\overline{w_i} = \frac{w_i}{w_1 + w_2}, \quad i = 1{,}2 \quad \text{Eq. 5.31}$$

Layer 4: The defuzzification method has been applied at this layer, sometimes known as the normalization layer, to produce the best possible input-output matching. The process of this layer is represented by Equation 5.32.

$$Q_i^4 = \overline{w_i}f_i = \overline{w_i}\,(\,p_i x + q_i y + r) \quad \text{Eq. 5.32}$$

where w_i is the previous output and pi, qi, and r are the subsequent parameters.

Layer 5: The overall output from all the signals can be represented in an output layer by Equation 5.33.

$$O_i^5 = \sum \overline{w_i} f_i = \frac{\sum_i w_i f_i}{\sum_i w_i} \qquad \text{Eq. 5.33}$$

The optimum ANFIS model can be developed by selecting the right amount of membership functions, fuzzification functions, the type of output function, the optimization method, the training algorithm, and the number of epochs. To attain the best simulation results, the ANFIS editor in MATLAB allows modification of the consideration. In the case of the fuzzy index, the number of membership functions was kept similar to the categorization of the water quality parameter. While performing simulation for the HI index, the standard values of the membership function as three were kept for all the input water quality parameters, and modeling was performed for the triangular, trapezoidal, general bell, and Gaussian membership functions and R^2 values are provided in Table 5.16.

Table 5.16 R^2 values for membership functions

Indices/ Memberships	**R^2 values for Fuzzy index**	**R^2 values for HI index**
Triangular	0.8413	0.99647
Trapezoidal	0.7832	0.20787
General Bell	0.8284	0.96544
Gaussian	0.8099	0.97770

The triangular membership function for both the Fuzzy and HI indexes gives the lower Root Mean Square Error (RMSE) values and is considered the optimal topology and used for further analysis. The detailed specifications of the ANFIS prediction model are presented in Table 5.17.

Table 5.17 ANFIS model properties for fuzzy and HI indexes

Properties	**Fuzzy**	**HI**
Number of Nodes	22566	4426
Number of Linear parameters	11250	2187
Number of Non-linear parameters	11362	63

Number of training data pairs	245	245
Number of checking data Pairs	0	0
Number of Fuzzy rules	11250	2187

The comparative analysis involved evaluating the predictive accuracy of the ANFIS model concerning the R^2 values. The ANFIS models demonstrate favourable predictive capabilities. However, from a statistical standpoint, the ANFIS model for the fuzzy index exhibits a R^2 value of 0.84, while the ANFIS model for the HI index exhibits a higher R^2 value of 0.996. The residual plots, as depicted in Figure 5.21, help to comprehend the predicted deviation from the experimental data.

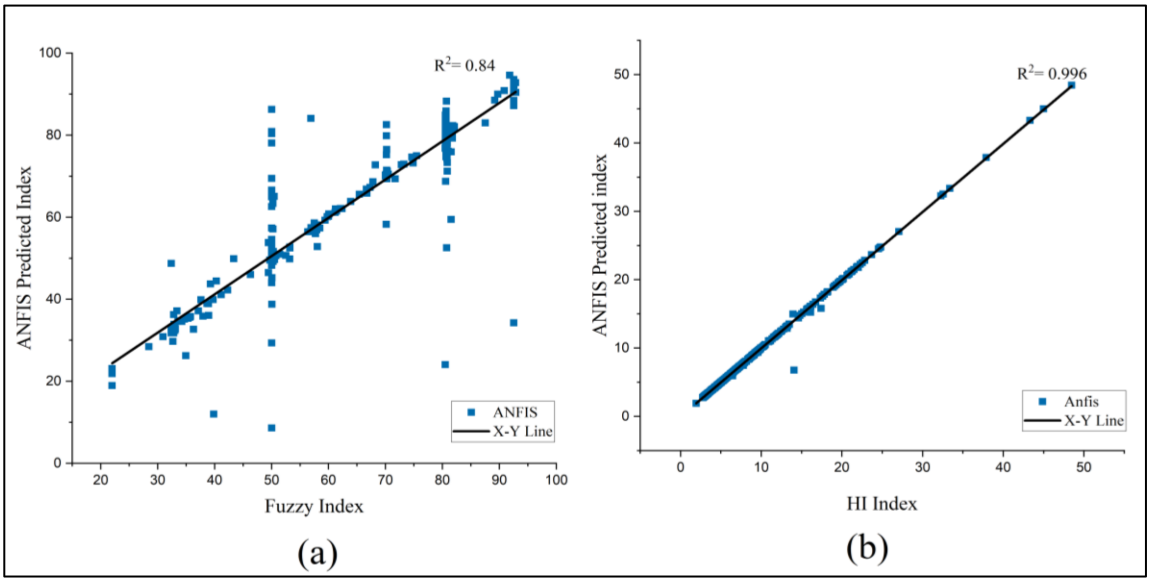


Figure 5.21 ANFIS predicted output for a) Fuzzy index and b) Hazard index

The study concluded that ANFIS proves a trustworthy and accurate approach for predicting WQI in the Jaipur Municipality region. The application of these methods automates the calculation of WQI and considerably decreases computation time; thus, it can be utilized in any aquatic environment across the world as an effective technique for forecasting water quality, particularly for specific water resource problems that demand high-precision forecasting and conventional methods cannot provide high accuracy.

5.2.6.3 Database creation

Infrastructure projects involve numerous activities that require multiple resources for their accomplishment. It is challenging to maintain and amend records manually in the field, resulting in excessive time and resource consumption (Assaf & Al-Hejji, 2006). In such cases, creating a digital database plays an important role and allows the handling of multiple issues efficiently imposed due to complex activities and the involvement of multiple stakeholders. Generally, infrastructure projects include various essential documents such as architectural plans, engineering schematics, as-built documentation, financial records, approvals, and certificates that must be updated and revised according to the as-built drawings and documents. To avoid confusion among stakeholders and reduce rework, it is necessary to store these components in an organized manner (Love et al., 2010). By maintaining data in a structured manner, databases enhance the collaboration and communication among all stakeholders (Chen et al., 2016). The created database as a single repository safeguards confidential financial data and proprietary designs while improving the transparency and integrity of essential data. In addition, databases offer speedy decision-making and proactive risk management with real-time insights into project progress, resource allocation, and potential issues (Jin, 2010). It intends to store a large amount of data that can be used for research and design by performing multiple analyses. Databases consist of tables with rows and columns representing different attributes or fields within a record.

In the proposed study, implementing RwHs at multiple locations requires various types of resource data and information. In such cases, creating a digital database is important to provide site-specific information. To create a digital database, the project management tool Primavera p6 was used. The created database includes the standard rates for resources derived from the BSR provided by the Public Works Department, City Circle Jaipur, and the ISR provided by the Rajasthan Urban Infrastructure Development Project. The capabilities of GIS have been used extensively to select sites and extract their properties. The created database and extracted site properties were used to assess the feasibility of the RwHs over multiple locations by developing BIM dimensions. The detailed procedure followed to create the database is shown in Figure 5.22 and explained in the subsequent section below.

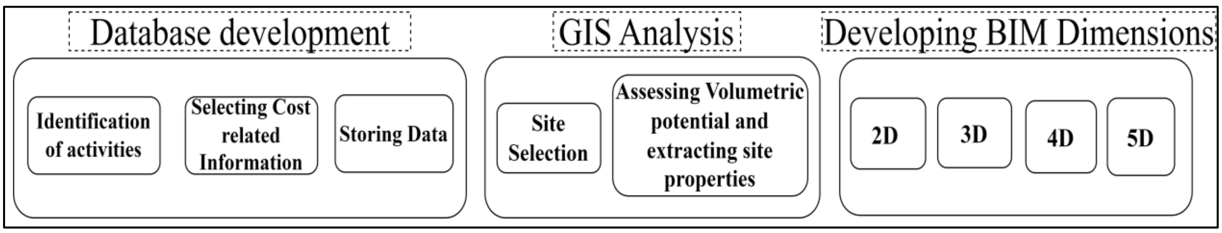


Figure 5.22 Methodology for database creation

a) Database development: The project management tool Primavera p6 was used to create a database. The Primavera p6 database provides a structured and organized method to handle complex information and facilitate various project management functionalities. The p6 pro standalone (SQLite) database stores resource specifications and cost data. In the context of Primavera p6, the term "SQL database" refers to a relational database management system (RDBMS) that uses a SQL to manage and manipulate data. SQL is a standardized language for interacting with relational databases, enabling data insertion, retrieval, updating, and deletion tasks. Primavera p6 leverages this SQL database as the underlying technology to store and organize all the information related to projects, activities, resources, and other aspects of project management. The structured nature of the SQL database ensures that data are stored in organized tables with well-defined relationships that accurately represent complex interdependencies and hierarchies in project management. The following steps were followed while developing the database for the proposed RwHs.

i) Identification of activities: Identifying activities marks the first step in project design and database development. This step involves creating an extensive list of activities involved in infrastructure projects and seeking multiple resources for accomplishment. Based on the type of infrastructure project, the activities involved were determined by the experience of a similar kind of project and expert knowledge. The organized list of activities allows for efficient planning and assigning resources to each activity to achieve the project goal. For this study, while storing data in the SQL database, the activities and resources involved were taken from the pilot study sections 5.2.3 and 5.2.4. The obtained activity list contains activities from site clearing to backfilling and finishing. A total of 21 activities were involved in the on-ground implementation of the sedimentation tank and storage tank over a single location.

ii) Determining resource cost: A careful assessment has been undertaken to determine the standard rates that dictate how much the resources used in the activity should cost. This assessment has involved considering the standard schedule rates provided by the local authority. The considered schedule rates serve as a crucial reference, like a thorough reference book, helping us to comprehend the proper cost for different resources; in addition to providing a general breakdown of costs, this guide offers specific resource information. This book also includes an in-depth exploration of their unique characteristics and the circumstances in which they were utilized. These standard rates serve as a valuable tool that allows us to make fair and well-informed decisions regarding the cost of resources while considering their unique attributes.

iii) Data Storing: For this study, the standard rates for the resources and the materials were derived from BSR and ISR. The rates provided in the BSR are established through a combination of historical data, market trends, and economic factors, providing a consistent reference point for evaluating project expenses. BSR includes the required labour type, equipment, material specifications, and standard rates. Simultaneously, the ISR refines the cost estimation process by accounting for project-specific conditions, site characteristics, design complexities, and other variables. Using the ISR's site-specific precision helps mitigate risks associated with uncertainties, optimizes resource distribution, and ensures that costs align closely with the intricacies of the project. The costs of the resources and activities were considered by the BSR and ISR.

The list of the activities and the resources involved have been added to the database hierarchically, along with its per unit cost, and appended in Appendix H. The stored data provide a consistent baseline for cost, enhancing decision making, and improving budget control during the conceptual stage. The database includes the activities and resources for the activities from site clearing and earthwork to finishing work. Along with resources, the cost involved in the carriage of material from the RwH site to the dumping site is also considered and added under the carriage category. The provided classes for the resources in Primavera p6 as material, labour and non-labour were used as the main classes and subclasses for each material, labour type and machinery involved were added along with standard working units and their cost. Figure 5.23 shows the database created in Primavera p6.

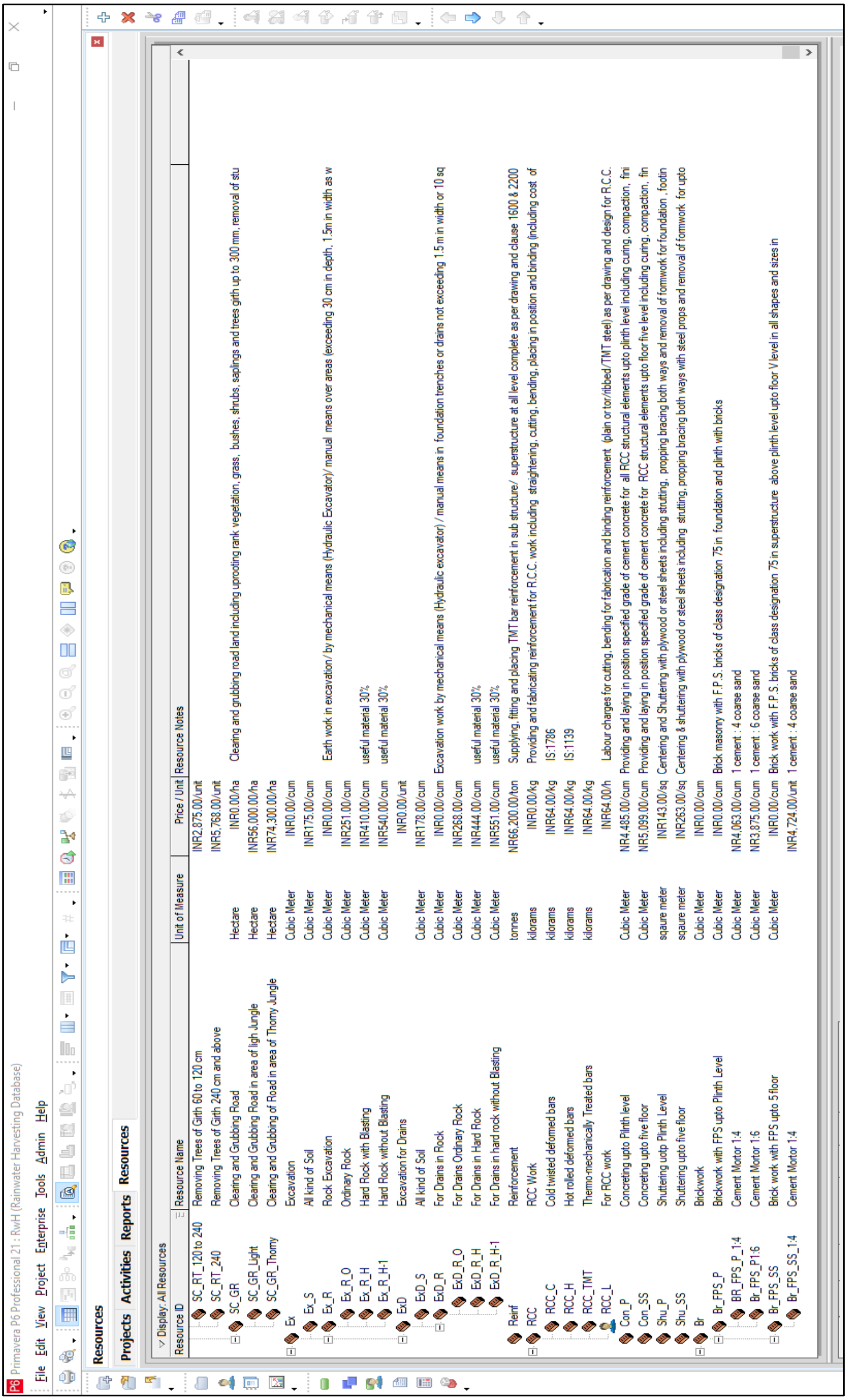


Figure 5.23 Database in Primavera p6

b) GIS analysis: In this study, the extensive capabilities of GIS were utilized to extract the site properties for the proposed RwHs over multiple locations in the Jaipur municipality regions. Advances in GIS tools have enabled data analysis and extraction to understand real-time site characteristics. The extracted site characteristics empower decision makers to determine strategies, develop design alternatives, and perform efficient resource allocation. Initially, wards were selected to determine their hydrological potential, and ground survey data and satellite images were imported to extract on-site site properties. The extracted site properties were used to select the type of resources involved in the activity at a specific site. The following subsections elaborate on the detailed procedure performed in GIS analysis.

i) Site selection: To evaluate the practical feasibility of the proposed RwHs, the multiple municipality wards over the Jaipur Municipal region have been selected randomly. These selected wards served as diverse samples, encompassing various municipal geographical and environmental characteristics. The selection of municipality wards allowed us to utilize the created database from different perspectives through added resources. Figure 5.24 shows the randomly selected wards over the municipality region of Jaipur.

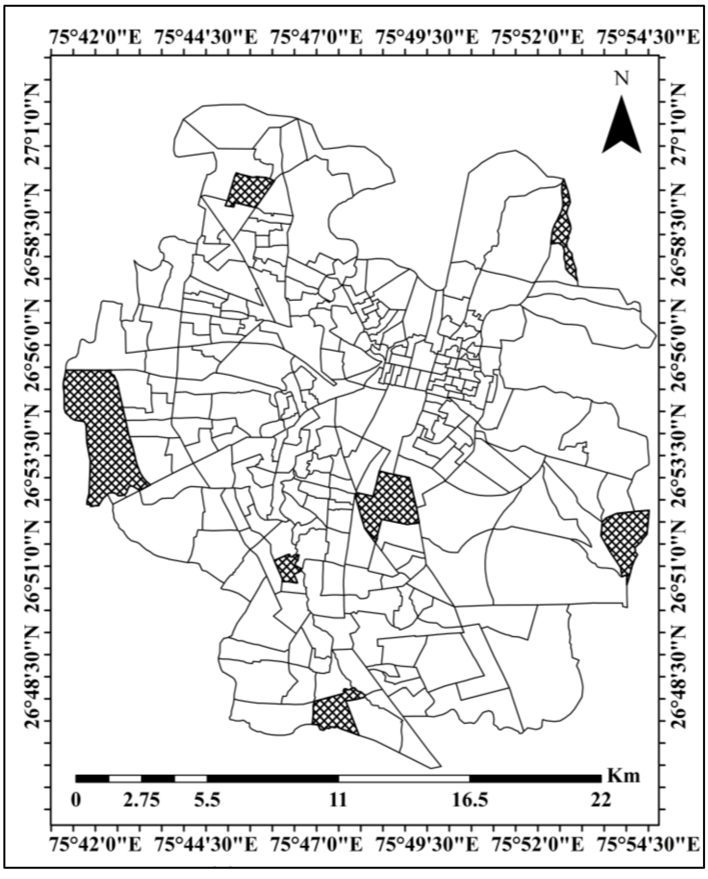


Figure 5.24 Selection of municipal wards

ii) Assessing volumetric potential and extracting site properties: Estimating the hydrological potential and extracting site-specific properties are important steps for the efficient implementation and design of the proposed RwHs. Therefore, hydro-spatial analysis was performed on each ward individually to determine the hydrological potential, which was used further to design the RwH components. For the hydro-spatial analysis, the DGPS survey over the municipality region was imported and clipped using the shape file of each selected ward. The clipped three-dimensional DGPS survey points were used to create a DEM map using the IDW interpolation method in ArcGIS. Furthermore, the DEM was utilized to generate the FA map. To develop the FA map, fill and flow direction tools were sequentially applied to DEM. The resulting FA map provides the flow line and the cumulative number of accumulated pixels. To estimate the runoff over the selected wards, 1 and 10 days of rainfall were considered. A raster calculator from the ArcGIS environment was used to perform raster multiplication.

The raster generated from the raster calculator provides the amount of runoff accumulated over each pixel along with its flow path. By observing the runoff raster over the municipality ward, pixels with the highest runoff values were selected manually and marked as RwH sites. The pinpointing serves as RwHs site locations with the estimated hydrological potential. The selected sites and their runoff potentials were used to determine the geometric characteristics of the sedimentation and storage tanks. Along with the hydrological potential, the extraction of site properties is important for understanding the real-time ground situation, which will affect the overall progress of the project. So, to visualize the ground situation, the Cartosat 3 satellite images were procured from the NRSC and imported into GIS as a base map. The imported map visualizes the exact ground conditions of the selected sites. The available vegetation information or type of land, such as (farmland or barren land) was extracted from the base map to estimate the resources involved in site-clearing activity.

While performing any construction activity, understanding the available soil type and its properties influences design considerations and implementation methodology. Therefore, to understand the available soil type and its properties, an extensive soil survey was conducted over the entire Jaipur municipality. The soil survey included parameters such as structure, consistency, porosity, permeability, bulk density, water holding capacity, and pH, assessed using the collected soil samples. The values of porosity, bulk density, and soil texture were used to determine the hardness of the soil. The inverse proportion between the porosity and hardness and linear relation between the bulk density and hardness used categorise the soil into soil, ordinary rock, and hard rock as per standard rates provided in BSR. The determined hardness of soil influences the resources involved in excavation activity. Based on the hardness of the available soil, the equipment types were decided for excavating the earth. Figure 5.25 shows the identified RwH sites and soil samples over the study region.

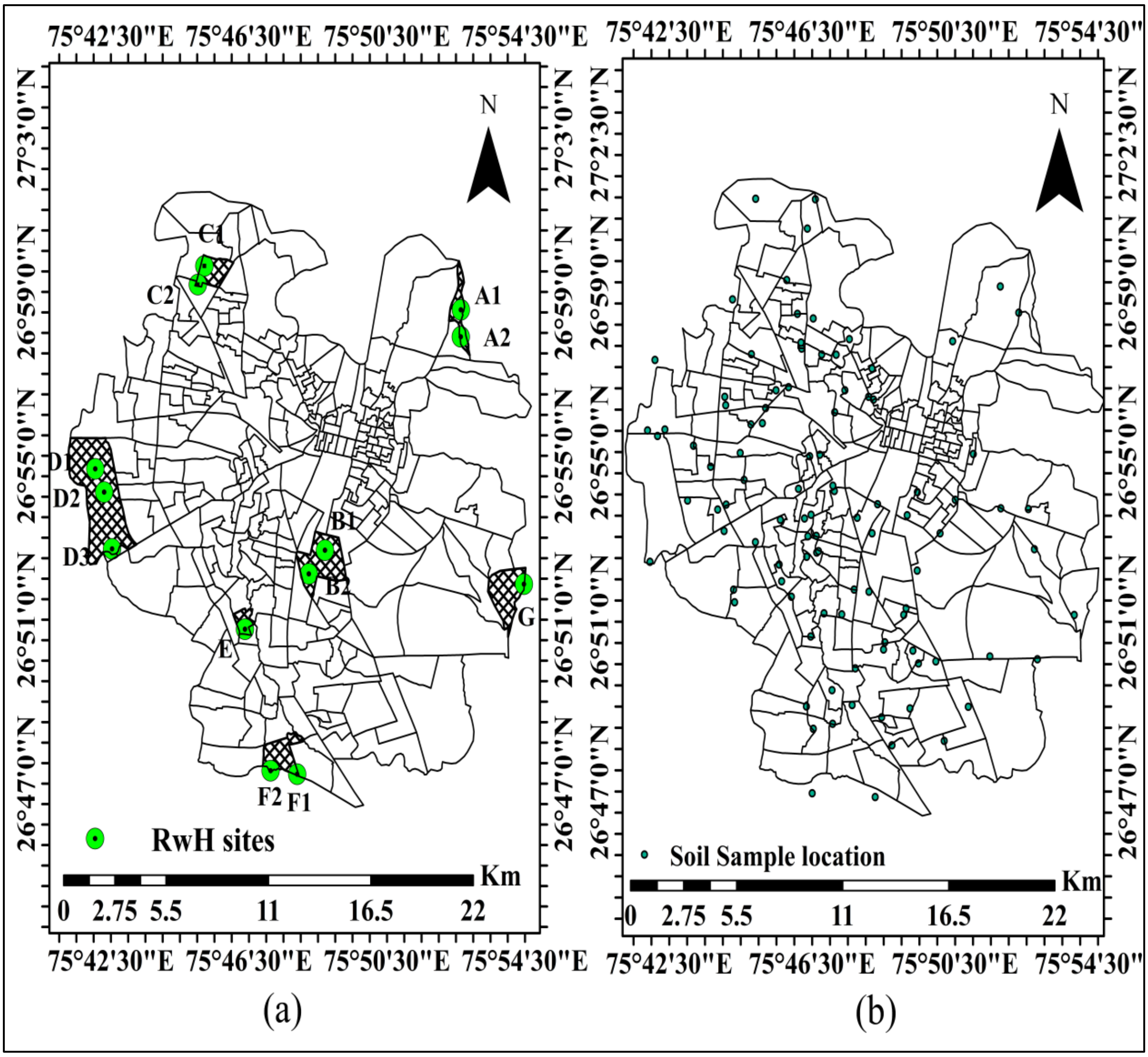


Figure 5.25 a) Identified RwH sites wards, b) Soil survey sampling location

After extracting the soil properties and vegetation information, proper disposal and carriage of the excavated earth and cleaned scrubs are required to reduce its adverse impact. To dispose of unwanted earth, the material must be transported from the site to other low-lying areas away from the city centre. Therefore, the distance between the RwH site and the low-lying area near the municipal boundary of the area was determined using Google Maps, DEM, and imported base maps. The shortest travel distance was calculated using Google Maps, which influenced the carriage cost of unwanted material near the municipality boundary. Table 5.18 provides the extracted site properties for each identified site.

Table 5.18 Extracted site properties

Site	Latitude	Longitude	Volume	Distance from Municipal Boundary	Soil Porosity	Site Condition
C1	26.993919	75.753428	7535	1.7 km	35	Barren Land
C2	26.986338	75.750301	9585.12	2 km	35	Farmland
F1	26.787215	75.7983	4849	60m	12	Farmland
F2	26.788636	75.785468	13518.5	30m	12	Farmland
D1	26.911395	75.700754	3165.77	1.5 km	55	Medium dense vegetation
D2	26.901926	75.705081	11152.95	1.7 km	55	Farmland
D3	26.878863	75.708878	12517.51	800m	35	Barren Land
B1	26.878323	75.811713	7077.48	9.2 km	35	Barren Land
B2	26.86867	75.803904	4966.97	7.5km	80	Barren Land
A1	26.976103	75.877339	4457.54	300m	12	Farmland
A2	26.965133	75.87733	1382.78	300m	80	Medium dense forest
G	26.864523	75.907832	14391.5	50m	12	Barren Land
E	26.846179	75.77309	3002.01	2.3km	35	Medium dense Vegetation

c) Development of BIM Dimensions: BIM is a crucial tool for assessing the viability of a project under diverse site conditions by providing multidimensional data representations. While creating the digital representation or developing dimensions of BIM, understanding the real-time on-ground situation is important when considering multiple design alternatives and performing resource optimization. Integrating GIS with BIM allows an understanding of site topography, vegetation, and surrounding objects using remotely sensed data to create site-specific BIM as a project information model. The developed site-specific BIM reveals the resource and time consumption, which aids in early cost and resource management. The created database helps to incorporate site conditions by providing different resources and their specifications based on regional and physical constraints while developing BIM dimensions. In the proposed study, the development of the BIM dimensions for the proposed RwHs was done with the help of GIS analysis and a created database. This development starts from the

2D, i.e., performing design, to the 5D performing cost estimation. The following section elaborates on the detailed process involved in developing BIM dimensions.

i) 2D BIM: The performed hydro-spatial analysis provides the hydrological potential of the selected municipality wards that can be used to determine the geometric characteristics of the sedimentation and storage tank. The estimated one-day runoff values generated at each identified site were used to determine the dimensions of the sedimentation tank, and a 10-day runoff volume was used to design the storage tank. The standard procedure in sections 5.2.1.1 and 0, for performing the design, was followed individually for each identified site. Table 5.19 provides the geometric characteristics of RwH components.

Table 5.19 Geometric characteristics of sedimentation and storage tank

	Sedimentation Tank		Storage Tank	
Site	**Volume m^3**	**Dimensions(m) ($l * b * h$)**	**Volume m^3**	**Dimensions(m) ($l * b * h$)**
C1	125.8371	12.9*3.3*4	7535.15	45*31.9*6
C2	160.0715	14.6*3.6*4	9585.12	50*35.95*6
F1	80.9783	10.4*2.6*4	4849	30*30.93*6
F2	225.7589	17.3*4.3*4	13518.5	60*41.55*6
D1	52.86835	8.4*2.1*4	3165.77	30*21.58*6
D2	186.2543	15.7*3.9*4	11152.95	60*34.98*6
D3	209.0424	16.9*4.1*4	12517.51	60*38.77*6
B1	118.1940	12.5*3.1*4	7077.488	45*30.21*6
B2	82.94853	10.5*2.6*4	4966.978	30*31.59*6
A1	74.44091	9.9*2.5*4	4457.54	30*28.76*6
A2	23.09249	5.5*1.4*4	1382.784	30*11.68*6
G	240.3380	17.9*4.5*4	14391.5	60*43.97*6
E	50.13356	8.2*2*4	3002.01	30*20.67*6

ii) 3D BIM: The process of creating a visualization model for the components of RwHs by integrating it with real-world scenarios significantly enhances the understanding among stakeholders. The Autodesk Revit tool was used to create the 3D models of the RwHs components, and the developed components were imported into the Autodesk Infraworks Tool. This importing of the 3D models effectively situates the RwH components into the operational context, allowing stakeholders to visualize it with existing real-time surroundings. Beyond visualization, the developed 3D models provide valuable insights into the quantity of materials required for implementing RwH components. The storage tank and sedimentation tank model were developed in Revit and imported in Infraworks tool. The developed models allow the extraction of materials quantity that was used to plan and estimate the resources involved.

iii) 4D BIM: Performing scheduling for the RwHs enables a clear understanding of the time required to complete the activity. The PERT method was applied to schedule the execution of the RwHs. While assigning the time estimates, extracted site properties, such as present vegetation, available soil type, and distance from the boundary, were considered. The considered parameters influence the time involved in the execution of the activities. Considering these parameters, the expected time for each activity was calculated using the t_o, t_p, and t_m. Table 5.20 provides the total duration of implementing the sedimentation and storage tank.

Table 5.20 Site specific schedule estimate

Site	**Duration involved in implementing Sedimentation Tank**	**Duration involved in implementing storage Tank**	**Total Duration**
C1	56	65	121
C2	60	74	134
F1	50	52	102
F2	69	102	171
D1	48	44	92
D2	64	86	150
D3	67	101	168
B1	56	73	129
B2	51	57	108
A1	56	58	114
A2	46	37	83
G	74	118	192
E	50	42	92

iv) 5D BIM: The developed database served as a comprehensive repository of the resources involved in the activities for implementing RwHs. Scheduled materials from the developed 3D models were used to estimate the cost of each activity. The properties of the extracted site influence the selection of resources, which affects the overall cost of the project. The cost estimation reflects the feasibility of the proposed system for the site by revealing its total cost. The cost of carriage of the excavated material from the RwH site to the dumping site was also considered by the BSR. Table 5.21 provides the total cost involved in the implementation of RwHs.

Table 5.21 Site specific cost estimate

Site	Cost involved in implementing Sedimentation Tank	Cost involved in implementing storage Tank	Total Cost
C1	571182	2464570	4211078
C2	643275	3691315	4868547
F1	423602	2175459	2599061
F2	805401	4815151	5620552
D1	325670	1678279	2003949
D2	716915	4246890	4963805
D3	781616	5247744	6029360
B1	549612	3984577	4534189
B2	427236	2536172	2963407
A1	418557	3548852	3967409
A2	240649	1078647	1319296
G	916276	9265301	10181577
E	334840	1894228	2229068

The development of 4D and 5D BIM over multiple locations reveals that the extracted site properties highly influence the overall duration and cost involved in the project. Figure 5.26 provides the relationship between the duration, cost, and volume of the identified RwH sites.

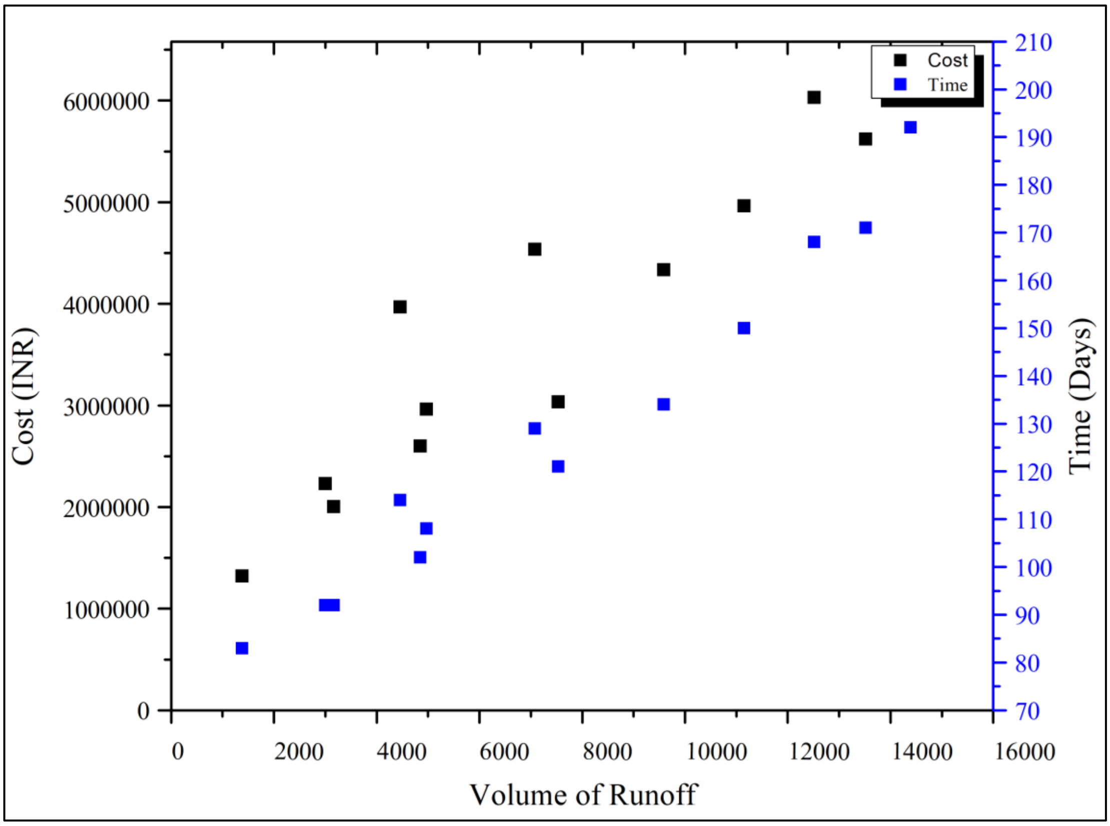


Figure 5.26 Relation between Volume of Runoff, Estimated Cost, and Time

This methodology strengthens the ability of stakeholders to make accurate decisions by assessing the practical feasibility of community RwHs in diverse physical and topographical conditions. The developed BIM dimension using the database acts like a bridge between conceptual planning and practical implementation, supporting estimation accuracy and boosting decision-making confidence at the conceptual stage.

5.2.6.4 BIM cloud platform

The current study used an Autodesk cloud-based technology called Collaborate-Pro to address the issue and improve FM. It allows to upload the data in *.rvt, *.shp, and pdf formats with different modification levels. The uploaded documents can be reviewed by assigning them to the responsible stakeholder, and issues such as revision and clash detection can be reported on the same platform. The uploaded Revit model on the BIM cloud, which the site engineer and stakeholders can review. The analysed data, conducted ground survey data, calculated involved in estimated geometric characteristics, estimated LPCD, assessed water quality, and created database shared on the platform. Figure 5.27 shows the Autodesk Collaborate Pro platform with shared documents and related information.

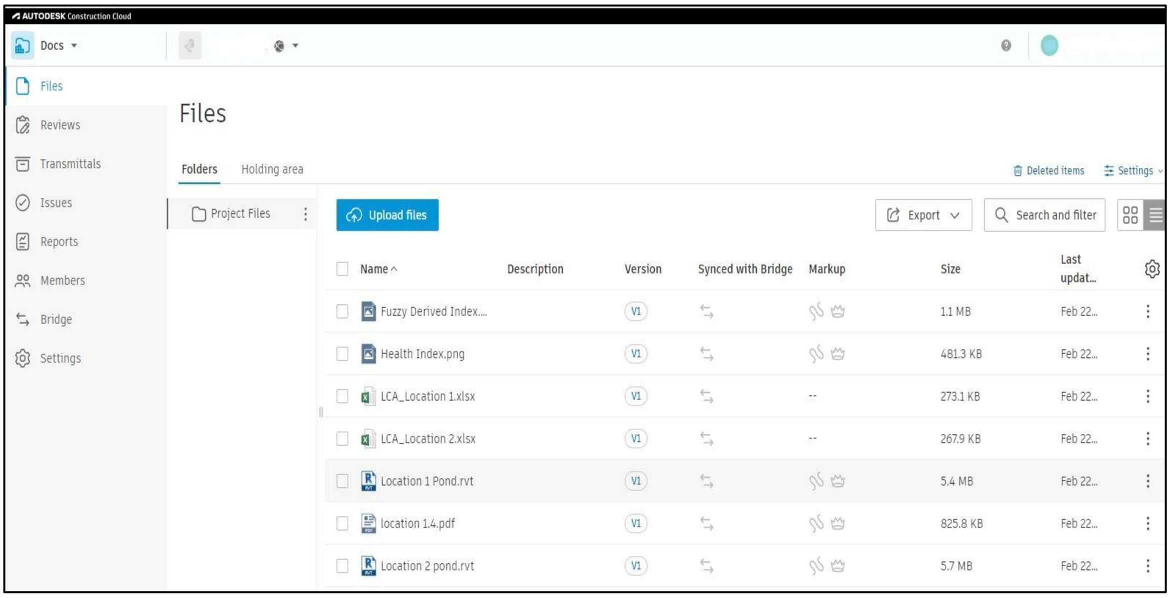


Figure 5.27 BIM cloud platform for FM

The shared design, technical information, and drawing facilitate identifying, assessing, and mitigating potential risks associated with the activities. This platform promotes collaboration and coordination between designers, contractors, safety professionals, and facility managers, ensuring that safety considerations are integrated into the design, construction, and operation phases.

5.2.7 8D BIM: Safety management

Safety management is another important factor recognized and incorporated into this study as the 8D BIM. Construction safety regulations are violated by stakeholders, leading to an increase in fatality rates during the execution phase. Assessing the risk factors associated with construction operations results in maintaining on-site worker safety. With the help of BIM technology, risk assessment and the formulation of safety rules for project operations ensure the safety of on-site workers. On the other hand, risk analysis aids workers in identifying potential hazards, safety precautions, and real-time threats. Generally, risk evaluation follows the Occupational Safety and Health Administration (OSHA) guidelines using a 5 × 5 matrix approach. Out of the three matrix sizes, 3x3, 4x4, and 5x5, the chosen format of the 5x5 matrix provides extensive risk evaluation (Bedfordshire Council, 2009). Equation. 5.34, provided by the International Labour Organization 2019, calculates the risk and evaluates the likelihood and consequence levels associated with each activity. The likelihood and consequence scores for the diverse circumstances in the 5 × 5 matrix system ranged from 1 to 5, as shown in Table 5.22.

$$\text{Risk} = \text{Likelihood} * \text{Consequence} \quad \text{Eq. 5.34}$$

Table 5.22 Values for Likelihood and Consequences

Likelihood		**Score**	**Consequences**		**Score**
Rare	10 % chance of the risk occurring	1	**Insignificant**	Without causing serious harm	1
Unlikely	It can happen but only with a less than 50 % chance	2	**Minor**	Leading to mild injuries or illnesses	2
Moderate	Likely to occur (50% of chance)	3	**Significant**	Harm that may require short-term treatment	3
Likely	More possible to happen	4	**Major**	Leading to long-term damages	4
Almost certain	Highly probable to happen (more than 80% chance)	5	**Severe**	Resulting in Death	5

The product of the acquired scores results in colour classification in a 5x5 matrix with four colours, as shown in Figure 5.28.

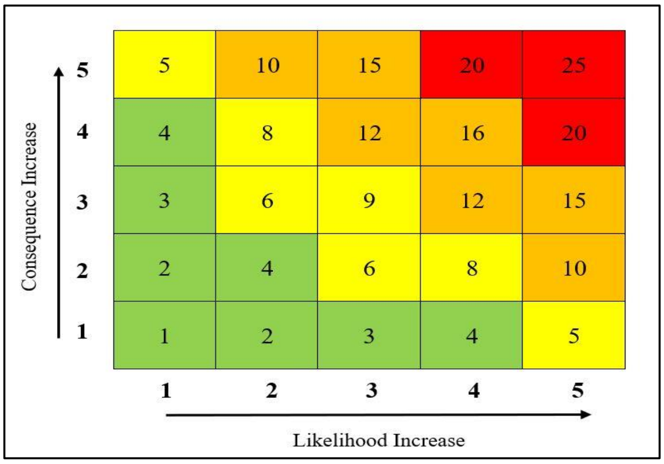


Figure 5.28 Risk assessment matrix

The questionnaire was shared (via. Google Forms) among the stakeholders to understand the severity and risk involved in the respective activity; subsequently, the responses were collected, and the collected responses are provided in Appendix I. The average of the collected responses was used to estimate the risk involved in an activity. The four classifications, acceptable, adequate, bearable, and unacceptable, determine the activity's ultimate risk assessment. Table 5.23 provides the explanation and colour code for the activity classification.

Table 5.23 Risk assessment based on colour code

Range	Colour	Classification	Description
1-4		Acceptable	Further action is not required; however, ensure control measures.
4-9		Adequate	Safety measures seek improvement at the next review.
9-16		Tolerable	Require improvement in safety measures within a specific timeline.
16-25		Unacceptable	Suspend the activity and make instant corrections.

As per Table 5.23, the list of activities involved in the execution of the RwHs implementation has been assessed and classified for risk level and presented in Table 5.24, and the safety dashboards were shared through the BIM cloud platform. The carried work revealed that 32% of the activities fell under the acceptable, 34% within the adequate, 23% within the tolarable, and 11% activities within the unacceptable classification.

Table 5.24 Activities and their risk classification

Activity	Risk Value	Category
Drainage Construction		
Drainage Layout Marking	3.30	
Site Clearing (Removing debris and trees)	3.97	
Excavation (Depth 2.72 m)	4.49	
Levelling and RCC	3.54	
Vertical Reinforcement (Height 2.72m)	9.86	
Formwork Placing	9.73	
Vertical Concreting	5.42	

Curing	1.83
Removal of Formwork	4.90
Drainange Cover and Curing	4.4
Backfilling and Finishing	4.27
Sedimentation Tank Construction	
Site Clearing and Layout Marking (Removing debris and trees)	3.22
Excavation and Levelling (Depth 5m)	13.27
Foundation and Curing	14.6
PCC Bed Concrete and Curing (at Depth 5m)	18.61
Installation of Reinforcement (For Bed slab at depth 5m)	10.51
Base Concreting and Curing	19.45
Vertical Wall Construction (5m height)	9.45
Plastering	3.11
Curing	1.93
Provision of Inlet and Outlet Connections	4.43
Waterproofing (Base and walls)	2.54
Backfilling and Finishing	4.66
Storage Tank Construction	
Site Clearing and Layout Marking (Removing debris and trees)	3.97
Excavation (6m Depth)	20
Levelling and Blinding	9.55
Base Compaction (Compactors)	9.25
Construction of Outlet Structure and Percolation Well (Percolation well 30m depth)	19.45
Slope Stabilization and Tank Lining	5.27
Stone Bunds and Boundary Construction	4.97
Curing and Drying	3.18
Finishing Work	4.49
Finishing work	
Cleaning of Drains	5.62
Tank Cleaning	3.34

The safety analysis revealed that the activities executed below the ground surface involve more risk and need to follow more precautions than those executed at the ground level. Out of 35 activities, four showed a high risk, falling under an unacceptable category, which needed suspension, and instant correction measures were followed. Incorporating safety management as the 8D BIM allows implementing Prevention through Design (PtD) practices, which improve safety practices, reduce accidents, and provide a safe working environment for all stakeholders involved in the project.

5.3 Result and Discussion

The evolution of BIM dimensions represents the evolution of technology for addressing various aspects of construction and infrastructure projects. Over the past few years, BIM has progressed in multiple aspects, emphasizing the effectiveness of using various types of information for efficient lifecycle management. Initially, the application of BIM started with a 2D design expanded into a nD information model that incorporated dynamic and virtual analyses, including scheduling, costing, stability, sustainability, maintainability, evacuation simulation, and safety. These models provide a database that allows useful information to be retracked (Kang et al., 2007; Ma & Ren, 2017; Mallasi et al., 2006; Sacks & Barak, 2008). Based on the type and complexity of the project, sustainability, project lifecycle, safety, energy, construction records, as-built, and as-is information were considered 6D BIM (Charef et al., 2018; Nicał & Wodyński, 2016; Park & Cai, 2017). In the proposed study, the unique BIM dimensions for the proposed implementation of community RwHs were developed and results were mentioned in subsequent sections.

5.3.1 2D

The development of BIM starts with 2D BIM by consuming results from the hydro- spatial and MCDM analysis. In this study 2D BIM delt with the determination geometric characteristics of RwHs components such as storage tanks, sedimentation tanks and stormwater drainage networks. Sedimentation is a crucial element of the RwHs and plays a pivotal role in removing larger suspended particles from water by allowing them to settle. This natural process was harnessed in the study to design an efficient sedimentation tank. A rectangular sedimentation tank was considered for its low maintenance cost, high inflow capacity, and other parameters such as specific gravity, overflow rate, and detention period. The estimated design characteristic satisfies the design criteria by providing values of 747.56 lit/hr/m^2 and 753.6 lit/hr/m^2 for overflow velocity in a plain rectangular sedimentation tank. When determining the geometric characteristics of the storage tank, URwH and URwH+IW were considered from the results of the AHP analysis. Based on the identified most suitable sites, geometric properties were determined for the estimated runoff accumulation as a trapezoidal section. Finally, the geometric characteristics of the mapped drained network were determined using the Manning equation and peak flow values. The depth of the outfall drains was calculated to be 2.72m, whereas the depth of the lateral drains was determined to be 0.5m.

5.3.2 3D

The application of 3D BIM successfully yielded in the detailed visualization of RwHs components. The transition to 3D modeling with the incorporation of material properties and ground conditions has marked a significant advancement in project design and communication. The integration of a 3D model with real-world scenarios using Autodesk Infraworks tool enhances stakeholder comprehension, aids in early-stage decision-making, and serves as essential input data for scheduling and cost estimation, thereby contributing to more efficient and informed project management. Figure 5.29 shows the arial view of integration of 3D model with on-ground scenario.

Figure 5.29 Infraworks model for proposed RwHs

5.3.3 4D

The application of PERT for RwHs implementation enables a robust management by considering the range of time estimates for each activity. The incorporation of PERT allows to acknowledge uncertainties, allowing for better planning and resource allocation by ensuring realistic timelines. The PERT method revealed that the total expected duration involved in the implementation of RwHs was 204 days. This time estimation allows the control of the overall project duration and mitigates the risk by facilitating clear communication and guiding the timely completion of the complex activities involved.

5.3.4 5D

Cost analysis allows decision makers to generate different design alternatives to make the project more economically sustainable. It also addresses the gap in early design by allowing quantification of current project design costs and how potential improvements may affect the project using multiple perspectives. It also improves the ability to specify the project scope precisely by including multiple factors such as site conditions, building materials, and phasing. Ultimately, 5D BIM provides a more efficient and comprehensive approach to quantity take off, ensuring accurate estimations based on the generated 3D BIM model. In this study, the cost estimation was performed using the standard rates of resources provided by the BSR and ISR provided by the local administrative authority. The utilization of Primavera p6 provides three resource classes: Labour, Non-labour, and Material, and was assigned to each activity involved in the proposed implementation of RwHs. The total planned cost involved in the implementation of RwHs is 56248754.66 INR (i.e., 674442.82 USD). The costs involved in each project phase were extracted from the Primavera p6 and shown is in Figure 5.30.

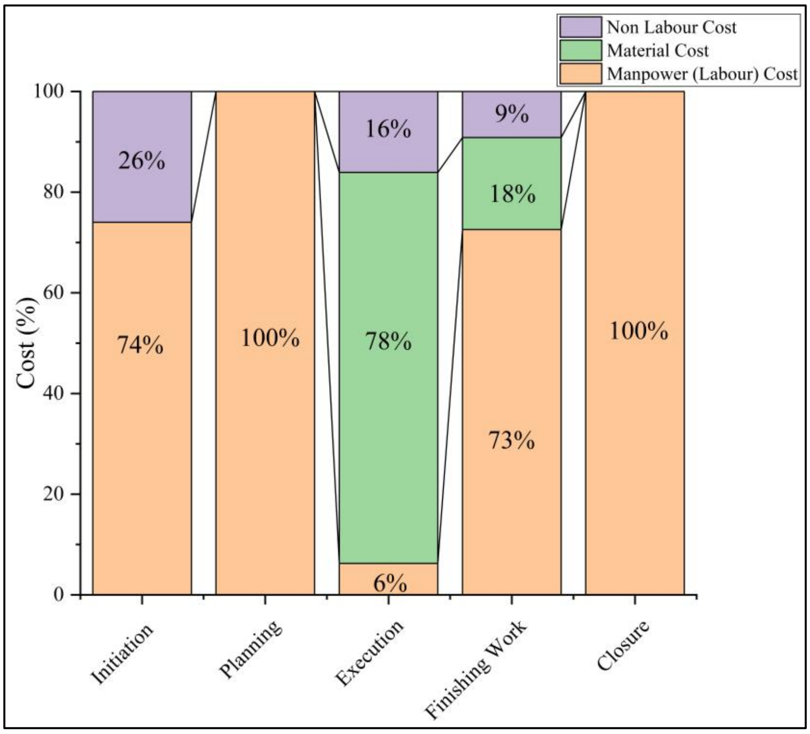


Figure 5.30 Project phase-wise cost involved in the project

5.3.5 6D

To assess the environmental sustainability of the proposed RwHs, an LCA analysis was performed using the Tally plugin from the Autodesk Revit tool. LCA analysis estimates carbon emissions as a composition of GHGs such as Carbon dioxide (CO2), methane (CH4), and nitrogen dioxide (NO2). The performed LCA estimates that the 83,750.32 (kgCO2eq), 87,724.20 (kgCO2eq), and 3438890.59 (kgCO2eq) of GWP associated with Site B, Site C, and the entire drainage system over the considered study area, respectively. Appendix J provides the sample results of the LCA analysis. Figure 5.31 shows the results of the LCA analysis performed in the Tally plugin for Site B and Site C, as per the TRACI categorization. As the drainage construction utilized reinforced concrete, all the estimated carbon emissions are associated with a single material and was excluded from the visualization.

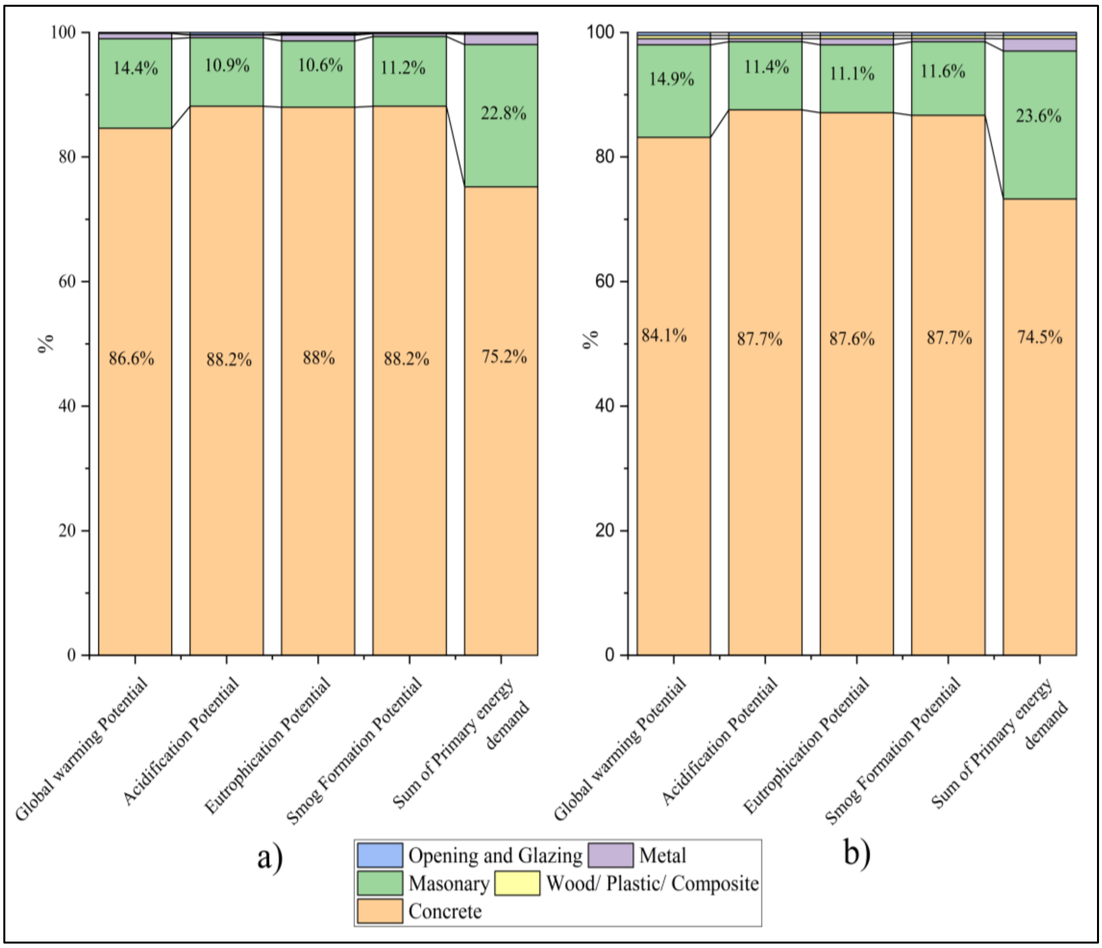


Figure 5.31 LCA analysis results for a) site C, and b) Site B

5.3.6 7D

7D BIM deals with Fm, which deals with data and information related to maintenance, repair, renovation, and decommissioning. In this study, the Autodesk Collaborate Pro platform was utilized to facilitate information sharing. Along with data sharing, multiple steps were performed to facilitate and analyse the implementation of the proposed system in other municipal areas. These steps include estimation of the optimized LPCD, water quality assessment, and creation of a database. The estimated optimized LPCD revealed that the optimum range of LPCD for the municipal zones varies from 106.52 to 129.58. These optimized LPCD values help reduce the extra strain from the existing water supply system and allow the optimum design to be performed. In addition to the LPCD, water quality assessment was performed using the novel weight-integrated health hazard index and fuzzy index. Water quality assessment revealed that poor water quality was associated with high risk. Finally, a database was created by incorporating the standard rates of resources involved in implementing RwHs. While creating a database, the cost-identified resources required to fulfil the activities with their descriptions have been added to the SQL database in Oracle Primavera p6. The created database helps to assess the practical feasibility of RwHs over multiple locations by incorporating site-specific rates while developing BIM.

5.3.7 8D

BIM plays a crucial role in risk assessment and the formulation of safety rules, resulting in the identification of potential hazards, safety precautions, and real-time threats. In this study safety analysis was performed as 8D. The likelihood and consequence levels for different scenarios were assessed using a 5 × 5 matrix approach in accordance with OSHA guidelines. The risk for each activity was estimated using responses to a questionnaire distributed to stakeholders to ascertain risk levels. Four categories were used to categorize the activities: acceptable, adequate, bearable, and unacceptable. The analysis revealed that 32% of the activities were acceptable, 34% were adequate, 23% were bearable, and 11% were unacceptable, contributing to enhanced on-site worker safety during the proposed implementation of RwHs.

5.4 Chapter Summary

This chapter presented the evolving dimensions of BIM developed for the proposed RwHs. The results of the GIS analysis were used as input data to develop the BIM dimensions. The development of dimension of initiates with the 2D design of the RwHs components using CAD tools which will serve as input to create the 3D visualization of entire system. The advancement in modeling tools allowed the creation of real-time ground visualization of the developed 3D models, which enhanced the understanding among stakeholders and served as an input to perform scheduling and cost estimation for RwHs. Scheduling and cost estimation were considered as 4D and 5D BIM, respectively. The estimated time and cost involved in the proposed implementation of the RwHs serve as sustainability indicators in terms of resource consumption and economy. Further, to assess environmental sustainability, LCA analysis was performed using the developed 3D model which was considered as 6D BIM. In addition to the pilot study, to facilitate the implementation of the proposed RwHs over other municipality areas, several attempts have been made, such as estimating the optimum LPCD, wate quality assessment, and creation of a database. To share the generated information, analysis results and reports, the Autodesk Collaborate Pro platform was utilised and considered as 7D BIM. The utilization of the platform will not only facilitate the (O&M) of the proposed system throughout its lifecycle, but also allow assessment of its feasibility under various conditions. Finally, the risk assessment of the activities involved in the proposed implementation was analysed using the OSHA guidelines. The integration of GIS for BIM development provides a comprehensive data-enriched model. This integration of data sources further contributes to a more robust and informed BIM representation, thereby strengthening its applicability across various stages of the project lifecycle.

6. Conclusion

6.1 Chapter overview

This chapter encompasses an in-depth discussion of the important findings, ideas, and conclusions drawn from this study. The chapter also discussed how study utilizes the extensive capabilities of GIS and BIM were integrated and utilized for efficient planning and design of infrastructure. It also concludes the study by summarizing the important issues identified in earlier chapters and offering insightful findings.

6.2 Infrastructure management

The importance of infrastructure management has increased because of the complexities of urbanization and challenges posed by resource scarcity and environmental concerns. This entails developing strategies that extend the life of assets, promote environmental sustainability, and ensure community well-being. Efficient infrastructure development and management are the foundations of resilient and long-term societal growth. To carry a sustainable infrastructure development a strategic framework methodology was proposed. The proposed framework methodology was initiated with study area analysis, which represents the drawbacks and capabilities of the study area. The results of the study area analysis guide further micro-level planning for infrastructure assets. Micro-level planning allowed us to estimate the optimum asset characteristics. To maintain and assess the sustainability of infrastructure projects, modeling of infrastructure assets allowed the comparison of different design alternatives, which was performed as the final stage in the framework. To validate the proposed methodology, GIS and BIM were integrated as a case study. Adopting GIS in the initial phase brought geographic and environmental aspects, facilitating site analysis, topographical considerations, and infrastructure planning based on spatial and topographical relationships. On the other hand, BIM provided an intelligent and comprehensive digital representation of the physical and functional characteristics of structures. This integrated approach can be applied to identify the most suitable sites and evaluate design alternatives for various infrastructure projects, including roads, pipe networks, airports, dams, terminal buildings, energy stations, and more. In transportation infrastructure development, microscale planning enables the integration of specific information about existing infrastructure, surroundings, and design alternatives, leading to optimal resource utilization (Irizarry et al., 2013). Similarly, for energy infrastructure projects, adopting modeling techniques facilitates the assessment of environmental sustainability, thereby minimizing damage to the existing ecosystem

(Yamamura et al., 2017). The collaborative power of GIS and BIM has enabled enhanced decision-making, streamlined communication among stakeholders, and improved project visualization.

Unplanned growth and rapid urbanisation pose several issues, including inadequate health and infrastructure, an ineffective transportation system, and an imbalance between the supply and demand for water and electricity, which diminishes overall sustainability. To overcome the water related issues, effective urban planning, efficient infrastructure development, and water management strategies are required. Community RwHs have proven to be an efficient method of curtailing water scarcity by substituting it as an alternative water resource, which also helps to mitigate the risk of flooding caused by heavy rainfall. The integration of the GIS and BIM was implemented to plan and design the community RwHs as integral part of sustainable water infrastructure over a Jaipur (India) municipal area. The outcomes of the analysis are discussed in the subsequent sections.

6.3 GIS analysis

Infrastructure development highly influence by the available land type, and land use patterns. So, to understand the land use patterns and available land resources LULC analysis played an important role. Additionally, it allows the assessment of the long-term effects of development and make strategic decisions to maximize resource allocation, reduce environmental degradation, and increase sustainability by applying prediction models. In this study, initially, the LULC change analysis performed as the study area analysis over the past three decades (for the years 1990, 2000, 2010, 2015, and 2020) revealed that urban expansion increased in the western and southern directions of Jaipur city by 46.55%, whereas available barren land and vegetation decreased by 27.06% and 19.49%, respectively. By consuming the area change analysis results, the MLP and CA models were applied to predict future expansion and create a map for the year 2030. The simulated map reveals that the barren and vegetation land has been transformed into an urban area with approximately 651.02 km^2 out of 928 km^2. In addition, a ward-by-ward study was conducted for Jaipur Heritage and Jaipur Greater Corporation to execute the predicted map, showing that most medium-density wards will be converted to high-density wards by 2030, with an urban compactness ratio of 70%. The presented land use transition illustrates that urban (built-up) land areas are rapidly expanding by transforming the surrounding agricultural and barren land. The novel built-up land density maps developed for the municipality area guide sustainable and resilient infrastructure development, ensuring optimal land utilization and minimizing negative environmental impacts.

To minimize the adverse effects of rapid urbanization and infrastructure development on the existing water supply system, implementing community RwHs is considered an alternative water source. Therefore, for efficient design of the RwHs, establishing a relationship between the topography and hydrological parameters was performed using the spatial analysis tool for extracting the hydrological characteristics such as FA, flow direction, and basin formation using the acquired DEM. Hydro-spatial analysis was performed to estimate the maximum FA within the basin. To minimize the complexity of the number of basins and their volumetric potential, minimum basin area-based scenarios were developed with basin areas of 1, 2.5, 5, 7.5, and 10 sq. km of basin area. The developed scenarios, by considering the minimal basin area for the identified maximum FA locations, strengthened the practicality and feasibility of implementing community RwHs by providing a clear understanding of the hydrologic characteristics of the area. Simultaneously, the developed relationship paves a way to perform the micro level of planning by providing the basin information along with its volumetric potential.

For performing micro-level planning for community RwHs as a component water infrastructure, detailed analysis and evaluation of potential sites will result in the selecting the most suitable site. This site selection process incorporates numerous factors, such as topography, land use, environmental impact, proximity to resources, accessibility, and socio-economic considerations. To execute detailed planning, the study area was narrowed, considering a single municipality ward within the JMC area. Initially, six site alternatives were identified manually through topographic analysis, and five parameters such as 'Elevation,' 'Area,' 'Perimeter,' 'Distance from the centre,' and 'Potential volume' for identified sites were extracted. To assess site suitability, four MCDM methods named WASPAS, TOPSIS, VIKOR, and PROMETHEE-II were applied with two objective weight methods, Criteria Importance Through Intercriteria Correlation (CRITIC) and Entropy. The applied objective weighing methods help to increase the consistency of the decision by reducing human involvement and consideration. The site selection process revealed that sites C and B were the most suitable for RwHs.

On the other side of the micro-level planning and design, the design alternatives for RwHs components and their assessment were performed using the AHP technique. For AHP analysis, seven rainwater storage tank alternatives listed were Underground rainwater harvesting (URwH), Overhead rainwater harvesting (ORwH), Directional tunnel (DT), Infiltration well (IW), Underground rainwater harvesting with infiltration well (URwH+IW), Overhead rainwater harvesting with infiltration well (ORwH+IW), and Directional tunnel with infiltration well (DT+IW) and analysed using expert knowledge. The analysis revealed that Underground RwH tank and the Underground RwH tank with infiltration well were appropriate considering the RwH parameters. In addition to identifying appropriate design alternatives, interdependent components, such as the drainage network and treatment unit, are important for streamlining its operation. To design the drainage network, peak runoff values generated from rainfall were considered, and the path was traced using the generated stream order map from the hydro-spatial analysis as lateral, sub-main, main, and outfall drains. The developed drainage network emphasizes sustainability, water self-sufficiency, and general water resource management and conservation standards by effectively collecting rainstorm.

The incorporated design considerations along with the results from spatial and hydro-spatial analyses optimizes resource consumption and guide the decision-making process. In addition to GIS analysis, the conceptual design and implementation of the community RwHs as an infrastructure project needs collaborative design, exact visualization, cost estimation, clash detection, and FM to improve efficiency, reduce cost, enhance decision-making, and ensure the long-term sustainability of the system. In such cases, adopting BIM provides a comprehensive and collaborative platform that allows various stakeholders to work together through our project lifecycle.

6.4 Development of dimensions of BIM

Adopting BIM for RwH offers many advantages and potential for optimizing system design, development, and management. BIM also provides a collaborative and information-rich platform that enables stakeholders to effectively plan, visualize, and analyse RwHs. In this study, the results from the hydro-spatial analysis were utilized to develop the BIM for community RwHs. Initially, GIS analysis results was used to perform the 2D design of the RwHs components such as storage tank, sedimentation tank and drainage network following standard guidelines using CAD tools. To improve the system visibility and understanding, the developed 2D BIM models were used to develop 3D BIM models. The 3D models depict the RwHs components in greater detail, allowing stakeholders to perceive the system in three dimensions. The Autodesk Revit tool was utilized to facilitate the development of 3D visualizations. Revit has extensive modeling and design features for complicated infrastructure projects such as RwHs. In addition, the developed 3D BIM models were imported into Autodesk Infraworks, which allowed a realistic and immersive representation of the system in its real-world surroundings.

The addition of project information to the model results in a multidimensional BIM. The incorporation scheduling parameter is considered as 4D. To perform scheduling activities involved in the implementation, RwHs were listed based on expert knowledge and relied on previous project experiences. These activities encompass an array of tasks, such as site preparation, excavation, storage tank installation, and the construction of a treatment unit and collection unit. A total of 84 activities are involved in the implementation of RwHs, of which 34 activities are critical, with an expected duration of 204 days determined by applying the PERT method in the Primavera p6 tool. The performed scheduling acts as a benchmark for project scheduling, resource allocation, and project planning, which aids in sustainable economic planning by providing valuable insights for budget management and resource consumption.

Cost estimation is considered as the 5D BIM. Based on the BSR provided by the public works department, city circle Jaipur, and the ISR provided by the Rajasthan Urban Infrastructure Development Project, the estimated planned cost of the project is 56248754.66 INR (i.e., 674442.82 USD) (INR 3.28 per litre) from the initiation to the closure phase. The predefined three classes of resources in primavera p6 aid in allocating resources efficiently. Cost analysis allows decision-makers to generate different design alternatives to make the project more economically and environmentally sustainable.

In terms of sustainability, 6D BIM emphasizes the assessment of the environmental impacts of activities. Insights on the potential for global warming associated with tank construction at both locations and drainage networks were obtained from LCA analysis, which was carried out using the Tally plugin in the Revit tool. The analysis results reveal that Site B is associated with a GWP of 83,750.32 kgCO2eq, Site C with 87,724.20 kgCO2eq, and the construction drainage network with 3438890.59 kgCO2eq. The total carbon emissions from implementing the RwHs amounted to 3610.36 tCO_2eq. These findings emphasize the significance of considering sustainability and using sustainable practices while developing and implementing RwHs. By utilizing 6D BIM and conducting LCA analysis, decision-makers can make informed choices to minimize environmental impact and promote sustainable construction practices.

Nowadays, Significant improvements in project management and consequences have been made owing to the adoption of 7D BIM, which has encouraged improved collaboration and coordination among project stakeholders. In this study, the Autodesk Collaborate Pro platform was used to perform Fm. The utilization of the platform allowed the sharing and reviewing of the analysed water quality data through the city region, optimized LPCD water demand, created database, reports from the LCA analysis, 3D visualization, and standard codes for performing maintenance operations. The development of site-specific documents and information assists in spatial arrangement, uncovering design flaws, and optimizing resource allocation, while streamlining the project timeline. The shared documents and drawings empower stakeholders to optimize the operation, enhance sustainability, and improve overall efficiency to achieve long-term cost savings.

The adoption of safety assessment as the 8D BIM in the execution of RwHs has proven beneficial in detecting and managing potential risks in the conceptual phase. For our study, the safety assessment of the 35 activities included in the RwHs execution phase, performed using the OSHA assessment matrix, offered significant insights into the safety considerations required for each activity. The analysis revealed that the four activities were recognized as high-risk, falling into the unacceptable category during the execution phase of the project. The investigation also reveals that activities carried out below the ground surface offer greater risk, which emphasizes the significance of increased safeguards and safety measures to guarantee the well-being of personnel engaging in these activities. By recognizing the higher risk associated with below-ground activities, project stakeholders can allocate adequate resources and implement necessary safety protocols to reduce the likelihood of accidents and injuries. The prompt recognition of these high-risk activities enabled their suspension and the immediate deployment of corrective actions. This proactive approach demonstrates a commitment to placing safety first and eliminating any hazards as soon as they arise.

6.5 Conclusion on research findings

a) The study introduces a strategic framework methodology that spans macro-to micro-level of infrastructure management, encompassing development, design, and planning.
b) The methodology paves a new way to assess the environmental and financial sustainability of the infrastructure project.

c) The validity of the methodology was done through a multistage integration of GIS and BIM technologies.
d) The study methodology allowed to integrate the ancillary tools and techniques such as MCDM, AI and the GA, serving valuable decision support tools to enhance the efficiency and sustainability of the project.
e) The developed novel BIM dimensions serves as a foundation study to plan, design and analyse the RwHs at diverse site condition.

6.6 Limitation of study

This thesis delved into the conceptual design of community RwHs in the urban areas of developing countries. However, a challenge may arise to acquire the identified land area which seeks the water fetching to the alternate available area. The hydro-spatial analysis conducted in this study utilized remotely sensed data acquired at various specific time intervals, which in turn introduced some uncertainty in the design considerations. The absence of event-specific and real-time data linked to IoT sensors may create the voids in design consideration. Further the exploration of additional BIM dimensions, such as 9D and 10D, as study incorporates constrained with the conceptual planning and design of the community RwHs.

6.7 Future scope

a) The integration of GIS and BIM into RwHs requires an interdisciplinary and iterative approach. Future studies can explore the collaboration between civil engineers, geospatial experts, architects, and socioeconomic and environmental scientists. This multidisciplinary approach can lead to holistic and innovative solutions that consider both the technical and environmental aspects.
b) The study can delve deeper into sophisticated hydrological modeling and climate analysis. This includes the simulation of detailed rainfall patterns, runoff behaviour, and the design of complex drainage networks within the BIM environment.
c) The incorporation of water supply infrastructure – including pumps, outlet water bodies, pipe networks, material etc may be considered more rigorously in integration with hydraulic modeling.

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Journal Publications

1. **Patil, D.,** Kar, S., Shastri, V., & Gupta, R. (2023). *Qualitative and health risk assessment of water using a novel weight-integrated health hazard and fuzzy-derived indices*. Sustainable Water Resources Management, 9(2), 55 https://doi.org/10.1007/s40899-023-00832-3.
2. **Patil, D.,** Kar, S., & Gupta, R. (2023). *Classification and prediction of developed water quality indexes using soft computing tools*, Water Conservation Science and Engineering 8(1), 16 https://doi.org/10.1007/s41101-023-00190-3.
3. **Patil, D.,** Kumar, G., Kumar, A., & Gupta, R. (2022). *A systematic basin-wide approach for locating and assessing volumetric potential of rainwater harvesting sites in the urban area*, Environmental Science and Pollution Research, 1-15 https://doi.org/10.1007/s11356-022-23039-z.
4. **Patil, D.,** & Gupta, R. (2022). *GIS-based multi-criteria decision-making for ranking potential sites for centralized rainwater harvesting*, Asian Journal of Civil Engineering, 1-10 https://doi.org/10.1007/s42107-022-00514-z.
5. **Patil, D.,** & Gupta, R. (2023). *Spatiotemporal analysis and prediction of urban evolution patterns using ANN tool*, Proceedings of the Institution of Civil Engineers-Urban Design and Planning, 1-11 https://doi.org/10.1680/jurdp.22.00046.
6. **Patil, D.**, Raya, R. K., & Gupta, R. A *multistage integration of Remote Sensing and BIM tools for conceptualising and planning a communal rainwater harvesting system*, International Journal of Construction Management (In Review).
7. Gaurav Kumar, **Patil, D**., Akshay Kumar, Rajiv Gupta. *Top-down spatial scenario approach for identifying the locations of rainwater harvesting sites in an urban region*, Environmental Science and Pollution Research (In review).

Conference Publications

1. *A strategic design approach for implementing a rainwater management system using an integration of GIS and BIM tool*, **Deshbhushan Patil**, Raghavendra Kumar Raya, Abobakr Al-Sakkaf, Ashutosh Bagchi and Rajiv Gupta, 2nd

International Conference on Civil Infrastructure and Construction (CIC 2023), Qatar 5th to 8th Feb 2023 https://doi.org/10.29117/cic.2023.0168.

2. *An Efficient Urban Water Management Practice Based on Optimum LPCD Estimated Using the MLR-GA Optimization Approach- A Case Study for Jaipur, Rajasthan (India)*, **Deshbhushan Patil**, Soumya Kar, Rajiv Gupta, (2022), In 2023 IEEE Conference on Technologies for Sustainability (SusTech) 19th to 22nd April 2023 http://dx.doi.org/10.1109/SusTech57309.2023.10129533.
3. *State of the art for integrating modern technologies to develop a Sustainable Water Management Model*, **Deshbhushan Patil**, Rajiv Gupta, (2022), International Conference on Environment Management Solutions, ICEMS 2022 (ICEMS) 21st & 22nd April 2022 https://doi.org/10.14704/NQ.2022.20.16.NQ880555.

Other Publications

1. An Artificial Intelligence-based qualitative research approach for adaptive real-time monitoring of building construction activities, **Deshbhushan Patil**, Amit Chougule and Rajiv Gupta, SHMII-11: 11th International Conference on Structural Health Monitoring of Intelligent Infrastructure, Montreal, QC, Canada 8th to 12th August 2022.

2. Akshay Kumar, Gaurav Kumar, **Patil, D.**, Rajiv Gupta, Evaluation of state-of-art machine learning classifiers for object-based and pixel-based classification approaches for IRS high-resolution satellite images, Earth Science Informatics (In Review).

A. DGPS survey location

Point Id	Latitude	Longitude	Elevation (m)
1	26.8797	75.7435	464.826
2	26.8795	75.7445	464.296
3	26.8795	75.7455	464.131
4	26.8796	75.7466	463.522
5	26.8796	75.7479	463.587
6	26.8796	75.7487	463.621
7	26.8796	75.7506	463.127
8	26.8805	75.7506	462.928
9	26.8814	75.7505	462.662
10	26.8813	75.7494	462.622
11	26.8812	75.7485	462.899
12	26.8811	75.7478	462.828
13	26.8810	75.7471	463.604
14	26.8803	75.7480	463.593
15	26.8801	75.7472	464.012
16	26.8800	75.7457	464.003
17	26.8806	75.7456	464.325
18	26.8812	75.7456	464.448
19	26.8818	75.7460	464.114
20	26.8819	75.7470	463.892
21	26.8831	75.7470	464.221
22	26.8830	75.7466	464.333
23	26.8826	75.7468	464.235
24	26.8829	75.7462	464.209
25	26.8827	75.7453	464.511
26	26.8836	75.7448	464.64
27	26.8844	75.7446	465.59
28	26.8845	75.7455	465.018
29	26.8839	75.7457	464.459
30	26.8835	75.7468	464.221
31	26.8846	75.7465	464.396
32	26.8848	75.7472	463.94
33	26.8838	75.7477	464.015
34	26.8832	75.7481	463.795
35	26.8833	75.7493	463.646
36	26.8825	75.7493	463.307
37	26.8819	75.7497	462.945
38	26.8838	75.7497	462.909
39	26.8843	75.7492	463.04

B. Ward wise built up density

B1. Year 2020 (1-100)

Ward Number	Built-up Density	Ward Number	Built-up Density	Ward Number	Built-up Density
1	4.99	41	69.89	81	100
2	10.99	42	94.59	82	92.32
3	11.46	43	98.74	83	33.48
4	17.67	44	99.25	84	100
5	40.54	45	100	85	100
6	40.87	46	92.30	86	81.66
7	17.51	47	58.66	87	100
8	10.70	48	67.08	88	86.22
9	49.55	49	74.09	89	95.30
10	25.04	50	79.65	90	89.94
11	16.71	51	98.20	91	99.13
12	33.12	52	89.45	95	14.02
13	20.77	53	86.66	96	8.42
14	81.82	54	90.63	97	27.22
15	98.57	55	75.86	98	90.58
16	99.75	56	100	99	16.32
17	63.52	57	95.18	100	63.74
18	53.79	58	100		
19	98.07	59	100		
20	92.47	60	100		
21	100	61	100		
22	35.85	62	98.65		
23	99.74	63	100		
24	95.92	64	100		
25	100	65	99.25		
26	72.91	66	100		
27	89.94	67	98.09		
28	55.10	68	100		
29	99.09	69	100		
30	100	70	100		
31	91.21	71	100		
32	92.56	72	100		
33	99.74	73	100		
34	84.14	74	100		
35	61.85	75	100		
36	87.85	76	20.09		
37	92.14	77	92.20		
38	31.39	78	62.54		
39	54.58	79	100		
40	70.83	80	100		

B2. Year 2020 (1-150)

Ward Number	Built-up Density
1	31.62
2	52.49
3	83.25
4	76.62
5	71.35
6	91.38
7	94.94
8	81.10
9	99.85
10	93.19
11	93.56
12	99.17
13	93.73
14	99.59
15	99.87
16	99.50
17	96.48
18	100
19	100
20	88.07
21	91.07
22	54.53
23	82.30
24	92.42
25	73.59
26	93.58
27	95.12
28	99.16
29	84.33
30	93.25
31	83.36
32	98.23
33	100
34	100
35	45.78
36	98.66
37	91.40
38	97.25
39	98.39
40	97.69

Ward Number	Built-up Density
41	74.69
42	99.06
43	76.87
44	80.41
45	96.54
46	94.24
47	86.81
48	85.75
49	91.11
50	97.08
51	75.77
52	97.15
53	60.01
54	93.02
55	95.77
56	38.76
57	100
58	98.30
59	90.24
60	95.78
61	96.45
62	93.01
63	65.58
64	92.21
65	85.38
66	80.36
67	82.44
68	94.28
69	80.62
70	96.11
71	79.82
72	96.83
73	94.83
74	91.17
75	89.81
76	77.69
77	98.39
78	94.78
79	100
80	89.52

Ward Number	Built-up Density
81	98.47
82	78.84
83	88.28
84	76.79
85	80.67
86	77.01
87	67.37
88	83.32
89	91.94
90	65.12
91	67.84
92	99.03
93	87.46
94	77.93
95	65.41
96	60.68
97	45.92
98	69.95
99	66.71
100	87.94
101	82.06
102	76.14
103	72.10
104	65.74
105	87.37
106	79.65
107	10.22
108	84.90
109	61.68
110	88.77
111	18.85
112	39.26
113	75.05
114	60.38
115	51.08
116	56.67
117	74.82
118	62.00
119	62.88
120	47.01

Ward Number	Built-up Density
121	70.69
122	76.20
123	71.10
124	72.79
125	58.62
126	95.50
127	92.32
128	86.05
129	87.51
130	88.05
131	41.40
132	100
133	82.20
134	99.43
135	100
136	63.82
137	33.89
138	24.98
139	98.97
140	98.82
141	100
142	76.20
143	98.37
144	94.37
145	100
146	100
147	86.97
148	81.83
149	95.30
150	48.59

B3. Year 2030 (1-100)

Ward Number	Built-up Density
1	19.27
2	23.93
3	40.66
4	42.19
5	63.20
6	62.68
7	29.22
8	25.07
9	70.91
10	54.12
11	28.36
12	64.32
13	48.87
14	95.04
15	99.52
16	99.75
17	86.58
18	61.55
19	99.42
20	99.32
21	100
22	68.44
23	100
24	99.28
25	100
26	89.70
27	99.11
28	76.44
29	99.09
30	100
31	98.57
32	97.69
33	99.74
34	93.47
35	92.62
36	97.70
37	98.67
38	55.43
39	87.02
40	94.19

Ward Number	Built-up Density
41	89.23
42	99.19
43	99.82
44	99.75
45	100
46	97.73
47	83.62
48	81.14
49	92.60
50	91.87
51	99.59
52	98.05
53	96.47
54	97.98
55	97.99
56	100
57	100
58	100
59	100
60	100
61	100
62	99.25
63	100
64	99.62
65	100
66	100
67	99.58
68	100
69	100
70	100
71	100
72	100
73	100
74	100
75	100
76	32.22
77	99.51
78	77.38
79	100
80	100

Ward Number	Built-up Density
81	100
82	98.79
83	56.85
84	100
85	100
86	100
87	97.58
88	97.14
89	99.50
90	98.60
91	99.83
97	41.59
98	98.12
99	32.51
100	83.57

B4. Year 2030 (1-150)

Ward Number	Built-up Density
1	57.46
2	65.30
3	93.69
4	90.51
5	85.94
6	97.46
7	98.64
8	92.84
9	99.85
10	98.79
11	99.60
12	99.86
13	98.77
14	99.90
15	99.87
16	100
17	99.30
18	100
19	100
20	97.79
21	98.07
22	74.53
23	97.36
24	98.51
25	94.70
26	97.99
27	98.69
28	100
29	96.26
30	97.90
31	95.94
32	99.29
33	100
34	100
35	76.45
36	99.70
37	98.79
38	98.90
39	99.85
40	99.78

Ward Number	Built-up Density
41	93.93
42	99.88
43	93.59
44	95.80
45	99.55
46	99.05
47	98.48
48	96.32
49	98.53
50	98.59
51	96.37
52	99.51
53	81.46
54	98.73
55	99.17
56	64.82
57	100
58	99.72
59	97.92
60	98.23
61	98.60
62	98.42
63	92.09
64	100
65	97.36
66	96.31
67	97.02
68	98.85
69	97.01
70	98.87
71	96.21
72	98.14
73	99.12
74	98.89
75	97.18
76	94.27
77	99.55
78	99.25
79	100
80	97.14

Ward Number	Built-up Density
81	99.53
82	96.66
83	98.15
84	95.29
85	95.99
86	93.65
87	88.51
88	97.15
89	98.73
90	89.87
91	92.11
92	99.84
93	97.48
94	96.61
95	87.83
96	87.96
97	81.08
98	92.65
99	91.08
100	98.61
101	96.93
102	90.68
103	90.04
104	88.29
105	96.19
106	91.35
107	20.65
108	96.11
109	85.87
110	98.18
111	34.00
112	76.80
113	95.75
114	88.20
115	82.68
116	84.06
117	94.83
118	91.76
119	92.82
120	77.15

Ward Number	Built-up Density
121	93.58
122	96.05
123	90.56
124	96.66
125	80.77
126	98.74
127	98.31
128	96.57
129	96.21
130	98.71
131	70.91
132	100
133	95.50
134	99.43
135	100
136	85.63
137	64.43
138	53.09
139	99.71
140	100
141	100
142	92.98
143	99.67
144	99.09
145	100
146	100
147	97.62
148	96.87
149	99.33
150	71.18

C. Volume of water collected per scenario

C1. 1 sq.km area

Latitude	Longitude	Volume
27.021394	75.745206	46152.26
27.010893	75.782867	45141.48
26.990275	75.876737	31334.21
26.97654	75.877809	162028.2
26.970211	75.738386	162937.9
26.964579	75.802582	133180.5
26.960421	75.880041	82136.06
26.959101	75.880031	303699.3
26.949216	75.898514	48355.76
26.933042	75.909284	26381.38
26.913165	75.68942	22641.49
26.904958	75.694082	266785.5
26.897685	75.906056	50741.21
26.887387	75.906268	80781.62
26.8883	75.698986	163746.5
26.881083	75.901213	66428.53
26.879853	75.698639	58564.65
26.877658	75.900008	35296.47
26.870571	75.706826	26219.66
26.862302	75.906657	39157.66
26.856516	75.719102	20842.3
26.851958	75.732613	59393.49
26.850603	75.739375	151880
26.850338	75.739667	34932.58
26.846758	75.901529	798658.5
26.84103	75.752263	37115.88
26.824722	75.87899	33497.28
26.806175	75.752915	73605.07
26.805383	75.75291	20316.7
26.799354	75.882619	24440.69
26.796665	75.847294	376879.8
26.794889	75.87876	78396.17
26.794406	75.827565	13625.33
26.793372	75.823733	1437452
26.790536	75.856662	75444.7
26.790269	75.857248	58140.13
26.786812	75.769556	122870.5

C2. 2.5 sq.km

Latitude	Longitude	Volume
27.010893	75.782867	45141.48
26.97654	75.877809	161927.1
26.970211	75.738386	162857
26.964579	75.802582	133180.5
26.960421	75.880041	82136.06
26.959101	75.880031	303699.3
26.949216	75.898514	48355.76
26.904958	75.694082	266785.5
26.887387	75.906268	80680.53
26.8883	75.698986	163746.5
26.881083	75.901213	66448.74
26.879853	75.698639	58564.65
26.851958	75.732613	59413.71
26.850603	75.739375	151900.2
26.846758	75.901529	798537.2
26.806175	75.752915	73645.5
26.796665	75.847294	376839.4
26.794889	75.87876	78436.61
26.793372	75.823733	1437432
26.790536	75.856662	75444.7
26.790269	75.857248	58140.13
26.786812	75.769556	122951.4

C3. 5 sq.km

Latitude	Longitude	Volume
26.97654	75.877809	161947.3
26.970211	75.738386	162937.9
26.964579	75.802582	133160.3
26.959101	75.880031	303598.2
26.904958	75.694082	266785.5
26.8883	75.698986	163787
26.850603	75.739375	151981
26.846758	75.901529	798496.8
26.796665	75.847294	376879.8
26.793372	75.823733	1437432
26.786812	75.769556	123052.5

D. Responses for AHP analysis

D1. AHP Decision maker- 1
D1.1 Criteria

Criteria	Rainfall	Slope	Soil texture	LULC	Distance from settlements	Drainage	Runoff	Cost benefit ratio	Watershed size	Population density
Rainfall	1	4	1/9	9	1/6	5	7	2	6	9
Slope	1/4	1	5	6	7	8	4	6	2	8
Soil texture	9	1/5	1	1/7	1/6	1/4	1/2	5	4	3
LULC	1/9	1/6	7	1	1/9	2	4	1/5	7	7
Distance from settlements	6	1/7	6	9	1	6	4	3	6	7
Drainage	1/5	1/8	4	2	1/6	1	9	2	5	6
Runoff	1/7	1/4	2	1/4	1/4	1/9	1	3	5	5
Cost-benefit index	1/2	1/6	1/5	5	1/3	1/2	1/3	1	7	8
Watershed size	1/6	1/2	1/4	1/7	1/6	1/5	1/5	1/7	1	4
Population density	1/9	1/8	1/3	1/7	1/7	1/6	1/5	1/8	1/4	1

D1.2. Alternatives in-line with criteria:

D1.2.1 RAINFALL

	URWH	ORWH	DT	IW	URWH+IW	ORWH+IW	DT+IW
URWH	1	3	6	5	7	7	8
ORWH	1/3	1	1/2	1/6	5	1/4	1/6
DT	1/6	2	1	2	4	8	6
IW	1/5	6	1/2	1	2	3	1/7
URWH+IW	1/7	1/5	1/4	1/2	1	5	4
ORWH+IW	1/7	4	1/8	1/3	1/5	1	2
DT+IW	1/8	6	1/6	1/7	1/4	1/2	1

D1.2.2 SLOPE

	URWH	ORWH	DT	IW	URWH+IW	ORWH+IW	DT+IW
URWH	1	5	9	5	1/6	1/2	7
ORWH	1/5	1	2	6	8	4	6

DT	1/9	1/2	1	7	8	6	3
IW	1/5	1/6	1/7	1	1/4	1/6	6
URWH+IW	6	1/8	1/8	4	1	2	4
ORWH+IW	2	1/4	1/6	6	2	1	5
DT+IW	1/7	1/6	1/3	1/6	1/4	1/5	1

D1.2.3 SOIL TEXTURE

	URWH	ORWH	DT	IW	URWH+IW	ORWH+IW	DT+IW
URWH	1	3	6	4	1/5	1/7	1/6
ORWH	1/3	1	2	4	6	8	3
DT	1/6	1/2	1	1/3	1/5	5	1/7
IW	1/4	1/4	3	1	4	2	4
URWH+IW	5	1/6	5	1/4	1	4	5
ORWH+IW	7	1/8	1/5	1/2	1/4	1	7
DT+IW	6	1/3	7	1/4	1/5	1/7	1

D1.2.4 LAND USE AND LAND COVER

	URWH	ORWH	DT	IW	URWH+IW	ORWH+IW	DT+IW
URWH	1	7	2	4	8	6	9
ORWH	1/7	1	1/6	2	6	1/5	1/7
DT	1/2	6	1	8	3	4	8
IW	1/4	1/2	1/8	1	3	5	5
URWH+IW	1/8	1/9	1/3	1/3	1	1/6	4
ORWH+IW	1/6	5	1/4	1/5	6	1	1/3
DT+IW	1/9	7	1/8	1/5	1/4	3	1

D1.2.5 DISTANCE FROM SETTLEMENTS

	URWH	ORWH	DT	IW	URWH+IW	ORWH+IW	DT+IW
URWH	1	5	4	2	7	5	8
ORWH	1/5	1	5	6	2	6	1/5
DT	1/4	1/5	1	3	5	3	1/7
IW	1/2	1/6	1/3	1	5	4	6
URWH+IW	1/7	1/2	1/5	1/5	1	4	6
ORWH+IW	1/5	1/6	1/3	1/4	1/4	1	2
DT+IW	1/8	5	7	1/6	1/6	1/2	1

D1.2.6 DRAINAGE

	URWH	ORWH	DT	IW	URWH+IW	ORWH+IW	DT+IW
URWH	1	2	1/4	6	5	6	9
ORWH	1/2	1	3	5	1/6	1/2	3
DT	4	1/3	1	2	3	5	7
IW	1/6	1/5	1/2	1	4	2	5
URWH+IW	1/5	6	1/3	1/4	1	1/2	1/4
ORWH+IW	1/6	2	1/5	1/2	2	1	6
DT+IW	1/9	1/3	1/7	1/5	4	1/6	1

D1.2.7 RUNOFF

	URWH	ORWH	DT	IW	URWH+IW	ORWH+IW	DT+IW
URWH	1	7	2	4	8	6	7
ORWH	1/7	1	1/9	2	6	1/5	1/8
DT	1/2	9	1	7	7	6	9
IW	1/4	1/2	1/7	1	3	5	6
URWH+IW	1/8	1/6	1/7	1/3	1	1/2	4
ORWH+IW	1/6	5	1/6	1/5	2	1	1/5
DT+IW	1/7	8	1/9	1/6	1/4	5	1

D1.2.8 COST-BENEFIT INDEX

	URWH	ORWH	DT	IW	URWH+IW	ORWH+IW	DT+IW
URWH	1	2	5	5	8	9	7
ORWH	2	1	6	2	1/6	1/5	6
DT	1/5	1/6	1	5	7	1/3	7
IW	1/5	1/2	1/5	1	4	2	6
URWH+IW	1/8	6	1/7	1/4	1	1/4	5
ORWH+IW	1/9	5	3	1/2	4	1	4
DT+IW	1/7	1/6	1/7	1/6	1/5	1/4	1

D1.2.9 WATERSHED SIZE

	URWH	ORWH	DT	IW	URWH+IW	ORWH+IW	DT+IW
URWH	1	7	3	5	8	9	1/6
ORWH	1/7	1	5	2	1/5	5	2
DT	1/3	1/5	1	5	7	1/3	7
IW	1/5	1/2	1/5	1	6	4	2
URWH+IW	1/8	5	1/7	1/6	1	5	3
ORWH+IW	1/9	1/5	3	1/4	1/5	1	2
DT+IW	6	1/2	1/7	1/2	1/3	1/2	1

D1.2.10 POPULATION DENSITY

	URWH	ORWH	DT	IW	URWH+IW	ORWH+IW	DT+IW
URWH	1	2	5	5	8	6	7
ORWH	1/2	1	6	2	1/6	1/5	6
DT	1/5	1/6	1	4	5	1/3	7
IW	1/5	1/2	1/4	1	4	2	6
URWH+IW	1/8	6	1/5	1/4	1	1/4	5
ORWH+IW	1/6	5	3	1/2	4	1	4
DT+IW	1/7	1/6	1/7	1/6	1/5	1/4	1

D2. AHP Decision maker- 2
D2.1 Criteria

Criteria	Rain fall	Slope	Soil texture	LULC	Distance from settlements	Drainage	Run off	Cost-benefit ratio	Watershed size	Population density
Rainfall	1	1/8	1/6	1/5	2	2	2	1	1/2	2
Slope	8	1	5	6	2	3	2	8	5	6
Soil texture	6	1/5	1	3	4	1/2	1/5	6	1/3	5
LULC	5	1/6	1/3	1	1/3	1/2	1/2	4	1/3	3
Distance from settlements	1/2	1/2	3	3	1	1/4	1/4	6	1/5	3
Drainage	1/2	1/3	2	2	4	1	2	8	2	5
Runoff	1/2	1/2	2	2	4	1/2	1	7	2	6
Cost-benefit index	1	1/8	1/4	1/4	1/6	1/8	1/7	1	1/6	1/5
Watershed size	2	1/5	3	3	5	1/2	1/2	6	1	1/7
Population density	1/2	1/6	1/3	1/3	1/3	1/5	1/6	5	7	1

<u>D2.2 Alternatives in-line with criteria:</u>

D2.2.1 RAINFALL

	URWH	ORWH	DT	IW	URWH+IW	ORWH+IW	DT+IW
URWH	1	2	1/3	7	9	8	1/6
ORWH	1/2	1	1/6	1/4	5	7	1/4
DT	3	6	1	7	9	8	5
IW	1/	4	1/7	1	8	7	1/2
URWH+IW	1/9	1/5	1/9	1/8	1	1/2	1/5
ORWH+IW	1/8	1/7	1/8	1/7	2	1	1/6
DT+IW	6	4	1/5	2	5	6	1

D2.2.2 SLOPE

	URWH	ORWH	DT	IW	URWH+IW	ORWH+IW	DT+IW
URWH	1	6	8	1/7	3	4	8
ORWH	1/6	1	9	1/8	1/3	2	8

DT	1/8	1/9	1	1/7	1/5	1/6	3
IW	7	8	7	1	2	2	7
URWH+IW	1/3	3	5	1/2	1	5	5
ORWH+IW	1/4	1/2	6	1/2	1/5	1	6
DT+IW	1/8	1/8	1/3	1/7	1/5	1/6	1

D2.2.3 SOIL TEXTURE

	URWH	ORWH	DT	IW	URWH+IW	ORWH+IW	DT+IW
URWH	1	1/8	1/9	5	7	3	4
ORWH	8	1	3	8	9	5	6
DT	9	1/3	1	5	9	3	6
IW	1/5	1/8	1/5	1	8	5	4
URWH+IW	1/7	1/9	1/9	1/8	1	1/2	1/5
ORWH+IW	1/3	1/5	1/3	1/5	2	1	2
DT+IW	1/4	1/6	1/6	1/4	5	1/2	1

D2.2.4 LAND USE AND LAND COVER

	URWH	ORWH	DT	IW	URWH+IW	ORWH+IW	DT+IW
URWH	1	8	7	2	3	6	8
ORWH	1/8	1	4	1/6	1/5	2	5
DT	1/7	1/4	1	1/7	1/7	1	3
IW	1/2	6	7	1	3	3	5
URWH+IW	1/3	5	7	1/3	1	4	6
ORWH+IW	1/6	1/2	1	1/3	1/4	1	2
DT+IW	1/8	1/5	1/3	1/5	1/6	1/2	1

D2.2.5 DISTANCE FROM SETTLEMENTS

	URWH	ORWH	DT	IW	URWH+IW	ORWH+IW	DT+IW
URWH	1	2	6	1/4	2	2	7
ORWH	1/2	1	5	1/5	2	2	5
DT	1/6	1/5	1	1/9	1/6	1/7	3
IW	4	5	9	1	4	4	6
URWH+IW	1/2	1/2	6	1/4	1	3	5
ORWH+IW	1/2	1/2	7	1/4	1/3	1	4
DT+IW	1/7	1/5	1/3	1/6	1/5	1/4	1

D2.2.6 DRAINAGE

	URWH	ORWH	DT	IW	URWH+IW	ORWH+IW	DT+IW
URWH	1	3	6	1/2	3	5	6
ORWH	1/3	1	7	1/2	2	2	7
DT	1/6	1/7	1	1/8	1/5	1/6	2
IW	2	2	8	1	2	2	3
URWH+IW	1/3	1/2	5	1/2	1	3	2
ORWH+IW	1/5	1/2	6	1/2	1/3	1	5
DT+IW	1/6	1/7	1/2	1/3	1/2	1/5	1

DD2.2.7 RUNOFF

	URWH	ORWH	DT	IW	URWH+IW	ORWH+IW	DT+IW
URWH	1	4	5	3	4	5	3
ORWH	1/4	1	5	4	3	6	2
DT	1/5	1/5	1	1/6	1/4	5	2
IW	1/3	1/4	6	1	1/3	6	4
URWH+IW	1/4	1/3	4	3	1	3	4
ORWH+IW	5	1/6	1/5	1/6	1/3	1	5
DT+IW	1/3	1/2	1/2	1/4	1/4	1/5	1

D2.2.8 COST-BENEFIT INDEX

	URWH	ORWH	DT	IW	URWH+IW	ORWH+IW	DT+IW
URWH	1	2	1/6	1/2	3	3	1/3
ORWH	1/2	1	1/4	2	2	4	1/3
DT	6	4	1	4	5	5	2
IW	2	1/2	1/4	1	5	5	2
URWH+IW	1/3	1/2	1/5	1/5	1	1/5	3
ORWH+IW	1/3	1/4	1/5	1/5	5	1	2
DT+IW	3	3	1/2	1/2	1/3	1/2	1

D2.2.9 WATERSHED SIZE

	URWH	ORWH	DT	IW	URWH+IW	ORWH+IW	DT+IW
URWH	1	2	8	2	5	3	5
ORWH	1/2	1	9	3	4	4	5
DT	1/8	1/9	1	1/4	1/4	1/2	4
IW	1/2	1/3	4	1	2	2	6
URWH+IW	1/5	1/4	4	1/2	1	2	4
ORWH+IW	1/3	1/4	2	1/2	1/2	1	5
DT+IW	1/5	1/5	1/4	1/6	1/4	1/5	1

D2.2.10 POPULATION DENSITY

	URWH	ORWH	DT	IW	URWH+IW	ORWH+IW	DT+IW
URWH	1	1	1/4	1/2	3	4	1/8
ORWH	1	1	1/4	1/2	3	3	1/8
DT	4	4	1	3	6	8	2
IW	2	2	1/3	1	4	5	1/3
URWH+IW	1/3	1/3	1/6	1/4	1	2	1/4
ORWH+IW	1/4	1/3	1/8	1/5	1/2	1	1/4
DT+IW	8	8	1/2	3	4	4	1

D3. AHP Decision maker- 3
D3.1 Criteria

Criteria	Rainfall	Slope	Soil texture	LULC	Distance from settlements	Drainage	Runoff	Cost-benefit ratio	Watershed size	Population density
Rainfall	1	1/6	1/4	5	3	4	1/8	4	1/6	1/5
Slope	6	1	4	6	3	6	1/9	3	1/5	1/7
Soil texture	4	1/4	1	1/5	3	1/3	1/7	1/2	1/5	1/9
LULC	1/5	1/6	5	1	5	6	1/6	5	6	1/4
Distance from settlements	1/3	1/3	1/3	1/5	1	4	1/6	1/7	1/8	1/7
Drainage	1/4	1/6	3	1/6	1/4	1	3	4	1/6	1/4
Runoff	8	6	7	6	6	1/3	1	5	1/4	1/7
Cost-benefit index	1/4	1/3	2	1/5	7	1/4	1/5	1	5	1/8
Watershed size	6	5	5	1/6	8	6	4	1/5	1	1/5
Population density	5	7	9	1/4	7	4	7	8	5	1

D3.2 Alternatives in-line with criteria:

D3.2.1 RAINFALL

	URWH	ORWH	DT	IW	URWH+IW	ORWH+IW	DT+IW
URWH	1	8	9	6	4	1/4	9
ORWH	1/8	1	7	5	1/7	1/8	8
DT	1/9	1/7	1	1/6	1/5	1/7	1/2
IW	1/6	1/5	6	1	1/5	1/5	6
URWH+IW	1/4	7	5	5	1	7	7
ORWH+IW	4	8	7	5	1/7	1	8
DT+IW	1/9	1/8	2	1/6	1/7	1/8	1

D3.2.2 SLOPE

	URWH	ORWH	DT	IW	URWH+IW	ORWH+IW	DT+IW
URWH	1	1/5	5	3	2	1/7	4
ORWH	5	1	6	8	6	5	7
DT	1/5	1/6	1	1/6	1/6	1/6	1/3
IW	1/3	1/8	6	1	2	4	6
URWH+IW	1/2	1/6	6	1/2	1	0.17	6
ORWH+IW	7	1/5	6	4	6	1	7

DT+IW	1/4	1/7	3	1/6	1/6	1/7	1

D3.2.3 SOIL TEXTURE

	URWH	ORWH	DT	IW	URWH+IW	ORWH+IW	DT+IW
URWH	1	2	6	3	1/3	1/5	6
ORWH	1/2	1	7	8	3	1/7	6
DT	1/6	1/7	1	1/6	1/8	1/6	1/3
IW	1/3	1/8	6	1	1/3	1/5	5
URWH+IW	3	1/3	8	3	1	6	7
ORWH+IW	5	7	6	5	1/6	1	5
DT+IW	1/6	1/6	3	1/5	1/7	1/5	1

D3.2.4 LAND USE AND LAND COVER

	URWH	ORWH	DT	IW	URWH+IW	ORWH+IW	DT+IW
URWH	1	1/2	6	3	1/5	1/3	7
ORWH	2	1	7	3	5	1/7	1/7
DT	1/6	1/7	1	1/7	1/7	1/5	1/2
IW	1/3	1/3	7	1	5	1/7	6
URWH+IW	5	1/5	7	1/5	1	1/3	5
ORWH+IW	3	7	5	7	3	1	6
DT+IW	1/7	7	2	1/6	1/5	1/6	1

D3.2.5 DISTANCE FROM SETTLEMENTS

	URWH	ORWH	DT	IW	URWH+IW	ORWH+IW	DT+IW
URWH	1	5	8	2	1/7	1/6	7
ORWH	1/5	1	9	5	3	1/7	8
DT	1/8	1/9	1	1/8	1/7	1/9	1/3
IW	1/2	1/5	8	1	1/3	1/2	6
URWH+IW	7	1/3	7	3	1	4	8
8ORWH+IW	6	7	9	2	1/4	1	6
DT+IW	1/7	1/8	3	1/6	1/8	1/6	1

D3.2.6 DRAINAGE

	URWH	ORWH	DT	IW	URWH+IW	ORWH+IW	DT+IW
URWH	1	8	7	1/7	1/8	5	6
ORWH	1/8	1	5	1/7	3	1/8	7
DT	1/7	1/5	1	1/8	1/9	1/6	1/3
IW	7	7	8	1	1/7	2	7
URWH+IW	8	1/3	9	7	1	7	8
ORWH+IW	1/5	8	6	½	1/7	1	7
DT+IW	1/6	1/7	3	1/7	1/8	1/7	1

D3.2.7 RUNOFF

	URWH	ORWH	DT	IW	URWH+IW	ORWH+IW	DT+IW
URWH	1	8	9	6	1/3	8	9
ORWH	1/8	1	5	1/7	1/6	1/5	1/3

DT	1/9	1/5	1	1/8	1/9	1/5	1/3
IW	1/6	7	8	1	1/8	1/2	1/3
URWH+IW	3	6	9	8	1	8	9
ORWH+IW	1/8	5	5	2	1/8	1	6
DT+IW	1/9	3	3	3	1/9	1/6	1

D3.2.8 COST-BENEFIT INDEX

	URWH	ORWH	DT	IW	URWH+IW	ORWH+IW	DT+IW
URWH	1	1/3	8	3	6	7	6
ORWH	3	1	7	1/5	1/4	2	5
DT	1/8	1/7	1	1/6	1/7	1/7	2
IW	1/3	5	6	1	5	4	6
URWH+IW	1/6	4	7	1/5	1	3	5
ORWH+IW	1/7	1/2	7	1/4	1/3	1	7
DT+IW	1/6	1/5	2	1/6	1/5	1/7	1

D3.2.9 WATERSHED SIZE

	URWH	ORWH	DT	IW	URWH+IW	ORWH+IW	DT+IW
URWH	1	3	6	3	1/7	1/4	3
ORWH	1/3	1	7	6	1/5	1/4	2
DT	1/6	1/7	1	1/6	1/7	1/7	1/3
IW	1/3	1/6	6	1	1/8	1/6	3
URWH+IW	7	5	7	8	1	6	7
ORWH+IW	4	4	7	6	1/6	1	8
DT+IW	1/3	1/2	3	1/3	1/7	1/8	1

D3.2.10 POPULATION DENSITY

	URWH	ORWH	DT	IW	URWH+IW	ORWH+IW	DT+IW
URWH	1	7	9	3	1/5	1/6	1
ORWH	1/7	1	8	3	1/6	1/7	7
DT	1/9	1/8	1	1/7	1/9	1/8	1/3
IW	1/3	1/3	7	1	1/8	1/7	1/2
URWH+IW	5	6	9	8	1	3	6
ORWH+IW	6	7	8	7	1/3	1	7
DT+IW	1	1/7	3	2	1/6	1/7	1

D4. AHP Decision maker- 4

D4.1 Criteria

Criteria	Rainfall	Slope	Soil texture	LULC	Distance from settlements	Drainage	Runoff	Cost-benefit ratio	Watershed size	Population density
Rainfall	1	1/2	3	2	2	1/3	1/4	3	2	3
Slope	2	1	2	2	3	1/2	2	2	3	2
Soil texture	1/3	1/2	1	2	1/3	2	1/3	2	1/2	1/3
LULC	1/2	1/2	1/2	1	1/2	1/3	1/3	1/2	1/4	1/3
Distance from settlements	1/2	1/3	3	2	1	1/3	2	3	1/3	2
Drainage	3	2	1/2	3	3	1	1	3	2	3
Runoff	4	1/2	3	3	1/2	1	1	3	1/3	1/3
Cost-benefit index	1/3	1/2	1/2	2	1/3	1/3	1/3	1	1/3	1/2
Watershed size	1/2	1/3	2	4	3	1/2	3	3	1	2
Population density	1/3	1/2	3	3	1/2	1/3	3	2	2	1

D4.2 Alternatives in-line with criteria:

D4.2.1 RAINFALL

	URWH	ORWH	DT	IW	URWH+IW	ORWH+IW	DT+IW
URWH	1	5	4	2	1/5	4	1/3
ORWH	1/5	1	1/2	1/3	1/6	1/2	1/4
DT	1/4	2	1	2	1/3	2	1/5
IW	1/2	3	1/2	1	1/3	1/4	1/5
URWH+IW	5	6	3	3	1	3	3
ORWH+IW	1/4	2	1/2	4	1/3	1	1/2
DT+IW	3	4	5	5	1/3	2	1

D4.2.2 SLOPE

	URWH	ORWH	DT	IW	URWH+IW	ORWH+IW	DT+IW
URWH	1	3	1/3	2	1/3	3	3
ORWH	1/3	1	1/2	1/3	1/4	1/3	1/4
DT	3	2	1	1/2	1/3	4	1/3
IW	1/2	3	2	1	1/4	1/4	1/5
URWH+IW	3	4	3	4	1	2	3

ORWH+IW	1/3	3	1/4	4	1/2	1	1/2
DT+IW	1/3	4	3	5	1/3	2	1

D4.2.3 SOIL TEXTURE

	URWH	ORWH	DT	IW	URWH+IW	ORWH+IW	DT+IW
URWH	1	7	5	3	1/5	6	1/4
ORWH	1/7	1	1/4	1/4	1/7	1/3	1/5
DT	1/5	4	1	1/4	1/7	1/2	1/4
IW	1/3	4	4	1	1/5	1	1/3
URWH+IW	5	7	7	5	1	3	2
ORWH+IW	1/6	3	2	1	1/3	1	1/4
DT+IW	4	5	4	3	1/2	4	1

D4.2.4 LAND USE AND LAND COVER

	URWH	ORWH	DT	IW	URWH+IW	ORWH+IW	DT+IW
URWH	1	1/2	1/2	1/3	1/2	1/5	1/3
ORWH	2	1	3	2	2	1/3	3
DT	2	1/3	1	1/4	1/3	1/4	1/3
IW	3	1/2	4	1	2	1/5	1/3
URWH+IW	2	1/2	3	1/2	1	1/3	2
ORWH+IW	5	3	4	5	3	1	4
DT+IW	3	1/3	3	3	1/2	1/4	1

D4.2.5 DISTANCE FROM SETTLEMENTS

	URWH	ORWH	DT	IW	URWH+IW	ORWH+IW	DT+IW
URWH	1	3	2	2	1/3	2	3
ORWH	1/3	1	1/3	1/4	1/4	1/4	1/2
DT	1/2	3	1	1/4	1/3	1/3	1/2
IW	1/2	4	4	1	1/2	1/3	1/3
URWH+IW	3	4	3	2	1	3	4
ORWH+IW	1/2	4	3	3	1/3	1	1/4
DT+IW	1/3	2	2	3	1/4	4	1

D4.2.6 DRAINAGE

	URWH	ORWH	DT	IW	URWH+IW	ORWH+IW	DT+IW
URWH	1	2	3	1/3	1/4	1/4	1/2
ORWH	1/2	1	1/4	1/4	1/5	1/4	2
DT	1/3	4	1	1/3	1/3	1/3	1/4
IW	3	4	3	1	1/4	1/4	1/3
URWH+IW	4	5	3	4	1	1/2	1/2
ORWH+IW	4	4	3	4	2	1	1/3
DT+IW	2	2	4	3	2	3	1

D4.2.7 RUNOFF

	URWH	ORWH	DT	IW	URWH+IW	ORWH+IW	DT+IW
URWH	1	4	2	1/3	1/4	1	1/3

ORWH	1/4	1	1/5	1/6	1/6	1/3	1/6
DT	1/2	5	1	1/4	1/4	1/2	1/4
IW	3	6	4	1	1/5	1/5	1/4
URWH+IW	1/4	6	4	5	1	4	4
ORWH+IW	1	3	2	5	1/4	1	1/5
DT+IW	3	6	4	4	1/4	5	1

D4.2.8 COST-BENEFIT INDEX

	URWH	ORWH	DT	IW	URWH+IW	ORWH+IW	DT+IW
URWH	1	3	4	2	3	4	3
ORWH	1/3	1	1/2	1/3	3	2	2
DT	1/4	2	1	1/2	2	3	3
IW	1/2	3	2	1	4	4	2
URWH+IW	1/3	1/3	1/2	1/4	1	2	2
ORWH+IW	1/4	1/2	1/3	1/4	1/2	1	1/2
DT+IW	1/3	1/2	1/3	1/2	1/2	2	1

D4.2.9 WATERSHED SIZE

	URWH	ORWH	DT	IW	URWH+IW	ORWH+IW	DT+IW
URWH	1	3	3	2	1/3	1/4	1/2
ORWH	1/3	1	2	2	1/2	1/2	1/3
DT	1/3	1/2	1	1/3	1/4	1/4	1/4
IW	1/2	1/2	3	1	1/3	1/3	1/3
URWH+IW	3	2	4	3	1	3	3
ORWH+IW	4	2	4	3	1/3	1	1/3
DT+IW	2	3	4	3	1/3	3	1

D4.2.10 POPULATION DENSITY

	URWH	ORWH	DT	IW	URWH+IW	ORWH+IW	DT+IW
URWH	1	1/3	3	1/3	1/7	1/6	1/3
ORWH	3	1	4	4	3	1/4	3
DT	1/3	1/4	1	1/4	1/4	1/5	1/4
IW	3	1/4	4	1	1/3	1/6	1/3
URWH+IW	7	1/3	4	3	1	1/2	1/2
ORWH+IW	6	4	5	6	2	1	5
DT+IW	3	1/3	4	3	2	1/5	1

D5. AHP Decision maker- 5

D5.1 Criteria

Criteria	Rainfall	Slope	Soil texture	LULC	Distance from settlements	Drainage	Runoff	Cost-benefit ratio	Watershed size	Population density
Rainfall	1	9	6	7	9	9	5	4	6	9
Slope	1/9	1	5	9	5	5	5	7	9	6
Soil texture	1/6	1/5	1	7	7	6	5	6	6	5
LULC	1/7	1/9	1/7	1	9	6	1	6	7	2
Distance from settlements	1/9	1/5	1/7	1/9	1	5	8	5	7	8
Drainage	1/9	1/5	1/6	1/6	1/5	1	1	5	7	7
Runoff	1/5	1/5	1/5	1	1/8	1	1	7	8	8
Cost-benefit index	¼	1/7	1/6	1/6	1/5	1/5	1/7	1	8	8
Watershed size	1/6	1/9	1/6	1/7	1/7	1/7	1/8	1/8	1	8
Population density	1/9	1/6	1/5	1/2	1/8	1/7	1/8	1/8	1/8	1

D5.2 Alternatives in-line with criteria:

D5.2.1 RAINFALL

	URWH	ORWH	DT	IW	URWH+IW	ORWH+IW	DT+IW
URWH	1	5	5	1/5	1/9	1/8	1/8
ORWH	1/5	1	1/5	1/5	1/9	1/8	1/8
DT	1/5	5	1	9	5	4	4
IW	5	5	1/9	1	9	9	9
URWH+IW	9	9	1/5	1/9	1	9	5
ORWH+IW	8	8	1/4	1/9	1/9	1	1/5
DT+IW	8	8	1/4	1/9	1/5	5	1

D5.2.2 SLOPE

	URWH	ORWH	DT	IW	URWH+IW	ORWH+IW	DT+IW
URWH	1	9	1/5	1/5	1/9	1/8	1/9
ORWH	1/9	1	1/9	1/9	1/9	1/6	1/9
DT	5	9	1	1/8	1/8	1/5	1/9
IW	5	9	8	1	9	9	9
URWH+IW	9	9	8	1/9	1	9	7

ORWH+IW	8	6	5	1/9	1/9	1	1/5
DT+IW	9	9	9	1/9	1/7	5	1

D5.2.3 SOIL TEXTURE

	URWH	ORWH	DT	IW	URWH+IW	ORWH+IW	DT+IW
URWH	1	9	9	1/9	1/9	1/8	1/8
ORWH	1/9	1	1/5	1/9	1/9	1/8	1/8
DT	1/9	5	1	1/9	1/9	1/8	1/9
IW	9	9	9	1	9	9	9
URWH+IW	9	9	9	1/9	1	9	9
ORWH+IW	8	8	8	1/9	1/9	1	1/8
DT+IW	8	8	9	1/9	1/9	1/8	1

D5.2.4 LAND USE AND LAND COVER

0	URWH	ORWH	DT	IW	URWH+IW	ORWH+IW	DT+IW
URWH	1	9	9	1/9	1/9	1/8	1/9
ORWH	1/9	1	1/9	1/9	1/8	1/8	1/8
DT	1/9	9	1	1/9	1/9	1/9	1/8
IW	9	9	9	1	9	9	9
URWH+IW	9	8	9	1/9	1	9	8
ORWH+IW	8	8	9	1/9	1/9	1	7
DT+IW	9	8	8	1/9	1/8	1/7	1

D5.2.5 DISTANCE FROM SETTLEMENTS

	URWH	ORWH	DT	IW	URWH+IW	ORWH+IW	DT+IW
URWH	1	9	9	5	1/9	1/5	9
ORWH	1/9	1	1/9	1/9	1/9	1/5	1/9
DT	1/9	9	1	5	1/9	1/5	1/8
IW	1/5	9	1/5	1	8	9	9
URWH+IW	9	9	9	1/8	1	9	8
ORWH+IW	5	5	5	1/9	1/9	1	1/5
DT+IW	1/9	9	8	1/8	1/8	5	1

D5.2.6 DRAINAGE

	URWH	ORWH	DT	IW	URWH+IW	ORWH+IW	DT+IW
URWH	1	9	1	1	1	9	1/9
ORWH	1/9	1	1/9	1/9	1/9	1/9	1/9
DT	1	9	1	1	1	5	1/9
IW	1	9	1	1	1	1/9	1
URWH+IW	1	9	1	1	1	9	1
ORWH+IW	1/9	9	1/5	9	1/9	1	1/9
DT+IW	9	9	9	1	1	9	1

D5.2.7 RUNOFF

	URWH	ORWH	DT	IW	URWH+IW	ORWH+IW	DT+IW
URWH	1	9	1	1	1/9	9	1/9

ORWH	1/9	1	1/9	1/9	1/9	1/5	1/9
DT	1	9	1	1	1	1/8	1/9
IW	1	9	1	1	9	9	9
URWH+IW	9	9	1	1/9	1	9	1
ORWH+IW	1/9	5	8	1/9	1/9	1	1/9
DT+IW	9	9	9	1/9	1	9	1

D5.2.8 COST-BENEFIT INDEX

	URWH	ORWH	DT	IW	URWH+IW	ORWH+IW	DT+IW
URWH	1	9	5	1/7	1/9	9	8
ORWH	1/9	1	1/5	1/9	1/9	1/5	1/9
DT	1/5	5	1	1/2	1/5	1/9	1/9
IW	7	9	2	1	1/7	9	1/4
URWH+IW	9	9	5	7	1	9	1/2
ORWH+IW	1/9	5	9	1/9	1/9	1	1/9
DT+IW	1/8	9	4	2	2	9	1

D5.2.9 WATERSHED SIZE

	URWH	ORWH	DT	IW	URWH+IW	ORWH+IW	DT+IW
URWH	1	9	1	1	1	1/9	1
ORWH	1/9	1	1/9	1/9	1/9	1/5	1/9
DT	1	9	1	1	1	1/5	1
IW	1	9	1	1	1	1/5	1
URWH+IW	1	9	1	1	1	1/5	1
ORWH+IW	9	5	5	5	5	1	1/5
DT+IW	1	9	1	1	1	5	1

D5.2.10 POPULATION DENSITY

	URWH	ORWH	DT	IW	URWH+IW	ORWH+IW	DT+IW
URWH	1	1/9	9	1	1	1/9	1
ORWH	9	1	9	9	9	9	9
DT	1/9	1/9	1	1/9	1/5	1/9	1
IW	1	1/9	9	1	1	1/9	1
URWH+IW	1	1/9	5	1	1	5	9
ORWH+IW	1/9	1/9	9	9	1/5	1	6
DT+IW	1	1/9	1	1	1/9	1/6	1

E. Activity wise cost estimate

Code	Activity	Planned Cost
Initiation		598710
I1	Understanding Problem Statement	14000
I2	Preliminary Survey	451,710
I3	Collection of Data	21000
I4	Determining Tools and Technology	14000
I5	Documentation and Certification	98000
Planning		280000
GIS Analysis		56000
P1.1	Importing Spatial Reference Data	3500
P1.2	Developing methodology for identifying locations	24500
P1.3	Excluding areas of existing water bodies (Study area analysis)	3500
P1.4	Selection of Basin for performing pilot study	3500
P1.5	Selection of ward and clipping the extent	3500
P1.6	Classification and digitization of drain lines	3500
P1.7	Estimation of Runoff (Thematic Map Preparation)	14000
Designing		24500
P2.1	Determining Drain size	10500
P2.2	Design of Sedimentation Tank	7000
P2.3	Design of Storage Tank	7000
Modeling		59500
P3.1	Importing data	3500
P3.2	Performing Visual Modeling	14000
P3.3	Scheduling (4D)	7000
P3.4	Material Estimation (Quantity Takeoff)	7000
P3.5	Resource Allocation	14000
P3.6	Cost Estimation (5D)	14000
Tendering and Bidding		140000

Code	Activity	Planned Cost
P4.1	Tendering and Bidding	140000
Execution		40125177
Preparation		109500
E1.1	Allocation of Work	10500
E1.2	Purchasing and Ordering	63000
E1.3	Land Acquisition	36000
Drainage construction		33505801
E2.1	Drainage Layout Marking	6600
E2.2	Site Clearing	10000
E2.3	Excavation	4845500
E2.4	Levelling and RCC	12947900
E2.5	Vertical Reinforcement	9552216
E2.6	Formwork Placing	160125
E2.7	Vertical Concreting	5942860
E2.8	Formwork Removal	13600
E2.9	Curing	21000
E2.910	Backfilling and Finishing	6000
Sedimentation Tank Construction Site B		546358
E3.1	Site cleaning and Layout marking	3500
E3.2	Excavation and Levelling	27400
E3.3	Foundation and Curing	65708
E3.4	PCC Bed concrete and curing	65114
E3.5	Installation of Reinforcement	40423
E3.6	Base Concreting and curing	42705
E3.7	Vertical wall construction	59887
E3.8	Plastering	20317
E3.9	Curing	7700
E3.910	Provision of Inlet and Outlet connection	119945
E3.911	Water Proofing	80737
E3.912	Backfilling and Finishing	12920
Storage Tank Construction Site B		2469970

Code	Activity	Planned Cost
E4.1	Site Clearing and Marking	9200
E4.2	Excavation	1335200
E4.3	Levelling and blinding	11400
E4.4	Base Compaction	24180
E4.5	Construction of Outlet Structure and percolation well	659385.15
E4.6	Slope stabilization and Tank Lining	323880
E4.7	Stone bunds and boundary construction	94225
E4.8	Curing and Drying	3500
E4.9	Finishing work	9000
Sedimentation Tank Construction Site C		610434
E5.1	Site cleaning and Layout marking	610434
E5.2	Excavation and Levelling	9200
E5.3	Foundation and Curing	65719
E5.4	PCC Bed concrete and curing	86595
E5.5	Installation of Reinforcement	50172
E5.6	Base Concreting and curing	46484
E5.7	Vertical wall construction	67729
E5.8	Plastering	25090
E5.9	Curing	7700
E5.910	Provision of Inlet and Outlet connection	121945
E5.911	Water Proofing	84480
E5.912	Backfilling and Finishing	12920
Storage Tank Construction Site C		2883113
E6.1	Site Clearing and Marking	10500
E6.2	Excavation	1672900
E6.3	Levelling and blinding	15200
E6.4	Base Compaction	32240
E6.5	Construction of Outlet Structure and percolation well	659385
E6.6	Slope stabilization and Tank Lining	356889
E6.7	Stone bunds and boundary construction	125299

Code	**Activity**	**Planned Cost**
E6.8	Curing and Drying	3500
E6.9	Finishing work	7200
Finishing Work		49700
M1	Cleaning of Drains	21000
M2	Tank Cleaning	4000
M3	Fault detection and repair	24700
Closure		42000
C1	Taking out actual Quantities	14000
C2	Completion certificate	21000
C3	Handover	7000

F. Sample input data and estimated LPCD for municipality zone

Latitude	Longitude	Person	Income	Supply	Area	LPCD
26.88192	75.70163	4	100000	500	802	108.93
26.89336	75.72291	6	150000	1200	1500	
26.88187	75.70837	3	200000	500	1337	
26.8976	75.72026	5	90000	900	700	
26.88187	75.70837	3	200000	500	1337	
26.89327	75.72655	6	100000	1000	1000	
26.89327	75.72655	5	100000	1000	1000	
26.89313	75.72615	7	150000	1200	1200	
26.89337	75.72516	4	100000	1200	1200	
26.89327	75.72546	6	100000	1000	1000	
26.89217	75.72654	7	100000	1000	1000	
26.89205	75.72612	5	150000	1200	1200	
26.89195	75.72503	4	150000	1200	1200	
26.89205	75.72493	6	100000	1000	1000	
26.89327	75.72655	7	150000	1000	1000	
26.89326	75.72665	6	100000	1000	1200	
26.89327	75.72624	5	100000	1200	1100	
26.89327	75.72624	6	100000	1200	1000	
26.89326	75.72614	7	100000	1000	1000	
26.89326	75.72664	6	150000	1000	1000	
26.89325	75.72603	5	100000	1000	1200	
26.89325	75.72503	6	100000	1000	1200	
26.89321	75.7251	4	150000	1200	1500	
26.89322	75.72512	7	100000	1200	1000	
26.89326	75.72666	7	150000	1000	1000	
26.89326	75.72615	6	100000	1000	1200	
26.89317	75.72664	5	100000	1000	1200	
26.89322	75.72665	6	150000	1200	1000	
26.89321	75.72615	7	150000	1200	1000	
26.89317	75.72615	7	100000	1200	1200	
26.89316	75.72625	5	100000	1000	1200	
26.89315	75.72625	5	100000	1200	1000	

G. Sample data for water quality analysis

Latitude	Longitude	Population	DO	PH	TDS	CL	F	Hardness	Nitrates	Fe	Cu	Hi	Fuzzy
26.948	75.747	4000	11	7.6	748	100	0.2	220	45	0.8	1	0.9	57.9
26.945	75.746	3000	12	7	708	100	0.3	230	43	0.9	1.3	0.9	58.1
26.943	75.762	5000	14	7.2	466	100	0.1	150	25	0.8	1.5	0.7	49
26.564	75.452	4000	10	7.4	841	110	0.5	320	42	1	1.2	1.1	52
26.889	75.865	500	8	7.3	1550	250	0.8	520	41	0.9	0.9	1.6	57.9
26.908	75.891	5000	12	7	1760	450	1.1	600	42	0.9	0.9	1.9	35.9
26.905	75.866	50	11	7.1	1671	390	0.9	610	44	0.8	0.9	1.8	51
26.906	75.870	100	10	7.8	4060	500	1.9	1450	45	0.9	0.9	3.8	22
26.888	75.837	80	10	7.2	382	100	0.1	120	6	0.8	0.8	0.4	51
26.889	75.838	100	10	7.2	350	90	0.2	130	3	0.7	1	0.5	57.9
26.896	75.840	150	12	7	346	80	0.1	110	3	0.8	1	0.4	53
26.896	75.840	4000	14	7.5	2052	550	1.1	560	41	0.2	1	1.9	81.8
26.886	75.832	6000	12	7.6	363	100	0.2	110	3	0.5	0.2	0.3	80.6
26.877	75.837	150	13	7.1	421	80	0.3	130	22	0.8	1.2	0.6	58.4
26.939	75.757	3000	14	7.2	1009	170	0.6	380	44	0.6	1.3	1.3	66.6
26.940	75.757	2000	12	7.4	1025	170	0.8	370	41	0.4	1.5	1.3	62.1
26.944	75.749	1800	14	7.3	956	160	0.7	320	39	0.3	1.2	1.1	92.5
26.944	75.750	1800	13	7.1	774	120	0.6	230	44	0.2	1.3	1.0	81.5
26.947	75.743	2010	10	7	559	90	0.4	160	43	0.1	0.9	0.7	52
26.947	75.741	3500	12	6.9	800	90	0.7	200	42	0.5	1.2	0.9	57.6
26.950	75.749	3500	10	7.5	1966	470	1.0	540	45	0.5	1.5	1.9	70.1
26.949	75.748	5000	10	7.4	777	150	0.5	230	40	0.3	1.3	1.0	87.5
26.879	75.713	1000	15	7.7	707	100	0.3	160	128	0.2	1.2	1.1	50.7
26.867	75.718	4000	14	7.5	731	100	1.5	90	69	0.5	0.9	0.8	70.2
26.880	75.707	5000	14	7.3	607	40	0.4	150	87	0.6	0.8	0.9	60.0
26.883	75.711	2000	17	7.6	543	110	0.8	100	79	0.5	1.2	0.9	50.1
26.891	75.714	5500	18	7.3	677	200	0.5	80	161	0.4	1	1.2	59.7
26.887	75.717	4000	10	7.8	583	100	0.6	120	105	0.6	1	0.9	50.2
26.889	75.733	2500	9	7.6	850	120	0.2	370	200	0.3	0.2	1.6	32.3

H. Resource specification and cost information

H1. Carriage of materials

Description	Unit	Add for each 50 m	For 500 M	for 500 m(0,5km)	For 1 Km	Add for each 1km beyond 1st km(up to 5km)	for 5km	Add for each 1km beyound 5km(up to 10km)	for 10km	add for 1km beyond 10km	for 20km	add for each 1km beyond 20 km
Earth, Sand, Lime, Morrum manure or sludge	Cum	23	4	59	80	9	125	8	165	8	240	7
Building Rubbish Stone metal (Grit and ballast etc.)	Cum	30	5	72	80	9	125	8	165	8	240	7
Stone for Masonry work & soling	Cum	44	5	90	105	7	132	7	164	6	221	5
Bricks	1000 NOS	89	12	193	227	14	282	13	345	12	460	8
Cement, Stone blocks pipes and other heavy materials	MT	25	4	56	66	8	98	8	138	7	207	4
Steel, Tar bitumen, Timber and steam coal	MT	23	3	50	59	13	110	13	173	12	288	5
Earth Lifting												
Add extra for foundation/trenches/drains for every additional lift of 1.5 Mtr. or part thereof in												
All kinds of soil	cum											34
Ordinary or hard rock.	cum											61

H2. Item Description and Cost

Name	Unit	Rate
Site clearance work		
Clearing jungle including uprooting of rank vegetation, grass, brush wood, trees and saplings of girth upto 30 cm measured at a height of 1 m above ground level and removal of rubbish upto a distance of 50 m outside the periphery of the area cleared.	sqm	5
Clearing grass and removal of the rubbish upto a distance of 50 m outside the periphery of the area cleared.	sqm	2
Felling trees of the girth (measured at a height of 1 m above ground level) including cutting of trunks and branches removing the roots and stacking of serviceable material and disposal of unserviceable material		
Beyound 30 cm girth upto including 60 cm girth	Each	140
Beyound 60 cm girth upto including 120 cm girth	Each	620
Beyound 120 cm girth upto including 240 cm girth	Each	2875
Above 240 cm girth	Each	5768
Clearing and grubbing road land including uprooting rank vegetation, grass, bushes, shrubs, saplings and trees girth up to 300 mm, removal of stumps of trees cut earlier and disposal of unserviceable materials and stacking of serviceable material to a lead of 50 metres from road boundary including removal and disposal of top organic soil not exceeding 150 mm in thickness as directed by Engineer.		
In area of light jungle	hectare	56000
In area of thorny jungle	hectare	74300
Excavation		
Earth work in excavation by mechanical means (Hydraulic excavator)/manual means over areas (exceeding 30cm in depth. 1.5m in width as well as 10 sqm on plan) including disposal of excavated earth, lead upto 50m and lift upto 1.5 m , disposed earth to be levelled and neatly dressed: All kinds of soil	cum	175
Earth work in excavation/ by mechanical means (Hydraulic Excavator)/ manual means over areas (exceeding 30 cm in depth, 1.5m in width as well as 10 sqm on plan) including disposal of excavated earth, lead upto 50 m and lift upto 1.5 m , disposed earth to be levelled and neatly dressed:		
Ordinary rock	cum	251
Hard rock (requiring blasting) useful material 30%	cum	410
Hard rock(blasting prohibited) useful material 30%	cum	540
Excavation for Foundation		
Earth work in excavation by mechanical means (Hydraulic Excavator)/ manual means in foundation trenches or drains (not exceeding 1.5 m in width or 10 sqm on plan) including dressing of sides and ramming of bottoms, lift upto 1.5 m, including taking out the excavated soil and depositing and refilling of jhiri with watering & ramming and disposal of	cum	178

surplus excavated soil as directed with in a lead of 50 meter. All kinds of soils		
Excavation work by mechanical means (Hydraulic excavator) / manual means in foundation trenches or drains not exceeding 1.5 m in width or 10 sqm on plan including dressing of sides and ramming of bottoms lift upto 1.5 m, including getting out the excavated soil and disposal of surplus excavated soil as directed with a lead in a 50 meter including stacking of useful material if available		
Ordinary rock	cum	268
Hard rock (requiring blasting) useful material 30%	cum	444
Hard rock(blasting prohibited) useful material 30%	cum	551
Foundation Work		
Providing, laying and compacting plain/ reinforced cement concrete of specified grade in foundation/ levelling course/ pile cap using concrete mixer and vibrater complete including cost of form work, as per drawing and technical specifications and as per clause 1100, 1500,1700,2100 of MoRT&H specification including all scaffolding material, labour, machinery.		
PCC Grade M -15	cum	5,070.00
PCC Grade M -20	cum	5,560
PCC Grade M -25	cum	5,940
PCC Grade M -30	cum	5,970
RCC Grade M -20	cum	5,600
RCC Grade M -25	cum	5,990
RCC Grade M -30	cum	6,000
RCC Grade M -35	cum	6,080
Bored cast-in-situ R.C.C. pile with design mix concrete using batching plant, transit mixer and concrete pump, excluding reinforcement complete as per drawing and technical specifications and removal of excavated earth with all lifts and lead upto 1000 m. as per clause 1100, 1600 & 1700 of MoRT&H Specification including all material, labour and machinery.		
400 mm dia pile		
RCC Grade M -20 (Design mix)	cum	2630
RCC Grade M -25 (Design mix)	cum	2680
RCC Grade M -30 (Design mix)	cum	2685
RCC Grade M -35 (Design mix)	cum	2710
450 mm dia pile	cum	
RCC Grade M -20 (Design mix)	cum	2795
RCC Grade M -25 (Design mix)	cum	2860
RCC Grade M -30 (Design mix)	cum	2875
RCC Grade M -35 (Design mix)	cum	2900
Reinforcement Work		
Providing and fabricating reinforcement for R.C.C. work including straightening, cutting, bending, placing in position and binding (including cost of binding wire) all complete up to floor five level.		
Cold twisted deformed bars (IS : 1786).	kg	77

Name	Unit	Rate
Hot rolled deformed bars (IS : 1139).	kg	77
Thermo-mechanically Treated bars (Conforming of relevant IS code)	kg	77
Labour charges for cutting, bending for fabrication and binding reinforcement (plain or tor/ribbed/TMT steel) as per drawing and design for R.C.C. and R.B. work including cost of binding wire with all lead and lift up to floor five level complete.	kg	12
Concrete Work		
Providing and laying in position Ready mix concrete manufactured in fully automatic Batching Plant and transported to site in transit mixer for having continous agitated mixer, manufactured as per approved mix design of specified grade of RCC work including pumping of R.M.C. from transit mixer to site of laying , exculding the cost of centering, shuttering and reinforcement with all lead and lift including cost of admixtures in recommended portion as per IS 9103 to accelerate/ retard setting of concrete, improve workability without impairing strength and durability as per direction of Engineer in charge. All works upto floor V floor M20 grade Design Mix by using cement as per codal provision.	Cum	6089
Add extra for providing richer mixes respectively at all floors levels	Cum	
Providing M-25 grade concrete by using cement as per codal provision instead of M-20 grade design mix.	Cum	69
Providing M-30 grade concrete by using cement as per codal provision instead of M-20 grade design mix.	Cum	139
Providing M-35 grade concrete by using cement as per codal provision instead of M-20 grade design mix.	Cum	194
Providing M- 40 grade concrete by using cement as per codal provision instead of M-20 grade design mix.	Cum	242
Formwork		
Centering and Shuttering with plywood or steel sheets including strutting, propping bracing both ways and removal of formwork for foundation, footings, strap beam, raft , bases of columns etc.	sqm	157
Centering & shuttering with plywood or steel sheets including strutting, propping bracing both ways with steel props and removal of formwork for up to floor five level for:		
Walls (any thickness) including attached pilasters, buttresses plinth and string course.	sqm	289
Suspended floors, roofs, landings, staircases, balconies, girders, cantilevers, bands, coping bed plates, anchor blocks, sills, chhajjas, lintel, beam, plinth beam etc.	sqm	340
Brickwork		
Brick masonry with F.P.S. bricks of class designation 75 in foundation and plinth with bricks		
Cement mortar 1 : 4 (1 cement : 4 coarse sand)	cum	4469

Name	Unit	Rate
Cement mortar 1 : 6 (1 cement : 6 coarse sand)	cum	4263
Mud Mortor	cum	3265
Stonework (machine cut edges) for Wall cladding/ Veneering work up to 10m height with 20 to 30 mm thick Red Sand Stone (Karauli) and backing filled with a grout of 12mm thick cement mortar 1:3 (1 cement : 3 coarse sand) including pointing in white cement mortar 1:2 (1 white cement: 2 stone dust) with an admixture of pigment matching the stone shade :(To be secured to the backing by means of cramps which shall be paid separately).. 6.8.1 Exposed face rough dressed.	Sqm.	1649
MORTAR (Complete rate for mortar is inclusive of cost of material, T & P & cost of water with all leads and lifts involved)		
2.1 Cement sand Mortar 1 : 2 (1 cement : 2 sand)	Cum	5015
2.2 Cement sand Mortar 1 : 3 (1 cement : 3 sand)	Cum	4145
2.3 Cement sand Mortar 1 : 4 (1cement : 4 sand)	Cum	3401
2.4 Cement sand Mortar 1 : 5 (1 cement : 5 sand)	Cum	3001
2.5 Cement sand Mortor 1 : 6 (1 cement : 6 sand)	Cum	2658
2.6 Cement sand Mortor 1 : 8 (1 cement : 8 sand)	Cum	2200
2.7 Cement sand Mortar 1:10 (1 cement :10 sand)	Cum	1953
Cement Plaster		
Plaster on new surface on wall in cement sand mortar 1:3 including racking of joints etc. complete fine finish:		
25 mm thick	sqm	242
20 mm thick	sqm	211
12mm thick	sqm	164
Plaster on new surface on walls in cement sand mortar 1:4 including racking of joints etc. complete fine finish:		
25 mm thick	sqm	227
20 mm thick	sqm	202
12mm thick	sqm	163
Plaster on new surface on walls in cement sand mortar 1:6 including racking of joint etc. complete fine finish:		
25 mm thick	sqm	211
20 mm thick	sqm	190
12mm thick	sqm	160
Plaster on new surface on walls in cement sand mortar 1:8 including racking of joint etc. complete fine finish:		
25 mm thick	sqm	176
20 mm thick	sqm	164
12mm thick	sqm	140
Rough Plaster		
Rough cast plaster upto 10m height above ground level with a mixture of sand and gravel or crushed stone from 6mm to 10mm nominal size dashed over and including the fresh plaster in two layers, under layer 12mm cement plaster 1:4 (1 cement : 4 coarse sand) and top layer 10mm cement plaster 1:3 (1 cement : 3 fine sand) mixed with 10% finely grounded hydrated lime by volume of cement.Ordinary cement finish using ordinary cement.	Sqm	340

Name	Unit	Rate
Waterproofing		
Providing and laying water proofing treatment to vertical and horizontal surfaces of depressed portions of W.C., kitchen and the like consisting of:	Sqm.	513
a) Ist course of applying cement slurry @ 4.4 Kg/sum mixed with water proofing compound conforming to IS 2645 in recommended proportions including rounding off junction of vertical and horizontal surface		
b) IInd course of 20mm cement plaster 1:3 (1 cement: 3 coarse sand) mixed with water. proofing compound in recommended proportion including rounding off junction of vertical and horizontal surface.		
c) IIIrd course of applying blown or residual bitumen applied hot at 1.7 Kg per sqm. of area.		
d) IVth course of 400-micron thick PVC sheet (Overlaps at joints of PVC sheet should be 100 mm wide and pasted to each other with bitumen @ 1.7 Kg/sqm.)		
Basic Rates for Machinery		
Hire charges of Diesel Road Roller - 8 to 10 tonne	Day	1730
Hire charges of Diesel Truck - 9 tonne	Day	1500
Hydraulic Excavator (3D) with driver and fuel.	Day	8000
Surface Vibrator	Day	800
Hire and running charges of vibrating pile driving hammer complete with power unit and accessories.	Day	37000
Tractor with ripper attachment	Day	1
Tractor with trolley	Day	1300
Water tanker 5000-liter capacity	Day	1200
Basic Rates for Labour		
Engineer	Day	3500
Carpenter 1st class	Day	1000
Carpenter 2nd class	Day	800
Mason (for plaster of paris work) 1st class	Day	700
Mason (brick layer) 1st class	Day	700
Mason (brick layer) 2nd class	Day	600
Mason (for plain stonework) 2nd class)	Day	600
Driver (for Road Roller, Concrete Mixer, Truck etc.)	Day	700
Mistry	Day	700
Painter	Day	600
Operator (Pile/ Special machine)	Day	800
Sweeper	Day	800
Helper	Day	500
Rates For Materials		
Stone for masonry work	Cum	1000
Water proofing materials	kg	40
G.I. pipes 15 mm dia (B Class)	meter	160
G.I. pipes 20 mm dia (B Class)	meter	205
G.I. pipes 25 mm dia (B Class)	meter	290
G.I. pipes 32 mm dia (B Class)	meter	360

Name	Unit	Rate
G.I. pipes 40 mm dia (B Class)	meter	420
G.I. pipes 50 mm dia (B Class)	meter	600
G.I. pipes 65 mm dia (B Class)	meter	695
G.I. pipes 80 mm dia (B Class)	meter	890
R.C.C. pipes NP2 class 100 mm dia	meter	475
R.C.C. pipes NP2 class 150 mm dia	meter	520
R.C.C. pipes NP2 class 200 mm dia	meter	615
R.C.C. pipes NP2 class 250 mm dia	meter	700
R.C.C. pipes NP2 class 350 mm dia	meter	950
R.C.C. pipes NP2 class 450 mm dia	meter	1430
R.C.C. pipes NP2 class 500 mm dia	meter	1600
R.C.C. pipes NP2 class 600 mm dia	meter	2150
R.C.C. pipes NP2 class 700 mm dia	meter	2650
R.C.C. pipes NP2 class 800 mm dia	meter	3465
R.C.C. pipes NP2 class 900 mm dia	meter	4350
R.C.C. pipes NP2 class 1000 mm dia	meter	5000
R.C.C. pipes NP2 class 1100 mm dia	meter	5900
R.C.C. collarsNP2 class 100 mm dia	each	25
R.C.C. collarsNP2 class 150 mm dia	each	35
R.C.C. collarsNP2 class 200 mm dia	each	50
R.C.C. collarsNP2 class 250 mm dia	each	56
R.C.C. collarsNP2 class 300 mm dia	each	70
R.C.C. collarsNP2 class 450 mm dia	each	106
R.C.C. collarsNP2 class 500 mm dia	each	122
R.C.C. collarsNP2 class 600 mm dia	each	155
R.C.C. collarsNP2 class 700 mm dia	each	171
R.C.C. collarsNP2 class 800 mm dia	each	245
R.C.C. collarsNP2 class 900 mm dia	each	300
R.C.C. collarsNP2 class 1000 mm dia	each	35
R.C.C. collarsNP2 class 1100 mm dia	each	405
R.C.C. collarsNP2 class 1200 mm dia	each	470
F.P.S. bricks tile class designation 100	1000 N	4500
Modular bricks class designation 75	1000N	11000
Mild steel round bar 12 mm dia and below	quintal	7400
Mild steel round bar above 12 mm dia	quintal	7400
Average rate of Mild steel round bars for reinforcements	quintal	7400
Twisted steel / deformed bars	quintal	8000
Mild steel square bars	quintal	7400
TMT bar	quintal	8000
Coarse sand (zone III)	Cum	1800
Fine sand (zone IV)	Cum	1800
Portland Cement	tonne	7000
Reinforced HDPE Geomembrane 500 Micron Dollar,0.5mm THK, laminated HDPE woven fabric for waterproof lining, type II with IS:15351:2015	Sqm.	95

I. Expert responses for safety management

I1. Expert-1

Activity Name	Likelihood	Consequences
Stormwater Drainage Network		
Drainage Layout Marking	2	2
Site Clearing (Removing debris and trees)	2	2
Excavation by earth mover (Depth 2.72 m)	2	2
Site Levelling and RCC	2	2
Vertical Reinforcement	3	4
Formwork Placing	3	4
Vertical Concreting	2	2
Formwork Removal	2	2
Curing (Ponding method)	2	2
Backfilling and Finishing	2	2
Sedimentation Tank Construction		
Site Clearing (Removing debris and trees)	4	5
Excavation and Levelling (Depth 5m)	5	5
Foundation (Pile) and Curing	3	5
PCC Bed concrete and curing (at Depth 5m)	5	5
Installation of Reinforcement (For Bed slab at depth 5m)	4	4
Base concreting and curing	4	5
Vertical wall construction (5m height)	4	4
Plastering	5	2
Curing	2	2
Provision of Inlet and Outlet connections	3	2
Water proofing (Base and walls)	2	3
Back filling and Finishing	4	3
Rainwater Harvesting Tank		
Site Clearing (Removing debris and trees)	2	4
Excavation (6m Depth)	5	4
Levelling and Blinding	2	3
Base Compaction (Compactors)	3	4
Construction of Outlet Structure and percolation well (Percolation well 30m depth)	5	4
Slope Stabilization and Tank Lining (Slope Compactor)	1	4
Stone bunds and boundary construction (Along periphery of tank at 1m depth)	1	2
Curing and Miscellaneous work	2	3
Finishing work	4	4
Finishing work		
Cleaning of Drains	2	3
Tank cleaning	2	3
Leakage Detection and Repairing	3	1
Maintaining valves and Conduits	4	3

I2. Expert-2

Activity Name	Likelihood	Consequences
Stormwater Drainage Network		
Drainage Layout Marking	1	1
Site Clearing (Removing debris and trees)	3	1
Excavation by earth mover (Depth 2.72 m)	1	1
Site Levelling and RCC	1	2
Vertical Reinforcement	4	3
Formwork Placing	2	3
Vertical Concreting	3	2
Formwork Removal	1	1
Curing (Ponding method)	1	1
Backfilling and Finishing	2	2
Sedimentation Tank Construction		
Site Clearing (Removing debris and trees)	1	1
Excavation and Levelling (Depth 5m)	5	4
Foundation (Pile) and Curing	2	3
PCC Bed concrete and curing (at Depth 5m)	4	3
Installation of Reinforcement (For Bed slab at depth 5m)	3	2
Base concreting and curing	4	4
Vertical wall construction (5m height)	4	2
Plastering	1	2
Curing	1	1
Provision of Inlet and Outlet connections	2	2
Water proofing (Base and walls)	1	1
Back filling and Finishing	2	2
Rainwater Harvesting Tank		
Site Clearing (Removing debris and trees)	2	3
Excavation (6m Depth)	4	5
Levelling and Blinding	2	5
Base Compaction (Compactors)	3	4
Construction of Outlet Structure and percolation well (Percolation well 30m depth)	4	4
Slope Stabilization and Tank Lining (Slope Compactor)	3	2
Stone bunds and boundary construction (Along periphery of tank at 1m depth)	2	2
Curing and Miscellaneous work	2	2
Finishing work	3	2
Finishing work		
Cleaning of Drains	3	4
Tank cleaning	2	2
Leakage Detection and Repairing	4	4
Maintaining valves and Conduits	5	4

I3. Expert-3

Activity Name	Likelihood	Consequences
Stormwater Drainage Network		
Drainage Layout Marking	3	1
Site Clearing (Removing debris and trees)	3	2
Excavation by earth mover (Depth 2.72 m)	1	1
Site Levelling and Base RCC	1	1
Vertical Reinforcement	4	3
Formwork Placing	3	3
Vertical Concreting	2	2
Formwork Removal	3	1
Curing (Ponding method)	2	1
Backfilling and Finishing	2	2
Sedimentation Tank Construction		
Site Clearing (Removing debris and trees)	2	1
Excavation and Levelling (Depth 5m)	5	2
Foundation (Pile) and Curing	3	4
PCC Bed concrete and curing (at Depth 5m)	4	5
Installation of Reinforcement (For Bed slab at depth 5m)	3	2
Base concreting and curing	5	4
Vertical wall construction (5m height)	3	4
Plastering	1	1
Curing	1	1
Provision of Inlet and Outlet connections	2	2
Water proofing (Base and walls)	1	1
Back filling and Finishing	2	1
Rainwater Harvesting Tank		
Site Clearing (Removing debris and trees)	3	2
Excavation (6m Depth)	5	4
Levelling and Blinding	3	4
Base Compaction (Compactors)	3	3
Construction of Outlet Structure and percolation well (Percolation well 30m depth)	4	5
Slope Stabilization and Tank Lining (Slope Compactor)	2	2
Stone bunds and boundary construction (Along periphery of tank at 1m depth)	3	2
Curing and Miscellaneous work	3	2
Finishing work	2	2
Finishing work		
Cleaning of Drains	3	2
Tank cleaning	3	1
Leakage Detection and Repairing	3	1
Maintaining valves and Conduits	3	2

I4. Expert- 4

Activity Name	Likelihood	Consequences
Stormwater Drainage Network		
Drainage Layout Marking	2	4
Site Clearing (Removing debris and trees)	3	2
Excavation by earth mover (Depth 2.72 m)	4	2
Site Levelling and Base RCC	1	1
Vertical Reinforcement	3	2
Formwork Placing	4	4
Vertical Concreting	2	3
Formwork Removal	4	4
Curing (Ponding method)	1	1
Backfilling and Finishing	1	2
Sedimentation Tank Construction		
Site Clearing (Removing debris and trees)	1	2
Excavation and Levelling (Depth 5m)	4	5
Foundation (Pile) and Curing	2	4
PCC Bed concrete and curing (at Depth 5m)	4	4
Installation of Reinforcement (For Bed slab at depth 5m)	3	2
Base concreting and curing	5	4
Vertical wall construction (5m height)	3	2
Plastering	1	2
Curing	1	1
Provision of Inlet and Outlet connections	2	2
Water proofing (Base and walls)	2	2
Back filling and Finishing	2	2
Rainwater Harvesting Tank		
Site Clearing (Removing debris and trees)	2	1
Excavation (6m Depth)	4	4
Levelling and Blinding	1	5
Base Compaction (Compactors)	2	4
Construction of Outlet Structure and percolation well (Percolation well 30m depth)	5	4
Slope Stabilization and Tank Lining (Slope Compactor)	1	2
Stone bunds and boundary construction (Along periphery of tank at 1m depth)	2	3
Curing and Miscellaneous work	1	1
Finishing work	2	1
Finishing work		
Cleaning of Drains	2	1
Tank cleaning	1	1
Leakage Detection and Repairing	2	1
Maintaining valves and Conduits	2	2

I5. Expert-5

Activity Name	Likelihood	Consequences
Stormwater Drainage Network		
Drainage Layout Marking	2	2
Site Clearing (Removing debris and trees)	2	3
Excavation by earth mover (Depth 2.72 m)	3	4
Site Levelling and Base RCC	4	4
Vertical Reinforcement	4	3
Formwork Placing	3	4
Vertical Concreting	3	3
Formwork Removal	3	4
Curing (Ponding method)	4	4
Backfilling and Finishing	4	3
Sedimentation Tank Construction		
Site Clearing (Removing debris and trees)	3	3
Excavation and Levelling (Depth 5m)	5	4
Foundation (Pile) and Curing	5	4
PCC Bed concrete and curing (at Depth 5m)	5	5
Installation of Reinforcement (For Bed slab at depth 5m)	5	3
Base concreting and curing	5	4
Vertical wall construction (5m height)	3	4
Plastering	3	4
Curing	3	4
Provision of Inlet and Outlet connections	4	4
Water proofing (Base and walls)	3	4
Back filling and Finishing	3	4
Rainwater Harvesting Tank		
Site Clearing (Removing debris and trees)	3	3
Excavation (6m Depth)	4	4
Levelling and Blinding	3	5
Base Compaction (Compactors)	3	3
Construction of Outlet Structure and percolation well (Percolation well 30m depth)	5	4
Slope Stabilization and Tank Lining (Slope Compactor)	3	4
Stone bunds and boundary construction (Along periphery of tank at 1m depth)	3	4
Curing and Miscellaneous work	3	4
Finishing work	3	3
Finishing work		
Cleaning of Drains	3	4
Tank cleaning	3	4
Leakage Detection and Repairing	4	4
Maintaining valves and Conduits	5	3

I6. Expert-6

Activity Name	Likelihood	Consequences
Stormwater Drainage Network		
Drainage Layout Marking	2	1
Site Clearing (Removing debris and trees)	3	2
Excavation by earth mover (Depth 2.72 m)	4	3
Site Levelling and Base RCC	2	2
Vertical Reinforcement	3	3
Formwork Placing	4	3
Vertical Concreting	2	3
Formwork Removal	3	2
Curing (Ponding method)	1	1
Backfilling and Finishing	2	2
Sedimentation Tank Construction		
Site Clearing (Removing debris and trees)	2	2
Excavation and Levelling (Depth 5m)	2	3
Foundation (Pile) and Curing	3	4
PCC Bed concrete and curing (at Depth 5m)	4	3
Installation of Reinforcement (For Bed slab at depth 5m)	3	3
Base concreting and curing	5	5
Vertical wall construction (5m height)	3	2
Plastering	2	1
Curing	1	1
Provision of Inlet and Outlet connections	2	1
Water proofing (Base and walls)	1	1
Back filling and Finishing	2	1
Rainwater Harvesting Tank		
Site Clearing (Removing debris and trees)	2	1
Excavation (6m Depth)	5	4
Levelling and Blinding	2	5
Base Compaction (Compactors)	4	2
Construction of Outlet Structure and percolation well (Percolation well 30m depth)	4	4
Slope Stabilization and Tank Lining (Slope Compactor)	2	2
Stone bunds and boundary construction (Along periphery of tank at 1m depth)	3	3
Curing and Miscellaneous work	1	1
Finishing work	2	1
Finishing work		
Cleaning of Drains	2	1
Tank cleaning	2	1
Leakage Detection and Repairing	1	1
Maintaining valves and Conduits	2	2

I7. Expert-7

Activity Name	Likelihood	Consequences
Stormwater Drainage Network		
Drainage Layout Marking	3	3
Site Clearing (Removing debris and trees)	1	1
Excavation by earth mover (Depth 2.72 m)	2	2
Site Levelling and Base RCC	2	2
Vertical Reinforcement	4	2
Formwork Placing	3	3
Vertical Concreting	2	2
Formwork Removal	2	2
Curing (Ponding method)	1	1
Backfilling and Finishing	1	1
Sedimentation Tank Construction		
Site Clearing (Removing debris and trees)	1	1
Excavation and Levelling (Depth 5m)	2	2
Foundation (Pile) and Curing	3	2
PCC Bed concrete and curing (at Depth 5m)	5	5
Installation of Reinforcement (For Bed slab at depth 5m)	4	4
Base concreting and curing	4	5
Vertical wall construction (5m height)	2	3
Plastering	1	1
Curing	1	1
Provision of Inlet and Outlet connections	2	1
Water proofing (Base and walls)	1	1
Back filling and Finishing	1	2
Rainwater Harvesting Tank		
Site Clearing (Removing debris and trees)	1	1
Excavation (6m Depth)	5	5
Levelling and Blinding	2	4
Base Compaction (Compactors)	2	3
Construction of Outlet Structure and percolation well (Percolation well 30m depth)	5	5
Slope Stabilization and Tank Lining (Slope Compactor)	2	2
Stone bunds and boundary construction (Along periphery of tank at 1m depth)	1	1
Curing and Miscellaneous work	1	1
Finishing work	1	1
Finishing work		
Cleaning of Drains	2	2
Tank cleaning	1	1
Leakage Detection and Repairing	2	2
Maintaining valves and Conduits	1	1

I8. Expert-8

Activity Name	Likelihood	Consequences
Stormwater Drainage Network		
Drainage Layout Marking	1	2
Site Clearing (Removing debris and trees)	2	2
Excavation by earth mover (Depth 2.72 m)	3	3
Site Levelling and Base RCC	4	3
Vertical Reinforcement	5	2
Formwork Placing	2	3
Vertical Concreting	2	3
Formwork Removal	3	2
Curing (Ponding method)	1	1
Backfilling and Finishing	3	4
Sedimentation Tank Construction		
Site Clearing (Removing debris and trees)	2	2
Excavation and Levelling (Depth 5m)	4	5
Foundation (Pile) and Curing		
PCC Bed concrete and curing (at Depth 5m)	4	5
Installation of Reinforcement (For Bed slab at depth 5m)	4	5
Base concreting and curing	4	5
Vertical wall construction (5m height)	4	4
Plastering	3	2
Curing	2	2
Provision of Inlet and Outlet connections	2	3
Water proofing (Base and walls)	2	3
Back filling and Finishing	3	4
Rainwater Harvesting Tank		
Site Clearing (Removing debris and trees)	2	3
Excavation (6m Depth)	5	5
Levelling and Blinding	4	4
Base Compaction (Compactors)	4	3
Construction of Outlet Structure and percolation well (Percolation well 30m depth)	4	5
Slope Stabilization and Tank Lining (Slope Compactor)	4	4
Stone bunds and boundary construction (Along periphery of tank at 1m depth)	3	4
Curing and Miscellaneous work	2	3
Finishing work	3	4
Finishing work		
Cleaning of Drains	3	4
Tank cleaning	3	3
Leakage Detection and Repairing	3	2
Maintaining valves and Conduits	2	3

J. Sample result sheet for LCA analysis

J1. LCA analysis results as per Environmental Impact Categories

Sum of Acidification Potential Total (kgSO2eq)	Sum of Eutrophication Potential Total (kgNeq)	Sum of GWP Total (kgCO2eq)	Sum of Ozone Depletion Potential Total (CFC-11eq)	Sum of Smog Formation Potential Total (kgO3eq)	Sum of PED Total (MJ)	Sum of Non-renewable Energy Demand Total (MJ)	Sum of Renewable Energy Demand Total (MJ)	Sum of Mass Total (kg)
229.57	13.73	83,750.32	-4.61 E-05	4,346.77	8,23,378.66	7,72,215.49	50,786.51	2,26,662.73

J2. LCA analysis result as per product lifecycle stage

	Sum of Acidification Potential Total (kgSO2eq)	Sum of Eutrophication Potential Total (kgNeq)	Sum of GWP Total (kgCO2eq)	Sum of Ozone Depletion Potential Total (CFC-11eq)	Sum of Smog Formation Potential Total (kgO3eq)	Sum of PED Total (MJ)	Sum of Non-renewable Energy Demand Total (MJ)	Sum of Renewable Energy Demand Total (MJ)
Product	190.36	11.68	67,655.99	1.71E-06	3,556.81	6,69,336.50	6,18,665.12	50,191.68
Transportation	3.94	0.32	849.39	2.91E-11	130.05	12,351.94	12,056.36	298.69
Maintenance and Replacement	0.47	0.06	341.68	2.06E-10	9.46	6,547.01	5,771.25	781.65
End of Life	20.53	1.06	8,033.49	8.14E-10	407.03	75,783.68	70,862.45	5,007.14
Module D	14.27	0.61	6,869.77	-4.78E-05	243.41	59,359.53	64,860.31	-5,492.65

BRIEF BIOGRAPHY OF THE CANDIDATE

Mr. Deshbhushan Savindra Patil is a Research Scholar in the Civil Engineering Department, Birla Institute of Technology and Science, Pilani, Pilani Campus Rajasthan, India. His academic journey began at Shivaji University in Kolhapur, India, where he completed his Bachelor of Engineering (B.E.) in Civil Engineering from 2014 to 2018. Building on his undergraduate studies, he pursued a Master of Technology (M. Tech.) in Construction Technology and Management at VIT University, Vellore, India, from 2018 to 2020. During his Ph. D tenure, he was involved in the project titled "Structured Dialogues for Sustainable Urban Water Management" funded by the Department of Science & Technology, New Delhi. Beyond being a researcher, he has actively contributed to various professional circles. His student membership in the Indian National Academy of Engineering (INAE) acknowledges his dedication to the engineering discipline and his potential to influence its future. Additionally, his role as a scientific committee member for Watermatex-2023 Young Water Professionals reflects his commitment to address the critical issue of water management through research and development. Beyond academics and into real-world applications, his journey continues. From June to September 2020, he worked as an Assistant Engineer at Hardik Engineer, where he maintained and oversaw firefighting systems and contributed significantly to Indian Navy residential projects. His path also took him to GVK (Mumbai International Airport Pvt. Limited) and L&T Transportation Infrastructure Limited, where he was involved in the project planning and execution.

BRIEF BIOGRAPHY OF THE SUPERVISOR

Professor Rajiv Gupta is a distinguished Senior Professor in the Department of Civil Engineering at the Birla Institute of Technology and Science (BITS), Pilani, Rajasthan, India. With an impressive teaching career spanning over 35 years, he firmly established himself as a prominent character in the academic realm. His versatile career includes more than 15 years of experience in institutional development and decision making. He has taken on various roles, including the Dean of different units and the Assistant Unit Chief responsible for maintenance. Additionally, he served as a Group Leader in various domains at the BITS Pilani.

Professor Gupta's dedication to education culminated in his status as a Senior Professor and earned years of exceptional contributions to BITS Pilani. His influence extends to guiding 16 doctoral candidates, 30 dissertations, and M.E. projects, nurturing academic and research growth. He has been actively involved in research activities that have significantly contributed to the body of knowledge in his field. His impressive research portfolio included the publication of approximately 96 papers in refereed journals. These journals represent high-quality publications in which his work has been subjected to rigorous peer review. In addition, his research contributions extend to approximately 136 conference papers. He has also actively participated in the peer-review process by evaluating approximately 160 papers in reputed journals, emphasizing his commitment to maintaining the quality of academic publications.

One of the standout aspects of his career is his involvement in executing sponsored projects from agencies such as DST, CSIR, UGC, Ministry of Home Affairs, World Bank Washington, KK Birla Academy, Rajasthan Association of North America, Aditya Birla Group, Mumbai, Government of Himachal Pradesh, State Innovation Council, University of Virginia, Ministry of Road Transport & Highways, and Government of India. These projects, valued at over Rs. 1000 lacs, demonstrate his remarkable ability to secure funding for important research initiatives. His excellence is further highlighted by his outstanding achievement in securing a grant funding of $1,96,000 at the Global Development Marketplace organized by the World Bank in Washington in 2006. He was involved in construction work for more than 250 crores, emphasizing rainwater harvesting, green architecture, and campus development, underscoring his commitment to sustainable practices in construction and emphasizing environmental conservation and efficiency at BITS Pilani.

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