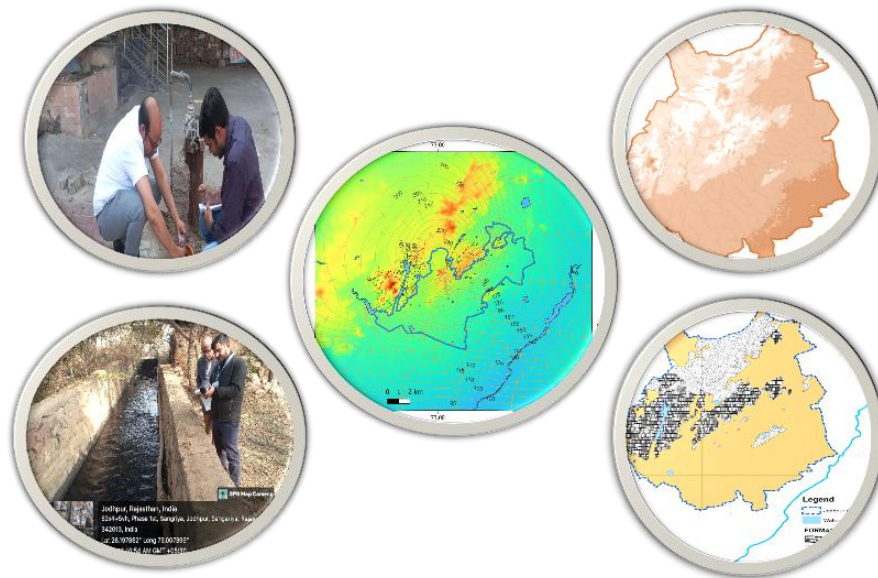


Assessment of the Water Level Rise Crisis in Jodhpur City, Rajasthan: A Comprehensive Follow-up Study with Challenges and Remedial Approaches

FINAL REPORT



Studied by:

National Institute of Hydrology
North Western Regional Centre, Jodhpur

Assessment of the Water Level Rise Crisis in Jodhpur City, Rajasthan: A Comprehensive Follow-up Study with Challenges and Remedial Approaches

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Executive Summary

Jodhpur, a prominent historical city in the arid western region of Rajasthan, has long been associated with water scarcity and drought vulnerability. Traditionally reliant on distant canal systems and limited natural recharge, the city has paradoxically witnessed a dramatic shift in its hydrological dynamics over the past two decades. Rather than continuing to face water deficits, central and low-lying urban areas of Jodhpur have experienced persistent groundwater level rise, resulting in severe waterlogging, damage to buildings and public infrastructure, and degradation of cultural heritage structures. This hydrological anomaly has prompted repeated investigations by several scientific and governmental bodies including the National Institute of Hydrology (NIH, 2011), National Geophysical Research Institute (NGRI, 2010), Central Ground Water Board (CGWB, 2015), and the Rajasthan Ground Water Department (GWD). While these studies contributed valuable insights—such as the role of local recharge and supply regulation—partial remedial efforts like selective pumping did little to reverse the situation. Instead, the crisis has deepened due to ongoing urban expansion, infrastructural neglect, unregulated recharge, and the absence of a coherent drainage or monitoring strategy.

The current study, led by the National Institute of Hydrology – NWRC, Jodhpur, represents a comprehensive and updated reassessment of this urban groundwater crisis. It combines recent advances in hydrological modeling, urban drainage analysis, isotopic tracing, and GIS-based spatial evaluation. Modern tools such as MODFLOW 6 (for groundwater flow simulation), EPA-SWMM 5.1 (for urban drainage), stable isotope analysis ($\delta^{18}\text{O}$ and δD), and high-resolution remote sensing datasets have been used to reassess the hydrological and infrastructural dynamics of Jodhpur city. The study builds upon previous findings while vastly expanding the spatial domain to 208.31 km² (compared to 76 km² in the 2011 study), enabling more robust scenario modeling and peri-urban integration.

The primary aim of this study is to investigate the causes and consequences of rising groundwater levels in Jodhpur and explore effective mitigation strategies. The specific objectives are:

1. To study the factors and sources contributing to the rising groundwater table in Jodhpur
2. To assess the impacts of the rising water level on the environment, infrastructure, and society
3. To explore potential mitigation strategies and provide recommendations to address the issue

To achieve these goals, a multidisciplinary methodology was adopted, integrating field surveys, public perception assessments, seasonal groundwater monitoring, hydrogeological mapping,

geochemical and isotopic tracing, and computational modeling of both surface and subsurface water flow.

Extensive field visits were conducted in the most affected localities, where physical indicators such as seepage, structural dampness, and foundation damage were documented. Public surveys were also administered to gather perceptions on the causes and consequences of waterlogging. Simultaneously, a network of 62 observation wells was seasonally monitored (winter, pre-monsoon, and post-monsoon) to analyze groundwater fluctuations and long-term trends. These data were instrumental in calibrating the groundwater model and validating hydrological behavior across different zones of the city. Remote sensing inputs—including Digital Elevation Models (ALOS), land use/land cover data (ESRI 2023), soil and lineament maps—provided essential spatial context for identifying recharge zones and topographic controls on surface flow.

One of the most significant components of the study was the development of a transient, three-dimensional groundwater model using MODFLOW 6 via FloPy (Python). This model simulated aquifer dynamics from 2013 to 2024 under varying recharge, abstraction, and structural scenarios. Strategic simulations demonstrated that vertical drainage wells could induced drawdowns of 1.0–3.0 meters in targeted areas so ultimately water level can be up to safe limit within 3-5 m in critical zone. However, in the absence of adequate surface drainage, the extracted water often stagnates or re-percolates locally, forming a cyclical loop of groundwater recycling that undermines dewatering efforts.

Hence Parallel urban drainage modeling using EPA-SWMM has been performed to exposed critical weaknesses in the city’s sewer and storm water network. Simulation of storm events revealed that topographic depressions, disconnected outfalls, and aged sewer lines severely hamper drainage, with many lines acting as infiltration corridors that recharge shallow aquifers rather than conveying water out. The SWMM model identified 16 high-risk junctions, particularly in central city wards, where even moderate rainfall events led to system surcharge and surface flooding. The lack of coherent drainage alignment and absence of integrated outfall systems—such as proper linkage to the Jajari River—further intensified the problem.

Geological and structural mapping using remote sensing and field validation highlighted that Jodhpur’s aquifers are composed of sandstone, shale, and Quaternary alluvium, whereas the Kaylana–Takhatsagar system is embedded in low-permeability rhyolite. Lineament analysis revealed NE–SW and NNE–SSW oriented fractures terminating outside urban bounds, ruling out subsurface seepage from reservoirs. Furthermore, a comprehensive urban water balance from

2014–2024 revealed that while surface water supply is around 70–73 MCM/year (largely from the Indira Gandhi Canal), unintended recharge from leaky infrastructure and sewer infiltration contributes an estimated 35–45 MCM/year—far exceeding natural recharge (15–20 MCM/year). In many instances, groundwater abstracted by PHED and private entities is only partially utilized, with the remainder draining into the sewer network and re-infiltrating into the aquifer—creating a persistent cycle of supply, leakage, and recharge.

Isotopic and hydro chemical analyses further validated these findings. Groundwater samples showed enriched $\delta^{18}\text{O}$ and δD signatures due to evaporation, which contrasted with the depleted isotopic profile of Kaylana Lake—suggesting no direct aquifer-lake interaction. While some samples exhibited superficial isotopic resemblance to reservoir water, their distinct geochemical fingerprints—especially differing Cl^- , SO_4^{2-} , and EC levels—confirmed dominant anthropogenic recharge sources. Hydrochemical facies were primarily $\text{Na}^+\text{--Cl}^-$ type with elevated total dissolved solids (TDS) and nitrate (NO_3^-) levels, signaling contamination from sewage, greywater return flows, and surface runoff. These indicators consistently point to urban infrastructure, particularly leaky water pipelines, over-irrigation, and sewer leakage, as the main contributors to groundwater rise.

The study results revealed that the aquifers beneath Jodhpur are hydraulically disconnected from the Kaylana–Takhatsagar reservoir system—similar to the earlier findings by NIH (2011)—and that post-monsoon water table depths within the core city typically range between 0–3 meters. These critically shallow levels foster persistent saturation and exacerbate infrastructure vulnerabilities.

In light of these findings, the study proposes a robust, multi-pronged remedial strategy. Key among the interventions is the expansion of Vertical Drainage Wells (VDWs) in critically waterlogged areas. These wells, equipped with automated sensors, should be mapped based on groundwater mounding zones identified through MODFLOW simulations and connected to functional surface drains to prevent water re-entry. Second, drainage retrofits and integrated outfall design are urgently needed. This involves rehabilitating key segments of the sewer and stormwater network—particularly in identified critical wards and aligning them to natural outfalls using insights from the SWMM model.

Equally important is the systematic detection of water supply leakages through zonal water audits, pressure testing, and SCADA-enabled sensors. Zonal rationalization of water supply to ensure equitable, need-based distribution will also reduce excess recharge. Continued

groundwater quality surveillance using hydrochemistry and isotopes is vital for tracking contamination evolution, and community-based urban water governance mechanisms should be fostered by engaging resident welfare associations (RWAs) in reporting and monitoring efforts.

In conclusion, the rising groundwater levels in Jodhpur constitute more than a hydrological irregularity—they pose a fundamental urban resilience challenge. If left unaddressed, the city risks ongoing degradation of its infrastructure, water quality, and built heritage. This follow-up study not only reaffirms earlier assessments but also introduces an updated, scientifically rigorous action framework rooted in modern hydrological tools. By implementing these integrated solutions, Jodhpur can shift from reactive crisis management to proactive hydro-sustainability, setting a precedent for other arid urban centers facing similar paradoxes.

CHAPTER 1: INTRODUCTION

1.1 Background

Jodhpur, a prominent urban centre located in the arid Thar Desert of Rajasthan, India, has long contended with extreme climatic conditions and chronic water scarcity. Characterized by intensely hot summers and low, erratic rainfall—averaging around 340–370 mm annually—the city has historically experienced recurring droughts and water-related stress (GSI, 2001; CGWB, 2014; NIH,2011). In response, a variety of indigenous water conservation systems were developed over centuries, including stepwells (*baoris*), earthen reservoirs (*talabs*), and rooftop rainwater harvesting structures. These traditional methods served as lifelines, reflecting the ingenuity and resilience of local communities in adapting to the harsh desert environment (GSI, 2001).

However, in recent decades, Jodhpur has encountered a paradoxical hydrological shift: the emergence of a rising groundwater table in what was historically a water-deficient region. Before the year 1997, domestic and municipal water supply in Jodhpur relied primarily on hand-pumps, tube-wells, stepwells, baoris, and surface water storage systems to meet drinking water needs. The water scarcity was acute, and reliance on groundwater was unsustainable due to limited recharge in the arid environment.

The turning point came in the 1997 with the introduction of a reliable surface water supply via the Indira Gandhi Canal Project (IGNP)—an ambitious project channelling water from the Himalayan rivers into Rajasthan’s arid zones. Initially seen as a solution to the city’s perennial water scarcity, this external supply significantly improved water availability (NIH,2011). The new system directed surface water into Jodhpur via the Rajiv Gandhi Lift Canal, storing it in the Kaylana-Takhat Sagar reservoirs. This transition significantly improved water availability and was considered a milestone in addressing the city’s long-standing water crisis.

However, this infrastructural transformation brought with it a new set of hydrological challenges. A steady rise in the groundwater level was observed soon after the canal water supply was introduced. This unexpected shift was due to factors such as over-supply of water with due consideration of existing water resources, seepage from unlined distribution systems, excessive irrigation of public gardens, and the lack of a matching sewerage and storm water drainage system. Artificial recharge due to these anthropogenic activities began to exceed the natural infiltration capacity.

Over the past two decades, waterlogging has emerged as a critical urban problem in Jodhpur. The situation is particularly severe in the old city areas, where persistent subsoil water rise is affecting buildings, streets, and sanitation. The excess moisture is also causing salinization, weakening foundations, and leading to the growth of waterborne and vector-borne diseases.

Yet, the lack of corresponding investments in sewerage infrastructure and storm water drainage has led to unintended consequences. Excess supply, Inefficient water distribution systems, poor drainage, excessive irrigation of public spaces, and widespread infiltration of untreated wastewater have all contributed to artificial groundwater recharge far exceeding natural rates (NIH, 2011). As a result, Jodhpur has witnessed a steady and abnormal rise in its water table.

1.2 Scope of work

To comprehensively address the problem, the study adopts an interdisciplinary approach encompassing hydrogeological, hydrological, and socio-economic analyses. The hydrogeological assessment explores the city's subsurface geology, geomorphology and aquifer dynamics, which are critical to understanding patterns of groundwater accumulation (CGWB, 2001). The hydrological component focuses on the water balance of the region—particularly the role of rainfall, evapotranspiration, and imported canal water supply in influencing recharge dynamics.

Simultaneously, a technical assessment of water supply networks, sewage systems, and storm water drainage infrastructure is carried out to understand the anthropogenic factors exacerbating the problem. These technical assessments are supplemented by community-level field surveys, capturing the lived experiences of residents in waterlogged localities. Based on the findings, the possible solutions and recommendations have been provided.

1.3 Significance of the Study

Addressing the rising groundwater issue in Jodhpur is of critical importance—not only from hydrological and engineering perspectives but also for safeguarding environmental quality, urban infrastructure, and public well-being. If unaddressed, the abnormal water table rise could result in saline intrusion, deterioration of historic structures, weakening of foundations, and widespread health and sanitation issues.

This study aims to fill the knowledge gap regarding this unique urban hydrological challenge. By integrating scientific assessments with infrastructure and social evaluations, Ultimately, the

research seeks to contribute to a sustainable water management framework for Jodhpur, aligning water security with environmental and urban resilience.

1.4 Objectives of the Study

The primary aim of this study is to investigate the causes and consequences of rising groundwater levels in Jodhpur and explore effective mitigation strategies. The specific objectives are:

1. To study the factors and sources contributing to the rising groundwater table in Jodhpur
2. To assess the impacts of the rising water level on the environment, infrastructure, and society
3. To explore potential mitigation strategies and provide recommendations to address the issue

The preliminary objective involves identifying and quantifying how various inputs—including water from the Indira Gandhi Canal, rainfall recharge, water level trends over the years, city outflow, leakages in water supply pipelines, and other anthropogenic or natural contributions—are collectively elevating the groundwater levels in the city. A thorough analysis of the hydrological and infrastructural systems will help isolate the most influential drivers.

The rising water table has multi-dimensional consequences. The second objective includes evaluating environmental impacts such as salinization and groundwater contamination; damage to buildings, roads, and public infrastructure due to seepage and dampness; and socio-economic impacts such as health risks, loss of property value, and increased repair costs for residents. Understanding these effects is essential for risk evaluation and public awareness.

Based on the analysis, the study final aims to evaluate feasible and context-specific solutions. These may include improvements in urban drainage and wastewater systems, controlled groundwater extraction, reuse or redirection strategies, and integrated water management practices. The ultimate goal is to support policymakers and urban planners in implementing sustainable solutions to manage groundwater levels and prevent further degradation.

The rising groundwater table in Jodhpur presents a unique and evolving urban water challenge, rooted in both natural processes and human-induced factors. This chapter has outlined the background, scope, significance, and objectives of the study, laying the foundation for a comprehensive investigation. The subsequent chapters delve deeper into the hydrogeological conditions, causative mechanisms, impacts, and potential management strategies to address this emerging crisis.

CHAPTER 2: STUDY AREA & DATA COLLECTION

2.1 Geographical Overview

Jodhpur, situated in the heart of the Thar Desert, is Rajasthan's second-largest and one of the fastest-growing urban centers, despite its harsh arid climate characterized by extreme heat and dryness. Jodhpur, despite its characteristically hot and dry climate, the city has seen significant urban sprawl, particularly towards the southeast, south, and southwest directions. Presently, Jodhpur covers an urban area of approximately 210 square kilometres, situated between latitudes 26°15'N to 26°20'N and longitudes 73°00'E to 73°04'E. (Figure 2.1).

The densely populated old walled city is located along the slope of the fort ridge, where the terrain is markedly undulating. Moving outward towards the south, southeast, and southwest, the land gradually flattens into an expansive alluvial plain. The northwestern periphery is distinguished by rugged hillocks composed mainly of shale and sandstone formations. Geologically, Jodhpur's core city developed over the Malani rock group, while subsequent urban expansions have occurred largely on Quaternary alluvial deposits.

Hydrologically, Jodhpur lacks any significant perennial river system. The only natural drainage feature near the city is the ephemeral Jodri River, flowing approximately 10 kilometers from the urban core. Historically, numerous water bodies were developed either through the construction of artificial tanks or the exploitation of natural depressions to capture monsoon runoff.

Among the most significant reservoirs are Kailana Lake and Takhsagar Reservoir, located about 5 kilometers west of the city. Both are formed within a continuous geological depression aligned in a north-southwest direction but have been separated by an embankment for operational control. Kailana Lake, situated upstream, has a maximum water spread area of 4.814 million cubic meters (MCM) at an elevation of 273.7 meters above mean sea level (amsl), whereas the downstream Takhsagar Reservoir holds 6.524 MCM at 269.75 meters amsl. Water flows between the two through gate-operated conduits and an open channel system, relying solely on gravity.

Given the limited monsoon runoff from their local catchment, both reservoirs are heavily dependent on external water sources, primarily the Rajiv Gandhi Lift Canal linked to the Indira Gandhi Nahar Project (IGNP). Today, these reservoirs, alongside the Umaid Sagar system, are central to Jodhpur's municipal water supply, replacing earlier reliance on traditional wells, baories, hand pumps, and tube wells.

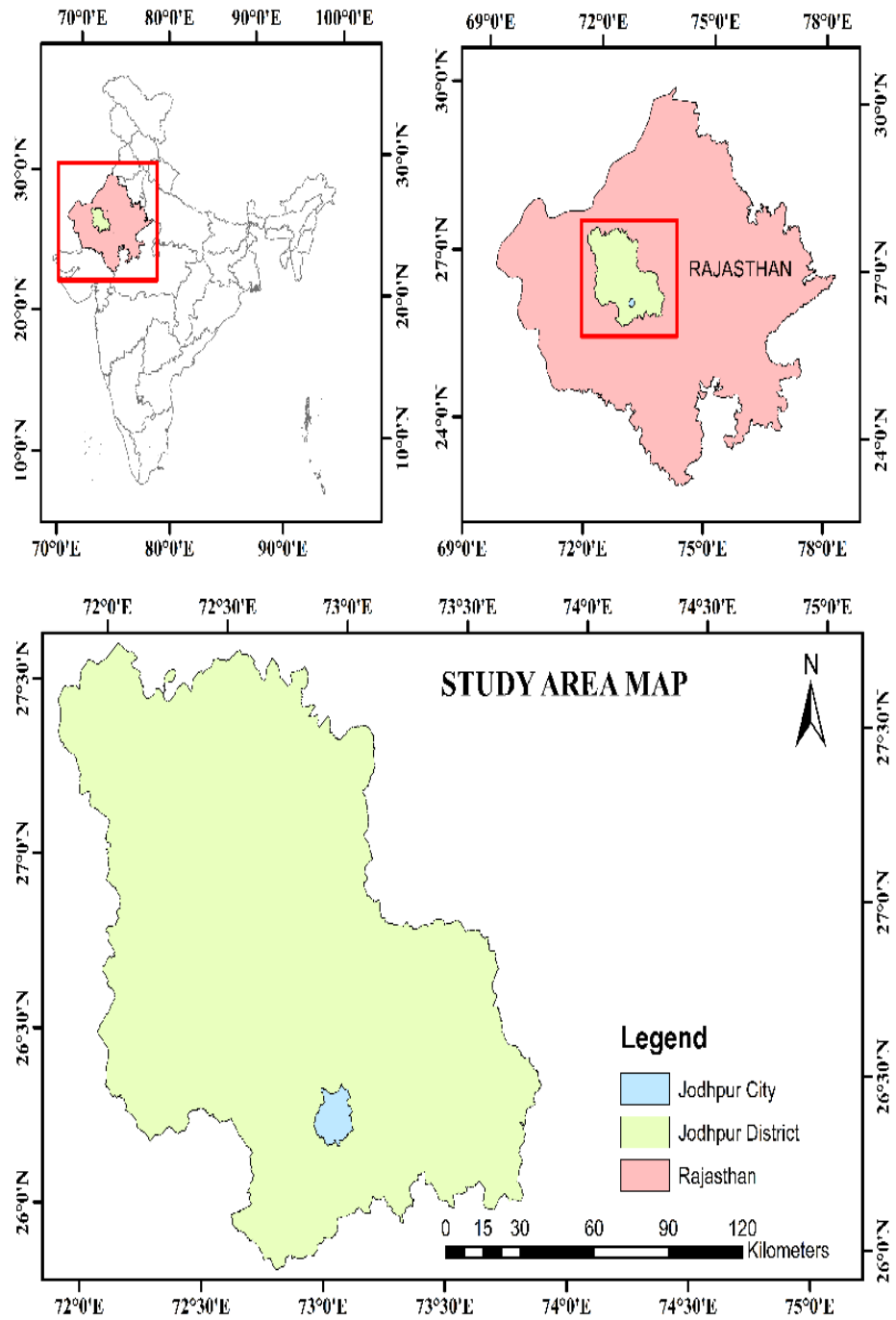


Figure 2.1: Jodhpur City Location Map

Land use across the city is predominantly urban, severely restricting natural groundwater recharge through infiltration. Agricultural activities are minimal, although green patches survive, especially in areas with fertile alluvial soils.

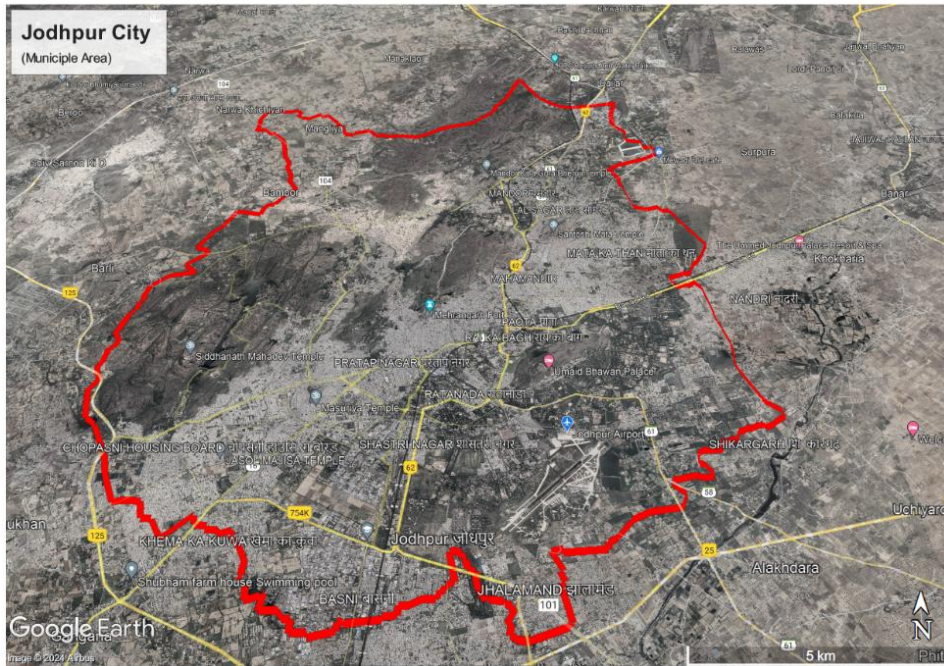


Figure 2.2: Jodhpur City Satellite location map

No perennial river or stream passes through the city, except for the ephemeral Jojri River, which flows roughly 10 kilometers from the city's periphery visible in Figure 2.2. The urban landscape hosts several water bodies, both natural and artificial. Historically, these were constructed to capture monsoon runoff or developed in natural depressions. Of particular hydrological significance are the Kailana Lake and Takhatsagar Reservoir, located on the western side of the city, about 5 kilometers away.

These interconnected storage systems, formed within a continuous geological depression, have been artificially divided by an embankment for operational purposes. Water flows from Kailana Lake to Takhatsagar Reservoir by gravity, aided by controlled gates and open channels. While the Kailana Lake has a water spread area of 4.814 MCM at 273.7 meters above mean sea level (amsl), the Takhatsagar Reservoir holds 6.524 MCM at 269.75 meters amsl. Despite their substantial storage, the reservoirs rely on external sources such as the Rajiv Gandhi Lift Canal (IGNP) to meet water demand, as the local catchment is inadequate to fill them from monsoon runoff alone.

The city's land use is dominantly urbanized, leaving little scope for groundwater recharge through natural infiltration. Agricultural activity is minimal, but greenery persists in areas with alluvial soil. Historically, before the integration of canal-fed systems, water supply for drinking and municipal use was met through step-wells, baories, tube-wells, and hand-pumps. Currently,

Kailana Lake and Takhatsagar Reservoir form the backbone of Jodhpur's municipal water supply infrastructure.

2.2 Topography and Drainage Characteristics

Topography

Jodhpur's topographic gradient predominantly trends toward the south, southeast, and southwest, with variations in slope across different parts of the city. The southern side exhibits a gentler gradient compared to the steeper slopes in the southwestern and southeastern directions. Digital Elevation Model (DEM) were generated (Figure 2.3) for city area using $12.5\text{ m} \times 12.5\text{ m}$ ground elevation data supplemented by ALOS satellite data (12.5 m resolution).

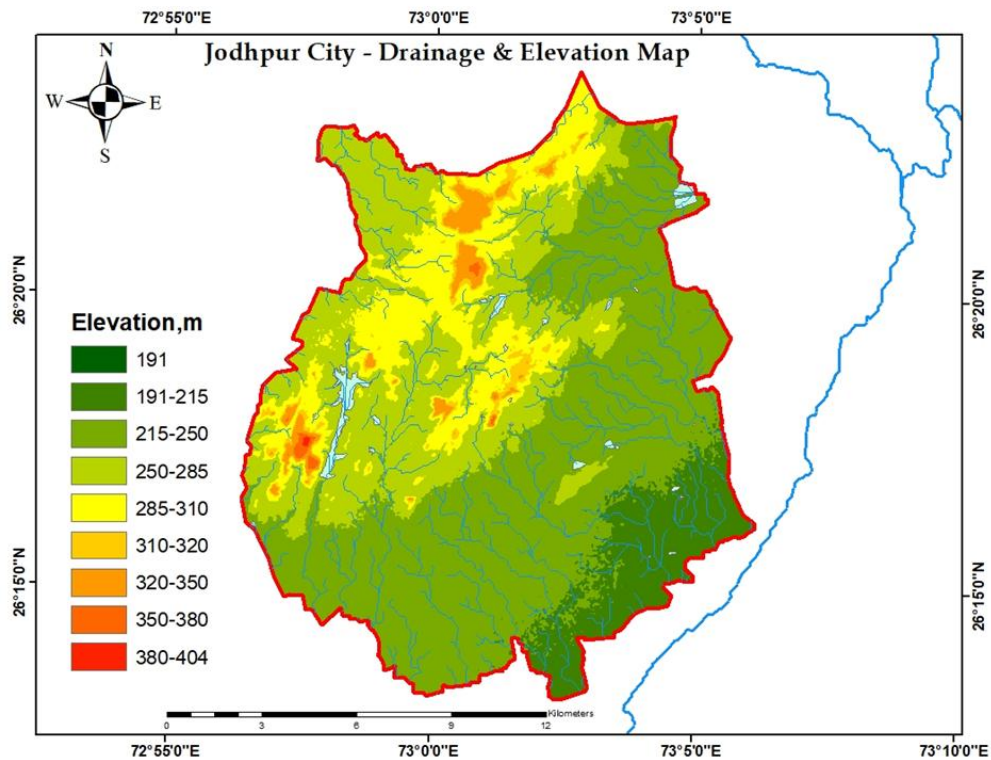


Figure 2.3: Digital Elevation map of Jodhpur city

The city's elevation ranges between 191 meters and 404 meters amsl, with the fort area exhibiting the highest point. Most of the city lies below 250 meters, whereas the Kailana Lake and Takhatsagar Reservoir lie at higher elevations (minimum elevations of 254 m and 251 m respectively). This positioning theoretically supports potential subsurface groundwater flow from the reservoirs toward the city, subject to hydraulic connectivity.

However, observations suggest that water-logging and rising groundwater levels occur primarily in the old city area, particularly along the northern slopes beneath the fort, where elevations range from 230 to 310 meters. Although contour maps and DEMs (Figures 2.2 to 2.4) suggest a possible alignment between these problematic zones and the reservoir axis, hydrogeological evidence indicates a lack of homogeneous hydraulic connectivity. If any linkage exists, it may result from deep subsurface conduits formed by rock fractures or geological lineaments.

Drainage

The water flow is observed towards south and southeast which follows the topographic gradient and ends up in the Jojari River, in the outskirts of the city. Additionally, the sewage drains laid out across the city transport the water into the Jojari River after it is treated by the Sewage Treatment Plants (STP). The drainage is not well developed on the surface, indicating that most of the untreated water is recharging the aquifers without being directed towards the Jojari River (CGWB, 2015). The drainage map (Figure 2.4) is prepared using ALOS Palsar DEM data

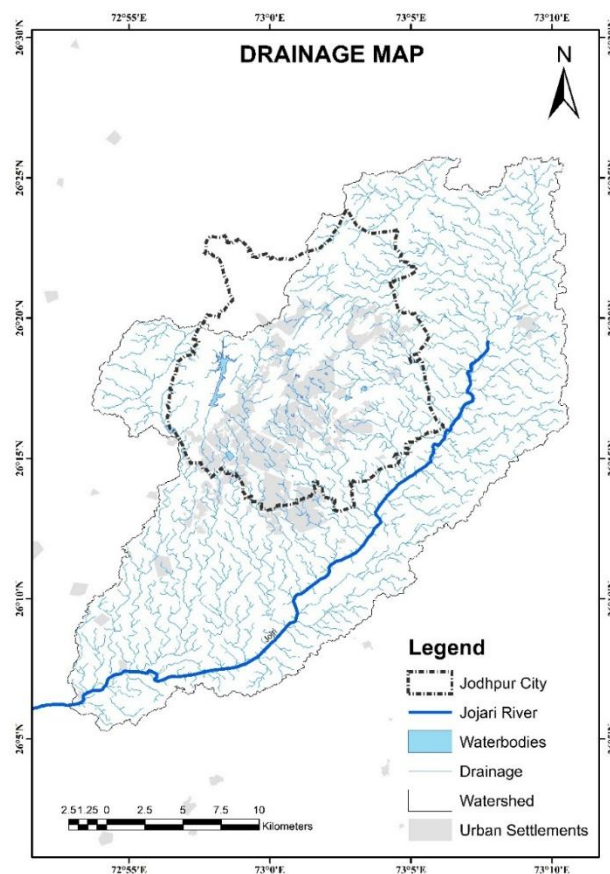


Figure 2.4: Drainage Map of Jodhpur city

2.3 Data Collection and Methodology

To address Jodhpur's decade-long challenge of rising groundwater levels, a comprehensive data collection and field investigation campaign was conducted to support hydrological analysis of groundwater conditions. This effort aimed to build a robust dataset on groundwater levels, water quality, and socio-environmental impacts, essential for understanding the persistent issue and formulating effective management strategies. Both primary field surveys and secondary data from reputed government agencies were integrated, providing diverse datasets critical for groundwater assessment, hydrological modelling, and spatial analysis. The data types, sources, and their justifications are detailed below:

2.3.1 Groundwater Level Data

Groundwater level data were sourced from the Central Ground Water Board (CGWB), State Ground Water Board (SGWB), and Public Health Engineering Department (PHED), covering 44 monitoring stations: 39 SGWB stations (2013–2024) and 5 CGWB stations (2013–2022). This long-term data is vital to establish the historical trend of rising water tables over the past decade, identifying key periods of increase. Additionally, levels were monitored at 62 observation wells during Winter 2023, Pre-Monsoon 2024, and Post-Monsoon 2024 to capture seasonal fluctuations and pinpoint waterlogging hotspots or abnormal rises, enabling trend analysis and hydrogeological modelling to address the ongoing crisis.

2.3.2 Groundwater Sampling & Quality

To assess the chemical and isotopic impacts of the rising groundwater, 32 samples were collected during Winter 2023, Pre-Monsoon 2024, and Post-Monsoon 2024, analyzed for physical parameters (pH, EC, TDS, ORP), major ions (Ca^{2+} , Mg^{2+} , Na^+ , K^+ , HCO_3^- , SO_4^{2-} , Cl^- , NO_3^- , F^-), and trace metals (Pb, Zn, Cu, Cr, Fe, Mn, Hg, Se, Ni, Co, and others). This data justifies the need to evaluate contamination (e.g., salinization, sewage percolation)

2.3.3 Sampling for Isotope Analysis

In order to gain deeper insights into the sources of recharge and potential contamination pathways contributing to the persistent waterlogging problem in Jodhpur, a total of 32 groundwater and surface water samples were collected and analyzed for stable isotopes ($\delta^{18}\text{O}$ and δD). The sampling was conducted during three key hydrological periods—Winter 2023, Pre-Monsoon 2024, and Post-Monsoon 2024—to capture seasonal variations in isotopic signatures. This temporal resolution allows differentiation between recent rainfall, canal seepage, and return flows from urban domestic or industrial sources. Isotopic fingerprints not only help trace the

origin of recharge but also reveal mixing trends, evaporation effects, and possible anthropogenic contamination. The findings from this isotopic investigation are critical for refining the conceptual hydrogeological model of the area and for formulating targeted strategies to mitigate the groundwater rise and urban flooding issues affecting central Jodhpur

2.3.4 Pumping & Supply Data

Groundwater abstraction data, including discharge rates and operational hours, were collected from PHED for 191 pumping wells. This dataset is required to quantify the extraction patterns, assess their role in either alleviating or exacerbating the rising water table, and inform sustainable pumping strategies.

2.3.5 Meteorological and Spatial Data

Meteorological data from the India Meteorological Department (IMD), including gridded rainfall data (1901–2023) and rainfall/evapotranspiration (ET) metrics, are essential. These long-term records help correlate rainfall patterns and ET with the decade-long groundwater rise, supporting water balance calculations and recharge estimations to understand climatic influences. Geology and geomorphology maps from GSI, 2023 Land Use/Land Cover (LULC) data from ESRI, Digital Elevation Models (DEM) from SRTM and ALOS satellites, and Sentinel-2B satellite imagery, support hydrological modeling and visualization. These are justified by the need to map urban expansion and land use. Subsurface lithological and hydrogeological data from CGWB, SGWB, and the Geological Survey of India (GSI) delineate aquifer properties and groundwater movement. This data is critical to explain how geological barriers have contributed to water table rise over the past decade, guiding subsurface management approaches.

2.4.1 Soil Map

Jodhpur City's soil composition, as depicted in the soil map given in Figure 2.5, varies across its landscape, significantly influencing groundwater dynamics. Approximately 40% of the area is covered by loamy soil in the northern and eastern zones, offering moderate permeability that enhances groundwater recharge, while 30% comprises loamy skeletal soil in the central and western regions, with low permeability that increases runoff.

Rock outcrops, occupying about 20% in the southern and southwestern parts, exhibit very low permeability, limiting recharge and promoting surface flow, whereas the remaining 10% of sandy soil in the southeastern zone facilitates rapid infiltration, boosting recharge but posing contamination risks due to its high permeability. This diverse soil distribution contributes to the

observed rise in the groundwater table, particularly in areas with loamy and sandy soils near water supply lines.

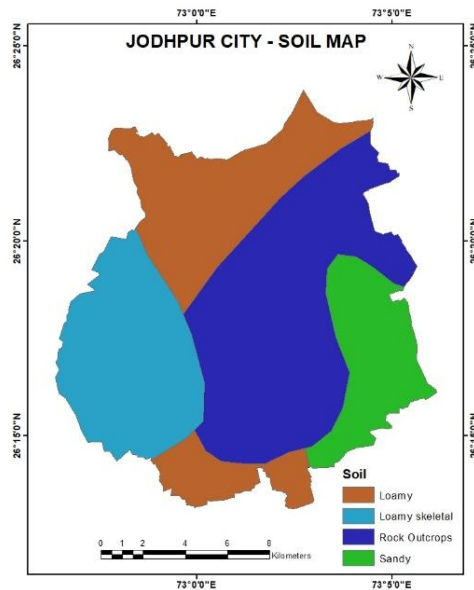


Figure 2.5: Soil Map of Jodhpur city

2.4.2 Land use & Land cover map

The Land Use/Land Cover (LULC) map (Figure 2.6) highlights Jodhpur’s rapid urbanization, with 60-70% of the area classified as urban land in the central and eastern regions, where impervious surfaces increase runoff and contribute to waterlogging. Barren land, covering 15-20% in the northern and western periphery, offers low recharge due to rocky and sandy terrain, while agriculture, spanning 5-10% in the southern and eastern outskirts, relies on irrigation over loamy and sandy soils, enhancing recharge.

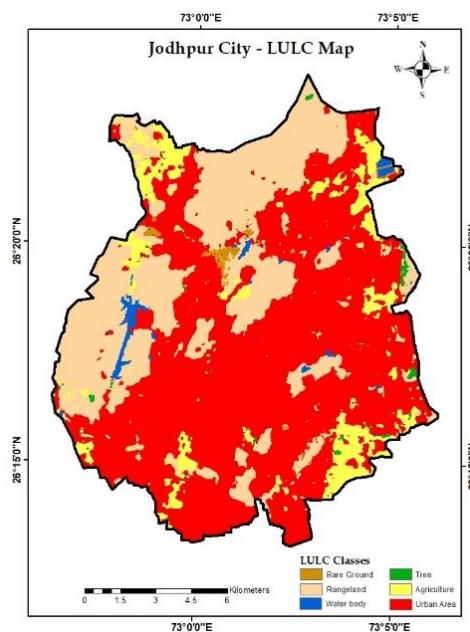


Figure 2.6: LULC Map of Jodhpur city

Water bodies, such as Kaylana Lake, account for less than 5% in the southwestern part, providing minor recharge despite geological barriers, and vegetation, scattered at less than 5%, supports limited local recharge. This land use pattern, combined with soil characteristics, underscores the need for targeted drainage and contamination management strategies to address the rising groundwater challenge.

2.5 Field Surveys and Socio-Environmental Insights

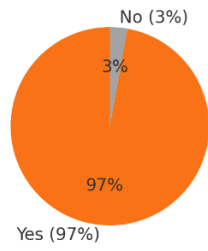
Primary data were gathered through structured questionnaire-based field surveys form (given in Annexures), targeting stakeholders on water sources (bore wells, piped supply), groundwater trend awareness, scarcity/waterlogging incidents, structural damage, bore well performance, health issues, and conservation practices. This data is justified by the decade-long socio-environmental impact, providing qualitative insights to complement physical data and address community-level effects of the rising water table.



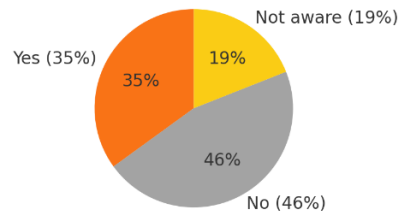
Figure 2.7: Field Survey, Observations and Sampling Glimpses from Jodhpur City

A structured public survey conducted across Jodhpur city with 250 respondents has revealed important insights into the ongoing issue of groundwater rise. An overwhelming 97% confirmed reliable access to primary water supply, indicating the effectiveness of piped distribution systems. However, 42% reported persistent drainage problems, and 26% acknowledged waterlogging, especially in low-lying areas—highlighting inadequate infrastructure to manage excess surface and subsurface water. Despite only 20% reporting water quality concerns and 16% noting water-borne diseases, a significant portion (over 30%) were unaware of such issues, reflecting low public awareness. Additionally, variations in household storage availability and poor seepage control may be contributing to uncontrolled recharge and rising water levels. These survey findings align with model simulations and field data, validating the presence of a shallow water table zone and emphasizing the urgent need for vertical drainage interventions, improved urban water management, and community awareness to sustainably manage Jodhpur’s aquifer system. The results of field survey given in Figure 2.8.

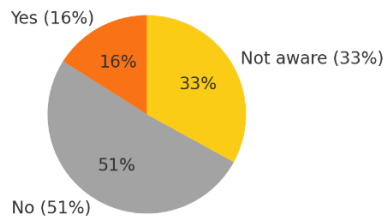
Primary Water Supply



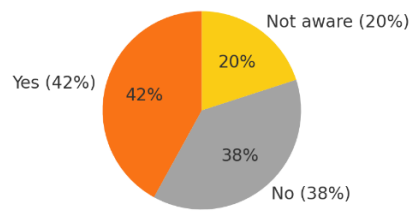
Water Scarcity Issue



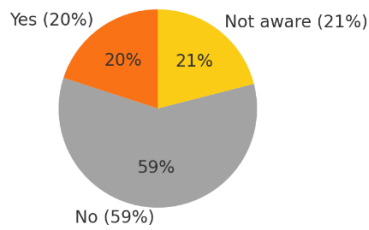
Household Storage Availability



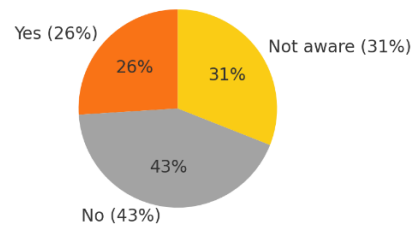
Drainage Problem



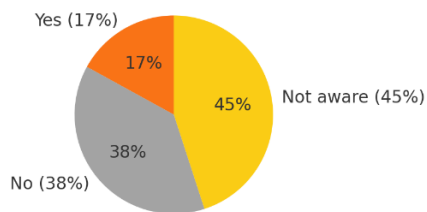
Water Quality Problems (Colour, Odor, Taste)



Waterlogging Issue



Infrastructural Damage



Incidence of Water-Borne Diseases

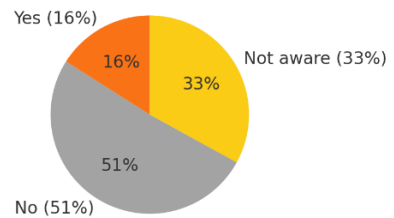


Figure 2.8: Field Survey Questionnaire Results – Jodhpur City, Rajasthan

CHAPTER 3: GEOLOGICAL FRAMEWORK AND STRUCTURAL LINEAMENTS

The geology of the Jodhpur region reflects a complex interplay of ancient volcanic rocks, sedimentary formations, and recent deposits, spanning from the Precambrian to the Quaternary periods. This geological diversity shapes the region's landforms, hydrogeology, and patterns of urban development.

3.1 Geological Framework

The geological foundation of the Jodhpur region is anchored in the Precambrian Malani Igneous Suite, predominantly composed of rhyolite, with occasional occurrences of tuffs and granite intrusions. These volcanic rocks form prominent ridges and are chiefly exposed in the western and northern parts of the area. The rhyolite, due to its relatively impervious nature, plays a critical role in restricting groundwater movement and significantly influences the region's hydrogeology.

Above the Malani rocks lies a sequence of Paleozoic sedimentary formations belonging to the Marwar Supergroup, particularly the Jodhpur Group. This group consists mainly of sandstone and shale and is spread across the central, eastern, and northwestern zones of the study area. These formations, classified under the Marwar and Vindhyan systems, contrast with rhyolite in their hydrogeological behavior. The moderately pervious nature of sandstone allows for limited groundwater percolation, making it an important aquifer unit in the region.

In the southern parts, the geological landscape is covered by Quaternary deposits of recent and sub-recent origin. These deposits include wind-blown sands and alluvium, contributing to the region's characteristic arid terrain.

Lithological and hydrogeological observations, derived from satellite imagery and field investigations, highlight several key features: the Kailana and Takhsagar reservoirs are located on rhyolite bedrock; Jodhpur city is mainly underlain by a mix of sandstone, shale, and alluvium; and the iconic Mehrangarh Fort is strategically situated on a rhyolite hill, taking advantage of the rock's stability and elevated topography.

Overall, the region's geological framework governs not only the movement and availability of groundwater but also shapes the surface topography and has historically influenced infrastructure placement and urban development.

Table 1: General Stratigraphy of Jodhpur

Era	Formation	Group	Lithology
Quaternary Unconformity	Recent to Sub-Recent	—	Wind-blown sand and alluvium
Paleozoic Unconformity	Marwar Supergroup	Jodhpur Group	Sandstone and shale
Precambrian	Malani Igneous Suite	—	Rhyolite with tuffs and granite

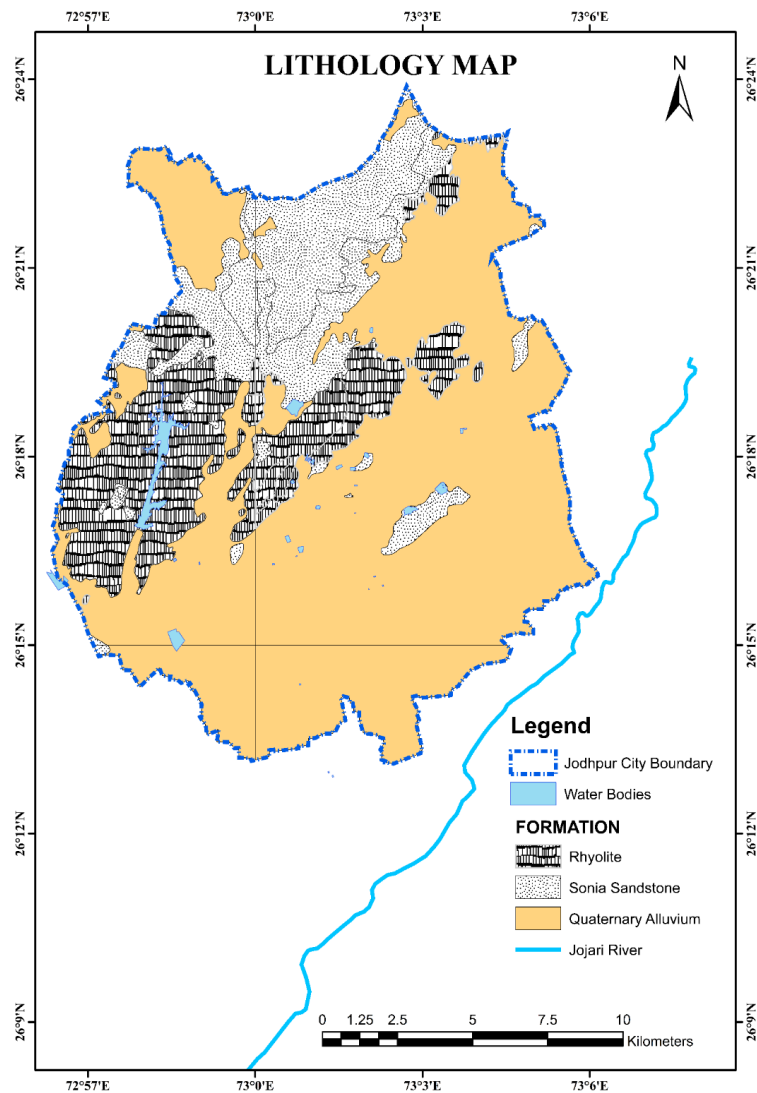


Figure 3.1: Geological Map of Jodhpur city

The densely populated old city is nestled on a hill slope near the base of the fort ridge, with topography that transitions from undulating terrain in the northwest to alluvial plains in the south and southeast. The northwest region is predominantly hilly, composed of shale and sandstone, while much of the city's expansion has occurred over the Quaternary alluvial formations, with

the old city situated on the Malani rock group. Figure 3.1 is depicting the geology map of Jodhpur city.

3.2 Geomorphological Characteristics

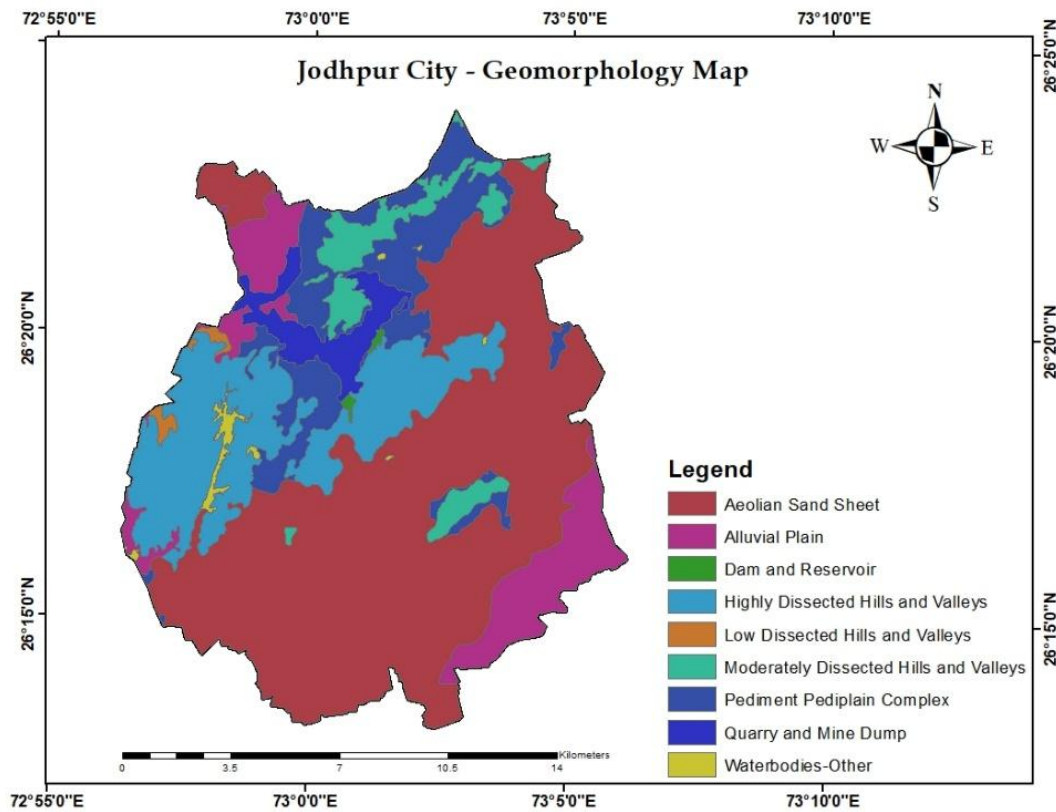


Figure 3.2: Geomorphological Map of Jodhpur city

The geomorphology of the Jodhpur region (Fig. 3.2) reflects the combined influence of ancient volcanic activity, sedimentary processes, and recent alluvial deposition, resulting in a complex and diverse landscape. The western and southwestern parts of the region are dominated by extensive aeolian sand sheets, characterized by smooth, gently undulating desert surfaces formed by wind-blown sands. In contrast, the southern and southeastern areas feature relatively flat alluvial plains composed of sand, silt, and clay deposited during intermittent stream flows. Dissected hills and valleys are prominent across the northern, eastern, and central parts of Jodhpur, with terrain varying from highly dissected rugged hills, predominantly over rhyolite and sandstone, to moderately and gently eroded landscapes. Transitional zones known as piedmont pediments, formed by the accumulation of eroded material at the foothills, also mark the transition from elevated terrains to flatter plains.

Anthropogenic and hydrological features further contribute to the geomorphology of the region. Notable among these are the man-made reservoirs such as Kailana and Takhatsagar, strategically developed by harnessing natural topographic depressions for water storage. Quarry and mine dumps, particularly in sandstone and rhyolite-rich areas, have modified the natural landscape through localized mining activities. Additionally, scattered minor water bodies and seasonal streams, primarily active during the monsoon season, punctuate the landscape, supporting limited surface water flow across the otherwise arid terrain.

3.3 Structural and Lineament Analysis

Lineament mapping of the Jodhpur region (Figure 3.3) indicates the presence of approximately 200 structural features, with a dense concentration around the Kailana-Takhatsagar (K-T) reservoirs. The majority of these lineaments are predominantly oriented along NNE–SSW and NE–SW directions. However, a notable observation is the absence of major lineament pathways directly connecting the K-T reservoir system to the Jodhpur urban area. This structural disconnection has significant hydrogeological implications, particularly concerning groundwater recharge and subsurface flow dynamics between the reservoirs and the city.

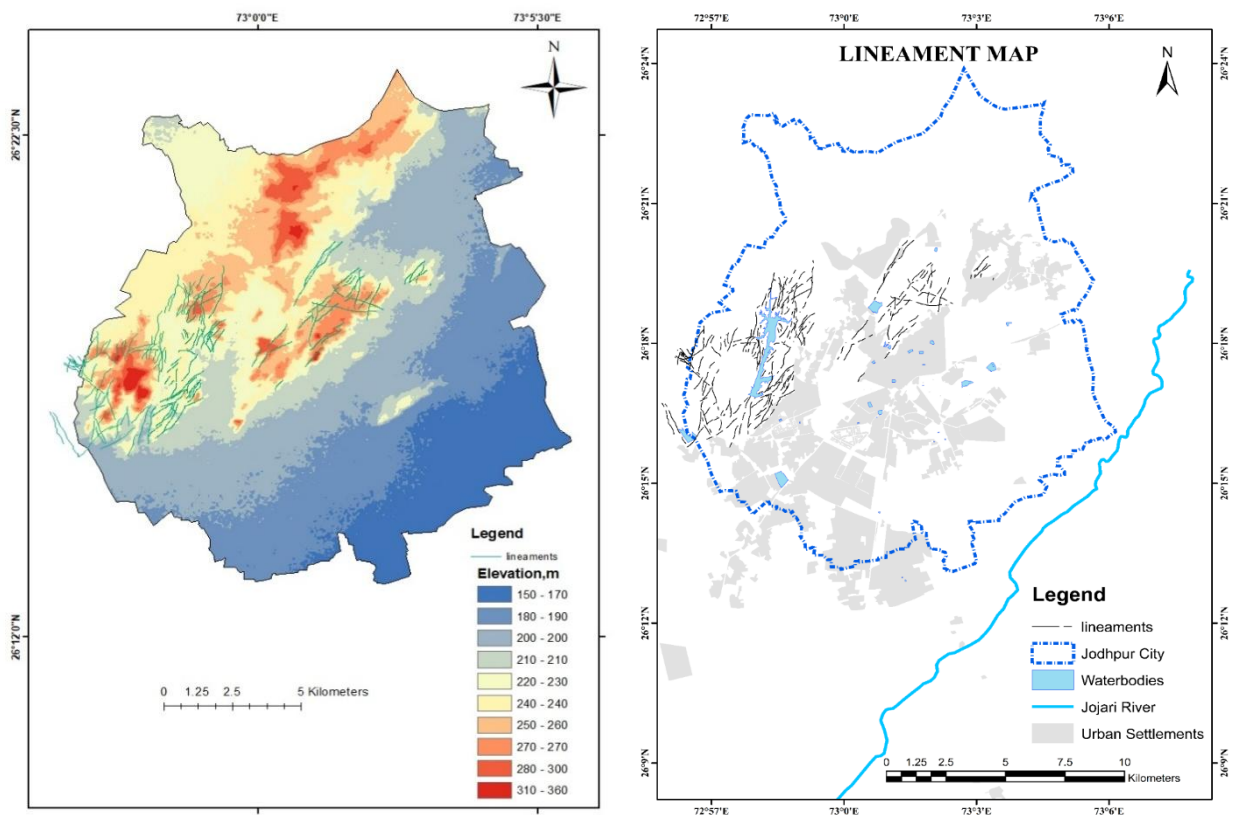


Figure 3.3: Mapped Lineament Features of Jodhpur City, Rajasthan

This structural disconnection has important hydrogeological implications:

- The lack of extended natural fracture zones restricts groundwater recharge from the reservoirs to the urban area.
- During intense rainfall events, the absence of subsurface drainage pathways results in **surface water accumulation**, causing **localized waterlogging** and **urban flooding**.
- The relatively **low-lying position** of Jodhpur city further exacerbates drainage congestion, leading to ponding and inefficient storm water management.

Thus, the combined geological, geomorphological, and structural settings critically influence water resource dynamics and urban infrastructure resilience in the region.

CHAPTER 4: URBAN GROWTH, WATER DEMAND & SUPPLY SCENARIO

4.1 Demographic Trends

Jodhpur, owing to its historical legacy, strategic significance, and administrative importance as the headquarters of the Western Air Command, has experienced consistent urban expansion. It is the second-largest city in Rajasthan after Jaipur. As per recent projections, the city continues to grow both demographically and spatially due to its role as a regional economic and defense hub.

According to earlier census data, Jodhpur's population increased from approximately 3.65 lakhs in 1971 to over 8.5 lakhs by 2001. A compound annual growth rate (CAGR) of 3.21% was established during this period. Based on this growth rate, the population was projected to reach 11.08 lakhs by 2010 and 12.75 lakhs by 2015.

The recent dataset provides actual and projected population data from 2014 onwards as shown in Figure 4.1. As per Table 4.1, Jodhpur's population in 2014 was approximately 10.79 lakhs, which increased to 11.14 lakhs in 2015 and is projected to grow consistently in subsequent years, maintaining the long-term growth trajectory.

Equation for Population Projection:

$$P = 5.1 \times 10^{-19} e^{(0.02788 X)} \quad \text{Eqn.(4.1)}$$

where P is the projected population and X is the calendar year. The model fits the historical data with a correlation coefficient $R^2=0.9976$, indicating high reliability. The trend in population growth is depicted in Figure 4.1.

Municipally, Jodhpur is divided into 60 wards (Figure 4.2), out of which 34 wards fall fully and 17 wards partially within the designated study area. Ward-wise projections up to 2015 were calculated using the uniform 3.21% annual growth rate (NIH, 2011 report).

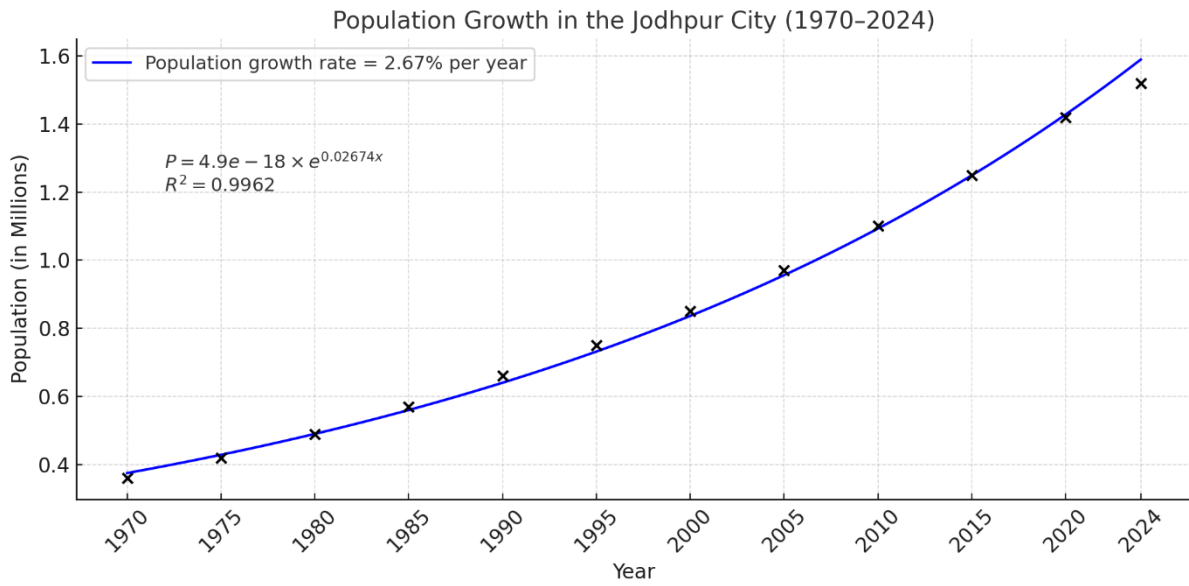


Figure 4.1: Population growth projection of Jodhpur City, Rajasthan

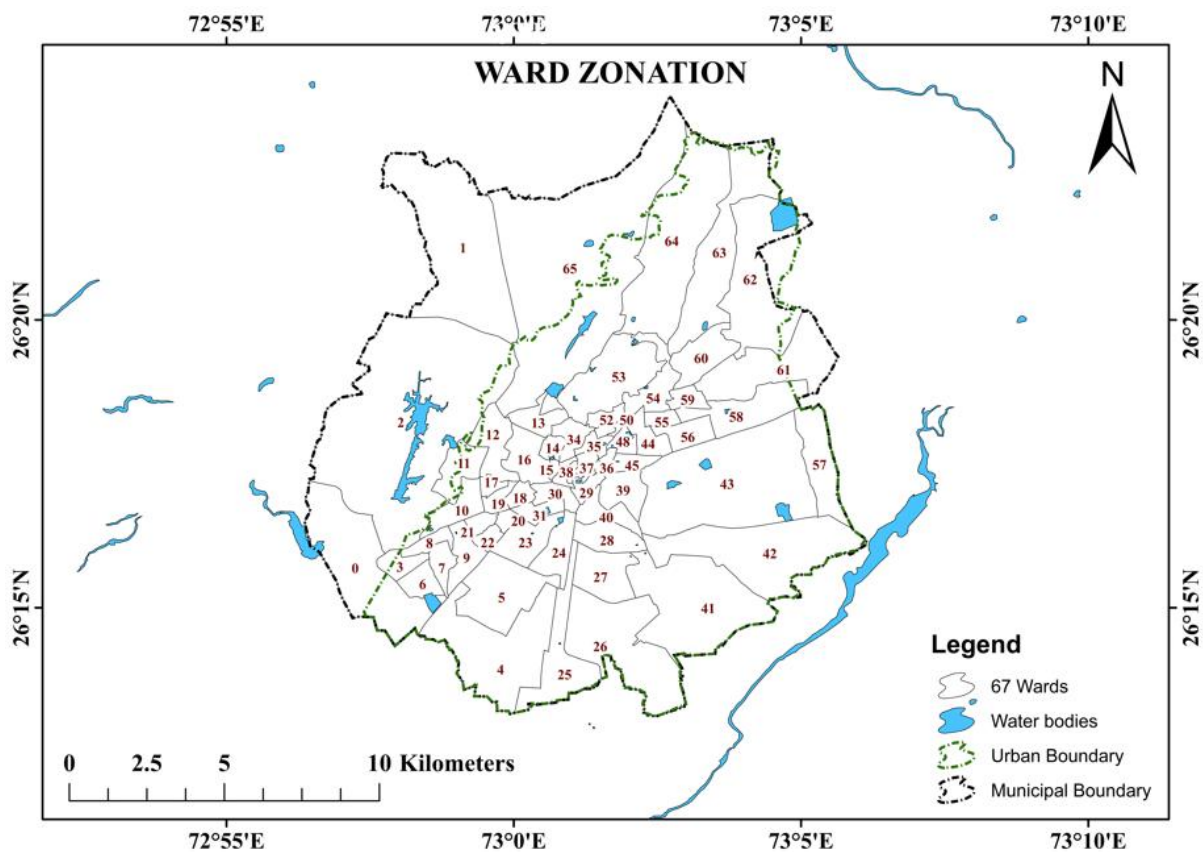


Figure 4.2: ward map of Jodhpur City, Rajasthan

4.2 Existing Water Supply System

Jodhpur, located in the arid belt of western Rajasthan, faces persistent water scarcity due to low and erratic rainfall, high evaporation rates, and limited local aquifer yield. In response, the city has developed a robust surface water supply system anchored by two key reservoirs — Kailana Lake and Takhatsagar Reservoir — supported by long-distance water conveyance from the Indira Gandhi Canal (IGC) system. Together, these reservoirs form the backbone of the urban water management framework, not only storing and regulating water but also ensuring supply continuity in a climate-stressed environment.

Both Kailana Lake and Takhatsagar Reservoir are situated on rhyolitic volcanic bedrock, part of the Precambrian Malani Igneous Suite. These rocks, characterized by their impervious and massive structure, provide a geologically stable and watertight foundation, making them ideal sites for water storage structures.

1. Water Conveyance and Kailana Reservoir

Water is lifted to Jodhpur from the Harike Barrage in Punjab via the Indira Gandhi Canal system, and conveyed through the Rajiv Gandhi Lift Canal (locally referred to as *Hathi Canal*) to Kailana Lake. Located at an elevation of 256 meters above mean sea level (m.s.l.), Kailana Lake extends between latitudes 26°17'58" N to 26°19'21" N and longitudes 72°58'01" E to 72°58'50" E. At Full Reservoir Level (FRL) of 273.7 meters m.s.l., it stores 4.814 million cubic meters (MCM) over a spread of 0.88 square kilometers.

Besides canal inflows, the lake receives surface runoff from adjacent catchments during the monsoon, enhancing seasonal recharge. The reservoir's capacity dynamics are governed by precisely derived stage–capacity and area–capacity relationships with strong statistical correlation ($R^2 > 0.998$), enabling accurate forecasting of available water volumes from observed lake levels.

2. Takhatsagar Reservoir and System Integration

Downstream of Kailana and structurally aligned along the same fault-controlled depression lies the Takhatsagar Reservoir, constructed by damming a natural valley. At an elevation of 241 meters m.s.l., it spans latitudes 26°16'51" N to 26°17'58" N and longitudes 72°57'51" E to 72°58'25" E, with an FRL of 269.75 meters m.s.l.. Its full storage capacity is 6.523 MCM over a 0.601 sq. km water spread area.

Takhatsagar receives water through regulated releases from Kailana, functioning as a secondary buffer and operational reservoir. Stage-capacity and area-capacity relationships ($R^2 > 0.972$) for Takhatsagar provide critical inputs for volumetric analysis and water supply planning. The Reservoir Stage capacity curve of Jodhpur city is given in figure 4.3.

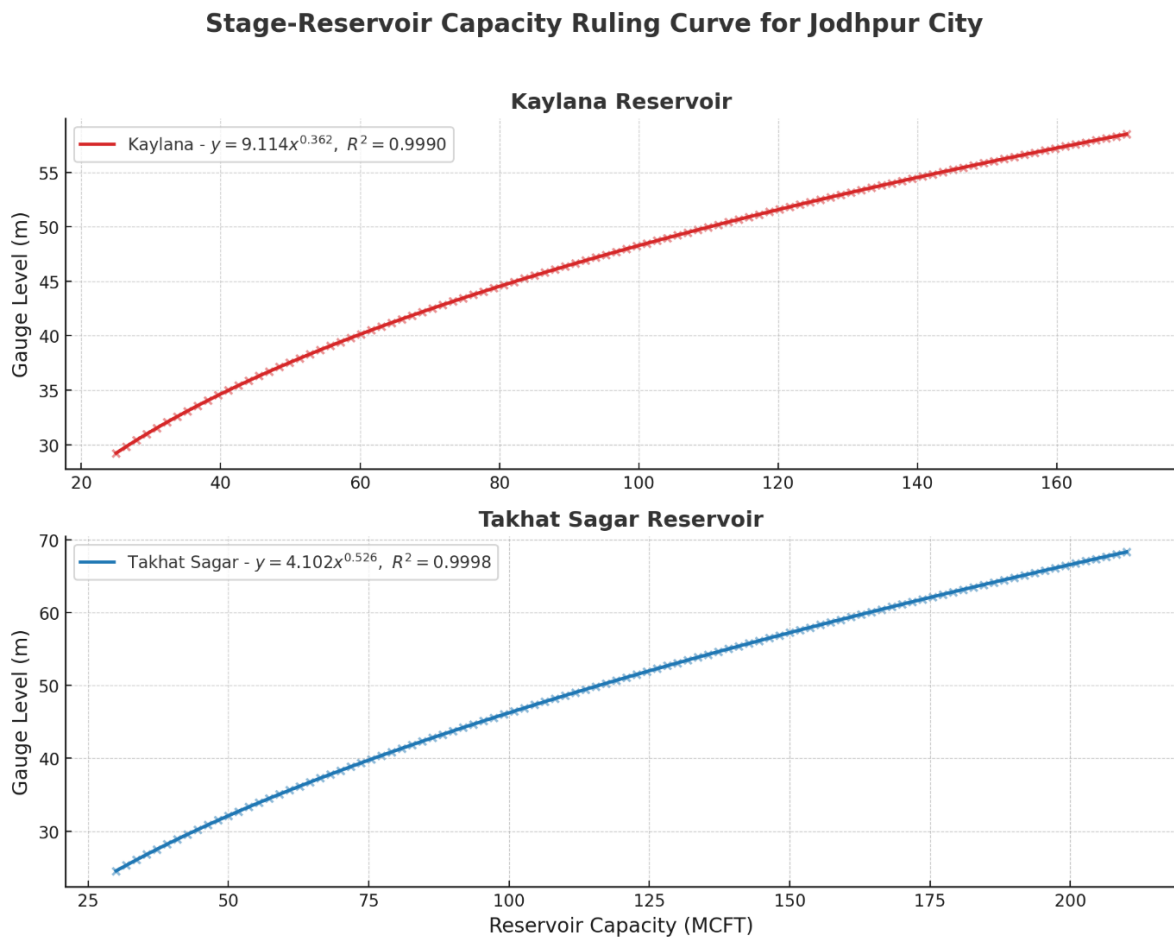


Figure 4.3: Stage Reservoir capacity curve of Jodhpur city

4.3 Water Requirement and Distribution

Water supply for domestic and municipal use in Jodhpur continues to be managed by the Public Health Engineering Department (PHED). Population projections and water requirements follow the Ministry of Works and Housing (MoWH) guideline of 140 litres per capita per day (lpcd). These provide a baseline for assessing water demand and supply balance in the city.

4.3.1 Demand and Supply Trends

Over the last decade, Jodhpur has witnessed a steady rise in population, growing from approximately 10.79 lakhs in 2014 to an estimated 14.8 lakhs by 2024. This demographic expansion has directly influenced the city's water demand, which increased from 151 MLD (399

lakh gallons/day) in 2014 to a projected 207 MLD (547 lakh gallons/day) in 2024. Historically, between 2014 and 2019, the actual water supply consistently surpassed the demand—for example, in 2018, the city required 171 MLD, but received 183.6 MLD (485 lakh gallons/day). However, the COVID-19 pandemic period (2020–2021) marked a significant disruption, with supply plummeting to just 59.7 MLD (157.7 lakh gallons/day) in 2020, far below the requirement of 182.6 MLD. This sharp decline can be attributed to the pandemic’s impact on municipal operations, labor availability, and data accuracy, as well as temporary migration and emergency redistribution measures that may have led to underreporting. In the post-COVID period (2022–2024), water supply figures show a gradual recovery, reaching 192 MLD in 2022 and stabilizing around 200 MLD in 2023 and 2024.

Due to the absence of official water supply statistics for the year 2024, the analysis has been carried out using 2023 water supply figures as a representative estimate to ensure continuity in the assessment of supply-demand trends and allows for consistent comparison with projected water requirements. The details are given as below in Table 2.

Table 2: Demand and Supply of Water for Jodhpur city

Year	Population	Water Demand (Lakh Gallon Per day)	Water Supply to City Volume (Lakh Gallon Per day)
2014	1079062	399.08	442.40
2015	1113700	411.89	486.36
2016	1149450	425.11	497.68
2017	1186347	438.76	505.64
2018	1224429	452.84	485.02
2019	1263733	467.38	423.15
2020	1304299	482.38	157.71
2021	1346167	497.87	384.00
2022	1389378	513.85	507.66
2023	1433978	530.34	528.32
2024	1480008	547.37	528.32

4.4 Key inferences

Jodhpur, situated in an arid and water-stressed region, must manage its water resources with utmost efficiency and equity. While water supply has generally exceeded demand in recent years, several challenges continue to undermine the effectiveness of water distribution. The city's aging

distribution system is prone to leakages and inconsistent pressure, further reducing service efficiency. In many areas, unregulated and continuous water use leads to unnecessary wastage, exacerbating not just scarcity concerns but also urban management issues as central part of city experiencing waterlogging.

The inefficient drainage of excess or misused water—especially during monsoons or periods of increased supply—often contributes to water stagnation in low-lying zones. This has compounded urban waterlogging issues in parts of the city, putting pressure on municipal services and affecting public health and mobility.

To address these interconnected challenges, a set of targeted measures is recommended. Strengthening ward-wise metering and monitoring will enable data-driven management of supply and usage. Prioritizing leakage detection and pipeline rehabilitation is critical to minimizing both water loss and surface accumulation. Real-time water leak detection sensors particularly in zones with historically high supply and drainage issues, will be beneficial for achieving long-term sustainability and reducing the risk of urban waterlogging.

CHAPTER 5: HYDRO METROLOGICAL INVESTIGATIONS

This chapter presents a detailed hydrological assessment of Jodhpur, focusing on the rainfall characteristics and groundwater behaviour that underpin the city’s current waterlogging and rising water table crisis. The hydrological regime of Jodhpur is shaped by its arid climate, monsoon-driven precipitation, and increasing anthropogenic interventions such as canal water importation and urban expansion.

A thorough evaluation of long-term rainfall records, seasonal groundwater monitoring, and spatial hydrological variability provides insight into the shift from historical water scarcity to emerging groundwater surplus. Particular emphasis is placed on the temporal and spatial behavior of rainfall, and on pre- and post-monsoon groundwater level variations observed in recent years. These analyses are essential for understanding the root causes of hydrological imbalance and for formulating sustainable groundwater management strategies.

5.1 Rainfall characteristics

Rainfall is the primary natural source of groundwater recharge in Jodhpur. However, due to its location in the arid belt of western Rajasthan, the city experiences low and erratic precipitation. Historical data from 1901 to 2024 reveals a climate characterized by significant inter-annual variability and frequent anomalies. As per long term rainfall anomaly, the rainfall in Jodhpur lies around 320 mm.

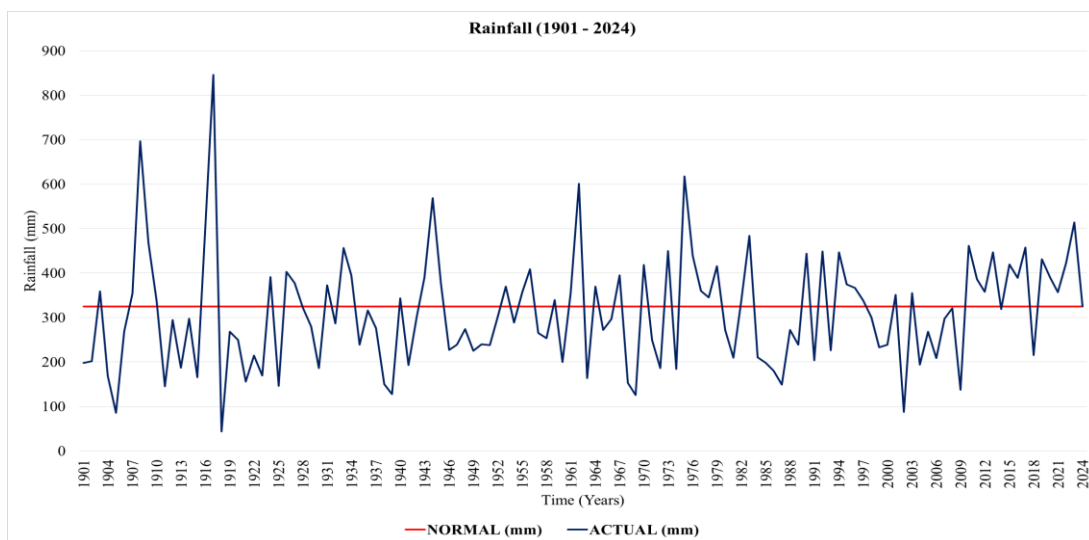


Figure 5.1: Temporal variation of Rainfall for Jodhpur city

However, the annual rainfall series exhibits large deviations from the mean, with occurrences of both drought years and short bursts of intense rainfall (Figure 5.1).

These irregularities highlight the region’s climatic instability and underscore the challenge of relying on rainfall as a consistent recharge source. Monsoonal Dependency: Approximately 85% of Jodhpur’s total rainfall occurs during the monsoon months (July–September), which makes the city highly dependent on a narrow seasonal window for groundwater replenishment. This seasonal skew means that any failure or delay in the monsoon has a direct and severe impact on the region’s water availability.

Spatial Variation: The spatial distribution of normal rainfall, as illustrated in Figure 5.2, shows a declining gradient from the northwest to the southeast of the city. This is influenced by elevation and local geomorphology. The north-western part, being hillier, receives slightly more precipitation, while the flatter south eastern plains remain more arid.

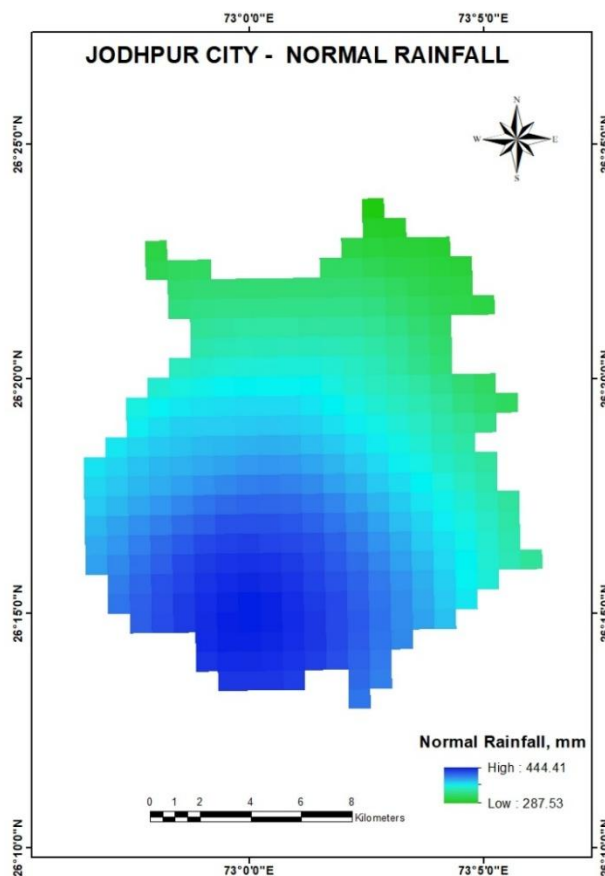


Figure 5.2: Normal Rainfall map of Jodhpur city

5.2 Trend Analysis of Rainfall & Rainy Days

Overall, the erratic and spatially imbalanced nature of rainfall in Jodhpur complicates recharge predictability, reduces planning accuracy for water resource development, and necessitates diversified and adaptive water management strategies.

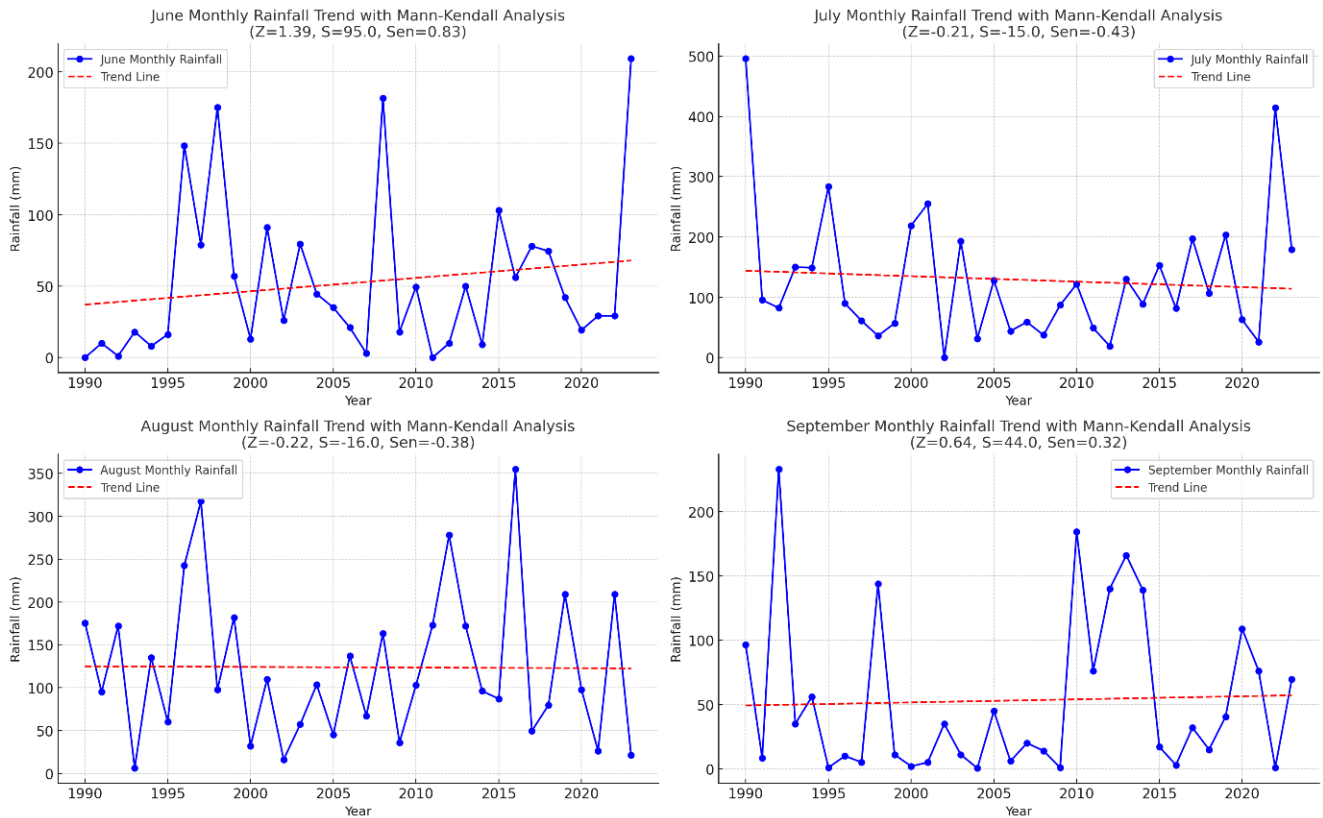


Figure 5.3: Trend Analysis of Monsoon Rainfall (June–September) in Jodhpur city

To assess the long-term trends in Jodhpur’s monthly rainfall, the Mann-Kendall (MK) test and Sen’s slope estimator were applied—two widely accepted non-parametric statistical methods for trend detection in climatological and hydrological time series. The MK test evaluates the presence of a monotonic (increasing or decreasing) trend without requiring the data to follow a specific distribution, while Sen’s slope quantifies the magnitude of that trend by estimating the median of all pairwise slopes in the series. When applied to the monthly rainfall dataset, the MK test results showed as following:

Table 3: Monthly trend statistics of Rainfall pattern for Jodhpur city

Month	Z-statistic	p-value	Sen's Slope	Trend with remark
Jun	1.39	0.16	0.830	Positive, Not significant
Jul	-0.21	0.84	-0.430	Negative, Not significant
Aug	-0.22	0.82	-0.380	Negative, Not significant
Sep	0.64	0.52	0.320	Slight Positive , Not significant
Total Rainy Days	3.0669	0.0022	0.387	Positive- Significant

The trend analysis of monthly rainfall data for Jodhpur using the Mann-Kendall test and Sen's slope estimator revealed no statistically significant trends in any of the individual months from January to December. The Z-statistics for each month showed values well within the non-significant range ($p > 0.05$), and the Sen's slope values were consistently 0.0, indicating no directional change in monthly rainfall over time. This suggests that, despite inter-annual variability, the monthly rainfall patterns have remained largely stable over the observed period. The lack of detectable trends is likely influenced by the inherently arid climate of Jodhpur, where many months exhibit negligible or zero rainfall, thereby limiting the sensitivity of trend detection at the monthly scale. These results underscore the need to evaluate trends at broader seasonal or annual scales to better capture long-term hydro climatic changes.

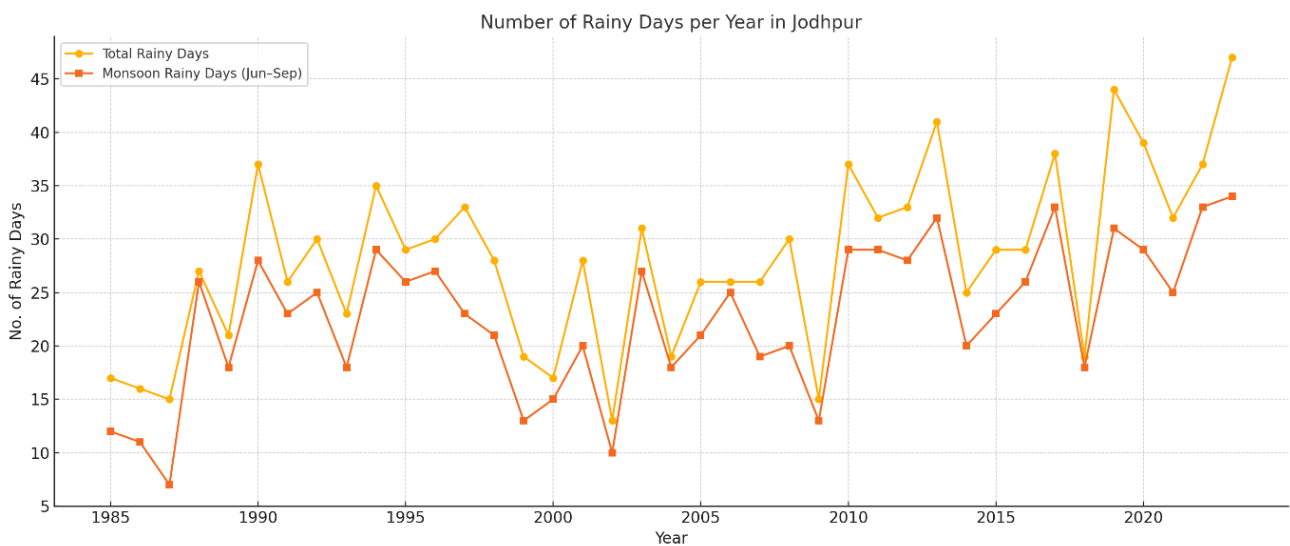


Figure 5.4: Trend in Number of Rainy Days Observed in Jodhpur

The trend analysis of annual rainy days in Jodhpur reveals a statistically significant increasing trend over the years. The Sen's slope of 0.3871 rainy days per year suggests a gradual but consistent increase in the frequency of rainy days annually. This finding highlights a notable shift

in Jodhpur's rainfall pattern, with implications for urban drainage planning, water resource management, and agricultural practices in the region.

5.3 Monthly Evapotranspiration variation

Evapotranspiration data is obtained from (Goyal, 2004). The Modified Penman method (MPM) is used to estimate the monthly evapotranspiration over the study area.

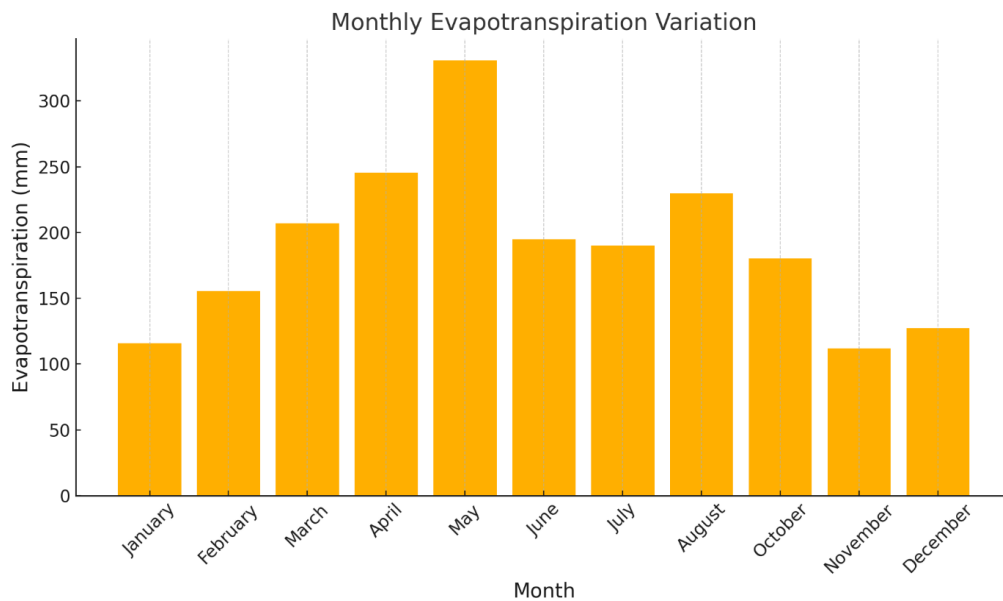


Figure 5.5: Monthly Evapotranspiration Variation in Jodhpur city

The above bar chart showing "Monthly Evapotranspiration Variation" in millimeters, indicating a clear seasonal trend. Evapotranspiration gradually rises from January, peaks in May at over 320 mm—coinciding with the hottest and driest part of the year—and then declines steadily, with a minor rise in August likely due to monsoonal humidity. The lowest values are observed in the cooler months of January and November, around 110–120 mm. This pattern reflects the climatic influence on evapotranspiration, with higher rates during summer and lower during winter.

5.4 Implication and Key inferences

Jodhpur receives approximately 320 mm of annual normal rainfall, with 85% occurring during July–September, leading to intense runoff and frequent waterlogging. Decadal monsoon rainfall analysis shows that the number of rainy days are increasing. These trends, combined with inadequate urban drainage, underscore the need for integrated water management and improved stormwater infrastructure.

CHAPTER 6: GROUNDWATER LEVEL ANALYSIS & TRENDS

6.1 Ground Water condition of Jodhpur district

Before conducting a detailed hydrogeological investigation specifically for the urban area of Jodhpur city, a broader district-level groundwater assessment was undertaken to understand general patterns and trends to all the surrounding areas.

The groundwater contour maps provided for different years (2011, 2016, and 2021) reveal the following key observations:

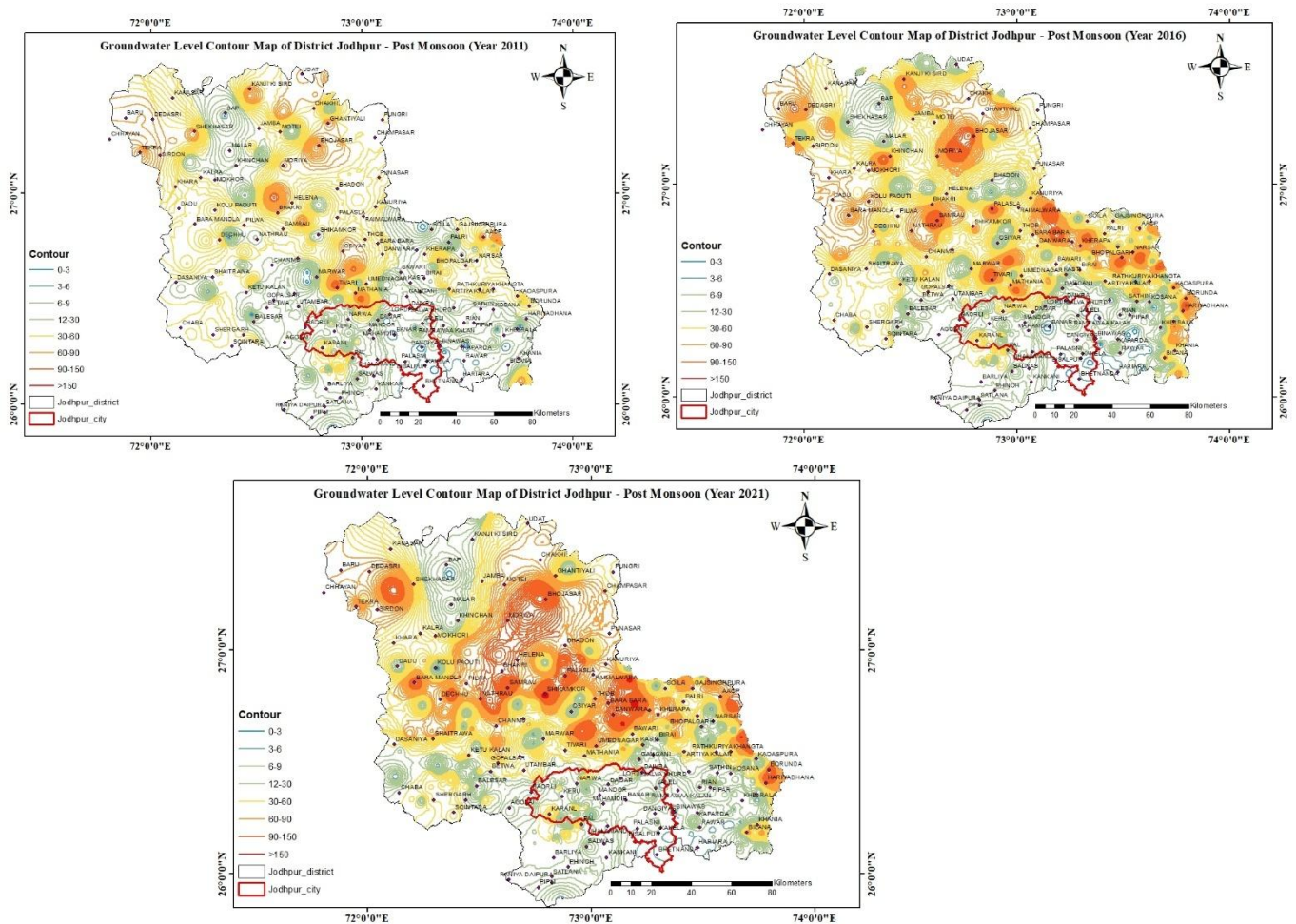


Figure 6.1 : Contour Maps Depicting Groundwater Table Variations – Jodhpur District

Groundwater levels across most parts of Jodhpur District during the post-monsoon period generally lie within the 6–30 meters below ground level (bgl) range, with deeper levels (30–60 meters and beyond) observed particularly towards the southwestern and northwestern areas, indicating regions with limited recharge or complex hydrogeological conditions. Spatially, the northeastern and central parts of the district exhibit relatively shallower groundwater levels (<10 m bgl), suggesting shallow aquifer conditions, whereas the southwestern, southeastern, and

extreme northwestern regions show deeper water tables (>30 m bgl), highlighting zones of groundwater stress. Temporal variation of water level reveals that over the years, the northern area above the Jodhpur city is getting the deeper GWL and stressed, however the Jodhpur tahsil or urban region is comparatively stable water conditions with maximum up to 30m.

6.2 Trend analysis of Ground water level

The Mann-Kendall trend analysis and Sen's slope estimates for post-monsoon groundwater levels (2013–2024) across 46 observation sites in Jodhpur city highlight a spatially heterogeneous pattern of groundwater behavior. While 29 sites show a positive trend, indicating groundwater accumulation likely due to recharge or reduced abstraction, 17 sites display a negative trend, signaling ongoing depletion. Notably, some central and low-lying areas exhibit rising trends, which aligns with frequent reports of seasonal waterlogging and shallow water tables, especially after the monsoon. To manage these conditions, localized groundwater pumping and drainage measures have been suggested in later sections of this report for certain saturated zones to lower the water table, prevent basement seepage, and mitigate urban flooding risks.

Interestingly, the analysis also reveals that a few central city locations now show a recent declining trend in groundwater levels, which may be attributed to continuous or intensified localized pumping efforts over the last few years. This suggests that such interventions are beginning to impact the groundwater regime, helping to control persistent waterlogging in saturated zones. At the same time, areas in the western and peripheral parts of the city continue to show significant declining trends, reflecting higher abstraction, lower recharge potential, or hydrogeological limitations.

These findings reinforce the need for a balanced and adaptive groundwater management approach—promoting strategic pumping in waterlogged zones, while enhancing artificial recharge and conservation in overexploited areas, to ensure long-term hydro-sustainability for Jodhpur city.

The Mann Kendall trend analysis have been performed for all the observation well data and following are the results for pre Monsson and Post monsoon data given in Figure 6.2 where blue color is increasing trend and Red color is depleting trend of WL. All the observations wells were plotted for time series trend analysis and their individual results are given in appendix -B.

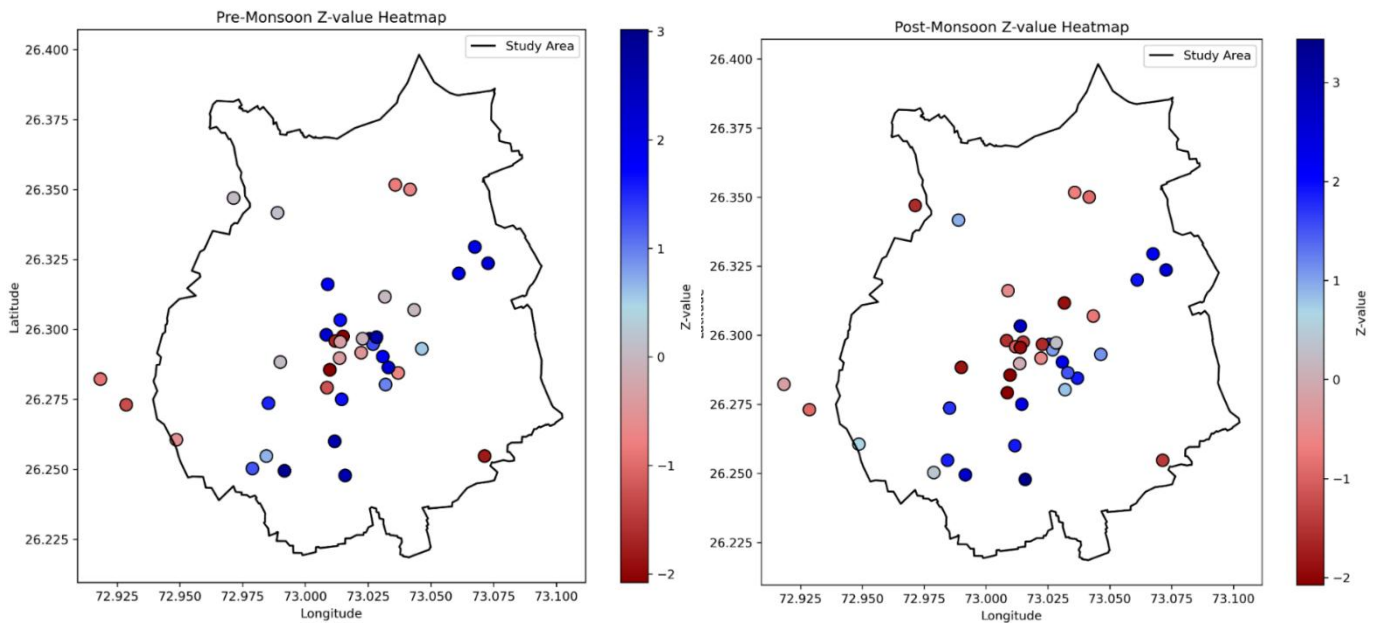


Figure 6.2: Trend Analysis of Groundwater Levels Using Mann–Kendall Z-values – Jodhpur City

6.3 Contour Mapping and Zonation

The below given Figures 6.3 & Figure 6.4 highlighting the pre-monsoon and post-monsoon groundwater contour maps of Jodhpur city (2015–2023) offer valuable insights into temporal groundwater fluctuations and emerging water management challenges. A comparative analysis reveals that post-monsoon contours, displayed in black, consistently form dense, concentric patterns in certain parts of the city, especially in the central region, north-east zone, and eastern low-lying areas. These visual patterns suggest zones of shallow water tables, likely in the range of 0–3 meters below ground level, immediately after the monsoon. In contrast, pre-monsoon contours (in red) are more widely spaced, indicating generally deeper water levels following months of groundwater withdrawal and evaporation.

The temporal repetition of these shallow zones in post-monsoon maps highlights aquifer mounding or localized recharge accumulation, particularly in areas with limited natural or engineered drainage capacity. The north-central slope also shows evidence of seasonal saturation that aligns with surface runoff convergence. These observations are consistent with reported cases of seasonal waterlogging, subsurface seepage into building foundations, and urban drainage stress. Although the maps do not include exact depth labels, their spatial patterns clearly indicate hydrogeological stress zones. These insights underscore the need for targeted water management interventions, including improved urban drainage planning in vulnerable regions of Jodhpur.

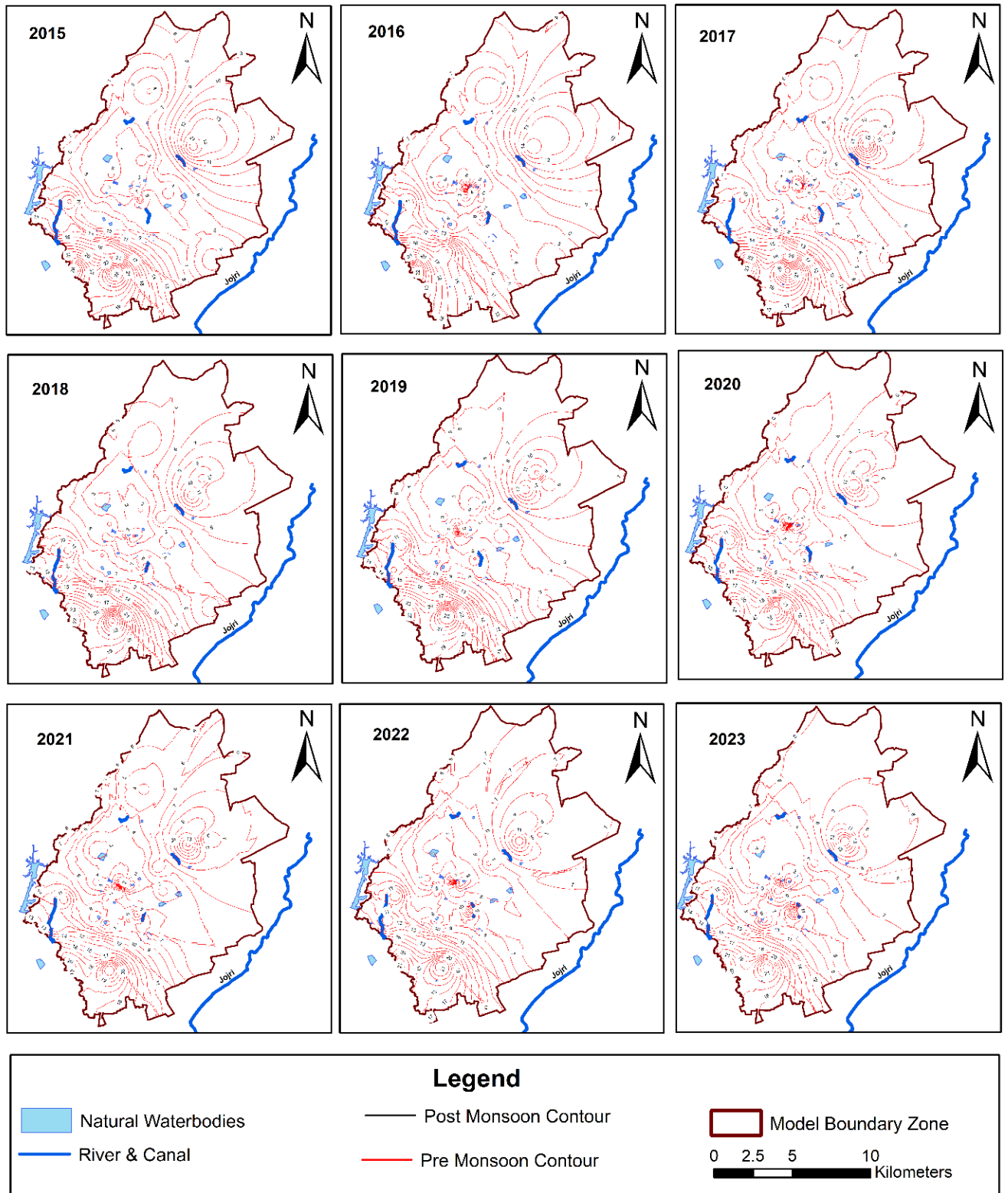


Figure 6.3: Pre Monsoon Contours of Groundwater Levels – Jodhpur City

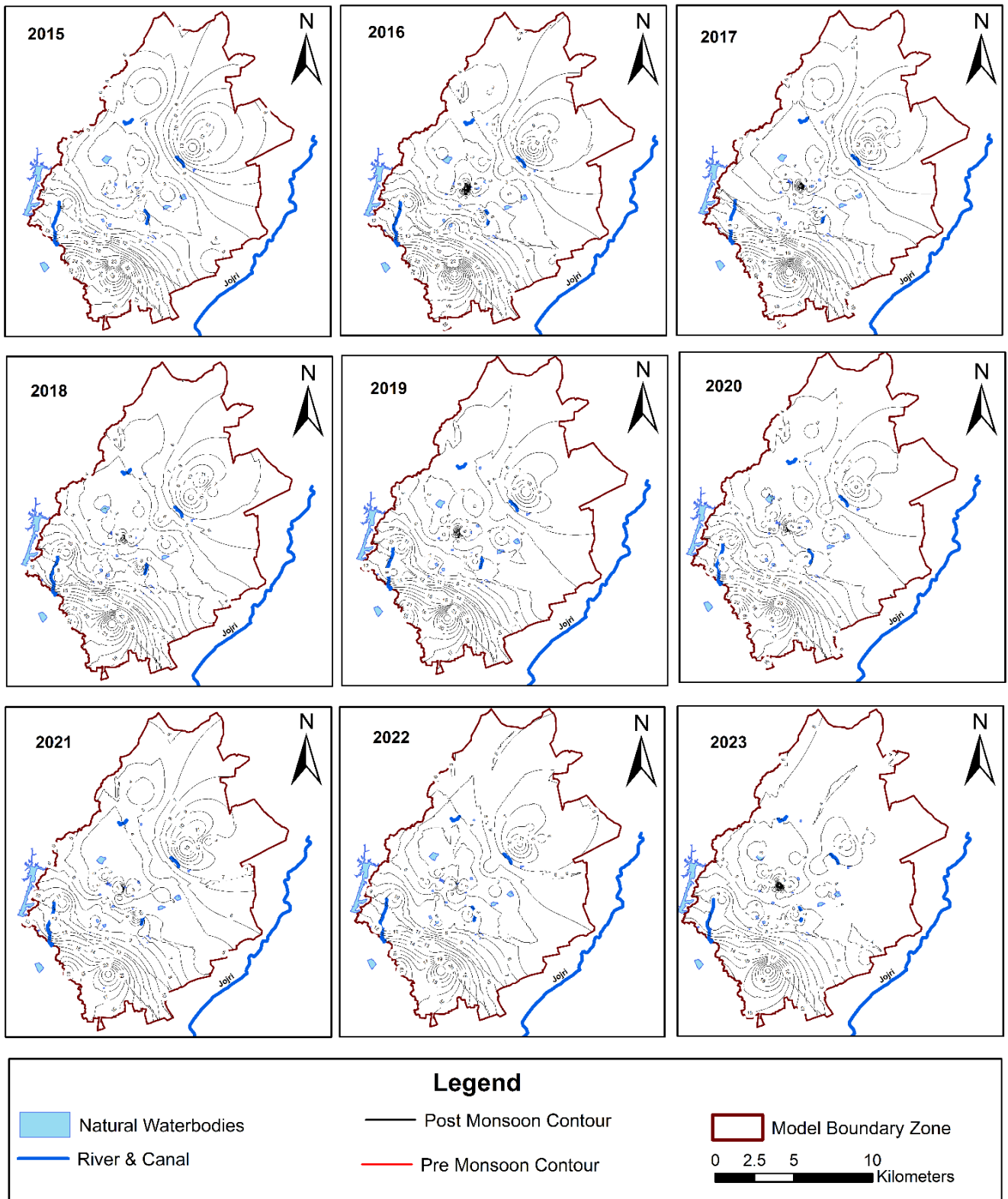


Figure 6.4: Post Monsson Contours of Groundwater Levels – Jodhpur City

The groundwater level interpolated maps (Figure 6.5) for Jodhpur city over the years (2011, 2015, 2019, and 2023) reveal significant seasonal and spatial variations between the pre-monsoon and post-monsoon periods

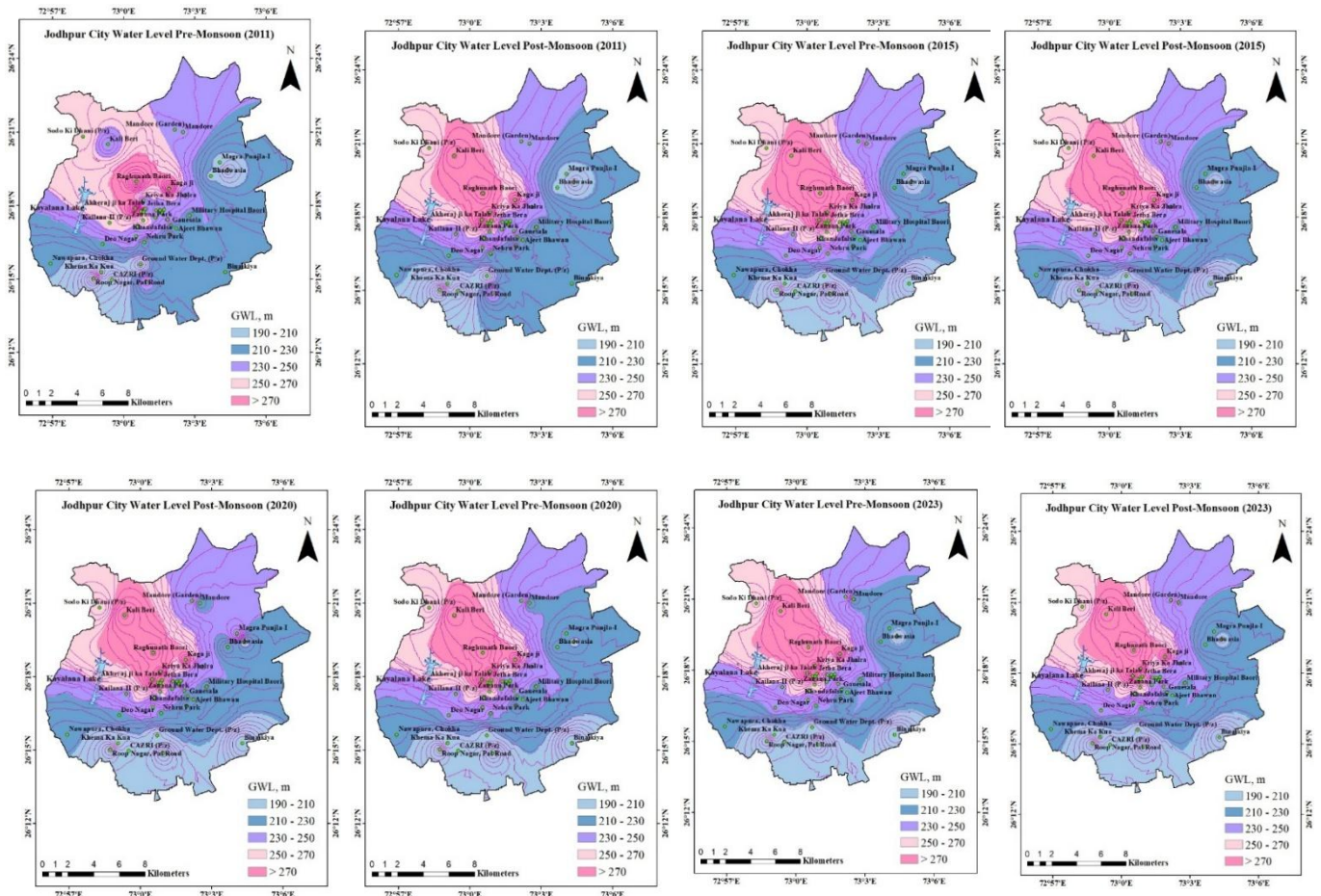


Figure 6.5: Spatio temporal Groundwater Levels variation – Jodhpur City

A consistent trend is observed where the northern and northwestern parts of the city, particularly beneath the old city and around the fort region, show relatively shallower groundwater levels, while the southern and southeastern areas exhibit deeper groundwater tables. Pre-monsoon maps generally indicate lower groundwater levels, especially in the southern sectors, whereas post-monsoon recharge improves groundwater conditions across much of the city. However, the improvements are localized, with the most substantial rise in groundwater levels occurring in areas that were already shallow. Year-wise comparison shows that 2011 and 2015 had better groundwater conditions post-monsoon compared to 2019, which appeared slightly drier, while 2023 reflected a moderate recovery. The natural topographic gradient, urban expansion, and

surface permeability strongly influence the groundwater dynamics, with recharge mechanisms and rainfall variability playing crucial roles.

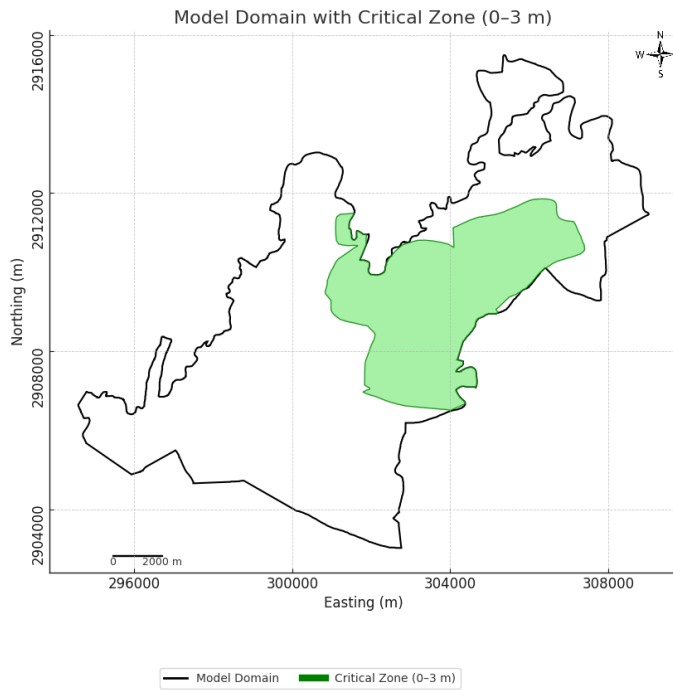


Figure 6.6: Critical problem zone area(0-3m) in the Jodhpur City

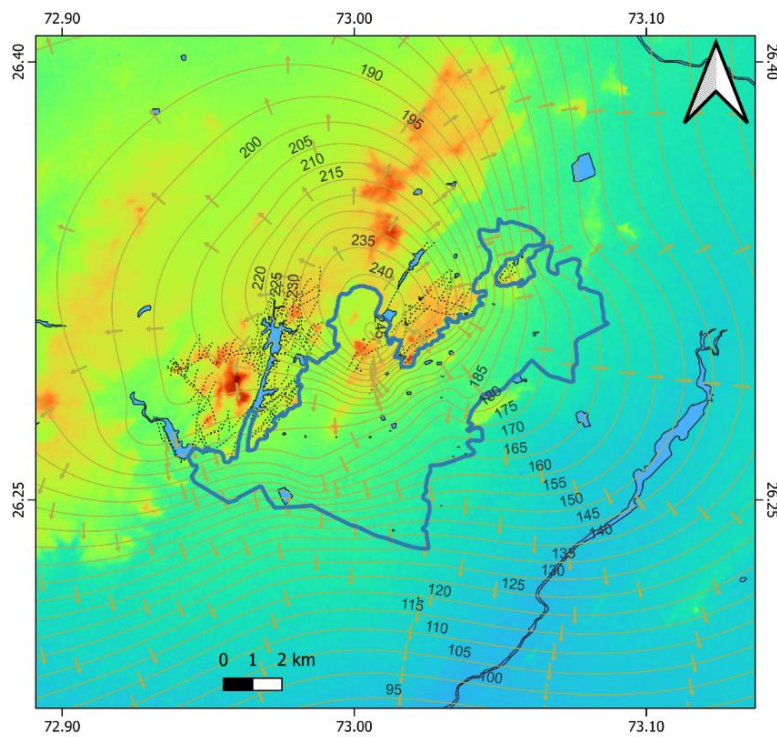


Figure 6.7: Flow Direction map of Jodhpur city

Critical zones consistently emerge in the central & northern parts of the city, which is nearly 18 km², where groundwater levels remain within 3 meters below ground surface post-monsoon, posing risks of waterlogging and urban drainage challenges. Despite the presence of major reservoirs like Kailana Lake and Takhatsagar to the west, the hydrogeological connection with the old city areas appears limited, suggesting localized recharge and complex subsurface conditions. The spatial alignment of groundwater contours further highlights a general flow tendency from the northwest towards the southeast, conforming to the city's slope. The broader interpretation emphasizes that although post-monsoon periods temporarily recharge the groundwater system, the issues of shallow water tables, potential flooding, and sustainable water management remain critical for Jodhpur's urban planning and resilience strategies.

CHAPTER 7: ISOTOPIC AND HYDROCHEMICAL CHARACTERIZATION

7.1 Seasonal Isotopic Sampling and Study Objective

To understand the dynamics of groundwater recharge and contamination sources contributing to waterlogging in Jodhpur, a total of 32 water samples were collected across three critical periods—Winter 2023, Pre-Monsoon 2024 (June), and Post-Monsoon 2024 (October). The isotopic analysis focused on δD and $\delta^{18}O$ signatures, aiming to identify recharge origins and the extent of evaporative influence, particularly to assess the role of Kaylana Lake in the local aquifer system.

7.2 δD vs $\delta^{18}O$ Plots and Seasonal Interpretation

To assess the recharge sources and possible interaction between Kaylana Lake and the surrounding aquifer system in Jodhpur, isotopic signatures of $\delta^{18}O$ and δD were analyzed from groundwater wells across different seasons—February, June, and October. The comparison with Kaylana Lake aimed to understand whether the lake acts as a major source of recharge to the aquifer.

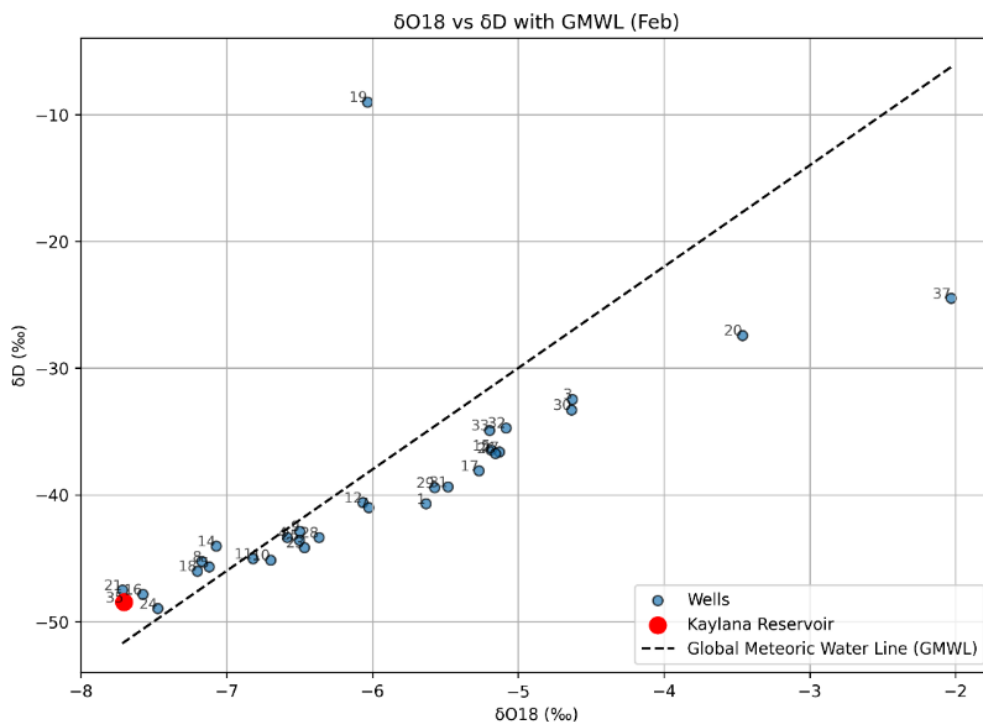


Figure 7.1. Isotopic Composition ($\delta^{18}O$ vs δD) of Groundwater and Reservoir (Feb)

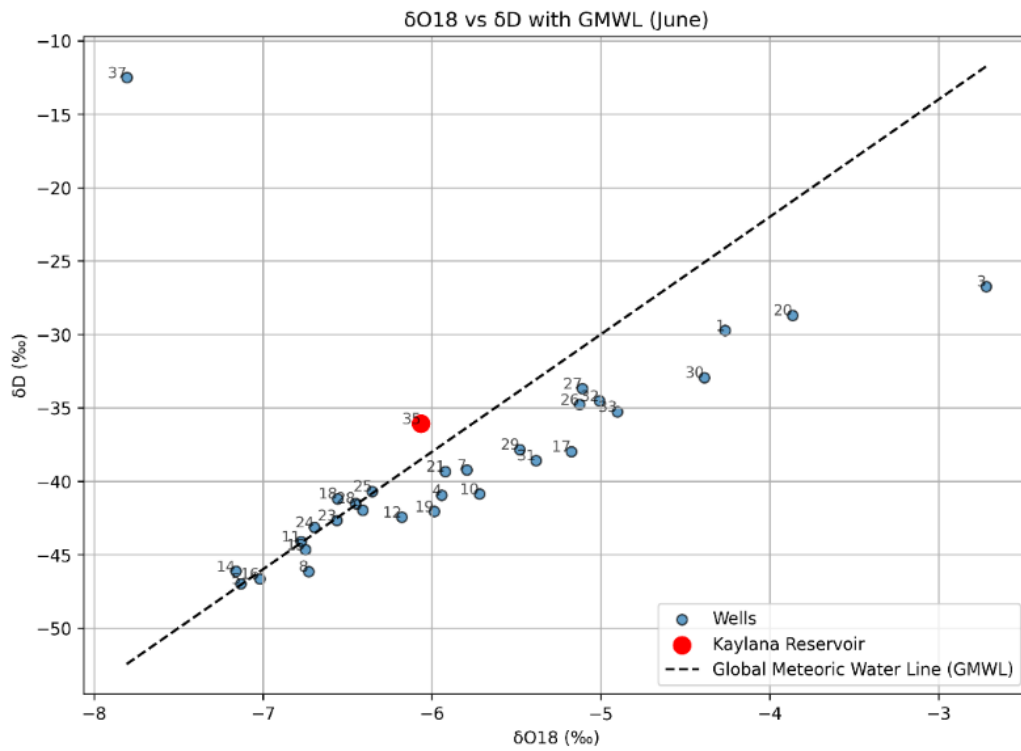


Figure 7.2. Isotopic Composition ($\delta^{18}\text{O}$ vs δD) of Groundwater and Reservoir (Jun)

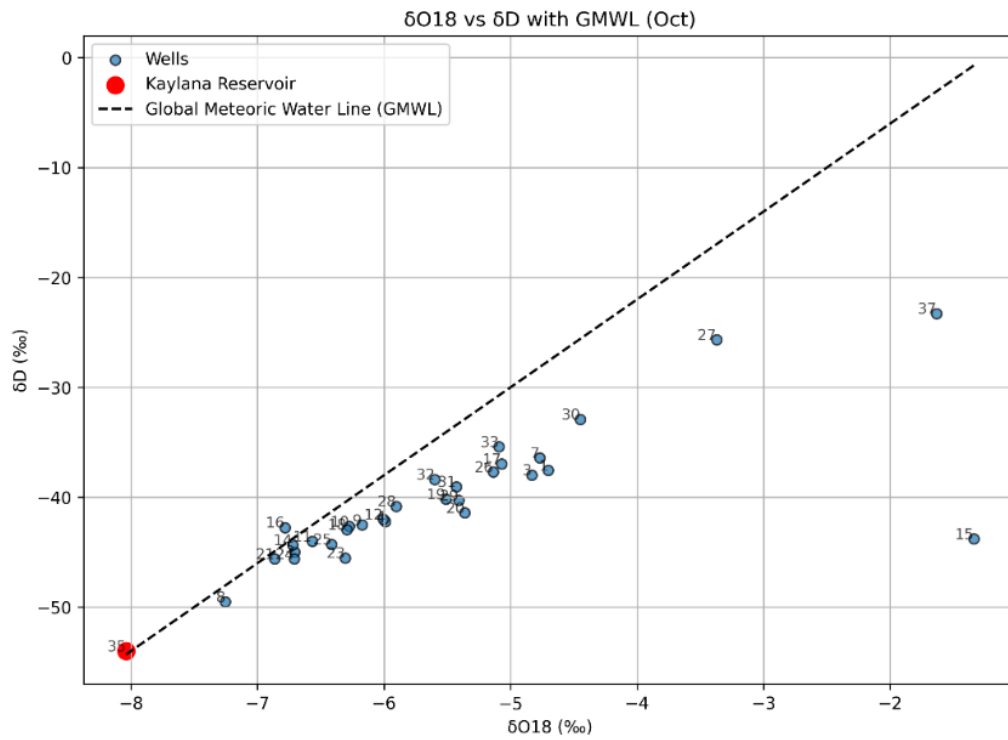


Figure 7.3. Isotopic Composition ($\delta^{18}\text{O}$ vs δD) of Groundwater and Reservoir (Oct)

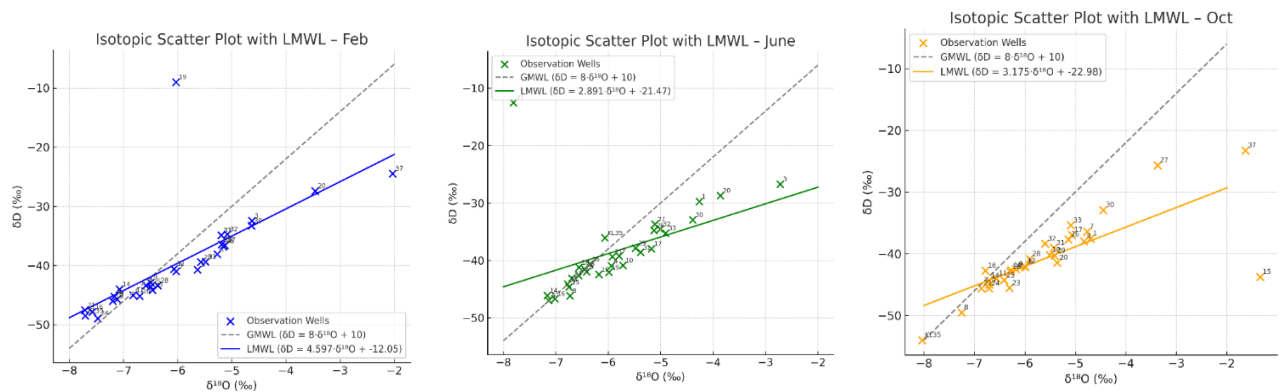


Figure 7.4 Seasonal Variation in Isotopic Composition of Groundwater Samples with Local Meteoric Water Line (LMWL)

The three δD vs. $\delta^{18}O$ scatter plots for the months of February, June and October provide clear insights into the isotopic characteristics of groundwater and the potential influence of Kaylana Lake in Jodhpur. Each plot compares groundwater sample points (marked with sample IDs) against the Global Meteoric Water Line (GMWL), which represents the theoretical relationship for precipitation-derived water with minimal evaporation. In all three cases, the groundwater samples deviate significantly from the GMWL, forming Local Meteoric Water Lines (LMWL) with shallower slopes—indicative of evaporation effects.

In the October plot, the LMWL has a slope of 3.186 and an intercept of +22.98, substantially lower than the GMWL slope of ~ 8 . This reduced slope reflects significant evaporative enrichment of groundwater. Most groundwater samples in October cluster between -4‰ and -7‰ in $\delta^{18}O$ and show δD values that place them well below the GMWL. This suggests that the recharging water has undergone evaporation before percolation into the aquifer. Notably, enriched wells such as 3, 20, 30, and 37 show relatively high $\delta^{18}O$ and δD values, suggesting influence from evaporated surface sources or urban runoff. In contrast, Kaylana Lake (sample 35) appears much more depleted, around -8‰ in $\delta^{18}O$ and -50‰ in δD , and is clearly isolated from the groundwater cluster, indicating minimal direct interaction with the aquifer.

In February, the LMWL slope increases to 4.626, with an intercept of -11.85 . This higher slope compared to October indicates reduced evaporation influence, likely due to cooler climatic conditions. The groundwater samples are slightly closer to the GMWL, suggesting recharge with less evaporative enrichment during this season. Still, several wells continue to show enriched signatures, and Kaylana remains isotopically distinct. This reinforces the pattern that the lake is not directly recharging the aquifer.

The June plot, representing the hot, dry pre-monsoon season, shows the lowest LMWL slope at 2.746 with an intercept of +22.20, indicating the strongest evaporation effect among the three months. Groundwater samples exhibit pronounced isotopic enrichment, with values deviating furthest from the GMWL. Enriched wells such as 3, 20, 27, and 30 are once again evident, pointing to recharge from surface water sources subjected to evaporation. Kaylana Lake continues to remain isotopically depleted and distinct, confirming the absence of direct lake-aquifer connectivity.

Overall, the isotopic patterns across the three seasons show consistent deviation from the GMWL and the formation of evaporation lines, confirming that groundwater recharge in Jodhpur is significantly affected by evaporated water sources, likely including urban runoff, wastewater, and delayed infiltration.

7.3 Spatial Patterns and Recharge Sources interpretations

The persistent isotopic separation between Kaylana Lake and groundwater wells across all seasons further supports the conclusion that Kaylana is not a major contributor to the groundwater system. Instead, local precipitation, surface evaporation, and anthropogenic sources dominate the recharge regime.

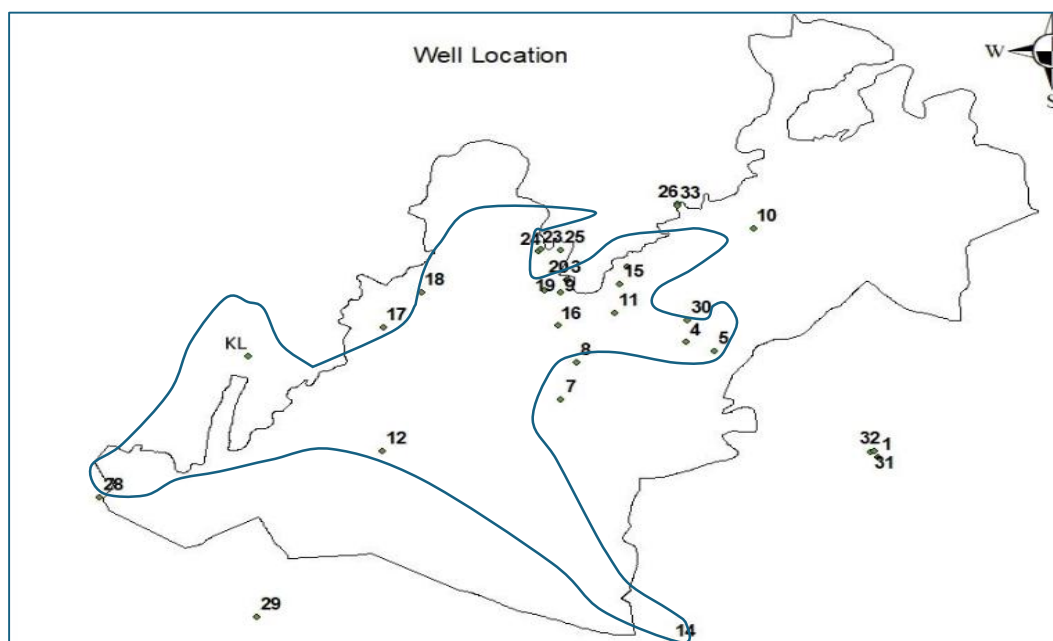


Figure 7.4 Spatial Patterns and Recharge Source Interpretations

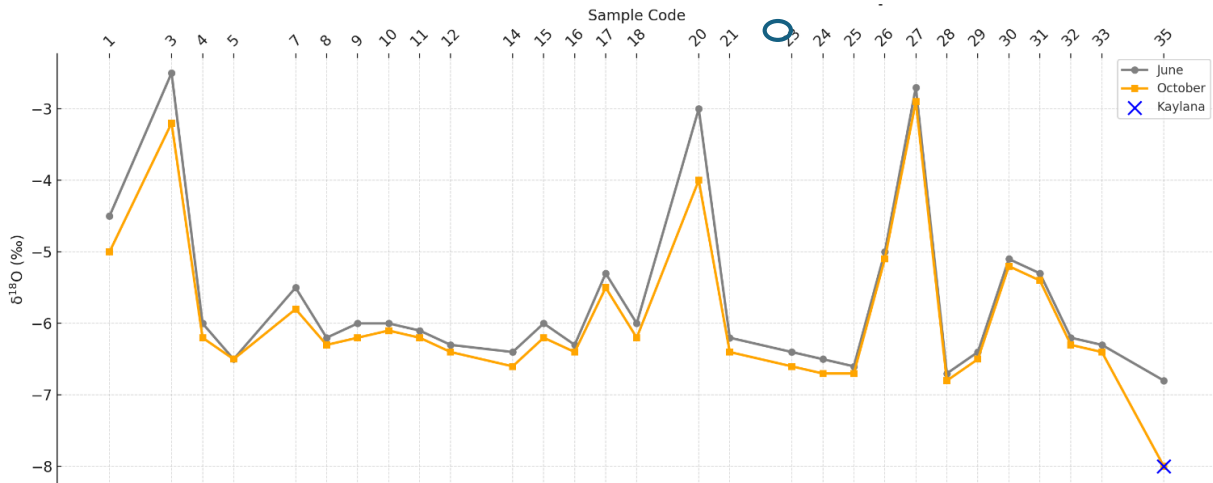


Figure 7.5 Seasonal variation on $\delta^{18}\text{O}$ ground water samples

Measurements from groundwater wells across seasons—particularly October and June—reveal notable spatial and temporal variability. Few groundwater samples show $\delta^{18}\text{O}$ values ranging from -4‰ to -7.5‰ , while Kaylana Lake (sample KL-35) consistently displays more depleted values (-6‰ to -8‰), indicating mixing with relatively fresh sources such as monsoon rainfall or canal water.

Despite the lake's proximity to several wells, their isotopic compositions are distinct, suggesting minimal direct recharge from the lake. This is especially evident in wells 3, 17, 20, 27, 30, and 37, which exhibit enriched $\delta^{18}\text{O}$ values (above -5‰), likely influenced by evaporation from urban runoff, wastewater, or surface ponds. Conversely, a smaller group of wells—such as 5, 8, 11, 14, 16, 21, 24, and 28—exhibit depleted signatures indicative of relative recharge or water mixing shown in graph. Such recharged water would bear an altered isotopic signature distinct from both the lake and rainfall.

Although some enriched wells are situated close to Kaylana Lake, their $\delta^{18}\text{O}$ values remain isotopically distinct. This further confirms that direct seepage from the lake into the aquifer is minimal. However, indirect influence via urban water distribution systems cannot be dismissed. Lake water used for domestic supply may infiltrate the shallow aquifer through leaky pipelines, sewers, or soak pits, particularly after undergoing evaporation.

Spatial distribution patterns confirm that wells with depleted isotopic values (-6‰ to -8‰ $\delta^{18}\text{O}$) align with zones of rainfall or canal recharge, whereas enriched wells correspond to urban and agricultural areas influenced by surface water exposure and anthropogenic return flows. Importantly, geographic proximity to the reservoir does not correlate with isotopic similarity, underscoring that physical closeness does not imply hydrological connectivity.

The consistency of isotopic separation between groundwater and lake water across seasons strengthens this interpretation. While groundwater shows relatively stable isotopic compositions throughout the year, only a slight enrichment is observed during the dry pre-monsoon period (June), likely due to evaporation. In contrast, Kaylana's values show minor seasonal depletion following monsoon inflow but remain isotopically distinct from nearby wells. This limited seasonal co-variation further suggests a lack of direct hydrological connectivity between the reservoir and the groundwater.

Scatter plots of δD versus $\delta^{18}O$ for all three seasons support these findings. Groundwater samples consistently deviate from the Global Meteoric Water Line (GMWL), forming Local Meteoric Water Lines (LMWLs) with shallower slopes—approximately 3.2 in October, 4.6 in February, and 2.7 in June. These slopes, well below the GMWL's value of ~ 8 , indicate isotopic enrichment from evaporation prior to infiltration. Kaylana Lake, in contrast, remains near the GMWL, highlighting its relatively fresh and less evaporated nature.

7.4 Isotopic Enrichment and Electrical Conductivity

Further support comes from the relationship between $\delta^{18}O$ and electrical conductivity (EC). Groundwater samples with EC values exceeding 2000 $\mu S/cm$ tend to be isotopically enriched, suggesting evaporation and salinity buildup. In contrast, samples with EC below 1000 $\mu S/cm$ show more depleted, fresher signatures, while those in the intermediate range likely reflect moderate evaporative influence.

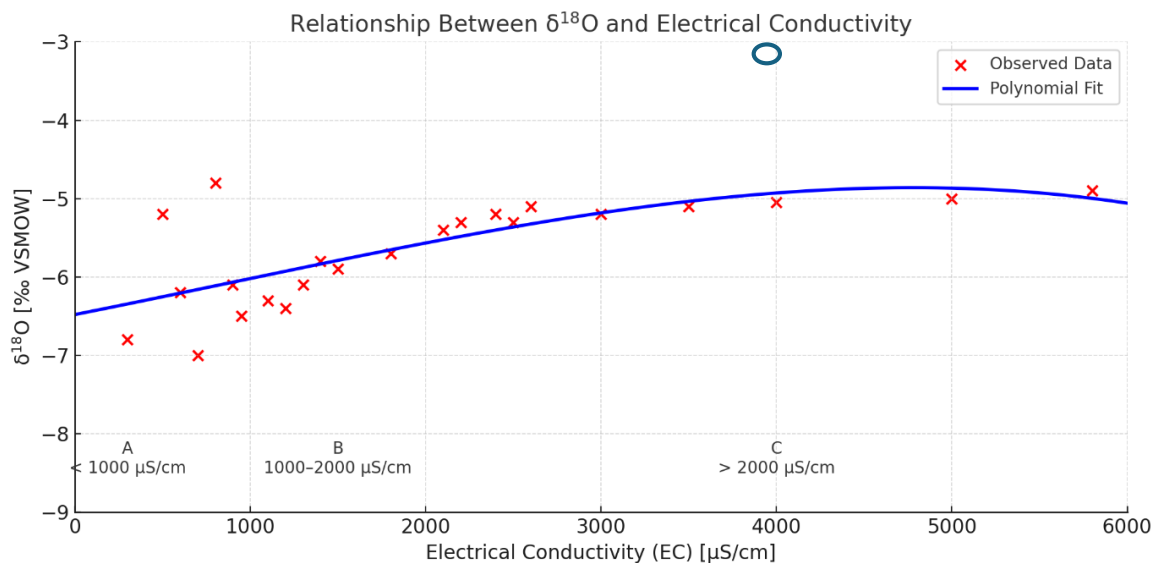


Figure 7.6 Variation on $\delta^{18}O$ with EC for different ground water samples

Kaylana Lake remains isotopically distinct across all seasons, with more depleted $\delta^{18}\text{O}$ values (-6‰ to -8‰) and consistently low electrical conductivity (EC) of $300\text{--}400\ \mu\text{S}/\text{cm}$. This suggests minimal direct hydraulic connectivity with the surrounding aquifer. Further support comes from the relationship between $\delta^{18}\text{O}$ and EC, where groundwater samples with $\text{EC} > 2000\ \mu\text{S}/\text{cm}$ show enriched $\delta^{18}\text{O}$ values—indicative of evaporation and salinity accumulation—while samples with $\text{EC} < 1000\ \mu\text{S}/\text{cm}$ show depleted, fresher isotopic signatures, characteristic of recent or unaltered recharge.

This spatial and seasonal isotopic divergence, combined with the lake's isotopic stability, points to local rainfall, wastewater percolation, leaky distribution networks, and return flows from irrigation or greywater as the dominant recharge sources. These findings align with earlier assessments by NGRI Hyderabad and NIH, 2011 report. which also concluded that seepage from Kaylana or Takhat Sagar into the aquifer is negligible. Instead, rising groundwater levels in waterlogged zones are more likely the result of urban water losses and poorly drained built environments, particularly in areas with shallow water tables and hard rock terrain.

7.5 Hydro chemical Insights from Piper Diagram

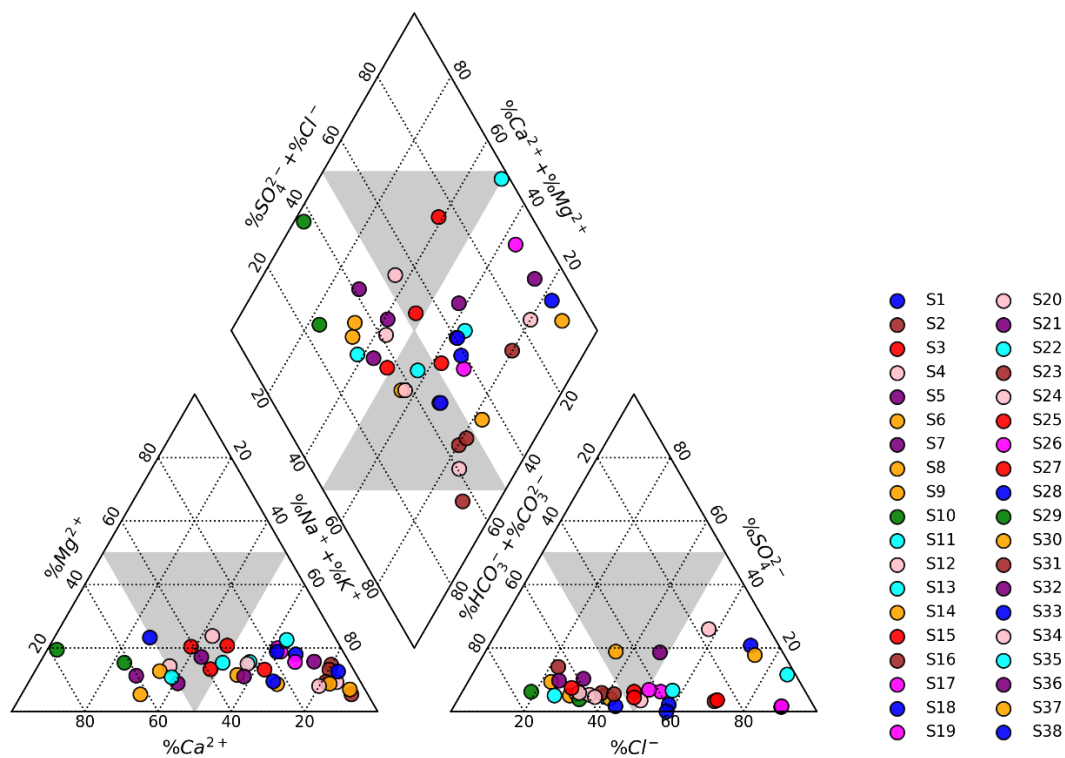


Figure 7.7 Piper diagram for different observed ground water samples

The Piper diagram representing 38 groundwater samples from Jodhpur provides valuable insight into the region's hydrochemical character. The left triangle of the plot, which shows the distribution of major cations, reveals the dominance of sodium (Na^+) and potassium (K^+) ions. Most of the samples cluster toward the $\text{Na}^+ + \text{K}^+$ apex, with comparatively fewer samples indicating calcium (Ca^{2+}) or magnesium (Mg^{2+}) dominance. This pattern is consistent with saline or mineralized groundwater commonly observed in arid regions like Jodhpur, where prolonged water-rock interaction and high evaporation rates elevate sodium concentrations.

In the anion triangle (right), the samples predominantly align toward the chloride (Cl^-) and sulfate (SO_4^{2-}) corners, while bicarbonate (HCO_3^-) and carbonate (CO_3^{2-}) levels appear comparatively lower. This reflects a typical chemical signature of older or evaporated groundwater with little influence from fresh recharge sources such as rainfall or surface water. The central diamond, which integrates both cationic and anionic compositions, further confirms that the majority of the samples belong to the $\text{Na}^+ - \text{Cl}^- - \text{SO}_4^{2-}$ water type. This hydrochemical facies is characteristic of brackish to saline groundwater, shaped by natural salinization processes, anthropogenic influences, and limited freshwater inflow.

Given this chemical profile, there is no evidence to suggest any significant contribution of freshwater from surface bodies like Kaylana Lake into the groundwater system. If leakage or recharge from Kaylana Lake were occurring, at least some groundwater samples would be expected to show a $\text{Ca}^{2+} - \text{HCO}_3^-$ type signature, indicative of recent recharge from freshwater sources. However, such a pattern is entirely absent in the current Piper plot. The dominance of sodium and chloride ions, coupled with the lack of bicarbonate-rich samples, strongly suggests that the lake is not influencing the city's groundwater — at least not in any measurable or sustained manner.

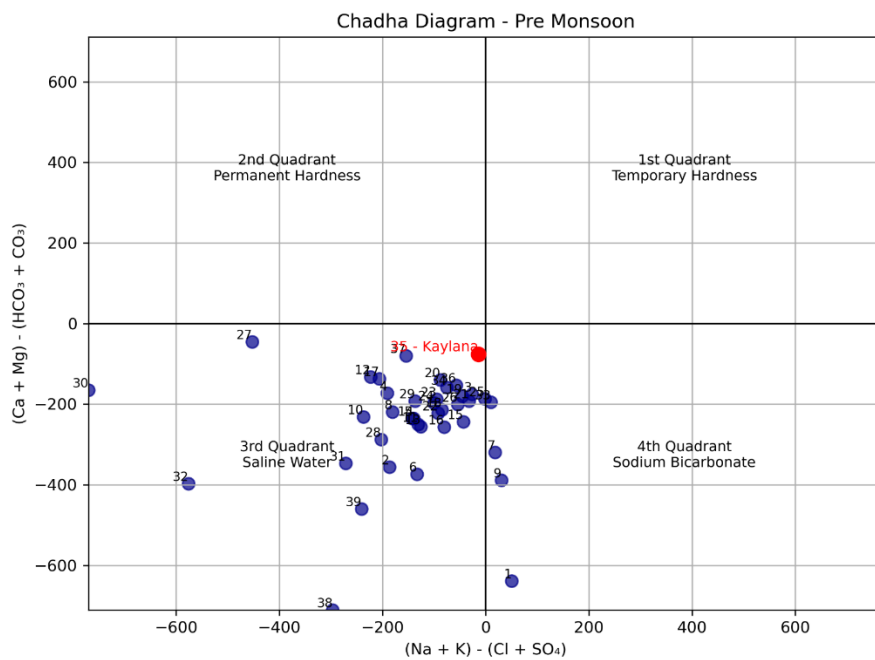
The hydro chemical evidence presented in the Piper diagram points to a groundwater system largely influenced by evaporation, mineralization, and possibly anthropogenic sources, with no indication of dilution or freshening due to leakage from Kaylana Lake. This finding reinforces the need for careful management of existing groundwater resources and consideration of artificial recharge strategies to mitigate the impacts of salinity and declining water quality in Jodhpur. Given this chemical profile, there is no evidence to suggest any significant contribution of freshwater from surface bodies like Kaylana Lake into the groundwater system. If leakage or recharge from Kaylana Lake were occurring, at least some groundwater samples would be expected to show a $\text{Ca}^{2+} - \text{HCO}_3^-$ type signature, indicative of recent recharge from freshwater sources. However, such a pattern is entirely absent in the current Piper plot. The dominance of

sodium and chloride ions, coupled with the lack of bicarbonate-rich samples, strongly suggests that the lake is not influencing the city’s groundwater — at least not in any measurable or sustained manner.

7.6 Hydrochemical interpretation using Chadha Diagrams

Also, the geochemical analysis of groundwater in the Jodhpur region, using Chadha diagrams for both pre-monsoon and post-monsoon seasons, provides insights into the dominant hydrochemical facies and the influence of natural and anthropogenic factors on groundwater quality.

In both diagrams, Kaylana water sample (Sample 35) consistently falls within the 3rd quadrant, which represents saline water types, characterized by a dominance of chloride (Cl^-) and sulfate (SO_4^{2-}) ions, and comparatively low concentrations of calcium and magnesium.



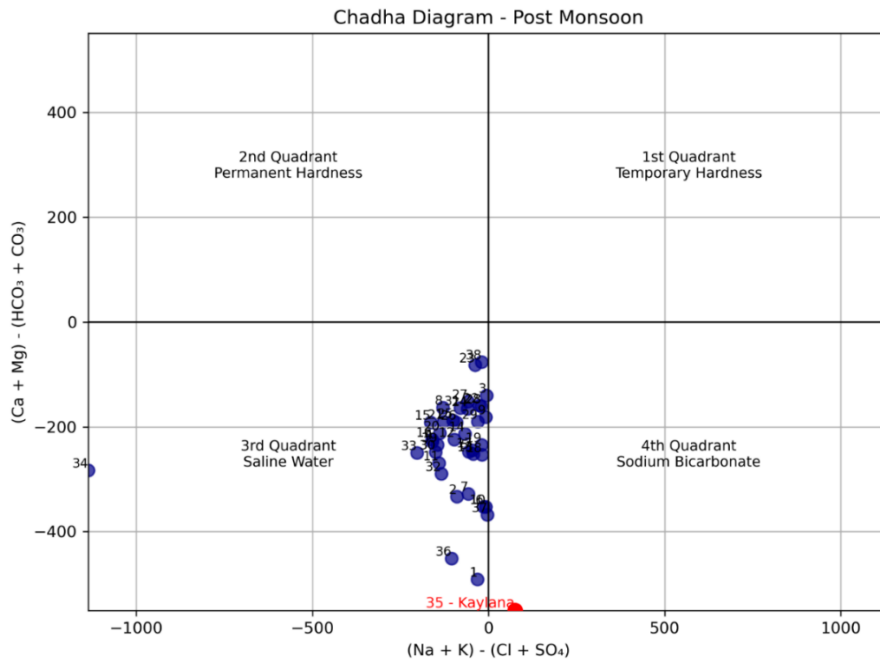


Figure 7.7 Chadha diagram (Pre & Post) for different ground water observations

However, during the pre-monsoon, the sample is positioned close to the origin, suggesting minimal differences in ion concentrations, indicative of fresh or only slightly mineralized water. This reflects a relatively unaltered geochemical signature, possibly influenced by direct recharge or limited anthropogenic impact. It also suggests absence of significant leakage from Kaylana Lake to the urban aquifer, supporting the idea that the lake is not a major source of contamination or mineral loading in nearby wells. In the post-monsoon diagram, the Kaylana sample remains in the same quadrant but shows a shift further into the saline region, likely due to concentration of salts following evaporation or infiltration of anthropogenic runoff during the monsoon season. This seasonal variation points to increased residence time or possible pollution inputs, consistent with patterns observed in arid and semi-arid zones, where groundwater systems are highly sensitive to evaporation and anthropogenic activities such as urban discharge or wastewater percolation.

Together, these observations suggest that while Kaylana water remains largely fresh or moderately mineralized in the pre-monsoon period, post-monsoon changes indicate rising salinity and potential influence from surface processes. The findings reinforce the need for continuous monitoring, especially post-monsoon, to detect shifts due to evaporation, runoff, or human-induced recharge, and highlight the critical role of source protection and wastewater management in maintaining the quality of groundwater in urban settings like Jodhpur.

7.7 Integrated Interpretation and Management Implications

The integrated isotopic and hydro chemical analysis strongly indicates that groundwater in Jodhpur is predominantly influenced by local recharge, evaporation, soil salinity, and anthropogenic return flows, rather than by direct seepage from nearby reservoirs such as Kaylana Lake. Seasonal δD vs. $\delta^{18}O$ scatter plots for October, February, and June consistently show groundwater samples deviating from the Global Meteoric Water Line (GMWL), forming Local Meteoric Water Lines (LMWLs) with shallow slopes—a signature of evaporative enrichment before infiltration. The strongest evaporation effect is observed in June (pre-monsoon), while February samples display fresher isotopic characteristics due to cooler temperatures and reduced evaporation.

Additionally, the limited seasonal variability in the aquifer's isotopic signature—despite dynamic surface water conditions—indicates a relatively slow aquifer response to short-term changes, further supporting the lack of active lake-aquifer interaction. These results also emphasize the sensitivity of Jodhpur's groundwater to climate factors like high evapotranspiration and rainfall variability, which are expected to intensify under future climate change scenarios.

CHAPTER 8: WATER BALANCE STUDY

8.1 Water Balance Equation

The following water balance equation used in the study accounts for all major inflows, outflows, and internal fluxes affecting urban groundwater storage, enabling assessment of hydrological sustainability.

$$\Delta G = P_r + Q_{sw} + R_{gw} + R_{rf} + L_{dist} - W_c - Q_{ro} - Q_{sd} - Q_{gw} - ET$$

Where:

- ΔG – Change in groundwater storage (MCM/year)
- P_r – Precipitation over the urban area (MCM/year)
- Q_{sw} – Surface water inflow (e.g., from Kaylana Reservoir) (MCM/year)
- R_{gw} – Direct groundwater recharge from rainfall infiltration (MCM/year)
- R_{rf} – Return flow from domestic use, sewer leakage, soak pits, etc. (MCM/year)
- L_{dist} – Losses in the water distribution system (leakage, unaccounted water) (MCM/year)
- W_c – Consumptive use in domestic, commercial, and small industrial sectors (MCM/year)
- Q_{ro} – Surface runoff generated during rainfall events (MCM/year)
- Q_{sd} – Discharge to sewerage (treated or untreated) (MCM/year)
- Q_{gw} – Groundwater abstraction or pumping (MCM/year)
- ET – Evapotranspiration losses from surface, vadose zone, and shallow aquifer (MCM/year)

8.2 RGLC Inflow

Since 1997, the city's water supply has transitioned from a mix of surface and groundwater to an entirely canal-dependent supply system in order to meet the rising demand. The water imported from the Rajiv Gandhi Link Canal (RGLC) is stored in the Kaylana- Takhatsagar Reservoir, from where it is pumped by Public Health Engineering Department (PHED) into the city. (Gupta, 2007). The information of RGLC supply to Jodhpur is given in Table-4.

Table 4: Rajeev Gandhi Link Canal Rural & Urban water supply information

Month	RGLC_Rural_Supply (ML)	RGLC_Urban_Supply (ML)	RGLC_Total (ML)
2023-10	2838.2	10390.6	13228.8
2023-11	2641	10097.9	12738.9
2023-12	2712.2	9500.8	12213
2024-01	2805.8	9794.3	12600.1

2024-02	2426.7	8501.2	10927.9
2024-03	2671.53	9807.81	12479.34
2024-04	3043.75	10820.3	13864.05
2024-05	3145.59	12009.63	15155.22
2024-06	2967.96	13172.58	16140.54
2024-07	2878.14	13725.56	16603.7

Table 1: RGLC Supply data (ML - Million Litres)

8.3 Groundwater Draft

The total groundwater draft from 191 significant discharge generated wells in the city (Figure 8.1) has been calculated using data supplied by PHED, 2024, the details of wells given in appendix C. Total draft of the city is currently 43.90 MLD.

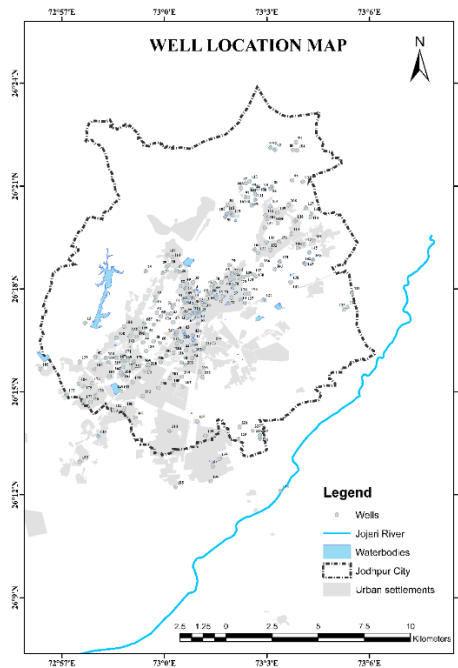


Figure 8.1: Pumping Well location in Jodhpur City

8.4 Rainfall contribution

For calculation of rainfall the following equation is used: -

$$P = \text{Area of City} \times \text{Rainfall Depth}$$

8.5 Sewage Discharge analysis

Sewage discharge data has been analysed from major urban drainage outfalls in Jodhpur city, including Salawas, Sangariya, and the Airport (Air Force) area, revealing a combined daily

outflow of approximately 130 MLD (Million Litres per Day). This estimation is based on hydrograph-based discharge monitoring and corroborated with flow records obtained from the Nagar Nigam Office, Jodhpur South Region.

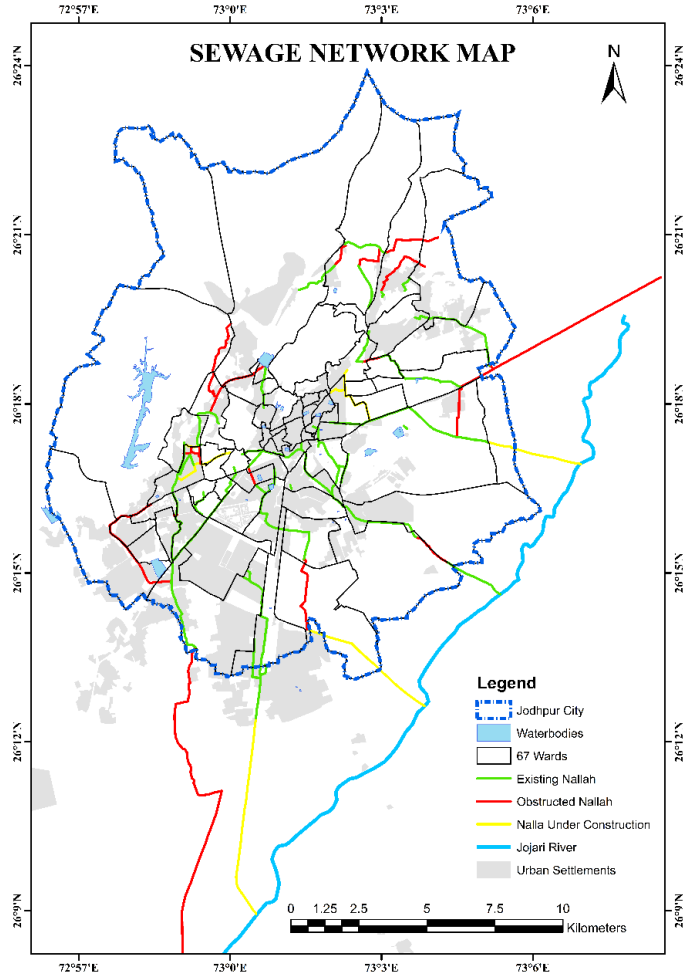


Figure 8.2: Sewage network of Jodhpur



Figure 8.3: Field observation photograph for discharge measurement

Figure8.3: Field observation photograph for discharge measurement

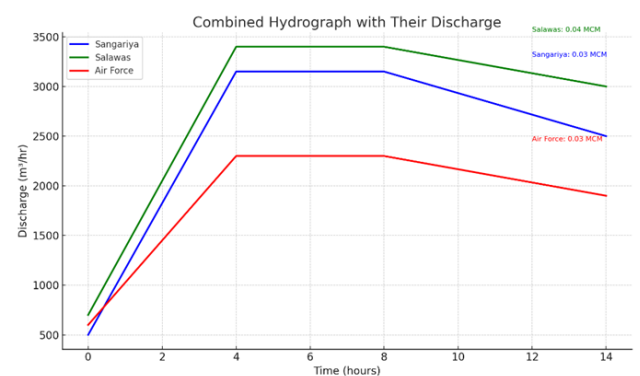
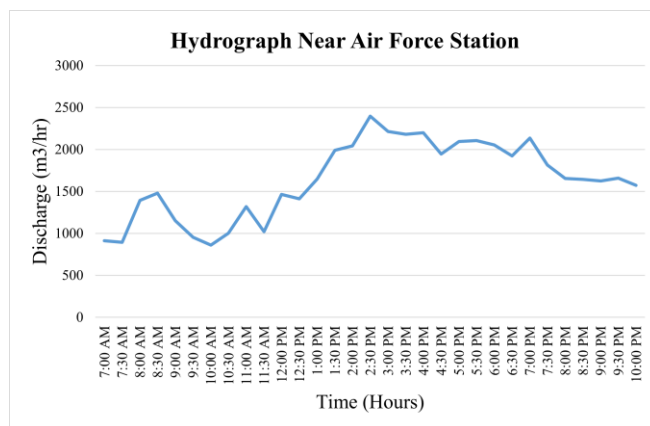
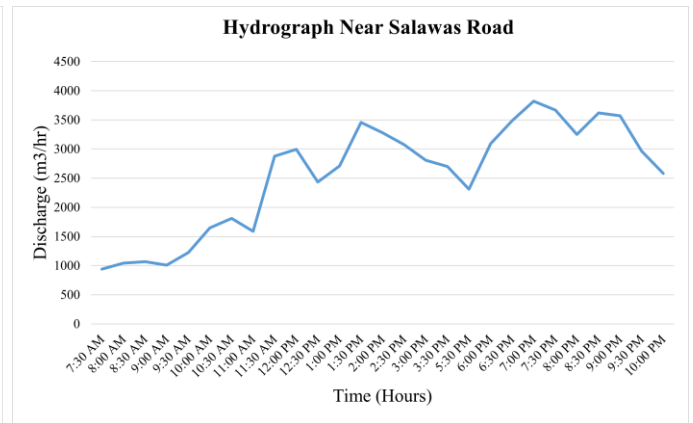
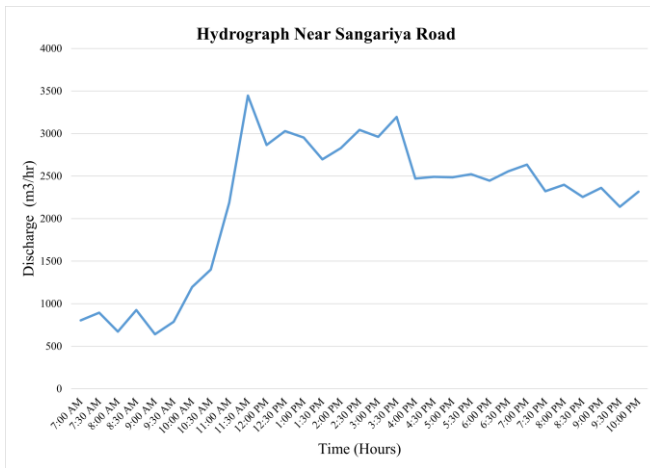


Figure 8.3: Observed Drainage hydrographs for Different measured sites

8.6 Surface Runoff

Surface runoff is the rainwater that flows over the ground surface instead of being absorbed by the soil. It can happen due to excess rainfall or storm phenomenon etc. Surface runoff calculation method is adopted from “Study on Rising Groundwater Table in Jodhpur City – NIH (2011)”. According to the report 40% of the rainfall is considered as immediate Evaporation, remaining 60 % characterizes runoff, infiltration, interception, depression storages, etc. Assuming 15 % of the rainfall as the interception and depression storage, and 15% as the infiltration rate. Runoff can be estimated using the following equation: -

$$R_s = (100\% - 40\% - 15\% - 15\%) \times (P)$$

8.7 Groundwater Recharge

Ground water recharge was evaluated from water fluctuation method using temporal observed water level data and specific yield of aquifer.

8.8 Evapotranspiration

Evapotranspiration data is obtained from (Goyal, 2004). The Modified Penman method (MPM) is used to estimate the monthly evapotranspiration over the study area.

Table 5: Monthly variation Evapotranspiration in Jodhpur city

Month	Avg. ET
1	115.8
2	155.3
3	207
4	245.6
5	297.2
6	330.8
7	194.9
8	190.3
9	229.9
10	180.4
11	112.1
12	127.2

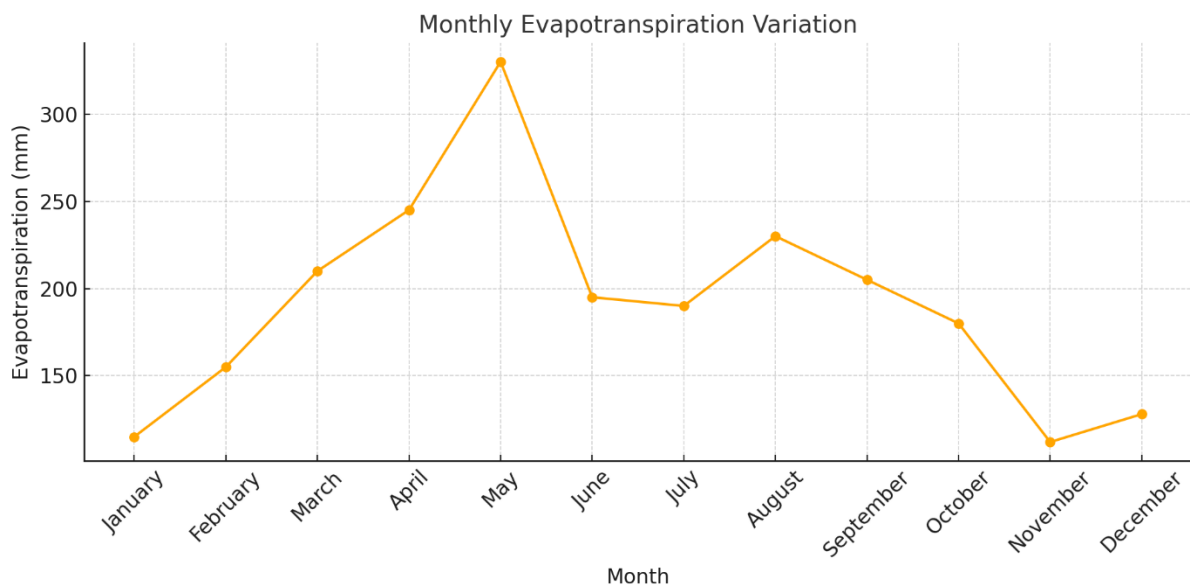


Figure 8.3: Seasonal variation of Evapotranspiration for Jodhpur city

8.9 Human Consumption

As per the National Census of India 2011, Jodhpur city had a population of 10, 33,756, which has grown up to around 15, 87,000 by 2024. This population projection is calculated by considering the population growth rate of 3.21% each year from 2011 onwards.

The latest guidelines and recommendations from the Ministry of Housing and Urban Affairs puts the daily urban human water supply at 140 litres per capita per day (LPCD).

8.10 Key inferences from Water balance study

The water balance system plot (Figure 8.4) shows the monthly variation of inflow, outflow and storage. This study shows that during the summer months the city is receiving adequate water as shown in the plot, however due to constraints of the sewage network, the outflow is not being directed to the Jojari River, and instead it is recharging the surface water bodies and aquifers.

Based on this water balancing study, a more realistic and useful water balance system can be developed with the availability of real time high frequency datasets which can be calibrated and validated to simulate real world conditions.

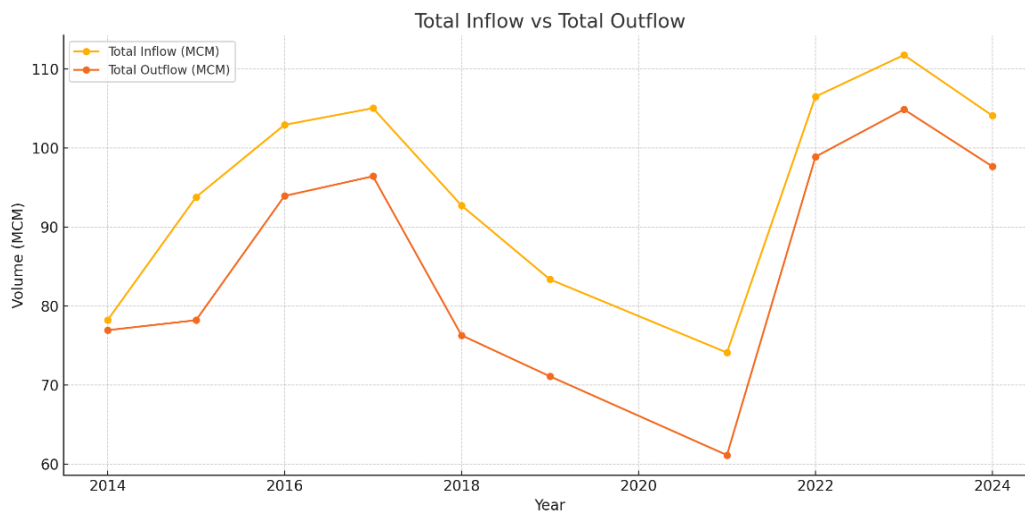


Figure 8.4: Comparison of total inflow with total outflow

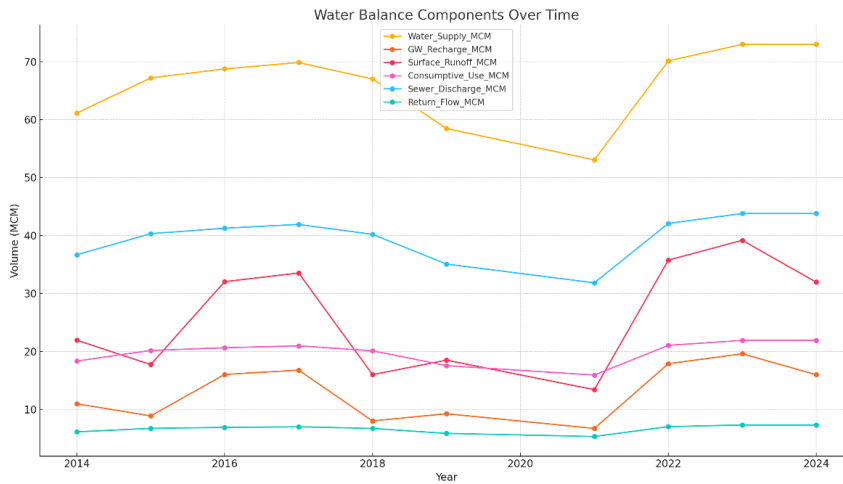


Figure 8.5: Comparison of Different water balance component with time

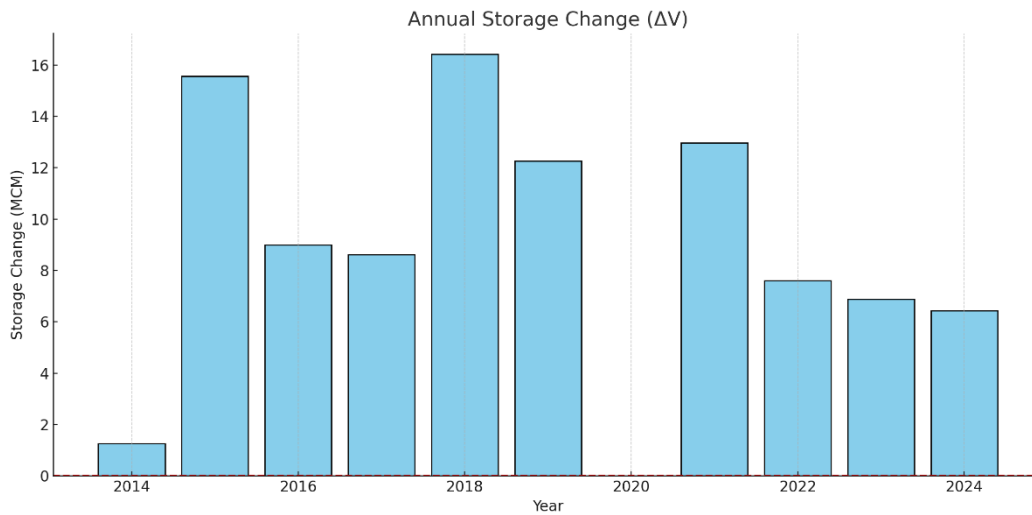


Figure 8.6: Variation of Storage change with respect to time

The decadal water balance assessment for Jodhpur city (2014–2024) provides a comprehensive understanding of the dynamics between urban water supply, recharge, runoff, and drainage, and reveals a critical linkage to the persistent waterlogging problem, particularly in the central parts of the city. As illustrated in Figure 8, the system exhibits considerable seasonal and inter-annual variability in inflows, outflows, and storage, largely influenced by rainfall patterns, water usage, and infrastructure performance.

Throughout the study period, the city has consistently received a substantial volume of water, with annual supply figures ranging from approximately 53 to 73 million cubic meters (MCM). Simultaneously, surface runoff and sewer discharge have remained high, reflecting the city’s low permeability and dense urbanization. However, due to inadequate or poorly connected sewer and

stormwater networks, much of the generated runoff and sewage does not reach the intended outfall—the Jojari River—but instead stagnates or infiltrates into surface water bodies and shallow aquifers within urban areas. This situation is most acute in the central zones of Jodhpur, which are characterized by low-lying terrain, legacy infrastructure, and high population density.

The groundwater recharge and sewer discharge components of the water balance provide strong evidence of this issue. In recent years, sewer discharge volumes have exceeded 40 MCM annually, yet a significant portion of this volume does not exit the system efficiently. Instead, it contributes to localized recharge and saturation, causing the groundwater table to rise alarmingly. In the core urban areas, groundwater levels are now frequently observed within 1 to 2 meters of the surface, creating persistent waterlogging, structural damage to buildings, and public health challenges.

These observations are supported by modeled storage changes and return flow data, which show that even in years with moderate rainfall, such as 2022 and 2024, the imbalance between inflow and effective drainage results in net positive storage—indicating rising groundwater levels. This unintentional and unregulated recharge from leakage, return flows, and surface accumulation acts as a driver of chronic waterlogging in central Jodhpur.

To address this, several hydrologically-informed interventions are recommended. Vertical drainage systems, using controlled groundwater pumping where the water table lies within 3 meters of the surface, can help draw down excess storage and mitigate saturation. Reconnection and expansion of the sewer and stormwater networks are also critical to ensure that inflows are routed towards natural drains such as the Jojari River or artificial recharge zones.

In conclusion, the water balance analysis reveals that while Jodhpur receives an adequate water supply, the mismatch between inflow, storage, and outflow—exacerbated by infrastructural limitations—has created a condition of hydrological stress in central and northern areas. The rising water table, combined with poor drainage, has led to long-term waterlogging. Addressing this issue will require an integrated approach that combines improved drainage infrastructure with groundwater management strategies and calibrated modeling tools.

Table 6: water Balancing of Jodhpur city

Year	Water Supply to City Volume (MCM)	Groundwater Recharge Volume (MCM)	Surface Runoff Volume (MCM)	Consumptive use	Sewer discharge (MCM)	Return Flow	Total Inflow (MCM)	Total Outflow (MCM)	Net Storage(MCM)
2014	61.12	10.96	21.93	18.34	39.728	14.6688	86.7488	79.998	6.7508
2015	67.19	8.86	17.73	20.16	43.6735	16.1256	92.1756	78.2	13.9756
2016	68.76	16.02	32.03	20.63	44.694	16.5024	101.2824	93.91	7.3724
2017	69.86	16.77	33.53	20.96	45.409	16.7664	103.3964	96.4	6.9964
2018	67.01	7.99	15.99	20.1	43.5565	16.0824	91.0824	76.29	14.7924
2019	58.46	9.24	18.48	17.54	37.999	14.0304	81.7304	71.1	10.6304
2021	53.05	6.7	13.39	15.92	34.4825	12.732	72.482	61.14	11.342
2022	70.14	17.87	35.75	21.04	45.591	16.8336	104.8436	98.87	5.9736
2023	72.99	19.58	39.17	21.9	47.4435	17.5176	110.0876	104.86	5.2276
2024	73	15.98	31.95	21.9	47.45	17.52	106.5	97.64	8.86

CHAPTER 9: GROUNDWATER FLOW MODELLING OF JODHPUR CITY

Groundwater plays a vital role in sustaining urban water supply, especially in arid and semi-arid regions like Jodhpur, Rajasthan. With rapid urban expansion and increasing water demands, understanding the subsurface hydrodynamics through a scientific modelling framework has become imperative. This chapter develops a transient groundwater flow model for Jodhpur City using MODFLOW-6 to quantify aquifer behavior under seasonal recharge and urban pumping. The model integrates DEM-derived topography, a layered hydro stratigraphic framework, and mapped PHED well operations, and is run over multi-year stress periods to capture monsoon and post-monsoon dynamics. Calibration against observation-well hydrographs employs a compact parameter set (hydraulic conductivity, storage, recharge, and a pumping multiplier) with objective metrics including RMSE, NSE, R^2 , and bias. Outputs—head maps, hydrographs, and mass-balance diagnostics—are exported alongside iteration logs to ensure full reproducibility and decision-grade transparency. The resulting tool supports scenario testing for waterlogging mitigation, managed aquifer recharge, and grid-wise abstraction planning across Jodhpur’s urban and peri-urban zones.

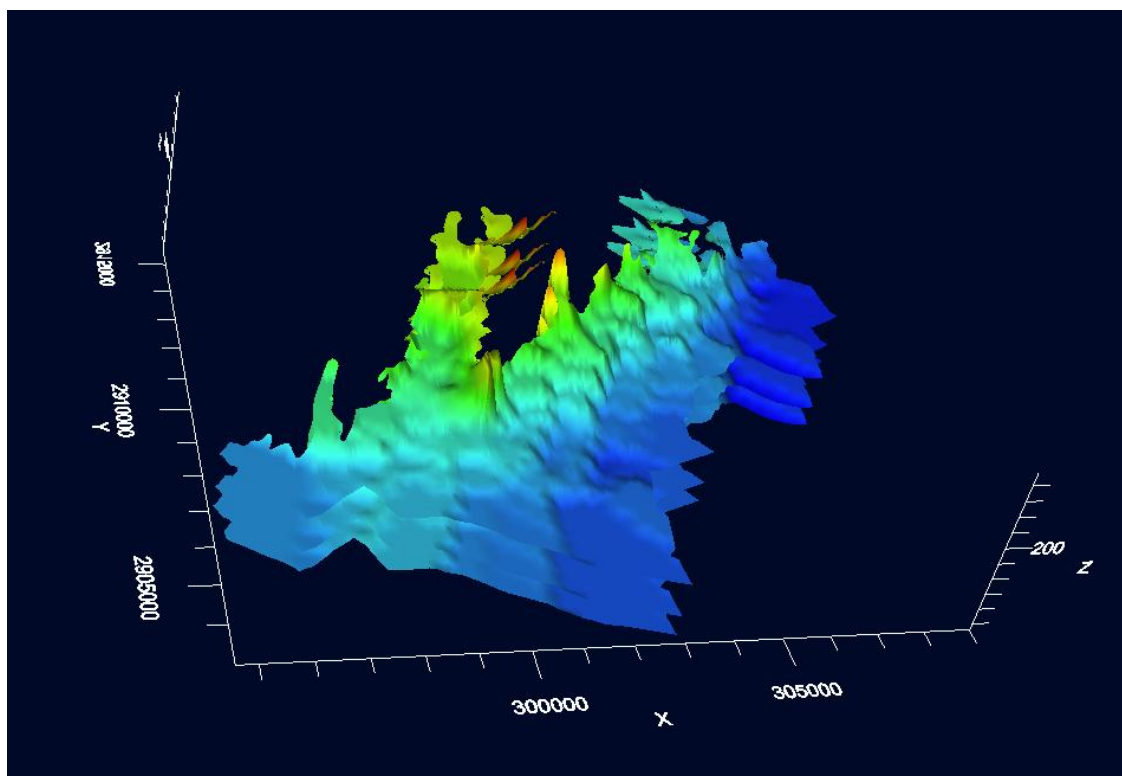


Figure 9.1: 3-D ground water layer view of Jodhpur city

9.1 Model Grid discretization and Domain Setup

The groundwater model was developed in MODFLOW to simulate three-dimensional flow beneath Jodhpur City. A representations of 3-D layers given in Figure 9.1. The study area was represented by a structured, rectilinear grid sized 72 columns \times 62 rows \times 3 layers, with 200 m \times 200 m cells, yielding 4,824 active cells over a model footprint of about 178.56 km². The domain was defined from the project boundary and mapped in UTM Zone 43N (EPSG:32643) to preserve distances and areas. Surface elevations used to shape the upper model surface (TOP) were derived from the ALOS PALSAR digital elevation model; where necessary, minor gaps were conservatively infilled to avoid artificial breaks in layer geometry. The boundary of the project area was used to deactivate fringe cells outside the polygon, ensuring numerical stability while keeping the interior grid fully regular. Locations of production and observation wells were positioned at their corresponding grid cells, and time-varying stresses (recharge and pumping) were applied at the same spatial resolution. This discretization provides a clear, decision-grade spatial framework for assigning hydrologic inputs and boundary conditions, supporting reliable simulation of heads and fluxes across the basin.

9.2 Input Data and Aquifer Characterization

Primary inputs comprise the ALOS PALSAR DEM, PHED pumping-well locations with time-varying discharges, and observation-well head time series used for calibration/validation. Secondary sources include lithological logs/descriptions (Figure 9.2), aquifer-test syntheses (GSI/NIH,2011), and formation-level priors for porosity, Sy, Ss, and transmissivity (T). All tables were standardized to a common schema; observation timestamps were mapped to 15-day stress periods, and PHED abstractions were Spatio-temporally located and unit-checked. The model inputs are summarized below.

Table 7. Input datasets and their role in the model

Dataset	Source	Resolution (Spatial / Temporal)	Role in Model
Domain boundary	Digitized city map	Polygon / static	Defines active domain (IDOMAIN)
DEM (ALOS PALSAR)	ALOS (12.5 m)	Raster / static	Surface elevation (TOP); informs layering

Observation wells	SGWB / CGWB	Points / 15-day	Calibration & validation targets
Pumping wells	PHED	Points / daily → 15-day SPs	Time-varying WEL stresses (Q)
Lithology & tests	Satellite / GSI / NIH,2011	Points/lines / static	Priors for NPF (K) and STO (Sy, Ss)
Recharge inputs	Rainfall / Water-Table Fluctuation (WTF)	Areal field / 15-day	RCH boundary condition (calibrated scale)

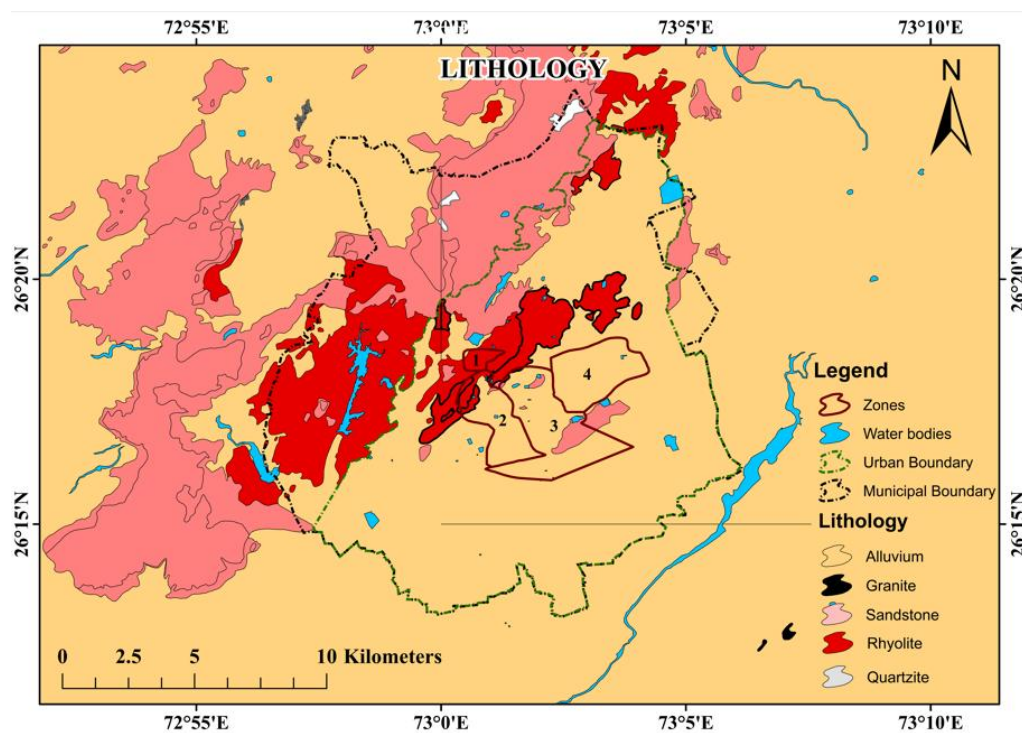


Figure 9.2: Lithology of Jodhpur city

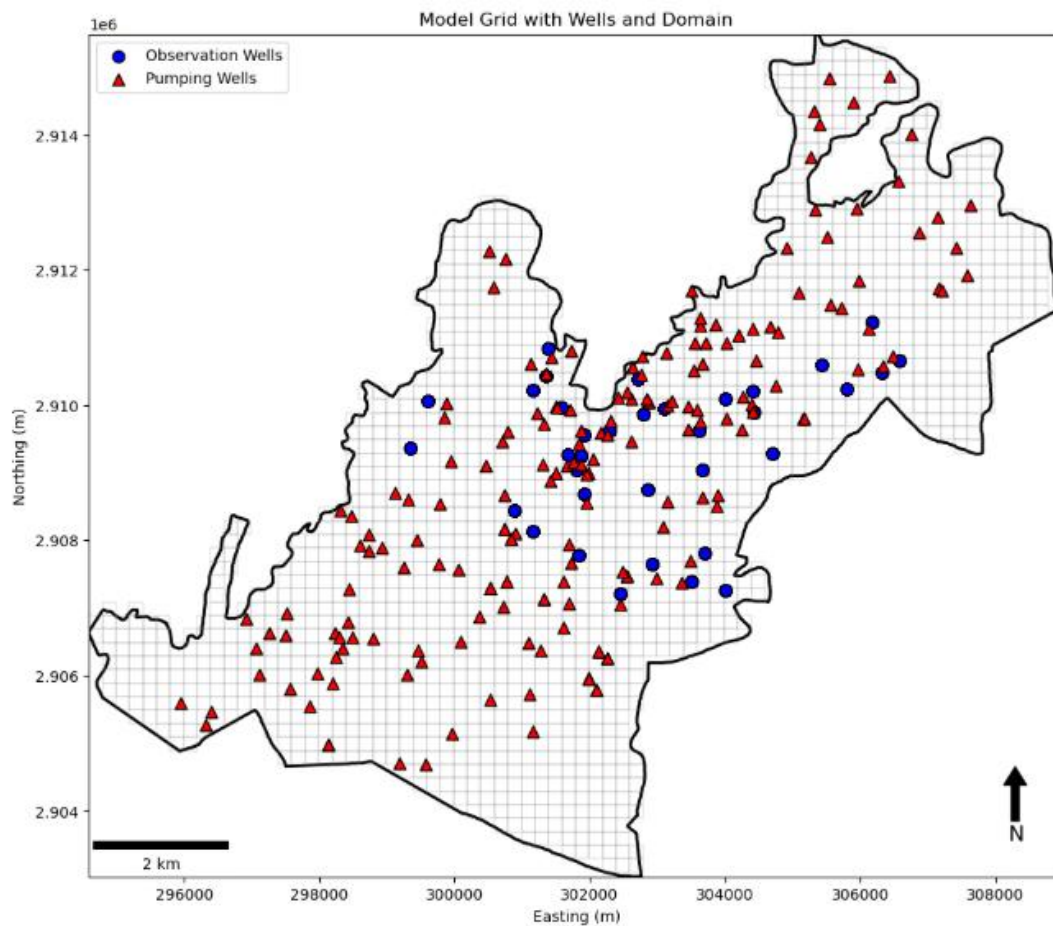
9.3 Hydrogeological Framework and Lithological Simplifications

Given the geological complexity of Jodhpur, a stratified representation was implemented in the model. To balance realism and parsimony, the model represents a five-unit sequence as given in table 8.:

Table 8: Hydrogeological framework of Model

Conceptual Unit	Typical depth (approx.)
Alluvium (unconfined)	0–18 m
Sandstone (unconfined)	18–30 m
Shale (unconfined)	30–40 m
Deeper consolidated (transition)	40–50 m
Rhyolite basement (base rock)	> ~50 m

This simplified but realistic hydro stratigraphy preserved key geologic controls while ensuring computational feasibility and efficient simulation.

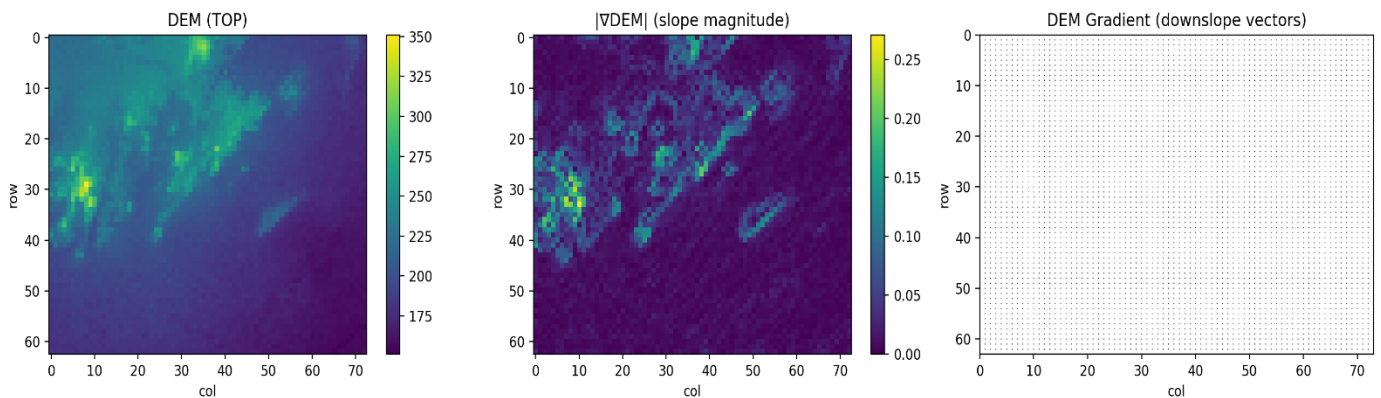


9.4

Figure 9.3: Observation and Pumping wells location in model domain

9.4 MODFLOW Setup

The simulation covers 2013–2023 using uniform 15-day stress periods (~24 per year). The aquifer is represented with five numerical layers (four active layers over a no-flow basement). Time-varying abstraction from 191 mapped PHED wells is applied each stress period, and 37 observation wells provide calibration and validation control (see Figure 9.3). A structured grid layered hydraulic properties, unconfined storage in the upper unit with convertible storage below, spatially distributed recharge, optional evapotranspiration from the top layer, and head-gradient-driven lateral exchange along selected boundaries together reproduces seasonal rises and dry-season drawdowns. Initial heads are set from pre-monsoon conditions and clipped to local layer bounds to avoid non-physical starts. Numerical tolerances are set conservatively with sufficient iteration caps to ensure stable convergence through wetting and drying, yielding reproducible heads, budgets, and observation time series for analysis. Following Figure 9.4 is



DEM derived top surface and gradient on grids discretized for Ground water model.

Figure 9.4: Model top derived from DEM and discretized gradient Map

9.4.1 Initial Head and Boundary Conditions

Initial groundwater levels were set to a pre-monsoon 2013 surface compiled from observation wells and, where needed, interpolated surfaces. To ensure a stable start, these levels were gently constrained between the local land surface and the top of the underlying layer, so the shallowest unit begins saturated where appropriate without creating artificial ponding or dry cells.

Boundary conditions mirror the basin’s hydrologic setting and are designed to preserve mass balance:

- Areal recharge (top boundary): Infiltration from rainfall and urban runoff is applied to the shallowest unit as a temporally varying rate informed by climate and land-use. A

single calibration factor adjusts this field to reflect regional uncertainty without imposing unrealistic spatial detail.

- Groundwater abstraction (internal sinks): Time-varying pumping is assigned to the mapped public-supply wells for each 15-day period. A global scaling factor is co-estimated during calibration to account for operational or reporting uncertainty; this can be refined by zone if future data warrant.
- Lateral inflow/outflow (side boundaries): Along selected edges of the model where regional gradients indicate exchange with adjacent areas, a head-driven formulation allows water to enter or leave the domain in proportion to the difference between internal and external water levels and the effective boundary conductance. This reproduces the behavior of a specified-flux boundary while remaining numerically robust.
- No-flow limits (perimeter and basement): The remaining perimeter is treated as hydraulically closed where connectivity is not supported (e.g., divides, bedrock highs, or administrative limits). The deepest layer functions as an impermeable floor.

Together, these choices let the model respond realistically to seasonal recharge pulses, spatial patterns of abstraction, and edge exchanges dictated by regional gradients, producing stable and interpretable heads and fluxes over 2013–2023 at a 15-day cadence.

9.4.2 Aquifer Properties and Parameters

The Table-9 summarizes the aquifer properties in Jodhpur. Quaternary alluvium exhibits the highest porosity (0.30) and transmissivity (50–245 m²/day), indicating good groundwater potential. In contrast, rhyolite and shale have low porosity and transmissivity, limiting their storage and transmission capacity.

Table 9: Aquifer Properties and Parameters

Geological Formation	Porosity (-)	Transmissivity, T (m ² d ⁻¹)	Storativity (-)	Notes
Quaternary Alluvium	0.30	50–245	2.71×10^{-4} – 2.337×10^{-1}	Unconfined; highest storage & K
Sandstone	0.27	4.32	3×10^{-4}	Convertible Semi-confined; moderate K
Shale	0.06	10.0	2×10^{-5}	Semi-Confined; low K, low storage
Rhyolite (basement)	0.02	~0–3	3×10^{-5}	Very low K; hydraulic floor

9.4.3 Inflow and Outflow Stresses

Aquifer behaviour is governed by a balanced mix of inflows and outflows that vary across space and time on a 15-day cycle. Inflows are dominated by infiltration from rainfall and urban runoff to the shallow zone, estimated from rainfall–runoff and water-table-fluctuation analyses and gently adjusted during calibration to reflect regional uncertainty. Additional water can enter along selected boundaries where regional gradients drive lateral exchange into the model area. Outflows include groundwater abstraction from mapped public-supply wells (varying through the year), evapotranspiration from shallow groundwater where the water table lies near the surface, and lateral discharge across boundaries where internal water levels exceed those outside. The deepest unit functions as an impermeable floor, preventing leakage to depth. Together, these elements capture monsoon/post-monsoon signals and operational changes while preserving mass balance and producing stable, interpretable heads and budgets. All the Spatio temporal stress considered in model is given in Table 9.5.

Table 9.5 Stress inventory and implementation.

Stress	MF6 package	Direction	Temporal treatment	Notes
Areal recharge	RCH	Inflow	Piecewise-constant over each 15-day SP (m d^{-1})	Derived from hydro-climate inputs
Lateral exchange	GHB	Inflow/Outflow	Computed each SP from head difference	Emulates specified-flux behavior via conductance
Pumping	WEL	Outflow	Time-varying per SP ($\text{m}^3 \text{d}^{-1}$)	PHED schedules;
Evapotranspiration (opt.)	EVT	Outflow	Piecewise-constant per SP	Uniform rate and extinction depth
Basement / perimeter	IDOMAIN (mask)	No-flow	—	Basement inactive; non-GHB edges sealed

9.4. Time Step and Simulation Period

The model runs in transient mode from 2013 to 2023 using uniform 15-day intervals (~24 per year). This choice balances seasonal fidelity with practical runtimes: it resolves monsoon/post-monsoon contrasts without injecting sub-monthly noise from poorly constrained inputs. Rates such as recharge and pumping are expressed on a daily basis and held constant within each interval. Stable numerical settings were adopted to ensure convergence through wetting/drying typical of semi-arid basins. With boundary conditions, aquifer properties, and stresses configured as described earlier, the system consistently reproduces heads and fluxes across the full period for analysis and mapping.

9.5 Simulation Results

The transient run captures the principal features of basin hydraulics over 2013–2023. Maps show higher water levels in recharge-dominated areas and drawdown aligned with production clusters and regional gradients, reflecting the interplay of infiltration, abstraction, and lateral exchange. Hydrographs at observation sites reproduce the seasonal rise from monsoon inputs and the dry-season decline; amplitudes are governed by the calibrated storage terms. Outputs are provided as gridded heads and water-budget summaries, along with a lattice of observation-cell time series for quick plotting (hydrographs, parity plots, and contour overlays). Together,

these diagnostics confirm that both the spatial gradients and temporal dynamics expected for the basin are well reproduced.

9.6 Calibration and Validation

Calibration covers 2013–2021 and validation spans 2022–2023. A compact parameter set adjusts layer-wise conductivity, near-surface specific yield, deeper specific storage, areal recharge, and a global pumping scale factor. An optimization routine minimizes a composite objective that rewards high explanatory power and penalizes excessive error while tracking bias to keep residuals centered. All trials are logged, and the final selection is summarized with parameter values and fit metrics. Independent validation confirms generalization beyond the fitting window. The Table 9.6 summarize the statistical values of calibration and validation of model.

Table 9-6. Statistical performance

Period	RMSE (m)	Bias (m)	MAE (m)	R ²
Calibration (2013–2021)	3.51	–0.28	2.62	0.94
Validation (2022–2023)	1.82	–0.20	1.36	0.98

These scores indicate close agreement between observed and simulated heads, low systematic error, and strong skill in both periods, supporting the model’s application to scenarios and planning analyses.

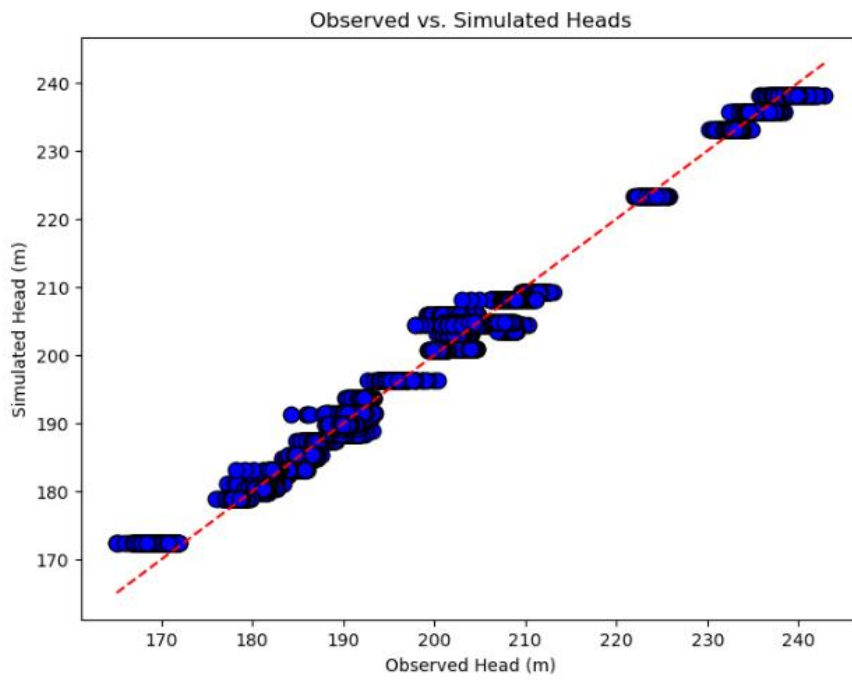


Figure 9.5. Observed vs Simulated Heads during Ground water simulation

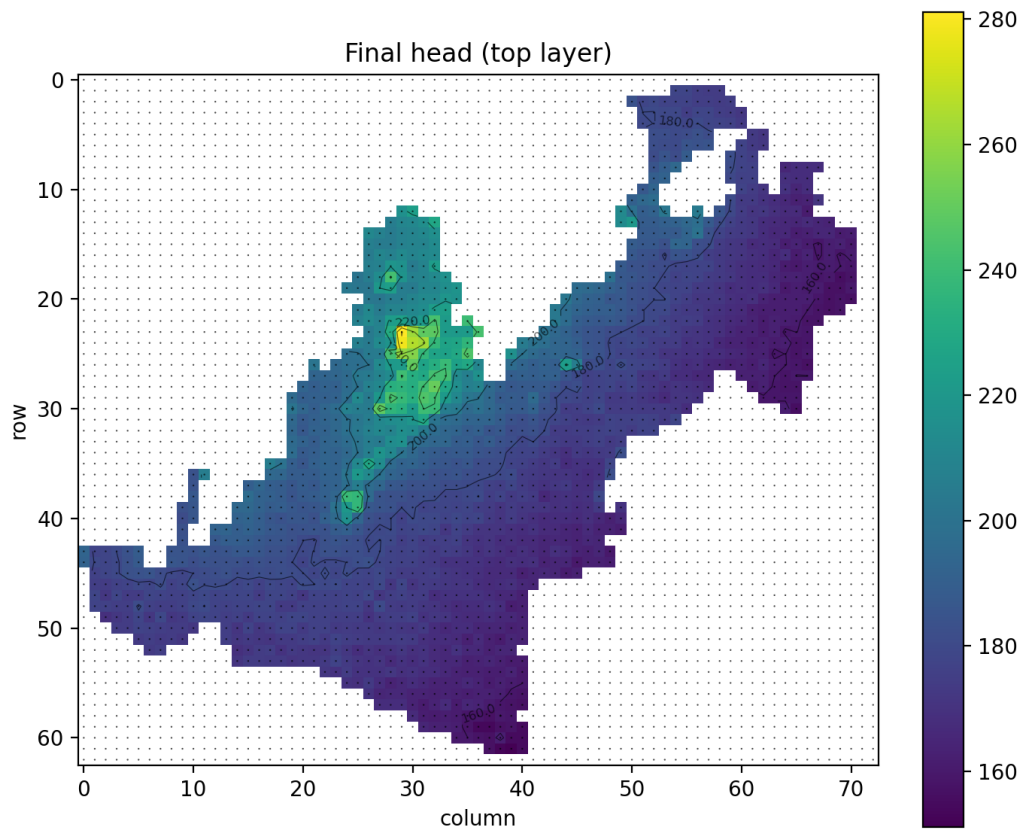


Figure 9.6. Simulated Groundwater Heads during Validation of Model

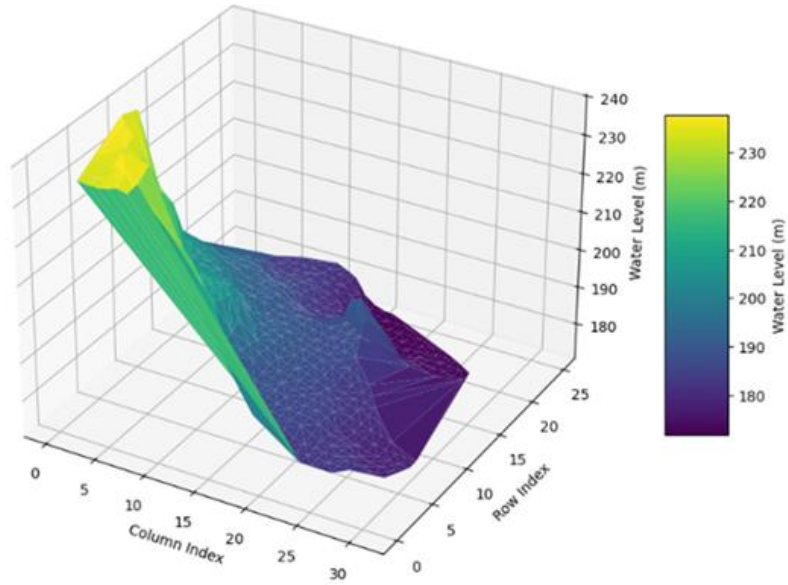


Figure 9.7. A view of 3-D Ground water model of Jodhpur city

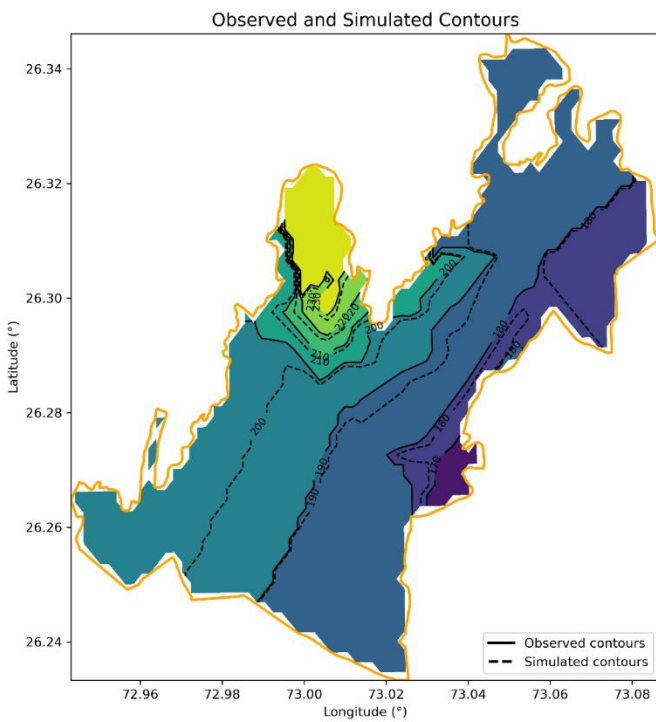


Figure 9.8. Contour Map Observed & Simulated Head wells

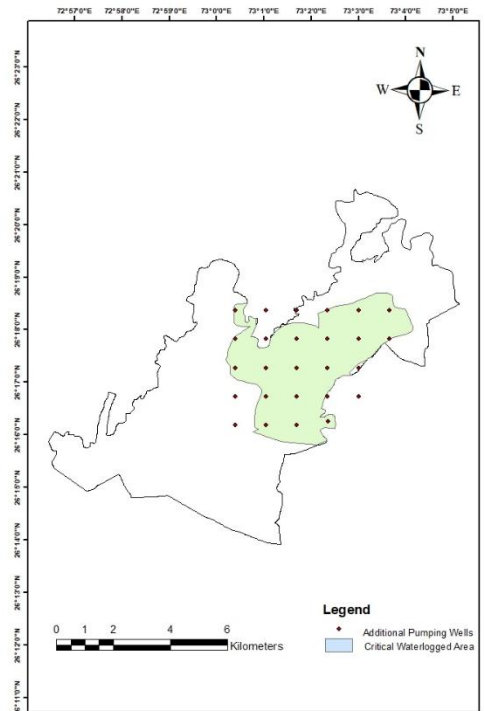


Fig 9.9 Location of additional abstraction wells

9.7 Simulation results and Interpretations

MODFLOW-based groundwater flow model developed for Jodhpur City provides a comprehensive and operationally relevant simulation of the urban aquifer system. It integrates DEM-derived topography, a multilayer hydrostratigraphic framework, spatially distributed hydraulic properties, and time-varying pumping into a simplified yet scientifically rigorous representation that can be run and updated as new data arrive. Calibration and validation against observation-well time series show that simulated heads reproduce spatial gradients and seasonal dynamics—monsoon-season rises and dry-season declines—with decision-grade fidelity. This combination of physical realism and operational practicality allows the model to function as an early-warning and planning tool for active management of shallow groundwater and waterlogging in built-up areas.

The MODFLOW-based groundwater flow model for Jodhpur delivers an operational, decision-grade picture of the urban aquifer. A core outcome is delineation—and validation—of a Critical Zone where depth to water table (DTW) is 0–3 m, covering ~18 km². This shallow zone, dominated by Quaternary alluvium interfingering with sandstone and shale, is prone to surface saturation and waterlogging in built-up areas. Planning-grade specific yield (Sy) of 2–4 % applied over an effective saturated thickness of ~4 m yields an extractable storage of ~2.16–2.88 MCM yr⁻¹ across the mapped extent—consistent with observed seasonal fluctuations and providing a realistic upper bound for short-term drawdown strategies that avoid unsafe dewatering.

The model supports controlled vertical drainage as the primary intervention for managing waterlogging in the most affected sub-areas. A pragmatic operating rule—approximately 275 m³ d⁻¹ per shallow well, deployed at one well per 800 × 800 m block (0.64 km²)—effectively stabilizes the water table around a 4 m depth while maintaining aquifer sustainability. Within the identified Critical Zone, the model delineates around 28 operational blocks, representing a theoretical extraction capacity of ~7,700 m³ d⁻¹. Considering downtime, seasonal variations, and practical constraints, an operational target of ~7,000 m³ d⁻¹ (equivalent to ~2.55 MCM yr⁻¹) remains adequate for sustainable waterlogging management.

Spatial overlays indicate close correspondence between observed and simulated groundwater contours, reinforcing the reliability of model conceptualization and parameterization. However, it is important to recognize that groundwater modeling inherently involves certain

simplifications—such as assuming uniform aquifer properties, idealized boundary conditions, and generalized recharge or pumping distributions. These assumptions may not fully capture the natural heterogeneity of the field environment. Hence, model results should be interpreted as indicative and continuous field monitoring are recommended to refine and validate the simulated outcomes.

While the model demonstrates decision-grade reliability for immediate management use, a deeper understanding of sub-grid heterogeneity will strengthen localized interventions and help address observed anomalies. Targeted fieldwork—such as short-duration pumping or slug tests in representative blocks, shallow hydro-geophysical surveys (resistivity/EM) along critical corridors, and tracer tests near suspected leakage zones—can provide refined data for model recalibration.

9.8 Key Inferences

The Jodhpur groundwater model offers a science-based, operationally feasible pathway for managing shallow groundwater and waterlogging in a hydrogeological complex urban setting. It is modular and replicable, allowing other cities with similar challenges to adopt the framework while retaining local fidelity for robust, place-specific decisions. The suggested effective management actions of controlled abstraction may be proceeded on the strength of current results to address waterlogging issue and the extracted pumping water may be utilized in industries, gardens, public utility, railways and other useful purpose.; However for future a strategically targeted, collaboratively sponsored geo-physical investigations will deepen the understanding where it most matters to study sub-surface strata and further future-proof the city's groundwater management.

CHAPTER-10 DRAINAGE MAPPING & PLANNING FOR JODHPUR CITY

10.1 Status of Existing infrastructure

Jodhpur, a rapidly growing city located in the arid zone of western Rajasthan, faces acute challenges associated with storm water management, particularly during the monsoon months. The flat terrain, inadequate drainage coverage, and increasing impervious urban surfaces have resulted in recurrent issues of waterlogging, surface flooding, and abnormal groundwater table rise. As a response, a focused study was undertaken to map the existing drainage infrastructure and evaluate ward-wise peak runoff discharges using advanced hydrological tools.

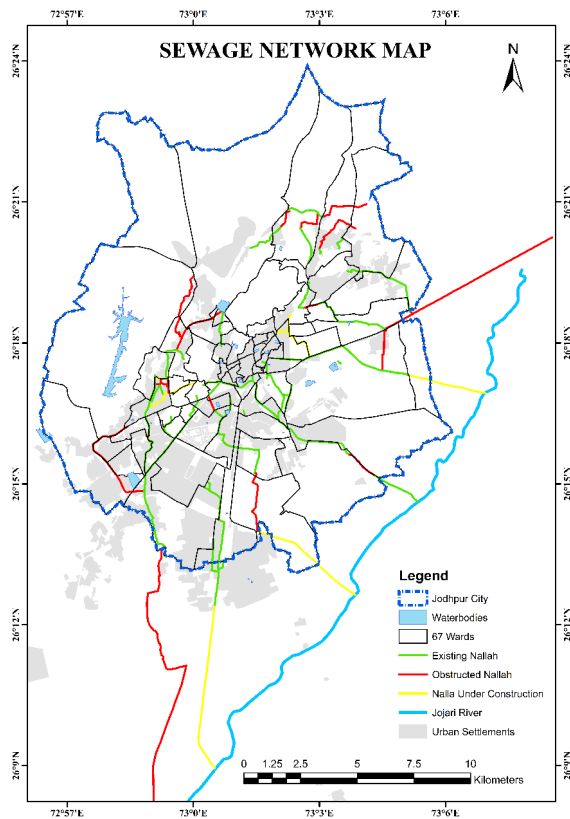


Figure 10.1. Digitized Sewer Drains of Jodhpur city

10.2 Mapping of Major City Drains

A detailed exercise was conducted to digitize the existing stormwater drains across Jodhpur using high-resolution satellite imagery and field surveys. This task enabled the identification of functional and non-functional drain segments. The digitized data was subsequently overlaid with the city's road network and municipal boundaries to assess gaps in drainage coverage. The analysis clearly revealed that several densely populated wards, especially in the old city and peripheral zones, lack formal drainage infrastructure altogether.

10.3 Assessment of Waterlogging and Conduit Layouts

To address localized waterlogging, the study introduced a system of stormwater conduits in areas currently lacking drainage. Proposed conduits were planned along existing roads to minimize encroachment and maximize use of public space. The layout design leveraged the natural slope of the city terrain, with drainage alignment optimized to follow gravitational flow paths.

10.4 Terrain Analysis

To accurately capture the terrain variations and natural drainage gradients, the ALOS PALSAR Digital Elevation Model (DEM) was employed. The high-resolution DEM provided critical inputs for slope estimation, flow direction, and elevation profiles. These parameters were essential in delineating hydrological sub-catchments across city wards and in ensuring that proposed conduits efficiently discharge to natural or planned outfalls.

10.5 IDF Analysis and Peak Discharge Estimation

Intensity-Duration-Frequency (IDF) curves were derived using long-term rainfall data from the Jodhpur meteorological station. The IDF data was used to simulate different storm scenarios (e.g., 2-year, 5-year, 10-year, 25-year return periods) for various rainfall durations. Each ward was analyzed as a separate hydrological unit, with surface runoff volumes and peak discharges calculated based on land use, imperviousness, and topography.

These discharge values were then used to approximate the size and capacity of stormwater channels required for each ward. The resulting network was modeled as part of a larger Storm Water Management Model (SWMM) setup to assess flow routing, potential surcharging, and effectiveness of the new conduit designs.

10.6 Urban Drainage Planning

The Storm Water Management Model (SWMM), developed by the U.S. Environmental Protection Agency, is a dynamic rainfall-runoff simulation model used for planning, analysis, and design of urban drainage systems. SWMM operates by dividing the urban area into smaller sub-catchments, modeling surface runoff generation, infiltration, evaporation, and routing through drainage conduits. It allows simulation of both single event and long-term continuous rainfall, making it ideal for cities like Jodhpur that face high-intensity, short-duration rainfall events.

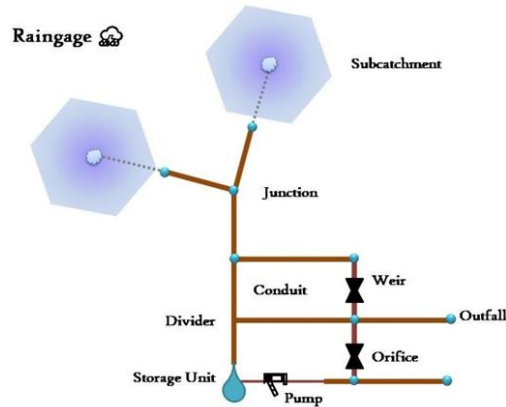


Figure 10.2 Overview of SWMM components

SWMM incorporates components such as rain gauges, sub-catchments, junctions, conduits, and outfall nodes, each representing different hydrological and hydraulic aspects of the drainage network. By integrating land use, slope, and rainfall data, the model dynamically simulates peak flows, runoff volumes, and potential points of flooding. For Jodhpur, the application of SWMM enables a detailed understanding of how stormwater moves through each ward and where drainage upgrades are most critically needed.

In addition, SWMM provides multiple hydrological process options such as infiltration modeling (Green-Ampt, Horton, and Curve Number methods), surface ponding, and snowmelt routines, which allow for better calibration in varying urban conditions. The model also supports dynamic wave flow routing, which enables the detection of backflows, surcharged junctions, and pipe overflow—all of which are common issues in Jodhpur's densely built-up zones.

Furthermore, the flexibility of SWMM allows it to incorporate time-varying data (rainfall, evaporation, inflows) and simulate pollutant transport and sediment buildup, which can later support water quality modeling in urban runoff—critical for evaluating impacts on downstream reservoirs and urban water bodies such as Kaylana Lake.

10.7 Drainage modeling using SWMM

The stormwater drainage layout for Jodhpur was developed using ArcGIS software and subsequently imported into the SWMM platform for simulation and analysis. Key hydrological and hydraulic components such as Zones, Junctions, Conduits, and Outfall Nodes were defined as per their spatial attributes derived from GIS mapping. Conduits were drawn based on the city's natural stream order, topography, and the existing network of drains (nallahs), ensuring

that the model reflects realistic flow paths. The ALOS PALSAR DEM was employed to compute slope and elevation parameters essential for determining flow direction and gravity-based routing.

Each conduit's length, junction elevation, and outfall invert level were extracted from the GIS database, with conduit lengths ranging between 45 meters to 2105 meters. The final drainage map comprised four major zones, 49 junction nodes, 49 conduit segments, and three designated outfalls with invert elevations at 227 meters, 273 meters, and 271 meters respectively. These outfalls represent terminal discharge locations where runoff exits the system, typically draining into existing natural depressions, reservoirs, or downstream water bodies. The GIS-SWMM integrated approach facilitated efficient network construction and accurate model input setup, laying the groundwork for simulation-based performance evaluation

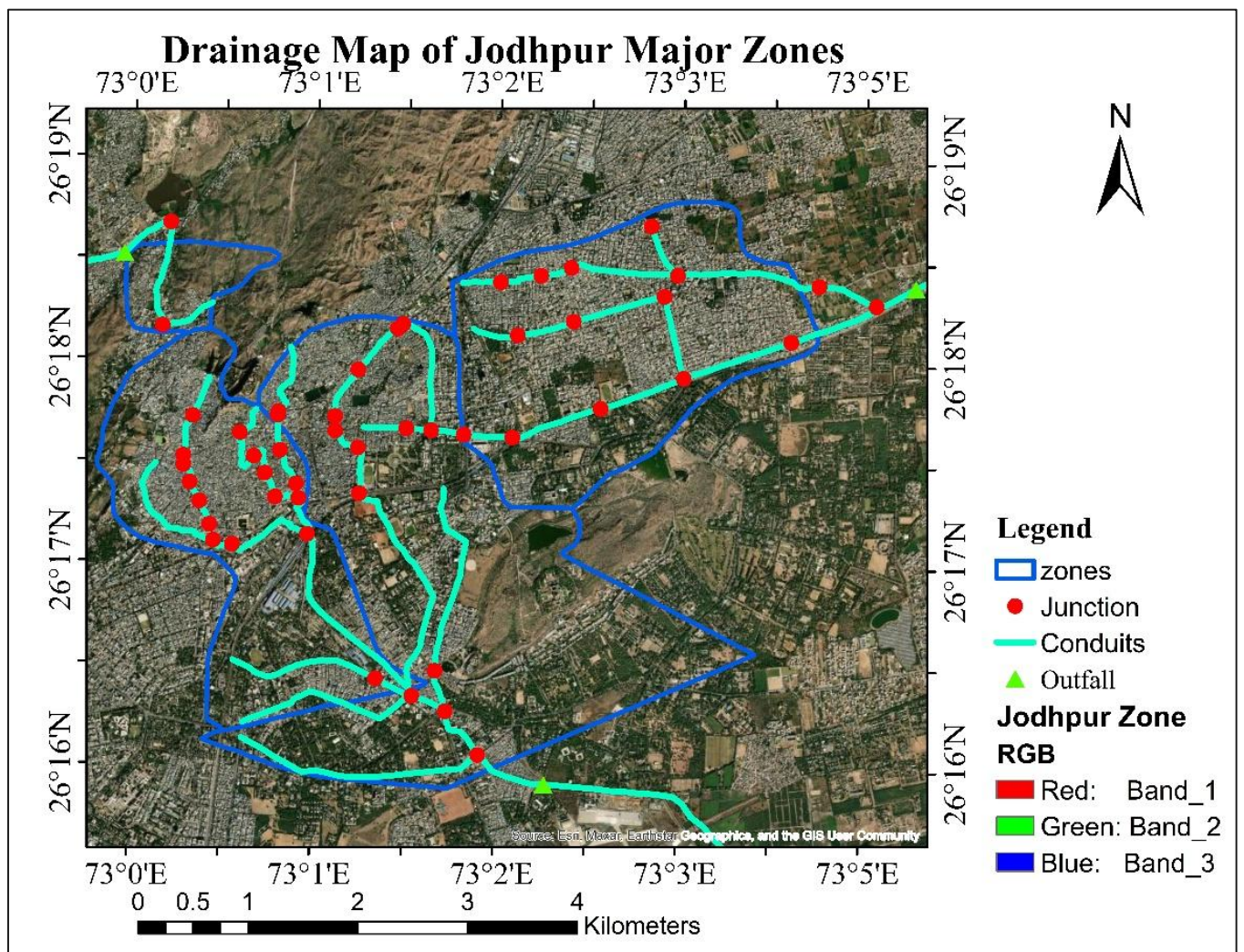


Figure 10.3 Drainage Map of Jodhpur major critical areas/zone

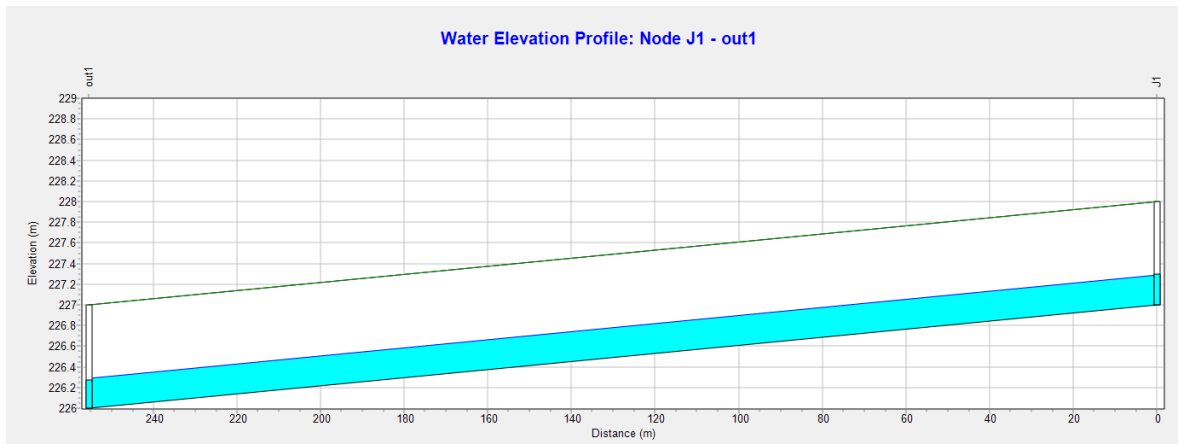


Figure 10.4 water elevation profile J1-Out1 consist of Conduit **depth 1m** and **width 1m**

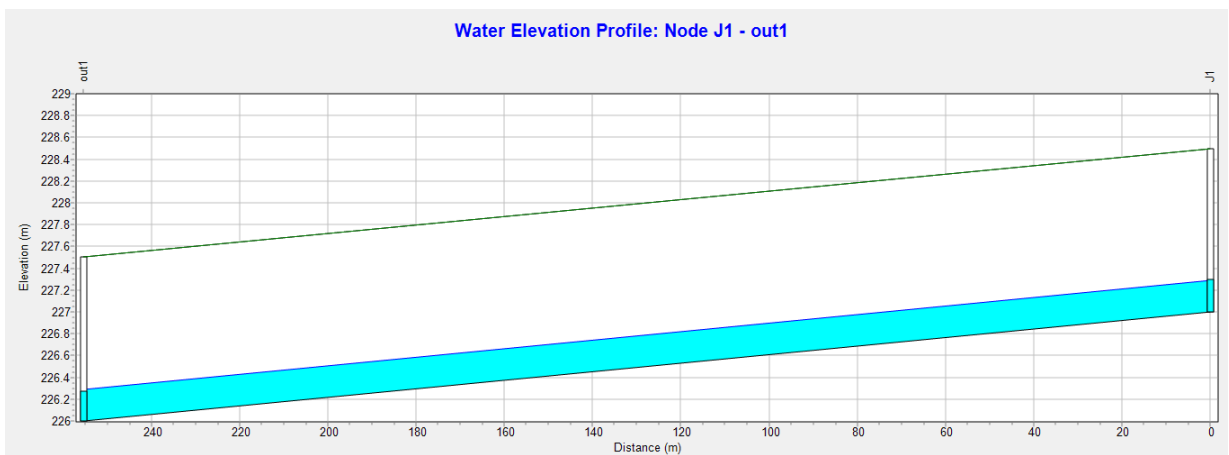


Figure 10.5 water elevation profile J1-Out1 consist of Conduit **depth 1.5m** and **width 1m**

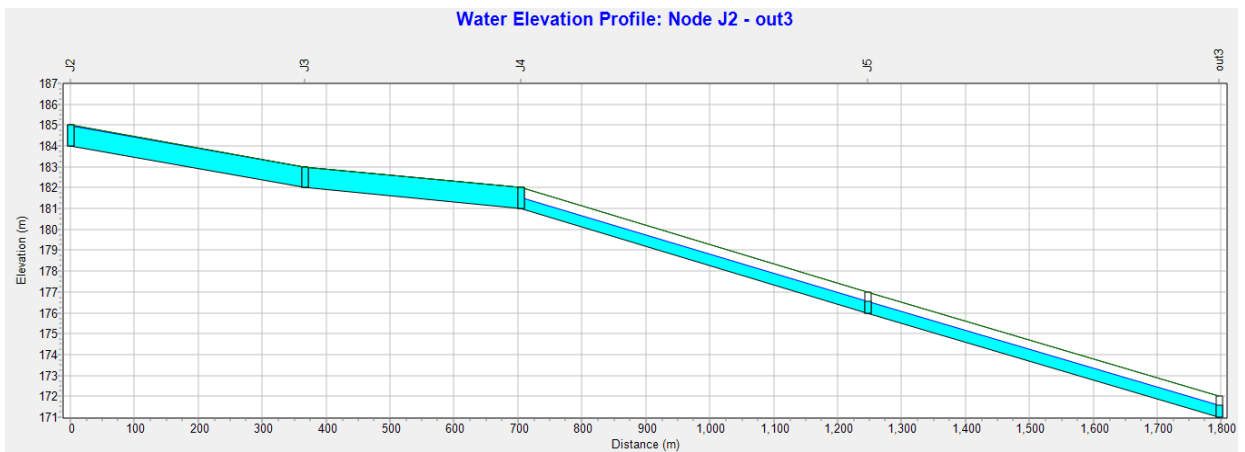


Figure 10.6 water elevation profile J2-Out3 consist of Conduit **depth 1 m** and **width 1m**

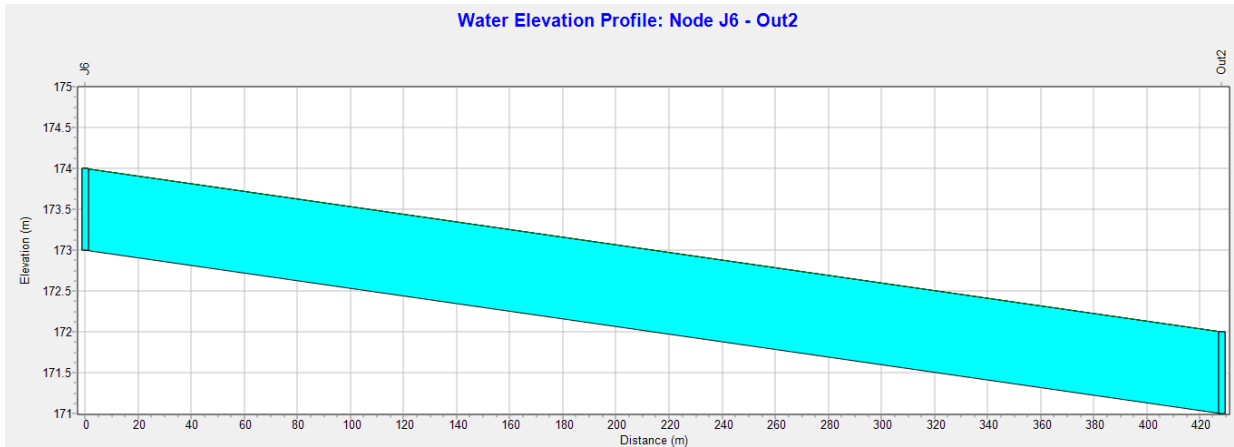


Figure 10.7 water elevation profile J1-Out1 consist of Conduit **depth 1.5m** and **width 1m**

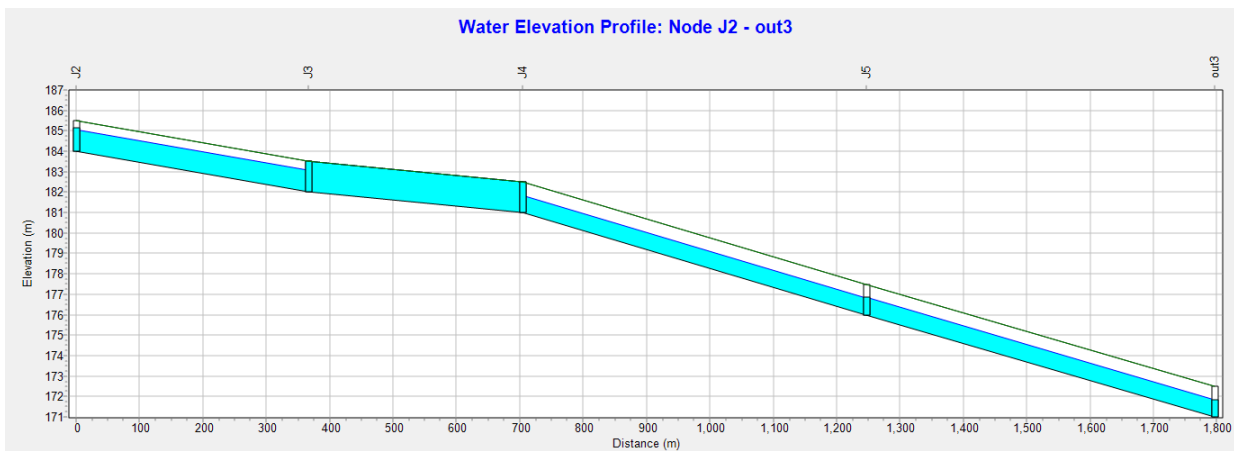


Figure 10.8 water elevation profile J1-Out1 consist of Conduit **depth 1m** and **width 1m**

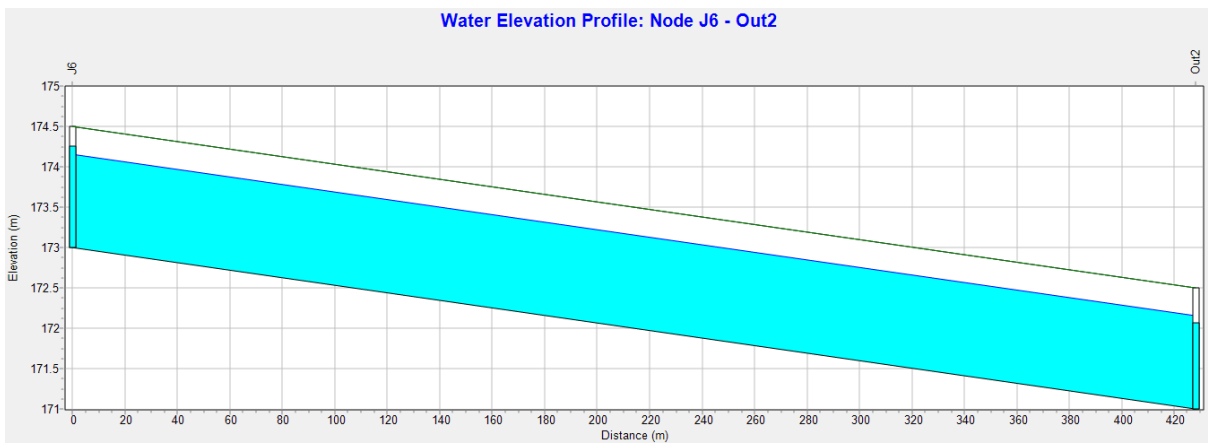


Figure 10.9 water elevation profile J2-Out3 consist of Conduit **depth 1.5 m** and **width 1m**

As per the model results, the details of outfall loading of all zones is given in table 10.

Table 10 - Outfall Loading of all Zones

Topic: Outfall Loading		Click a column header to sort the column.		
Outfall Node	Flow Frequency %	Average Flow CMS	Maximum Flow CMS	Total Volume 10 ⁶ ltr
out1	99.91	0.093	0.095	2.000
Out2	99.91	0.583	0.638	12.573
out3	99.91	0.836	0.909	18.037

10.8 Outcomes of Drain modeling

The integration of digitized drain networks, DEM-based slope analysis, and IDF-derived peak discharge helped create a ward-wise drainage master layout for the city. This layout includes:

- Identification of priority areas for drainage construction
- Mapping of natural gravity-based flow paths
- Sizing of conduits to handle projected peak runoff
- Linking of each ward's drainage to nearest functional outfalls

These inputs serve as foundational data for implementing the full SWMM-based urban drainage simulation. This approach ensures a robust, scalable, and spatially accurate drainage planning strategy tailored to Jodhpur's specific hydrological and topographic context. The results of this assessment are being further utilized in detailed simulations for network performance evaluation under different rainfall events, thereby guiding infrastructure upgrades and flood mitigation planning across the city.

CHAPTER-11 GROUNDWATER QUALITY DATA AND ANALYSIS

Groundwater quality assessment is critical for evaluating the suitability of groundwater for various uses, detecting contamination sources, and ensuring compliance with health and environmental standards. In the context of Jodhpur—an arid city experiencing rising groundwater levels and urban waterlogging—this evaluation is vital for identifying usable zones and potential contributors to groundwater degradation.

In this study, groundwater quality has been assessed against the permissible limits prescribed under the Bureau of Indian Standards (BIS) IS:10500 (1991) for drinking and other designated uses. The analysis focuses on both identifying groundwater zones suitable for use and detecting probable sources of contamination, particularly within the urban context of Jodhpur.

11.1 Groundwater Quality Monitoring and Data Considered

Groundwater quality is assessed based on physical, chemical, and biological parameters. Physical properties include temperature, turbidity, color, salinity, and total dissolved solids (TDS). Chemical characteristics cover pH, major ions like chloride (Cl^-), nitrate (NO_3^-), sodium (Na^+), potassium (K^+), calcium (Ca^{2+}), magnesium (Mg^{2+}), carbonate (CO_3^{2-}), and bicarbonate (HCO_3^-). Biological indicators such as coliform bacteria can signal fecal contamination. Key chemical indicators of contamination include high TDS (indicating potential chemical pollution), elevated NO_3^- (linked to sewage or agricultural runoff). The acceptable limits for major chemical constituents follow BIS 10500:1991 guidelines, detailed in Annexure Tables A12.1 and A12.2.

As per the survey conducted for groundwater quality monitoring at 39 locations in Jodhpur, analysing 13 chemical parameters. For spatial analysis, 10 key constituents—pH, TDS, Cl^- , NO_3^- , Na^+ , K^+ , Ca^{2+} , Mg^{2+} , CO_3^{2-} , and HCO_3^- —were selected across 30 sites (data in Annexure Tables). These parameters were chosen for their significance in evaluating groundwater chemistry, pollution levels, and irrigation suitability. Thematic spatial variation maps for pH, Cl^- , TDS, and NO_3^- were prepared using Kriging interpolation.

11.2 Spatial Analysis

To visualize and analyse the geographic distribution of water quality, thematic spatial variation maps were generated for both pre-monsoon and post-monsoon seasons. The Kriging interpolation method, a robust geostatistical technique, was employed to create continuous

surfaces from the discrete sample point data. This allows for the identification of hotspots, gradients, and spatial trends across the entire study area.

11.3 Spatial plots & contamination zoning

The following figures depict the seasonal and spatial distribution of critical groundwater quality parameters:

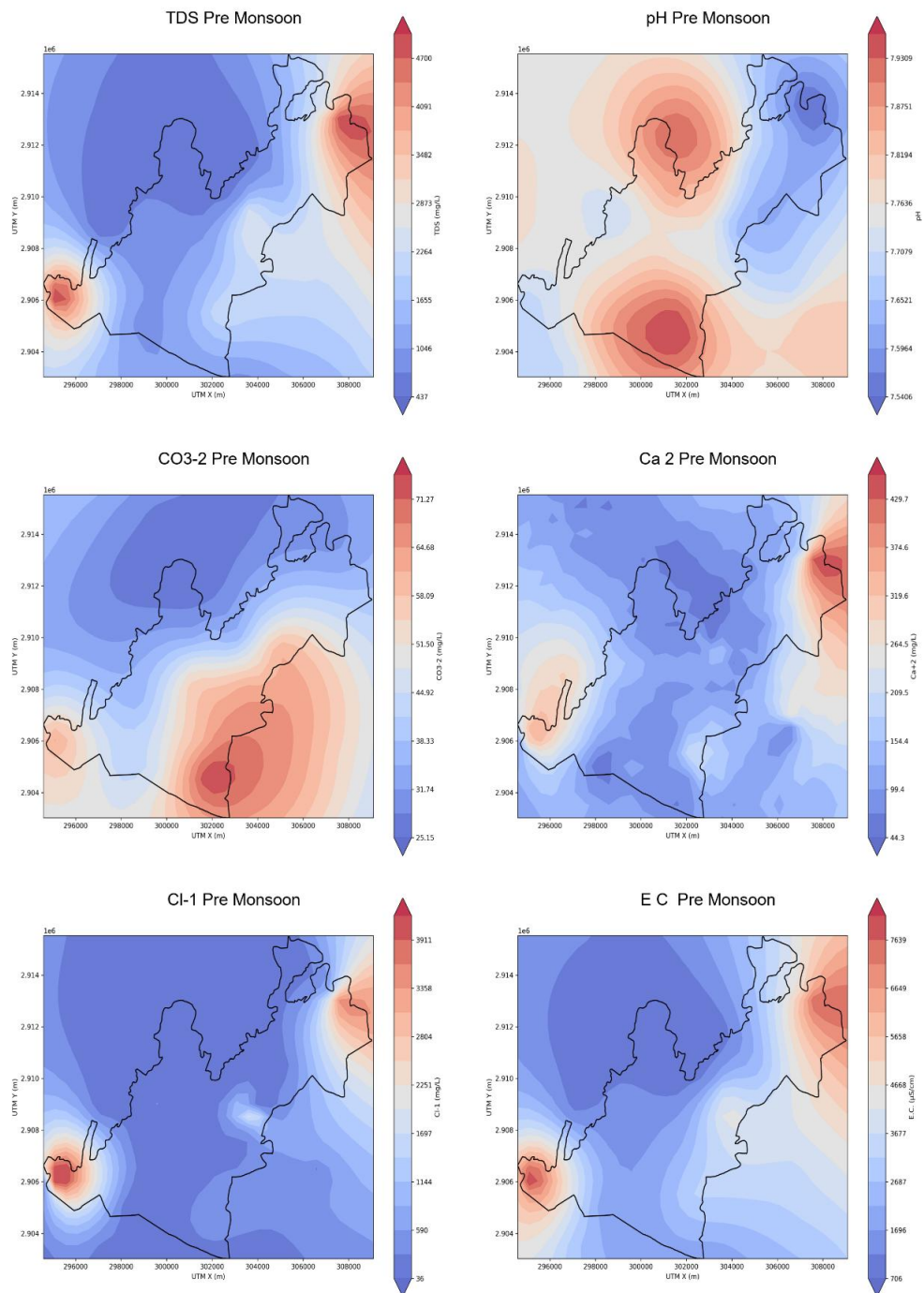


Figure 11.1: Spatial distribution of groundwater quality parameters (Pre-Monsoon) in the study area, including TDS, pH, CO₃²⁻, Ca²⁺, Cl⁻, and EC.

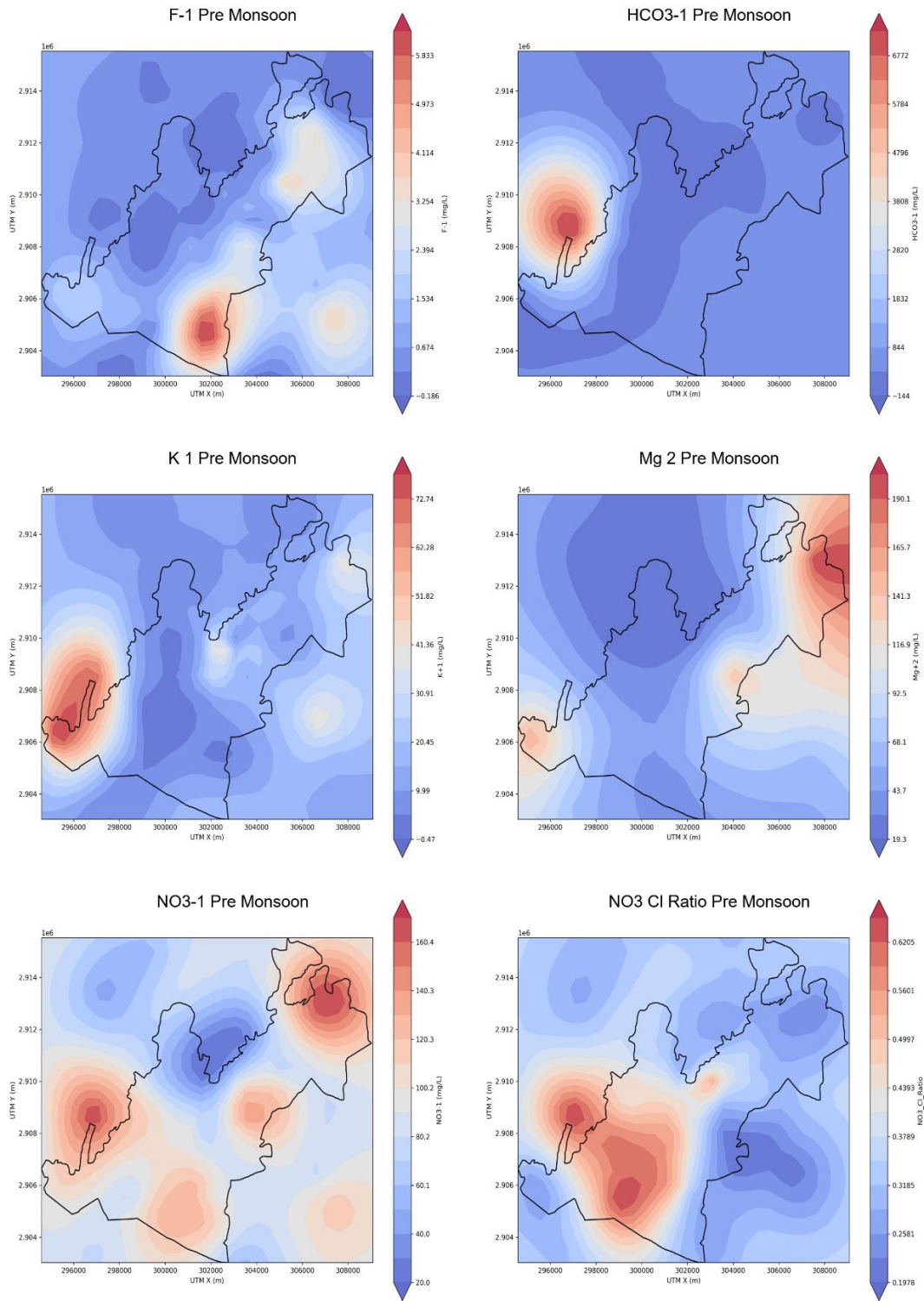


Figure 11.2. Spatial distribution of groundwater quality parameters (Pre-Monsoon) including F⁻, HCO₃⁻, K⁺, Mg²⁺, NO₃⁻, and NO₃⁻/Cl⁻ ratio in the study area

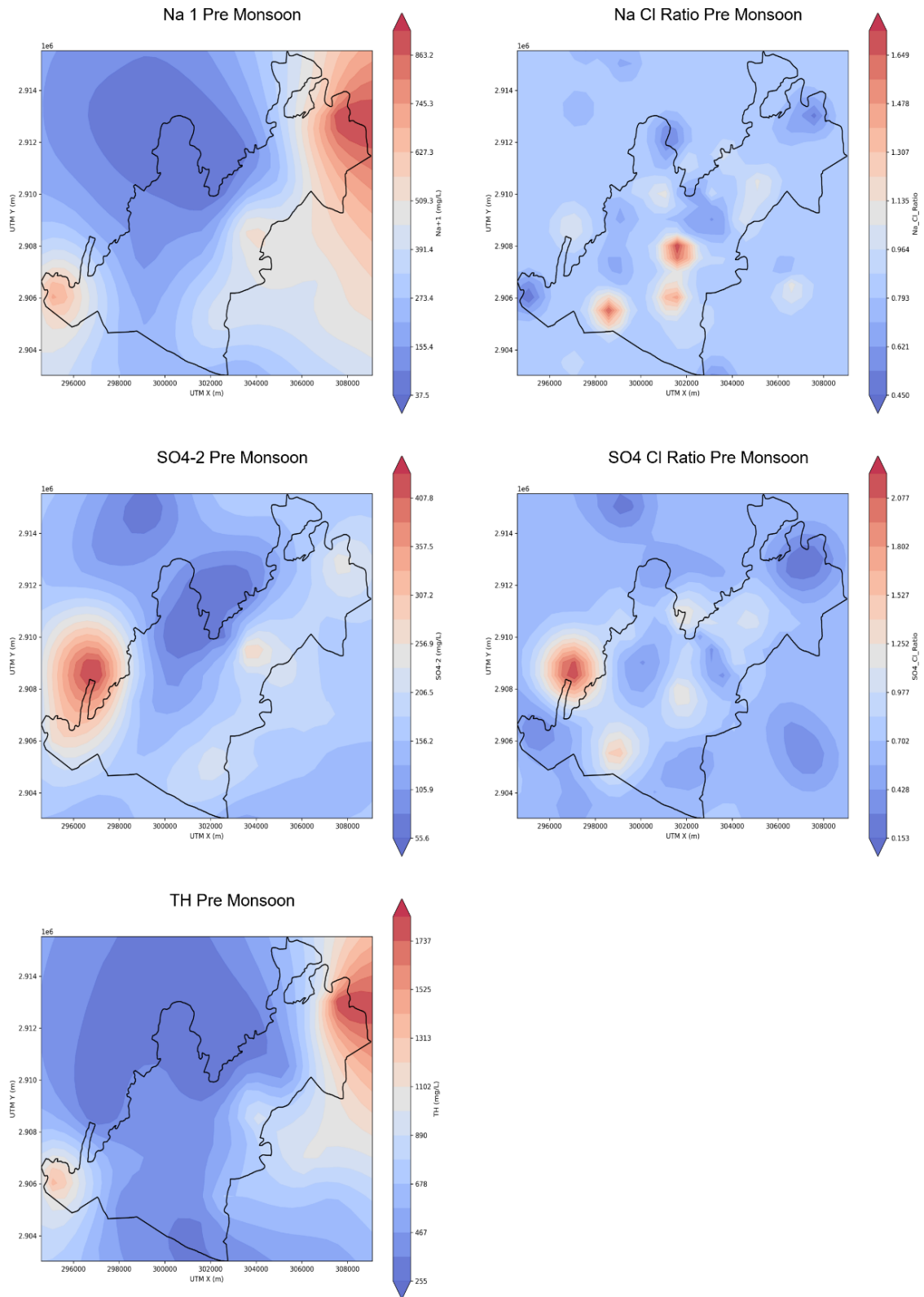


Figure 11.3 Pre-Monsoon spatial distribution maps for Na⁺, Na⁺/Cl⁻ ratio, SO₄²⁻, SO₄²⁻/Cl⁻ ratio, and Total Hardness (TH) in the study area

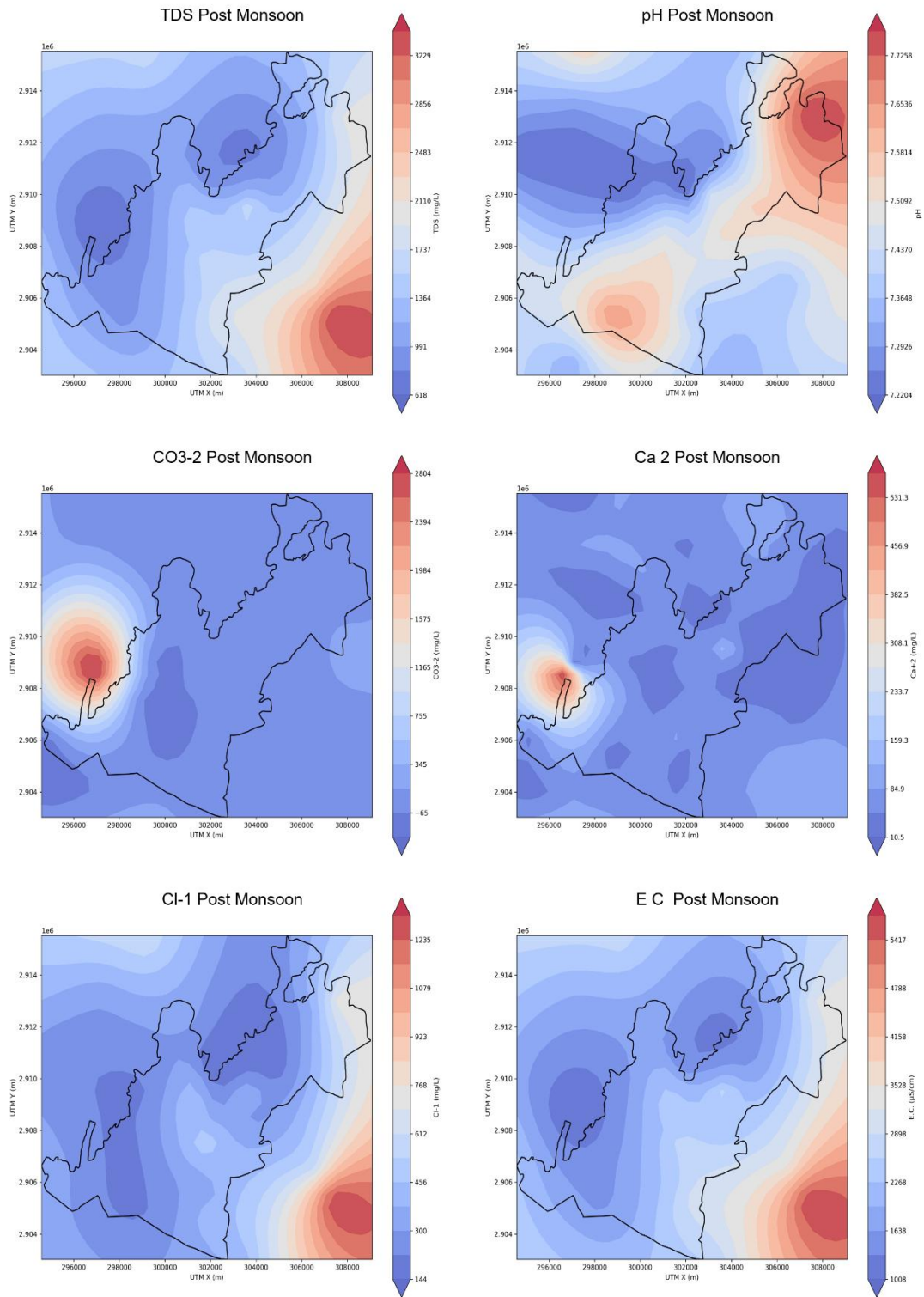
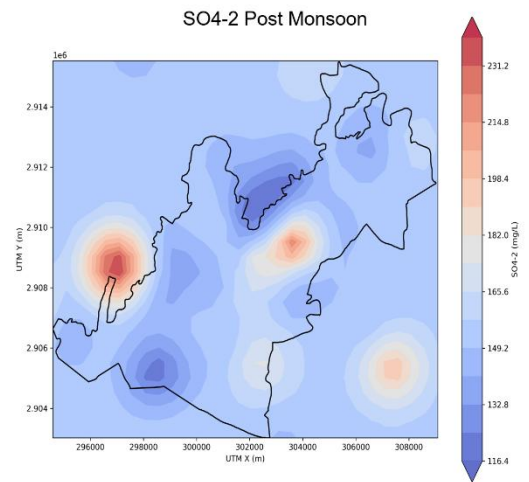
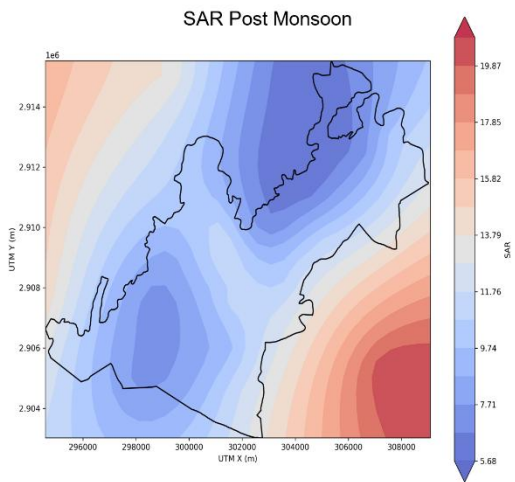
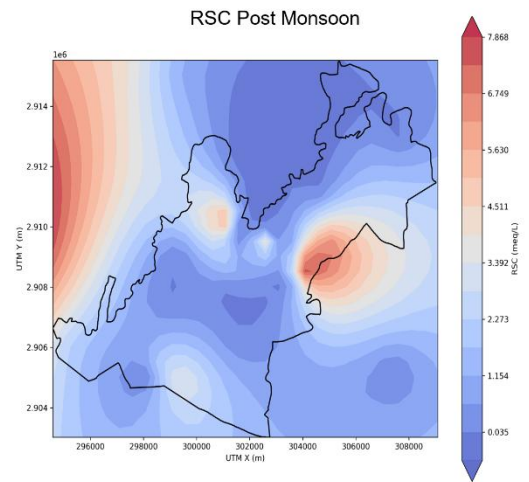
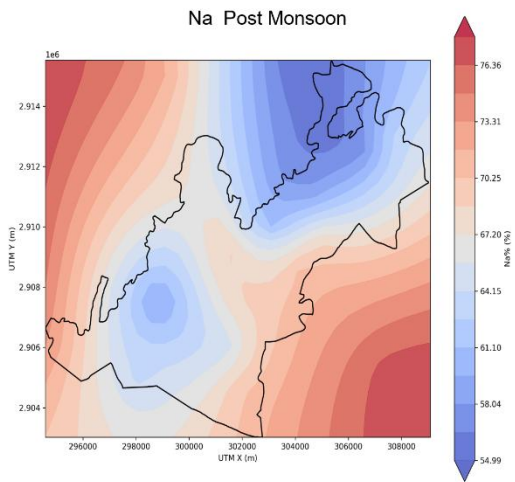
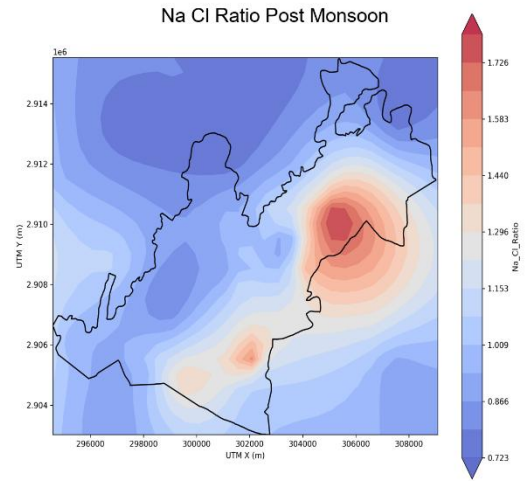
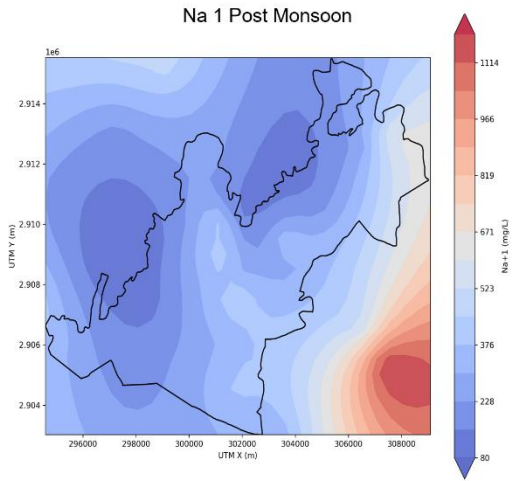


Figure 11.4: Post-Monsoon Spatial distribution of groundwater quality parameters (TDS, pH, CO_3^{2-} , Ca^{2+} , Cl^- , and Electrical Conductivity (EC)).



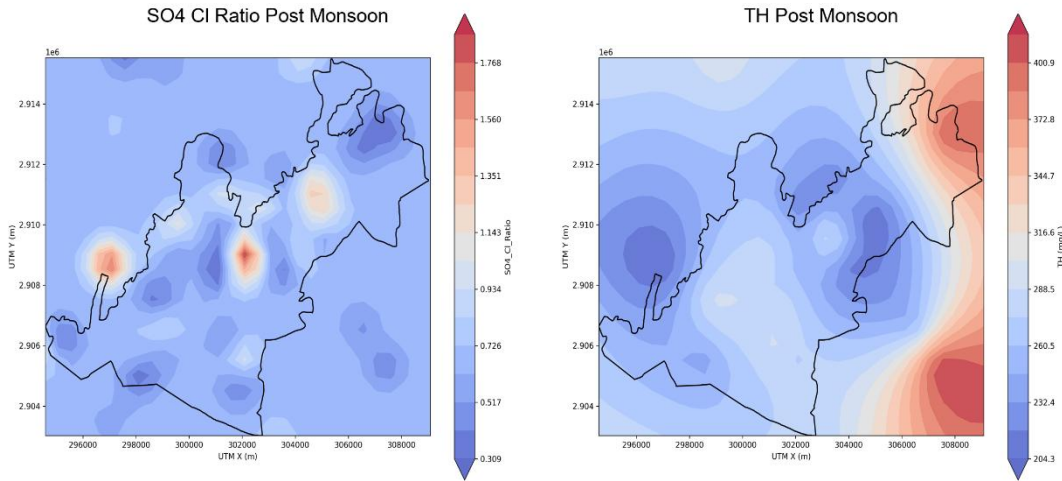


Figure 11.6: Post-Monsoon Spatial distribution of groundwater quality parameters (So₄ & TH)

11.3 BIS sessional Comparison and implications

Seasonal comparison between pre- and post-monsoon data shows minor dilution effects due to recharge but persistent hotspots of pollution, especially nitrate and salinity, remain unchanged in certain zones. Compliance with BIS limits varies across parameters and locations, highlighting the need for local, context-sensitive management. The details are given in table 11.

Table 11 BIS sessional comparison with observed pre & post monsoon water quality data

S. No.	Parameter	Acceptable Limit	Pre-Monsoon Range	Post-Monsoon Range
1	pH	6.5 - 8.5	7.12 - 8.61	6.98 - 8.39
2	EC ($\mu\text{S}/\text{cm}$)	< 1500	465 - 8350	610 - 8440
3	TDS (mg/L)	< 1000	300 - 5330	390 - 5400
4	Total Hardness (mg/L)	< 300	140 - 1462	134 - 1540
5	Alkalinity (mg/L)	< 200	130 - 740	120 - 670
6	Chloride (mg/L)	< 250	30 - 1860	30 - 1890
7	Sulphate (mg/L)	< 200	6 - 662	5 - 740
8	Nitrate (mg/L)	< 45	0.1 - 106	0.2 - 96
9	Sodium (mg/L)	< 200	24 - 1388	26 - 1430
10	Potassium (mg/L)	< 12	0.9 - 36	1.1 - 42
11	Calcium (mg/L)	< 75	24 - 288	26 - 310
12	Magnesium (mg/L)	< 30	10 - 176	12 - 182
13	Fluoride (mg/L)	< 1.0	0.2 - 3.1	0.1 - 2.9

11.4 Key Inferences

1. **pH:** Groundwater pH is within permissible limits, showing slight alkalinity. This may result from chlorine used in water treatment or natural buffering through carbonates.
2. **Chloride (Cl⁻):** Higher chloride concentrations suggest possible leakage from chlorinated water supply pipelines.
3. **TDS:** Elevated TDS levels are mostly observed in the southern part of the city, distant from waterlogged zones, indicating a geogenic source rather than anthropogenic contamination.
4. **Nitrate (NO₃⁻):** Concentrations exceed permissible limits in the southern belt, likely due to sewer system leakage. Localized nitrate hotspots within urban areas suggest sewer or septic tank leakage.
5. **SAR and Irrigation Suitability:** Sodium Adsorption Ratio (SAR) analysis indicates that groundwater is safe for irrigation purposes.
6. **Source:** based on the chemical analysis, waterlogging in the urban area indicating primarily due to return flows from domestic water use and leakage, rather than seepage from the natural recharge through Kailana-Takhatsagar reservoirs.

11.5 Detailed Interpretations

- The pH distribution pattern, particularly its gradient from southwest to northeast, confirms that the problematic area is not being influenced by inflow from western aquifers.
- Chloride levels, while elevated, support the hypothesis of leakage from potable water supply rather than untreated wastewater ingress.
- Higher TDS in isolated southern zones supports the idea of localized geogenic mineral dissolution.
- High nitrate concentrations in urban pockets cannot rule out leakage from sewer pipelines or septic tanks.
- The nature of waterlogging is predominantly anthropogenic, driven by inefficient water use and infrastructure leaks.

11.6 Key findings and Strategic Outlook

Groundwater quality across Jodhpur shows diverse challenges including localized chemical contamination, infrastructure-driven leakages, and agricultural pollution. However, most zones maintain sufficient quality for irrigation, if not direct domestic consumption. Following recommendation can be drawn from findings

1. **Utilize Pumped Water:** Pumped GW is not suitable for drinking purpose so it may be utilized for non-potable applications such as construction, dust suppression, and urban landscaping with salt-tolerant species.
2. **Zone-Based Water Use Planning:** Groundwater extraction and usage should align with localized quality zoning derived from spatial analysis.
3. **Infrastructure Upgrades:** Prioritize repair of water and sewer pipelines in contamination hotspots identified through NO_3^- and Cl^- mapping.
4. **Avoid Reinjection of Pumped Water:** Reinjecting pumped water into drains should be strictly avoided to prevent further elevating issue of waterlogging & degradation.
5. **Continuous Monitoring:** Implement a city-wide water quality monitoring framework with seasonal reporting to guide interventions.

CHAPTER-12: SUMMARY, CONCLUSION, AND RECOMMENDATIONS

12.1 Summary

This comprehensive internal study, undertaken by the North Western Regional Centre (NWRC) of the National Institute of Hydrology (NIH), Jodhpur, addresses the persistent groundwater rise and associated waterlogging issues in Jodhpur city, Rajasthan. Jodhpur, the second-largest city in Rajasthan and a critical urban center in the arid Thar Desert, has historically battled water scarcity and extreme climatic conditions. With an average annual rainfall between 340–370 mm, the city had long depended on traditional water harvesting systems such as baoris (stepwells), and talabs (ponds). This delicate balance was significantly altered with the advent of large-scale surface water transfer schemes.

The commissioning of the Rajiv Gandhi Lift Canal (RGLC) in 1997, designed to bring water from the Indira Gandhi Canal Project, marked a pivotal moment. While intended to alleviate chronic water shortages and support a growing population and industrial base, this intervention inadvertently set the stage for a new hydrological challenge. The once water-deficit city began experiencing a paradoxical situation: rising groundwater levels leading to urban flooding and chronic waterlogging in several core areas. This rising water table has had severe repercussions: waterlogging in central city areas, damage to public infrastructure and heritage buildings, groundwater salinization, and increased risk of vector-borne diseases. The 2011 NIH and 2010 NGRI studies had earlier hinted at these concerns, but infrastructure constraints, lack of drainage upgrades, and increased urbanization have aggravated the issue.

The current study, commissioned as an internal NIH project aims to reassess the situation using modern tools and expanded spatial data. It seeks to build upon previous findings while leveraging modern tools like MODFLOW 6, SWMM 5.1, isotope tracing, and GIS-based spatial analysis to systematically identify the principal drivers contributing to the groundwater rise, evaluate the associated environmental and socio-economic impacts, and deliver ground-level, actionable solutions that are scientifically sound and technically feasible. Through an integration of field diagnostics, high-resolution modeling, and spatial analytics, the study aims to support data-driven planning and infrastructure interventions for sustainable groundwater management in the city.

The study was designed with the following core objectives, aiming to provide a holistic understanding of the groundwater rise issue in Jodhpur and to guide the development of sustainable, science-backed management strategies:

- To study the factors and sources contributing to the rising water table in Jodhpur.
- To assess the impacts of the rising water level on the environment, infrastructure, and society.
- To explore potential mitigation strategies & provide recommendations to address the water rising issue.

To achieve these objectives, we adopted a comprehensive, interdisciplinary methodology that integrated hydrogeological, hydrological, and infrastructural analyses, underpinned by robust fieldwork and advanced analytical–modeling techniques. The approach was explicitly designed to triangulate evidence across spatial, temporal, and social dimensions.

First, a citywide field program combined structured household surveys with targeted site inspections. Surveys of 250 respondents representing diverse socio-economic groups captured perceptions of water-supply reliability, drainage performance, health risks, and awareness of groundwater quality. Parallel field inspections in persistently waterlogged localities documented physical manifestations—including wall dampness, foundation cracks, structural degradation, and localized flooding (especially post-monsoon)—thereby linking lived experiences to measurable urban-hydrological symptoms.

Second, systematic hydrogeological monitoring and archival data analysis established the temporal and spatial behavior of the aquifer. Seasonal measurements (winter, pre-monsoon, and post-monsoon) at 62 observation wells were used to assess water-table fluctuations, longer-term trends, and inputs for groundwater modeling. Historical datasets (2013–2024) from CGWB, SGWB, and PHED supported decade-scale interpretation, spatial zonation, and validation of field observations. Groundwater-level contour maps developed from prior-year measurements showed closely spaced contours in the waterlogged belt—diagnostic of low transmissivity—contrasting with wider spacing in the southern sector, indicative of relatively higher transmissivity and a thicker Quaternary alluvial package. Given the hilly terrain to the north (with no evident inflow from that direction) and the observed outward flow from the waterlogged zone, the accumulating water was inferred to be locally sourced, most plausibly from return flows linked to the potable-water distribution network and leakage from sewage infrastructure.

Third, remote sensing and GIS provided the spatial framework to delineate recharge controls and drainage behavior. High-resolution ALOS DEMs, soil maps, and LULC layers were integrated to map recharge zones, terrain-controlled flow paths, and hydrologic boundaries, while DEM- and satellite-derived drainage mapping clarified preferential flow directions and low-lying vulnerability. Within this geospatial scaffold, structural lineament analysis was used to examine subsurface geological controls and potential fracture connectivity between reservoirs and aquifers. The city's distinctive "bowl-shaped" morphology underlain by relatively impermeable rhyolites was found to inhibit natural drainage, effectively trapping excess water and facilitating groundwater mounding.

Fourth, isotopic and hydrochemical investigations established recharge sources, mixing processes, and quality risks. Water samples from 32 wells and surface-water bodies, analyzed for δD and $\delta^{18}O$ across three hydrological seasons, quantified recharge origin, evaporation effects, and lake-aquifer connectivity. Piper and Chadha diagrams characterized chemical facies and traced the evolution of groundwater chemistry, salinity gradients, and signatures of sewage influence. The results showed a dominance of $Na^+ - Cl^- - SO_4^{2-}$ facies, widespread elevation of EC ($>2000 \mu S/cm$), TDS, and NO_3^- above BIS drinking-water limits at multiple locations, and seasonal post-monsoon deterioration linked to increased surface infiltration and stagnation in shallow urban aquifers. While suitability for irrigation (SAR/RSC) was generally within permissible limits.

Fifth, the water-balance highlights the role of sewer outflows in driving urban return flows. On average, ~60% of the city's annual water supply is discharged to sewers. Under base-case conditions, about 16–17% of supply re-enters the aquifer as return flow (~27% of sewer discharge). Sensitivity scenarios parameterized at 24–28% of supply show that return flows can rival or exceed natural recharge inputs, reflecting conditions of high leakage, percolation, and inefficient drainage. These results underscore that sewer leakage and associated return flows are the dominant anthropogenic recharge mechanism sustaining groundwater mounding in Jodhpur.

Sixth, coupled hydrological-hydraulic modeling was undertaken to evaluate controls and interventions. A 3D transient groundwater model (USGS MODFLOW-6) for 2013–2024 was developed and calibrated against observed heads, enabling assessment of vertical dewatering scenarios. The model identified a ~18 km² "Critical Zone" with water levels persistently within 0–3 m of ground level and recommended controlled abstraction at ~275 m³/day per well grid, deployed at one well per 800 × 800 m grid (~0.64 km²), to depress water levels toward ~4 m.

The discharge value may be adjusted by increasing the number of wells and considering actual field conditions, as modeling generally involves simplifications of physical parameters. Across 28 such grid cells, the model indicates an approximate total extraction of ~2.55 MCM/year for sustainable waterlogging management. However, groundwater modeling has certain limitations—it assumes uniform aquifer properties, simplified boundary conditions, and idealized recharge or pumping scenarios. Therefore, field validation and continuous monitoring are essential to refine and validate the simulated results. In parallel, EPA SWMM 5.1 was used to evaluate sewer–storm water performance: four drainage zones, 49 junctions and conduits, and three outfalls were configured from DEM-derived slopes and natural flow paths, with conduit lengths from 45 to 2105 m. The GIS–SWMM workflow reproduced realistic routing, identified 16 surcharged nodes and critical connectivity gaps (particularly toward the Jajari outfall), and supported ward-wise sizing for peak flows and priority corridor planning for flood mitigation and network upgrades.

12.2 Conclusion

The rising groundwater table in Jodhpur is a multi-faceted urban hydrological crisis, rooted in a convergence of natural constraints and human-induced pressures. It reflects the paradox of a drought-prone arid city, historically known for water scarcity, now transformed into one grappling with chronic waterlogging. The underlying causes lie in the introduction of abundant surface water supply in an arid setting, unregulated artificial recharge from urban sources, inefficient and aging sewerage and drainage systems, and decades of uncoordinated urban development. The city’s natural lithology, low-permeability rhyolite overlain by shallow alluvial aquifers further traps water and exacerbates mounding. This hydrological inversion has led to salinization, structural damage (including heritage buildings), reduced land usability, and increasing public health concerns.

Based on an extensive and multi-layered investigation, the study unequivocally concludes that Jodhpur’s groundwater rise is a man-made phenomenon. While detailed findings have been presented earlier, the conclusions can be generalized under three dimensions:

1. There is no significant hydraulic connectivity indication found between the Kaylana–Takhatsagar reservoirs and the city’s aquifer system, as confirmed by isotopic, geochemical, lineament structural and flow direction evidence. Instead, a substantial portion of recharge nearly 35-40% annually originates from urban return flows, including leakage from aging pipelines, percolation through unlined sewers, over-

utilization, and unregulated discharges. These inputs, entirely avoidable under efficient infrastructure management, have become the dominant driver of waterlogging. The city's bowl-shaped terrain and low-permeability lithology restrict lateral drainage, locking surplus water within the shallow aquifer. Consequently, artificial recharge, coupled with natural geological constraints, has produced a self-sustaining water mound in critical zones.

2. The impacts of this imbalance are visible and severe. In central, low-lying wards, stagnant shallow water tables (0–3 m) are causing widespread structural damage to homes, public buildings, and heritage monuments, while dampness, mold, and foundation cracks compromise safety and livability. Public infrastructure including drainage systems, roads, and underground utilities has been significantly weakened, leading to recurring breakdowns and high maintenance costs. Groundwater quality is deteriorating, with elevated EC, TDS, and nitrate levels rendering it unsuitable for drinking without treatment. Survey feedback underscores the social dimension: nearly 42% of households report drainage failures and 26% face persistent waterlogging, translating into daily inconvenience, health risks, and financial burdens. Thus, what began as a technical hydrological problem has escalated into a major socio-economic challenge for urban sustainability.
3. The crisis is, at its core, a reflection of systemic shortcomings. Jodhpur's water management has historically focused on augmenting supply rather than managing surplus, leading to infrastructural oversupply in a naturally water-deficit region. Ineffective and outdated drainage and sewerage networks are not only failing to evacuate excess water but are also unintentionally exacerbating recharge through infiltration. Mitigation efforts, such as groundwater extraction, have shown some improvement but it has limited effectiveness due to poor discharge pathways and frequent recirculation, where pumped water re-enters the same urban catchments via drains or depressions. Unless a paradigm shift in urban water governance is initiated prioritizing infrastructure rehabilitation, regulation of artificial recharge in waterlogged area, and integrated urban water management the waterlogging crisis will continue to deepen.

12.3 Recommendations

Addressing the groundwater rise and waterlogging in Jodhpur requires a multi-pronged and

integrated strategy that combines scientific interventions, infrastructural improvements, and governance reforms. The following recommendations are drawn from the study's hydrological modeling, isotopic and hydrochemical analysis, GIS-based assessment, public surveys, and feasibility evaluations:

I. Vertical Drainage Systems

- Construct additional vertical abstraction wells in critical waterlogged areas (0–3 m depth zones).
- Ensure pumped water is taken to outfalls, retention ponds, or treatment plants, not discharged back into drains where it can re-infiltrate.

II. Drainage Network Rehabilitation (Based on SWMM Results)

- Upgrade and realign the city's storm water and sewerage network as identified in the SWMM model.
- Fix the surcharged nodes and undersized conduits and build new outfalls toward the Jojari River.
- Replace old unlined drains with lined concrete/HDPE drains to reduce infiltration.
- Add sump-and-pump stations in low-slope areas to improve drainage.

III. Interceptor Drains and Gravel-Filled Trenches

- Construct interceptor drains (cut-off drains) at the edges of waterlogged zones to capture shallow groundwater before it spreads into built-up areas.
- Construct gravel/pebble-filled trenches (up to ~4 m depth) with perforated pipes and geotextile wrapping to intercept and safely carry groundwater to outfalls.

IV. Leakage Control and Water Auditing

- Use sensors and regular hydraulic audits to detect and fix leakages in the old water supply system.
- Replace high-loss pipelines, especially in the old city.

V. Reuse of Pumped Water

- Reuse the pumped water for supplying to industries, railways and parks. It can also be supplied to water deficit areas near Jodhpur based on feasibility

VI. Preventive Measures near Reservoirs

- Although current evidence shows no seepage from Kaylana–Takhatsagar reservoirs, precautionary subsurface barriers /interceptors may be built in sensitive areas.

VII. Water Quality Monitoring

- Regularly monitor EC, TDS, nitrates, and isotopes ($\delta^{18}\text{O}$, δD).
- Create warning thresholds and take corrective action in contaminated zones.

VIII. Smart Water Supply and Demand Management

- Install ward-level smart meters for bulk supply and consumers.
- Promote water-use efficiency to reduce wastage and avoid unnecessary recharge.

IX. Building and Policy Measures

- Update building codes to ensure waterproofing, stronger foundations, and compulsory drainage linkages in vulnerable areas.

X. Continuous Monitoring and Future Research

- In future, it is proposed to carry out advanced geophysical investigation in collaboration with state/district agencies for better understanding of subsurface conditions/strata/fractures which may help fix the root cause of the issue, instead managing water level through abstraction.
- Adopt adaptive management by updating plans regularly based on monitoring data.

Concluding Remark

The waterlogging in Jodhpur is mainly due to unregulated recharge, leaking infrastructure, and poor drainage. These recommendations provide a practical and science-based roadmap. With proper implementation supported by governance, institutions, and public participation, the city can protect its infrastructure, improve livability, safeguard health, and ensure long-term water sustainability.

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ANNEXURES

Annexure- I - List of observation sites in Jodhpur city

S.No.	well location	Address/Location	Latitude	Longitude
1	Ajeet Bhawan	Near Restaurant, In Ajeet Bhawan	26° 16' 48.00" N	73° 2' 24.00" E
2	Akheraj ji ka Talab	Near Nag Dada Mandir	26° 18' 0.00" N	73° 0' 36.00" E
3	Bhadwasia	Ram Sagar, Punjla	26° 19' 12.00" N	73° 3' 36.00" E
4	Binaikiya	In the village, on main road	26° 15' 0.00" N	73° 4' 12.00" E
5	CAZRI (P/z)	Backside Library	26° 15' 0.00" N	72° 59' 24.00" E
6	Chaukha	1.5 West of the village	26° 16' 48.00" N	72° 55' 12.00" E
7	Chopasni	Opp. Nathdwara Krishna Mandir	26° 16' 12.00" N	72° 55' 48.00" E
8	Deo Nagar	Behind T.B. Hospital	26° 16' 12.00" N	72° 59' 24.00" E
9	Fateh Sagar	Near Ramanuj Kot Mandir	26° 18' 0.00" N	73° 1' 48.00" E
10	Gausala	Near Pawallion in Gausala Campus	26° 17' 24.00" N	73° 1' 48.00" E
11	Gorinda Baori	In main Tripolia Bazar	26° 17' 24.00" N	73° 1' 12.00" E
12	Ground Water Dept. (P/z)	Near Geophysical Lab	26° 15' 36.00" N	73° 0' 36.00" E
13	Gulab Sagar	Near Ghantaghar	26° 18' 0.00" N	73° 1' 48.00" E
14	Hathi Ram Ka Oda	R.H.S. of road towards Fateh Sagar	26° 17' 24.00" N	73° 1' 48.00" E
15	J.N. Vyas Park	In the Park	26° 18' 0.00" N	73° 0' 36.00" E
16	Jetha Bera	Opposite Chand Baori	26° 18' 0.00" N	73° 1' 12.00" E
17	Kaga ji	West of Sheetla Mata ji Ka Mandir	26° 18' 36.00" N	73° 1' 48.00" E
18	Kailana-II (P/z)	Near Kishan Nursery	26° 17' 24.00" N	72° 59' 24.00" E
19	Kali Beri	Near Kali Beri Bus stand, Backside of shops	26° 20' 24.00" N	72° 59' 24.00" E
20	Khandafalsa	Opp. Ayurvedic Hospital	26° 17' 24.00" N	73° 0' 36.00" E
21	Khema Ka Kua	L.H.S. on main Pal Road	26° 15' 0.00" N	72° 58' 48.00" E
22	Kriya Ka Jhalra	R.H.S. on main road of Vidhyashala to fort Road	26° 18' 0.00" N	73° 0' 36.00" E
23	Magra Punjla-I	Baori-Bera Near Balaji Rasayanshala shop	26° 19' 48.00" N	73° 4' 12.00" E
24	Magra Punjla-II	Bhadarwa Bera, Mata ka Than	26° 19' 12.00" N	73° 4' 12.00" E
25	Mahamandir Jhalra	Near Mansagar Talab	26° 18' 36.00" N	73° 2' 24.00" E
26	Mandore (Garden)	Near IInd Gate of Mandore Garden	26° 21' 0.00" N	73° 2' 24.00" E
27	Military Hospital Baori	Opp. Army Hospital, In unit area	26° 17' 24.00" N	73° 3' 0.00" E
28	Nav Chokiya	Opp. Police Thana, Khanda Falsa	26° 18' 0.00" N	73° 0' 36.00" E
29	Nawapura, Chokha	L.H.S. on road, leading to Chaukha from Chopasni	26° 15' 36.00" N	72° 57' 0.00" E
30	Nehru Park	Near Mahadev Temple & Pyau	26° 16' 48.00" N	73° 0' 36.00" E
31	New Campus Univ. (P/z)	Near Main gate of New Campus University & electric Pole	26° 15' 0.00" N	73° 1' 12.00" E
32	Police Line	Near Mahila Police thana Policeline	26° 16' 48.00" N	73° 1' 48.00" E
33	Raghunath Baori	Near Rameshwar ji Temple	26° 19' 12.00" N	73° 0' 36.00" E
34	Ramanuj Kot	In the Ramanuj Kot Mandir	26° 18' 0.00" N	73° 1' 48.00" E
35	Roop Nagar, Pal Road	Near the Pal Petrol Pump, Roop Nagar	26° 15' 0.00" N	72° 58' 48.00" E
36	Sardarpura	Backside of Kabra School	26° 16' 48.00" N	73° 0' 36.00" E
37	Siwanchi Gate	Nr. Maheshwari Dharamshala, Opp. Umaid Hosp	26° 17' 24.00" N	73° 0' 36.00" E
38	Sodo Ki Dhani (P/z)	In the campus of Middle school on Keru Road	26° 21' 0.00" N	72° 58' 12.00" E
39	Tunwar ji Ka Jhalra	Near RAS Haveli	26° 18' 0.00" N	73° 1' 12.00" E
40	Zanana Park	In campus of Public Park	26° 17' 24.00" N	73° 1' 48.00" E

Annexure-II - Details of Working Pumping Wells Considered in the Study

S.N	Location	Latitude	Longitude	Well Type
1	Indra park	26.284	73.025	EW
2	9th c road sardarpura	26.295	73.007	T/W
3	Aai mata mandir	26.336	73.052	Tubewell
4	Aakashwani	26.313	73.044	T/W
5	Accidental thana	26.259	73.011	EW
6	Achalnath mandir baori	26.320	73.022	Baori
7	Ajeet colony park	26.301	73.038	T/W
8	Ajit colony	26.302	73.038	T/W
9	Akad bhaunath	26.318	73.008	Tube well
10	Akashwani	26.297	73.017	Tubewell
11	Akhliya choraha	26.298	72.994	Tube well
12	Aksha masjid	26.336	73.059	Tubewell
13	Anand cinema	26.266	73.023	deep well
14	Anganbadi govt tulsi colony	26.323	72.999	Tube well
15	Annasagar gali no 3	26.340	73.065	Tubewell
16	Apna park ligh	26.294	72.987	EW
17	Ashok Nagar	26.322	73.048	Tubewell
18	Asia bai kabriathan	26.272	73.017	Tube well
19	Aun road	26.311	73.031	Tube well
20	Baire ke pass	26.266	73.023	deep well
21	Balaji park sector 1	26.289	72.984	EW
22	Bharat seva sansthan	26.313	73.043	Tubewell
23	Bholi bai ka mandir sinwanchi gate	26.316	73.018	Tube well
24	Braham bagh	26.305	73.019	O/W
25	Braj bawadi	26.339	73.007	Tubewell
26	Central academy school	26.273	72.984	EW
27	Chainpura pipali	26.348	73.064	Tubewell
28	Chaturawata	26.348	73.055	Tubewell
29	Children park	26.298	73.008	T/W
30	Chippa colony	26.321	73.036	Tube well
31	Chippa samaj nyati nohra	26.313	73.036	Tube well
32	Chopsani school shishu vihar ward 11 s	26.259	72.959	EW
33	Chopsani sunder balaji gali nos 8 s	26.266	72.971	EW
34	Cyber park	26.258	73.000	EW
35	Damodar colony	26.324	73.039	Tubewell
36	Dhanmandi	26.322	73.044	Tubewell
37	Dharampura ward no 24	26.316	73.013	Tube well

38	Dilip nagar	26.345	73.059	Tubewell
39	Dr rs gahlot	26.313	73.044	T/W
40	Durgadas park	26.316	73.060	T/W
41	Esr sector 21 campus	26.271	72.980	EW
42	Fateh sagar	26.314	73.032	Pond
43	Gabbu khan ka chowke	26.310	73.035	Tubewell
44	Gandhi colony	26.266	73.023	T/W
45	Ganesh garh ke pass	26.317	73.013	Tube well
46	Ganga maiya temple jatiya colony	26.321	73.037	Tubewell
47	Ghanchi colony	26.264	73.022	T/W
48	Ghanchiyo ka samsan	26.316	73.005	Tubewell
49	Gol nadi ummed chowk	26.320	73.026	Tube well
50	Golamdajan ki masjid moti chowk jodhpur	26.318	73.023	Tube well
51	Golnadi	26.320	73.026	Baori
52	Gorinda baori	26.317	73.026	Baori
53	Goushala maidan	26.302	73.037	O/W
54	Gulab sagar	26.314	73.029	Pond
55	Gulab sagar	26.314	73.028	Pond
56	Guljar nagar	26.312	73.042	Tubewell
57	Gyaneshwar prak sector 11	26.272	72.983	EW
58	Hakim colony 5th road	26.299	73.009	Tube well
59	Hakim mazid colony	26.305	72.998	Tube well
60	Hari nagar park ward-13	26.259	72.963	EW
61	Harizan basti	26.295	73.007	deep well
62	Heerala bera	26.334	73.071	Tubewell
63	Icchapurna balaji sector 16	26.277	72.973	EW
64	Indra colony	26.290	73.005	deep well
65	Jai narayan vyas balika uchha madhyamic vidhyalaye	26.315	73.014	Tube well
66	Jaimal nagar	26.329	73.074	Tubewell
67	Jalap baori	26.316	73.019	O/W
68	Jaljog choraha	26.292	73.008	T/W
69	Jangid hostel kila road	26.323	73.031	Tubewell
70	Jat jati nohra	26.281	73.026	deep well
71	Jay colony bhomiya ji ke than ke pass	26.284	73.013	Tube well
72	Jda circle	26.281	73.025	T/W
73	Jogmaya mandir	26.322	72.999	Tube well
74	Kabutoron ka chowk	26.317	73.020	Tube well
75	Kaga meghwal swargasharm	26.324	73.036	Tubewell
76	Kallal colony	26.324	73.036	Tube well
77	Karni bagh	26.280	73.030	T/W

78	Khetaanaadi	26.340	73.049	Tubewell
79	Kheteshwar mandir	26.342	73.055	Tubewell
80	Killi khana	26.324	73.024	Tube well
81	Kings hospital	26.298	73.008	deep well
82	Kila raod	26.326	73.028	Tube well
83	Kotwali well navchakia	26.320	73.017	O/W
84	Krishan mandir ke pas	26.292	73.008	deep well
85	Krishan park bhagat singh marg	26.321	73.040	Tubewell
86	Krishna nagar	26.332	73.069	Tubewell
87	Kriya ka jalra	26.327	73.017	Tube well
88	Kumaron ka bas	26.285	73.001	T/W
89	Kuta chatri bhomiya ji than	26.284	73.013	Tubewell
90	Langa colony gali no 8	26.294	72.992	Tube well
91	Latiyaleshwar mahadev park sector 21	26.270	72.982	EW
92	Laykan mohalla	26.324	73.023	Tube well
93	Lehriya sweets k pas	26.263	73.020	T/W
94	Lions club	26.273	72.982	T/W
95	Ln school	26.305	72.991	T/W
96	Loharon ki gali	26.313	73.040	O/W
97	Mg govt school sector 11	26.274	72.983	EW
98	Madarsa ansar knn 1 st ward 5 s	26.293	72.986	EW
99	Mahadev mandir	26.319	73.007	Tube well
100	Mahadev nagar basni tamboliya	26.331	73.057	Tubewell
101	Mahamandir thana	26.323	73.042	Tubewell
102	Mahamandir thana	26.323	73.042	Tubewell
103	Maheshwari bhawan	26.302	73.032	Baori
104	Mahila bag jhalra	26.314	73.028	Jhalra
105	Mahilla maha vidhlaya knn 1st ward no 2 s	26.304	72.993	EW
106	Majisa pyau sector 19	26.270	72.976	EW
107	Maliyo ki gali	26.290	73.005	deep well
108	Mansagar park	26.323	73.047	Tubewell
109	Mata ka kund	26.328	73.012	O/W
110	Mdm hospital	26.268	73.011	Baori
111	Meva froose asiya kabristan	26.306	73.009	Tube well
112	Mhpratap children park	26.316	73.063	T/W
113	Mirchi bazaar	26.320	73.020	O/W
114	Mmc gali no 3	26.266	72.995	EW
115	Mmc gali no 6	26.265	72.996	EW
116	Mmc gali no 8	26.263	72.993	EW
117	Naini bai ka mandir	26.318	73.037	O/W

118	Najarji ki boari	26.315	73.020	O/W
119	Namra masjid samrat hotel knn 1st ward 5 s	26.293	72.989	EW
120	Narayan vihar	26.328	73.076	Tubewell
121	Narsingh vihar naya pura	26.346	73.054	Tubewell
122	Narsinghdara	26.315	73.020	O/W
123	Naya baas gokul garden	26.339	73.005	Tubewell
124	Naya talab	26.321	73.050	Pond
125	Nayapura holi chowke	26.346	73.053	Tubewell
126	Near patel diary rajiv gandhi colony	26.273	72.988	EW
127	Near ummaid school	26.324	73.045	Tube well
128	Nehru park	26.288	73.018	O/W
129	Nph chowki	26.257	73.011	EW
130	Nph quarter	26.259	73.006	EW
131	Panchwati colony	26.280	73.034	T/W
132	Paota b road	26.313	73.044	T/W
133	Phed office sector 8	26.279	72.975	EW
134	Pokaran house	26.281	73.026	T/W
135	Prithvipura park	26.313	73.052	T/W
136	Pwd coolony main road	26.279	73.025	T/W
137	Rajeev nagar	26.330	73.051	T/W
138	Rajiv gandhi sadbhawan park ward 5 s	26.294	72.988	EW
139	Rajmata school ke pass	26.290	73.005	deep well
140	Rajput sabha bhawan	26.314	73.048	T/W
141	Ram mohalla meghwal basti	26.323	73.037	Tubewell
142	Ramdev dosa ke pass	26.264	73.020	deep well
143	Ramdev mandir ke pas mata ka than	26.335	73.076	Tubewell
144	Rasala road	26.313	73.052	Tubewell
145	Rawla bera	26.344	73.068	Tubewell
146	Roop nagar	26.316	73.061	T/W
147	Roop nagar i	26.262	72.981	Tubewell
148	Roop nagar ii	26.262	72.981	Tubewell
149	Sai nath mandir masuriya hill	26.293	72.998	Tube well
150	Samaj kalyan hostel	26.266	73.023	T/W
151	Santoshi mata park sector 11	26.273	72.982	EW
152	Sector 15	26.276	72.976	EW
153	Sector 17e	26.271	72.971	EW
154	Shakti colony	26.264	73.022	deep well
155	Shastri nagar a	26.288	73.004	EW
156	Shastri nagar d	26.286	73.007	EW
157	Shastri nagar g	26.265	73.001	EW

158	Shastri nagar h	26.266	73.012	EW
159	Shindhi muslim basti ward number 26	26.279	72.969	Tube well
160	Shingyo ki gali mahadev mandir near shamasan	26.334	73.006	Tube well
161	Shitala mata temple openwell	26.334	73.037	Openwell
162	Shiv mandir	26.328	73.062	Tubewell
163	Shiv shakti mandir devi road chandana bhakar ward no 3 s	26.300	72.988	EW
164	Shivam udhyog	26.260	72.995	EW
165	Shri hospital sector 11	26.273	72.984	EW
166	Shri krishna mandir	26.281	73.037	O/W
167	Shri manchapurn mahadev temple ward 4 knn 2nd s	26.300	72.988	EW
168	Shri ram nagar park	26.266	72.978	EW
169	Shriram nagar park i	26.332	73.072	Tubewell
170	Shriram nagar park ii	26.332	73.072	Tubewell
171	Sindhi bhuto ka bas	26.316	73.020	Tube well
172	Sindhi muslim basti	26.281	73.017	Tube well
173	Sindhi sahbjado ka mohalla	26.316	73.019	Tube well
174	Sindhion ka bas siwanchi gate	26.316	73.019	Tube well
175	Subhash cowk	26.302	73.031	O/W
176	Sukheshwar badi chandi hall dabgarion ki gali	26.316	73.022	Tube well
177	Suraj kund	26.326	73.010	Baori
178	Tapi baori	26.319	73.018	Baori
179	Teja park	26.316	73.063	Tubewell
180	Tilak nagar park	26.333	73.052	Tubewell
181	Tulsi colony badi masjid ke peche kabeer nagar	26.325	72.999	Tube well
182	Turji ka jhalra	26.324	73.022	Jhalra
183	Udai mandir asan	26.314	73.040	O/W
184	Uit park ward-13	26.260	72.964	EW
185	Vaid raj ka bera	26.261	72.995	EW
186	Vidhashala school bada ramdwara chandpole	26.327	73.014	Tube well
187	Vishnoyion ka bas	26.343	73.054	Tubewell
188	Vyas park	26.320	73.015	pond
189	Vyas park volley ball garden	26.320	73.012	Tube well
190	Unknown well	26.320	73.015	Tube well

Annexure III - Details of the Small Water Bodies in and Around Jodhpur City

S.No	Waterbody Name	Longitude	Latitude	Perimeter (km)	Area (sq. km)
1	Baiji ka Talab	73.0336	26.3001	0.5676	0.017702
2	Balsamand Lake	73.0217	26.3324	1.3688	0.058785
3	Fateh Sagar	73.0295	26.2965	0.5291	0.015306
4	Gulab Sagar	73.0254	26.2970	0.6139	0.017686
5	Guru ka Talab	72.9820	26.2979	2.1151	0.061934
6	Jaswant Thada	73.0246	26.3040	0.5394	0.007698
8	Kaylana Lake	72.9732	26.3079	23.6186	0.824213
9	Manasagar	73.0431	26.3082	0.4653	0.012666
10	Padamsar Talab	73.0157	26.2994	0.6296	0.008227
11	Ranisar Talab	73.0166	26.2990	0.5490	0.006955
12	Sursagar	73.0110	26.3129	1.0337	0.048338
13	Takht Sagar	72.9692	26.2889	12.0486	0.486942
14	Tal Sagar	73.0554	26.3314	1.6055	0.038024
15		72.9621	26.2973	0.3079	0.001735
16		72.9624	26.2986	0.6593	0.010696
17		73.0464	26.2860	0.8684	0.023305
18		73.0378	26.2746	0.4230	0.009298
19		73.0388	26.3134	0.4116	0.006187
	Total			48.3543	1.660000

Annexure IV - Pre-Monsoon and Post-Monsoon Trend Analysis of Obs Wells

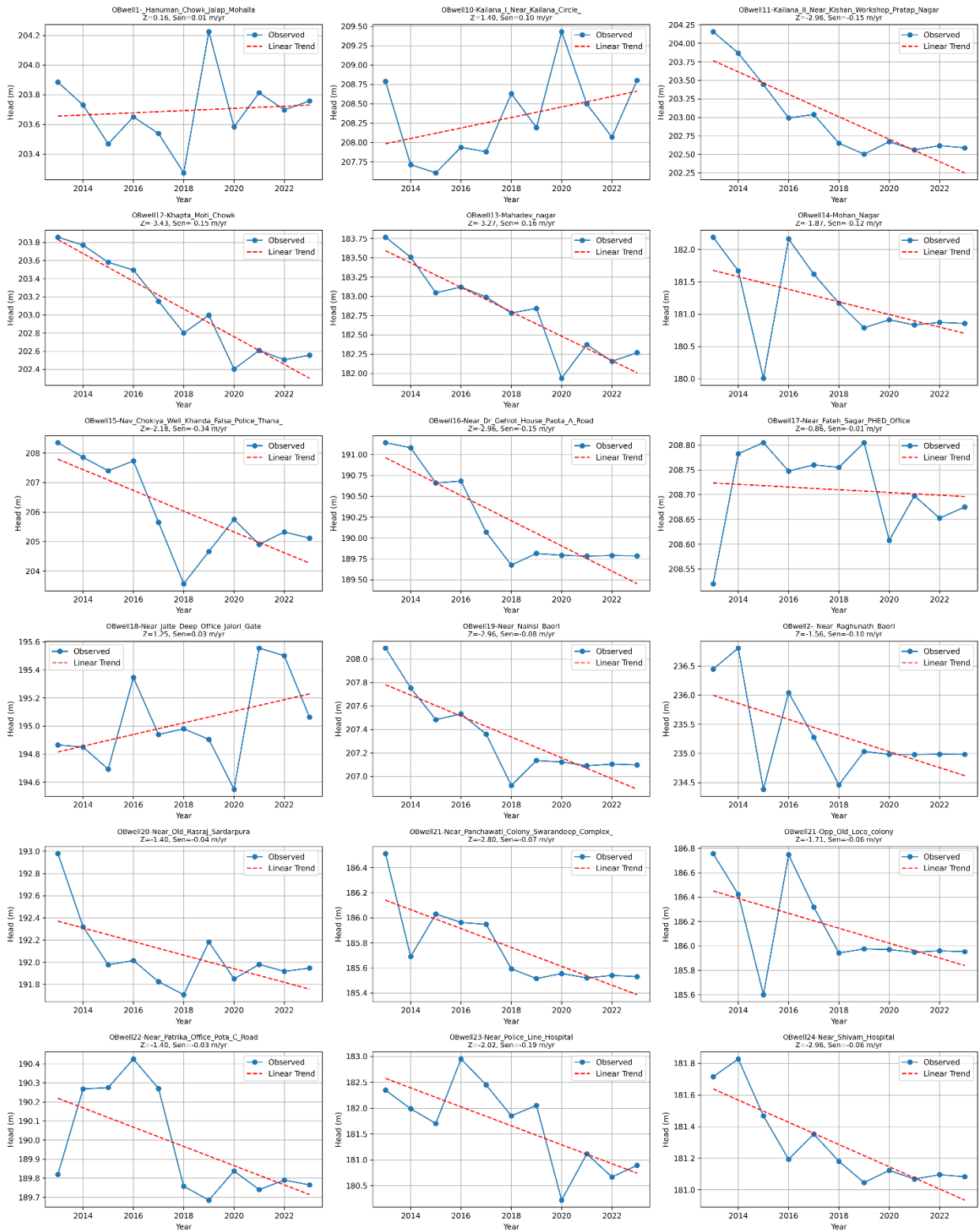
Pre-Monsoon Groundwater Head Trend Analysis (Jodhpur City)



Pre-Monsoon Groundwater Head Trend Analysis (Jodhpur City)



Post-Monsoon Groundwater Head Trend Analysis (Jodhpur City)



Post-Monsoon Groundwater Head Trend Analysis (Jodhpur City)



Annexure V - Performa for Groundwater Conditions Survey

उत्तर पश्चिमी क्षेत्रीय केंद्र, जोधपुर
राष्ट्रीय जल विज्ञान संस्थान

भूजल सर्वेक्षण प्रश्नावली

नाम:.....

आयु:.....

लिंग:.....

पता:.....

स्थान पर रहने का समय (वर्षों में):.....

अक्षांश:.....

देशांतर:.....

कुओं संख्या:.....

1. आप अपनी दैनिक जरूरतों के लिए मुख्य रूप से पानी कैसे प्राप्त करते हैं?
क) सार्वजनिक जल आपूर्ति ख) निजी कुओं
ग) बोललबंद पानी (कैमर) घ) अन्य (कृपया निर्दिष्ट करें)
 2. क्या आपने कभी अपने क्षेत्र में पानी की कमी की समस्या का अनुभव किया है?
क) हाँ, अक्सर ख) हाँ, कभी-कभी ग) नहीं, कभी नहीं
 3. क्या आप स्थानीय भूजल की स्थिति से परिचित हैं?
क) हाँ, बहुत परिचित ख) कुछ हद तक परिचित ग) बिल्कुल भी परिचित नहीं
- *यदि उपरोक्त का उत्तर (क) या (ख) है, तो: 4:
4. क्या आप जानते हैं कि आपके स्थान पर भूजल स्तर की अनुमानित गहराई क्या है?
क) 0-5 मीटर, ख) 5-10 मीटर, ग) 15-20 मीटर, घ) 20-25 मीटर
ङ) 25-30 मीटर, च) >30 मीटर छ) अनिश्चित
 5. क्या आप जानते हैं कि पिछले 10-15 वर्षों में भूजल की गहराई बढ़ी है या घटी है?
क) हाँ ख) नहीं ग) अनिश्चित
 6. यदि हाँ, तो पिछले 10-15 वर्षों में भूजल की गहराई में किसनी वृद्धि/गिरावट हुई है?
क) 0-1 मीटर ख) 1-2 मीटर ग) 2-3 मीटर
घ) 3-4 मीटर ङ) 4-5 मीटर च) >5 मीटर छ) अनिश्चित

7. क्या आपने पानी के स्तर में वृद्धि/गिरावट के कारण किसी समस्या का अनुभव किया है?
क) सोलन/नमी ख) जल जमाव ग) पानी की कमी घ) कोई अन्य, निर्दिष्ट करें
8. क्या आप अपने क्षेत्र में किसी भी भूजल पम्पिंग से अवगत हैं? यदि हाँ, तो पंप किए जा रहे भूजल का विवरण दें:
(i) मोटर के चलने के घंटे: 1 घंटा, 2 घंटे, 3 घंटे, 5 घंटे, 8 घंटे, 10 घंटे, कोई अन्य
(ii) चलने की आवृत्ति: दैनिक, साप्ताहिक
(iii) मोटर एचपी (HP): 1 एचपी, 2 एचपी, 3 एचपी, 5 एचपी, अन्य निर्दिष्ट करें
9. क्या आपने हाल के वर्षों में अपने नल के पानी के स्वाद, गंध या रंग में कोई बदलाव देखा है?
क) हाँ, महत्वपूर्ण परिवर्तन ख) हाँ, मामूली परिवर्तन ग) नहीं, कोई ध्यान देने योग्य परिवर्तन नहीं
10. क्या आपने अपने समुदाय में पानी की खपत से संबंधित कोई जलजनित बीमारियाँ या स्वास्थ्य संबंधी समस्याएँ देखी हैं?
क) हाँ, अक्सर ख) हाँ, कभी-कभी ग) नहीं, कभी नहीं
11. क्या आप अपने क्षेत्र के किसी ऐसे उद्योग या गतिविधियों से अवगत हैं जो भूजल पदार्थों में योगदान कर सकते हैं?
क) हाँ, विशिष्ट उद्योगों/गतिविधियों से अवगत हूँ (यदि हाँ, तो निर्दिष्ट करें)
ख) हाँ, लेकिन विशिष्ट उद्योगों/गतिविधियों के बारे में निश्चित नहीं हूँ
ग) नहीं, अवगत नहीं हूँ
12. क्या आप घर पर किसी भी जल संरक्षण उपाय/जल संरक्षण संरचना का अभ्यास करते हैं?
क) हाँ ख) नहीं
13. कृपया यदि भूजल संचयन संरचना आपके यहाँ बनी है, निर्दिष्ट करें:.....