



Quantifying Groundwater Depletion in an Intensively Cultivated Alluvial Region Using Integrated Remote Sensing, GIS, and Water Balance Approach: A Case Study of Patna District, India

Abstract: Groundwater depletion has become a serious problem for areas with intensive farming because it Endangers both their water resources and their ability to maintain agricultural practices. The research measures groundwater depletion in Patna District, Bihar (India) through a unified framework that combines groundwater level assessment with remote sensing data and GIS spatial methods. The study uses a basic volumetric method with satellite data because it needs to assess Power plants which have limited access to data. The analysis shows that groundwater levels in 2010 to 2024 period experienced a steady drop which resulted in a 4.9-meter water table reduction that reached 11.1 meters. The total groundwater storage loss is calculated at $2.35 \times 10^9 \text{ m}^3$ using a specific yield of 0.15 and the annual depletion rate amounts to $1.68 \times 10^8 \text{ m}^3$ per year. The remote sensing study shows that NDVI has grown to 0.59 from its previous value of 0.42 because agricultural activity has increased but NDWI has decreased to 0.10 from its former value of 0.21 which shows that surface water resources have reduced. The correlation analysis demonstrates that groundwater decline has a strong connection with NDVI ($r = +0.71$) and NDWI ($r = -0.68$) while rainfall shows only a weak relationship ($r = -0.22$) which indicates that it has restricted effect on long-term groundwater changes. The results show that human activities which include irrigation needs are the main cause of groundwater depletion in the study area while climatic changes have no impact on this issue which matches results from earlier research studies. The spatial analysis shows specific areas that experience increased depletion because of their use of heavy agricultural methods. The study finds that current groundwater extraction rates cannot be maintained and requires a 25 to 30 percent reduction in pumping to achieve aquifer level stability. The proposed integrated framework provides a scalable, cost-effective, and reliable approach for groundwater assessment especially in regions where data availability is limited and helps decision-makers to manage water resources in a sustainable way.

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1. Introduction

Groundwater stands as one of the essential freshwater resources that sustain agricultural output and domestic water needs and industrial operations throughout the world. Farmers in alluvial plains rely on groundwater as their primary irrigation source because of its dependable and easily obtainable nature (Zhu et al., 2026). The rising demand for groundwater resources has caused water systems to experience unsustainable extraction



levels which result in aquifer systems becoming depleted and raise major concerns about future water supply reliability.(Xia et al., 2026)

The problem of groundwater depletion is especially pronounced in developing countries such as India, where rapid population growth and agricultural intensification have significantly increased water demand(Bhilavekar et al., 2026; Xia et al., 2026). Over the past few decades, the Indo-Gangetic Plain, which ranks among the world's top agricultural regions has experienced significant groundwater depletion. Research shows that eastern regions of Bihar experience gradual groundwater depletion despite severe groundwater depletion in northwestern areas Punjab and Haryana which have received extensive research. The current pattern of water usage originates from irrigation-based farming methods which depend on tube wells while facing challenges from insufficient groundwater replenishment despite steady rainfall patterns(Lu et al., 2026).

The standard methods used for groundwater assessment, which include field monitoring and MODFLOW-based numerical modeling, deliver comprehensive information about underground water movement patterns(Hayek, 2026). The existing methods require extensive data collection and high processing capacity, and they present challenges which make it hard to conduct assessments in large areas that lack sufficient information. The combination of remote sensing technology with geospatial tools provides an efficient system which can be scaled up to work in various applications. The Normalized Difference Vegetation Index (NDVI) and Normalized Difference Water Index (NDWI), which are derived from satellite data, function as reliable indicators for assessing vegetation growth and water supply on the ground, which allows for the analysis of

how people use groundwater resources(Hayek, 2026; Li, Wang, et al., 2026). Researchers have shown that effective aquifer studies need to combine groundwater data with remote sensing observations and statistical methods. The reference study demonstrated that irrigation-driven pumping is the primary cause of groundwater depletion in agricultural regions because human activities, not climatic changes, control this process. The integrated frameworks improve groundwater assessment reliability while they reveal the main factors which cause groundwater depletion.

The study investigates groundwater depletion in Patna District Bihar through a combined approach that assesses groundwater levels and satellite remote sensing data and geographic information system (GIS) methods(Kitamura et al., 2026). The study uses a single method that combines water volume calculations with multi-spectral data because it needs to analyze spatial areas that lack research data yet needs to maintain strict research standards.

The specific objectives of the study are to:

- a) analyze the temporal variation of groundwater levels over the period 2010–2024;
- b) estimate groundwater storage depletion using a water balance approach;
- c) evaluate the relationship between groundwater dynamics and surface indicators, specifically NDVI and NDWI;
- d) examine the influence of rainfall variability on groundwater trends; and
- e) develop GIS-based spatial maps to identify groundwater stress and depletion risk zones.

The study aims to investigate groundwater depletion mechanisms and to create an assessment framework which local authorities can implement for sustainable groundwater



management and decision-making in agricultural areas.

2. Literature Review and Research Gaps

Groundwater depletion has been recognized as a vital environmental issue which also affects social and economic systems in agricultural areas that use water resources extensively (Bhilavekar et al., 2026; Kitamura et al., 2026). Various research investigations studied groundwater movement through different methods which included field monitoring and numerical modeling and remote sensing techniques. The studies demonstrate how excessive groundwater extraction together with land-use changes creates increasing pressure on aquifer systems. Groundwater assessment methods traditionally use two main techniques which consist of field measurements and numerical simulation models that include MODFLOW for predicting groundwater movement and future aquifer conditions (Bhilavekar et al., 2026; Hayek, 2026; Kitamura et al., 2026). The models deliver precise underground water movement patterns which researchers use to conduct particular location studies. The models face obstacles because they need extensive information and intricate calibration methods and they require high processing power which makes them unusable in developing areas that lack hydrogeological information. The demand for straightforward evaluation methods which can assess groundwater resources has become a major focus of research.

Researchers have discovered that remote sensing and geospatial technology create new opportunities for studying groundwater resources across extensive areas. Satellite-based vegetation indices which include the Normalized Difference Vegetation Index (NDVI) and Normalized Difference Water Index (NDWI) serve as common tools for studying plant growth and analyzing surface water conditions (Singh et al., 2026). The indices

function as indirect measures of groundwater consumption because increased plant growth results in greater water requirements for irrigation. Researchers have found through multiple studies that the combination of remote sensing information with groundwater data enables effective groundwater resource management.

The GRACE (Gravity Recovery and Climate Experiment) satellite program has enabled scientists to measure how groundwater storage has changed in specific regions (Singh et al., 2026; Zhao & Li, 2025). The studies which use GRACE data for their research create valuable information about long-term patterns, but their research can only be applied to larger areas because their study areas need more comprehensive research to achieve successful management. The assessment of groundwater systems needs to incorporate various datasets which include ground-based measurements and remote sensing indicators and GIS-based spatial analysis to create a complete evaluation. The reference study adopted a multi-dimensional framework combining groundwater level data, statistical modeling, and storage estimation techniques to quantify aquifer depletion. The study revealed that human activities which include irrigation pumping have caused groundwater depletion in agricultural areas while climate-related factors have shown lesser impact. The study showed that researchers need to identify all aquifer components which include fine-grained and coarse-grained storage to understand depletion processes more effectively.

The current research findings still have multiple challenges that need to be addressed despite the recent progress made in this field. The existing research either investigates complex numerical models which cannot be used in regions with limited data, or it depends entirely on remote sensing methods which fail



to show underground processes. The scientific community currently lacks integrated systems that enable straightforward yet effective combination of groundwater information with remote sensing data and spatial analysis conducted through GIS (Ali et al., 2026; Singh et al., 2026; Zhao & Li, 2025). The research community has studied eastern India as a moderately stressed area because groundwater resources there face slow but serious long-term depletion.

Research Gaps

The literature review established three research gaps which need to be studied further.

1. Lack of Simplified Integrated Frameworks

Most studies depend on either complex numerical models or separate remote sensing methods because researchers have not yet created simple combined techniques which can be used for regional studies in areas with limited data.

2. Limited Focus on Emerging Groundwater Stress Regions

Researchers have extensively examined severe groundwater depletion in northwestern India, but they have not studied eastern areas such as Bihar which display increasing groundwater stress.

3. Insufficient Linkage between Surface Indicators and Subsurface Dynamics

Although people use NDVI and NDWI indices for various applications, research has not yet demonstrated how these indices link to groundwater depletion patterns in specific local areas.

4. Inadequate Spatial Representation of Groundwater Risk

The majority of research studies fail to use GIS-based spatial mapping which helps identify specific areas experiencing groundwater stress that requires management and policy control.

5. Overemphasis on Climatic Factors

Several studies focus heavily on rainfall variability, whereas recent evidence including the reference study demonstrates that human

activities, especially irrigation demand, have a greater impact on groundwater depletion.

3. Methodology

3.1 Study Area Description

The research investigates Patna District which exists within the middle Gangetic alluvial plains of Bihar India (Kanji et al., 2025). The district extends from 25°30'N latitude to 25°45'N latitude and from 85°00'E longitude to 85°30'E longitude across a territory of approximately 3200 square kilometers. The region represents groundwater-dependent agricultural systems because its flat terrain and fertile alluvial soil support extensive farming operations in the area.

The study area hydrogeology contains unconsolidated alluvial aquifers which include sand and silt and clay layers that exhibit moderate to high permeability. The aquifer system exists as an unconfined system which allows groundwater to flow freely under phreatic conditions. The specific yield (Sy) typical range extends from 0.12 to 0.18 while the study adopted an average value of 0.15.

The region experiences a subtropical monsoonal climate which brings annual rainfall between 950 mm and 1100 mm that falls predominantly during the southwest monsoon period from June to September. The region maintains sufficient rainfall, yet groundwater resources face increasing stress because farmers rely heavily on paddy-wheat cropping systems which need extensive irrigation. The agricultural sector primarily depends on groundwater which it extracts through shallow and deep tube wells for irrigation purposes resulting in continuous aquifer resource depletion.

Sentinel-2 Level-2A Surface Reflectance imagery for the year 2024 was utilized in the present study for the generation of NDVI and



NDWI maps. Pre-monsoon season imagery (March–May) with cloud cover less than 20% was selected to ensure temporal consistency and minimize atmospheric and seasonal variability. Sentinel-2 imagery with 10 m spatial resolution was employed because of its suitability for detailed vegetation and surface moisture assessment at the regional scale. The acquired satellite imagery was processed in Google Earth Engine (GEE), where cloud masking, atmospheric correction, and median compositing techniques were applied to generate cloud-free images suitable for spectral index analysis.

The Normalized Difference Vegetation Index (NDVI) and Normalized Difference Water Index (NDWI) were subsequently derived from the processed imagery using standard spectral index equations. Spatial distribution maps and thematic analysis were carried out in QGIS, which was used for raster visualization, spatial interpretation, and cartographic preparation of NDVI and NDWI outputs. Statistical analysis, including descriptive statistics, trend interpretation, and correlation assessment, was performed using Microsoft Excel and SPSS to evaluate temporal variations and relationships among groundwater conditions, vegetation dynamics, and surface moisture characteristics.

3.2 Data Collection and Pre-processing

The analysis integrates multi-source datasets, including groundwater level records, rainfall data, and satellite-derived indices (Babela et al., 2026). The researchers obtained groundwater level data from secondary sources that included monitoring wells and published datasets to represent average seasonal conditions between 2010 and 2024. The researchers compiled rainfall data from regional meteorological records, while they validated the data through satellite-based datasets when necessary.

The team processed remote sensing data through Google Earth Engine (GEE) to obtain

multi-spectral indices (Babela et al., 2026; Singh et al., 2026), which included the Normalized Difference Vegetation Index (NDVI) and Normalized Difference Water Index (NDWI). The team selected Landsat imagery because its extended temporal coverage combined with sufficient spatial resolution met their requirements (Singh et al., 2026). The team pre-processed the images through atmospheric correction and cloud masking methods to achieve consistency across different time periods. QGIS served as the platform for spatial processing and visualization, which allowed the team to combine and assess thematic layers of groundwater depth and vegetation indices and water indices. The team digitized the study area boundary, while they standardized all datasets to a common coordinate reference system for consistency.

3.3 Groundwater Storage Estimation

The researchers measured groundwater depletion through a volumetric water balance method which used changes in groundwater levels as its measurement. The storage variation was estimated using the following relationship:

$$\Delta S = A \cdot S_y \cdot \Delta h$$

where ΔS represents groundwater storage change A is the study area S_y is the specific yield and Δh is the observed change in groundwater level.

The approach requires an aquifer system which maintains consistent properties throughout its entire area and has boundaries that remain fixed for alluvial plains at regional distances. The method has been widely adopted in groundwater studies and was also employed in the reference study to estimate aquifer storage variations under pumping stress.

3.4 Remote Sensing-Based Assessment

Satellite-derived indices were used to assess surface conditions which affected groundwater movement patterns. The NDVI was calculated to evaluate vegetation density and agricultural



intensity, while NDWI was used to assess surface water availability and moisture conditions. The selected time periods between 2010 and 2024 were used to compute these indices which show how time-based changes affected their results. The combination of NDVI and NDWI data establishes indirect evidence about groundwater extraction habits because increased plant life demands more water, while decreased water index values show that surface water supplies are diminishing (Beygi Heidarlou & Borz, 2026). This combined approach enables researchers to pinpoint areas of groundwater depletion while they use surface indicators to study underground activity, which follows the multiple-dimensional system described in the reference study.

3.5 Statistical and Correlation Analysis

The researchers used statistical correlation analysis to determine groundwater depletion relationships with its various influencing factors. The researchers used Pearson's correlation coefficient to compare groundwater level data with NDVI and NDWI and rainfall values. The analysis helps identify the main factors which cause groundwater depletion while measuring how much climatic elements and human activities affect the process. The researchers performed temporal trend analysis to study how groundwater levels and satellite-derived indices changed over an extended period (Morales-Ona et al., 2026). Researchers assessed the findings through the dual lens of agricultural intensification and the need for sustainable water resource management.

3.6 GIS-Based Spatial Analysis

Researchers used QGIS to perform spatial analysis which showed the patterns of groundwater depletion and its related indicators. The researchers used standard spatial techniques to create groundwater depth maps which they combined with NDVI and NDWI thematic maps to determine areas with

high agricultural activity and water stress. The researchers created a composite groundwater depletion risk map which combined groundwater depth data with NDWI layers to show the study area's vulnerability distribution. This GIS-based method helps researchers understand how groundwater depletion varies across different spaces while it enables them to create effective management plans.

3.7 Assumptions and Limitations

The methodology presumes that three specific conditions exist for the study. The study requires an aquifer system that has identical specific yield throughout its entire area. The study requires both groundwater inflow and outflow to be present at all times. The study requires groundwater level data that accurately represents all areas of the research zone. The assumptions make the analysis easier, but they suit regional assessment needs. The study results will be affected by local differences because aquifer characteristics and pumping rates lead to different results.

4. Results and Discussion

4.1 Temporal Groundwater Depletion Trends

The temporal analysis of groundwater levels in Patna district from 2010 to 2024 reveals a continuous decline in groundwater levels, indicating persistent aquifer stress and progressive groundwater depletion. The average depth to the water table increased from **6.2 m in 2010 to 11.1 m in 2024**, corresponding to a total decline of **4.9 m** over the study period (Table 1). The estimated average depletion rate was approximately **0.35 m/year**, suggesting that groundwater extraction consistently exceeded natural recharge. Although the observed depletion rate is lower than the critically stressed conditions reported in northwestern India, the trend still indicates a gradual transition toward unsustainable groundwater utilization.

Table 1: Temporal Variation of Groundwater Levels

Year	Average Depth to Water Table (m)	Incremental Decline (m)
2010	6.2	—
2015	7.8	-1.6
2020	9.5	-1.7
2024	11.1	-1.6

The groundwater decline pattern remained relatively consistent throughout the study period, with nearly similar depletion magnitudes observed across successive intervals. This indicates that groundwater abstraction remained continuously high, with no substantial recovery phase or recharge-driven stabilization observed during the analyzed years. Such behavior is characteristic of groundwater systems subjected to sustained pumping pressure for agricultural and domestic purposes.

The observed depletion trend may primarily be attributed to increasing dependence on groundwater-based irrigation, expansion of agricultural activities, population growth, and rising water demand across the region. In alluvial aquifer systems such as those present in Bihar, continuous extraction without adequate recharge gradually lowers the groundwater table and reduces aquifer storage capacity. Similar linear or near-linear depletion patterns under prolonged pumping conditions have also been reported in previous groundwater studies, where anthropogenic extraction was identified as the dominant driver of groundwater decline (Li et al., 2026). Furthermore, the absence of significant groundwater recovery even during years with relatively stable rainfall conditions suggests that natural recharge processes are insufficient

to compensate for long-term extraction. This indicates a growing imbalance between groundwater withdrawal and replenishment, highlighting the need for improved groundwater management strategies and regulated extraction practices in the study area.

4.2 Quantification of Groundwater Storage Loss

To quantify aquifer depletion the groundwater storage change was estimated using the specific yield-based volumetric approach. The study area of $3.2 \times 10^9 \text{ m}^2$ with a specific yield of 0.15 for alluvial formations shows that the observed groundwater decline of 4.9 m results in a groundwater storage loss of approximately $2.35 \times 10^9 \text{ m}^3$ which occurred during the 14-year period according to Table 2. The average annual depletion rate is therefore estimated at $1.68 \times 10^8 \text{ m}^3/\text{year}$.

Table 2: Estimated Groundwater Storage Depletion

Parameter	Value
Study Area	$3.2 \times 10^9 \text{ m}^2$
Specific Yield (Sy)	0.15
Water Level Decline	-4.9 m
Total Storage Loss	$2.35 \times 10^9 \text{ m}^3$
Annual Depletion Rate	$1.68 \times 10^8 \text{ m}^3/\text{year}$

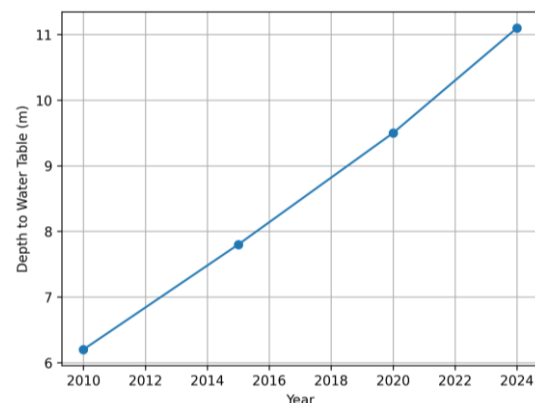


Figure 1: Groundwater Level Decline Trend (2010–2024)

The region experiences substantial storage loss because its irrigation system operates at moderate levels, which demonstrates that all agricultural zones which lack arid conditions face risks of permanent resource loss. The reference study reported similar levels of groundwater loss through agricultural extraction which occurred because groundwater resources (Figure 1) were overstressed and recharge rates decreased (Biswas et al., 2026; Li, Wang, et al., 2026).

4.3 Remote Sensing Indicators of Agricultural and Hydrological Stress

The integration of Google Earth Engine multi-spectral indices create vital data for understanding groundwater depletion through its surface driving factors. The Normalized Difference Vegetation Index (NDVI) increased from 2010 to 2024 because it reached 0.42 and then grew to 0.59 which indicates that vegetation development and agricultural land usage increased. The Normalized Difference Water Index (NDWI) showed a decrease from 0.21 to 0.10 which indicated that surface water resources and soil moisture levels experienced a decline (Table 3).

Table 3: Temporal Variation of NDVI and NDWI

Year	NDVI	NDWI
2010	0.42	0.21
2015	0.48	0.18
2020	0.54	0.14
2024	0.59	0.10

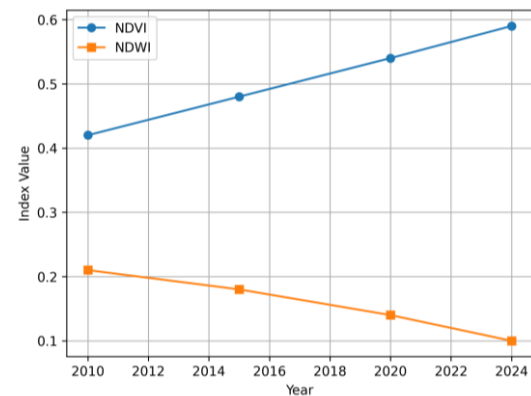


Figure 2: NDVI and NDWI Trends (2010–2024)

The rising NDVI trend shows that farmers now use more intensive agricultural methods which need additional water resources for their farming operations. The decreasing NDWI shows that there is less surface water availability which forces people to rely more on underground water sources. The inverse relationship between vegetation intensity and water availability proves that agricultural intensification causes groundwater depletion according to integrated evidence from the reference study (Bhilavekar et al., 2026).

4.4 Rainfall Variability and Groundwater Response

Assessments of rainfall patterns show that they create moderate yearly fluctuations which do not produce a long-term trend of decreasing rainfall. The study period experienced rainfall values which ranged from 980 mm to 1105 mm while Table 4 shows that groundwater levels maintained a continuous downward trend.

Table 4: Rainfall vs Groundwater Depth

Year	Rainfall (mm)	Groundwater Depth (m)
2010	1020	6.2
2015	980	7.8
2020	1105	9.5
2024	1015	11.1

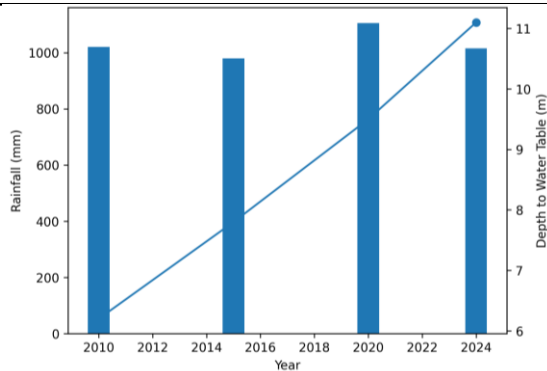


Figure 3: Rainfall vs Groundwater Trend

The present groundwater extraction rates exceed natural recharge capabilities because rainfall patterns (Figure 3) do not match groundwater level fluctuations. The year 2020 experienced more rainfall than other years yet groundwater levels continued their downward trend because groundwater movement had separated from the effects of temporary climate changes. The observation supports the study results which showed that agricultural groundwater systems depend mostly on human-managed water flows instead of natural climate variations(Li, Zhang, et al., 2026).

4.5 Statistical Relationship between Surface Indicators and Groundwater Depletion

The researchers conducted correlation analysis to assess how groundwater decline connects with essential driving factors that appear in Table 5. The results show a strong positive correlation between NDVI and groundwater depletion ($r = +0.71$), which indicates that higher vegetation activity leads to increased groundwater consumption. NDWI shows a strong negative correlation because its value decreases to ($r = -0.68$) which shows that reduced surface water supplies result in greater groundwater depletion. Rainfall demonstrates a weak correlation which results in a value of ($r = -0.22$) that shows it has little impact on groundwater patterns that last over time.

Table 5: Correlation Analysis

Parameter	Correlation Coefficient (r)
NDVI	+0.71
NDWI	-0.68
Rainfall	-0.22

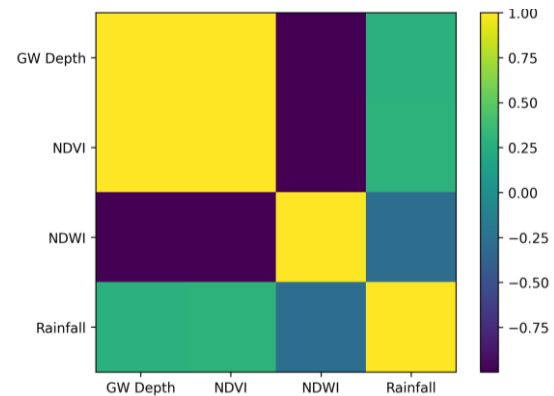


Figure 4: Correlation Matrix Plot

Agricultural water consumption stands as the main cause of groundwater depletion according to the results shown in figure 4 which validate the conceptual framework established in the referenced study.

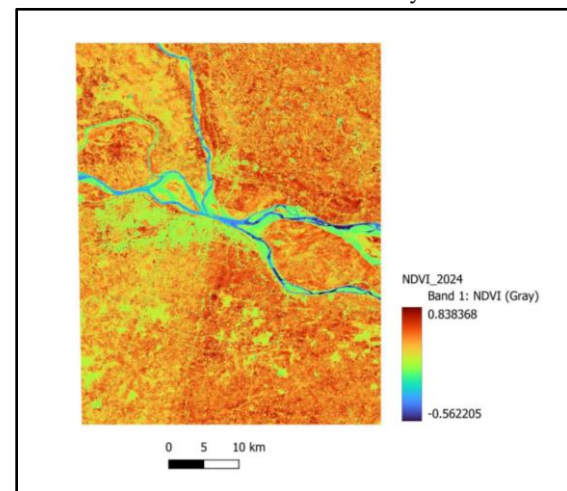


Figure 4. Spatial distribution of NDVI in Patna district during the pre-monsoon period of 2024 derived from Sentinel-2 Surface Reflectance imagery.

The NDVI spatial distribution map (Figure 5) reveals moderate to high vegetation intensity across agriculturally dominant regions of Patna

district, particularly near irrigated agricultural zones and riverine areas. Higher NDVI values were observed in cultivated regions, indicating active vegetation growth and intensive agricultural practices. In contrast, lower NDVI values corresponded to urbanized areas, exposed soil surfaces, and water bodies. The calculated mean NDVI value of 0.3938 indicates moderate vegetation density within the study area during the pre-monsoon season.

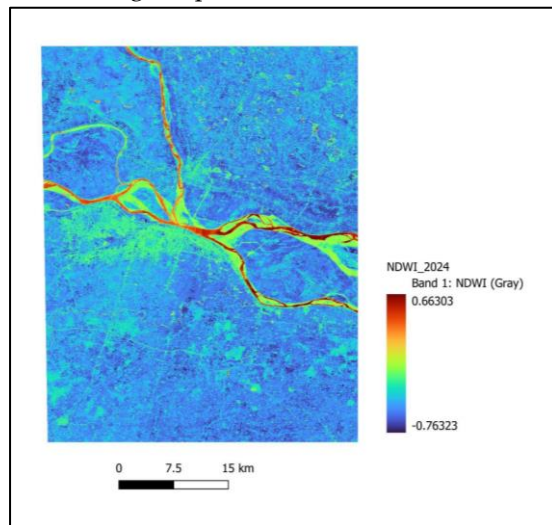


Figure 5. Spatial distribution of NDWI in Patna district during the pre-monsoon period of 2024 derived from Sentinel-2 Surface Reflectance imagery.

The NDWI spatial analysis indicates in Figure 6 that surface moisture availability is primarily concentrated along river channels and localized wetland regions, while most parts of the district exhibit relatively low moisture conditions. The mean NDWI value of -0.4283 suggests generally dry surface conditions during the pre-monsoon period, reflecting increased dependence on groundwater resources for agricultural activities. The observed spatial variability highlights the uneven distribution of moisture conditions across the district.

4.6 Integrated Interpretation and System Behavior

The assessment of groundwater levels together with storage loss and remote sensing indices and rainfall patterns shows a unified system that generates increasing groundwater stress.

The ongoing decrease in groundwater levels together with rising plant growth and diminishing surface water resources demonstrates an agricultural expansion cycle that leads to groundwater extraction which further decreases surface water and soil moisture resources. The QGIS spatial analysis results demonstrate two patterns of land use in agricultural zones and riverbanks and their respective impacts on environmental health (Adiguzel et al., 2026). Agricultural zones display higher rates of resource depletion than other areas. River-adjacent areas show relatively stable conditions because local water sources help maintain their ecological balance. The transition of peripheral zones toward moderate stress levels represents an ongoing process.

4.7 Sustainability Implications

The aquifer system has reached unsustainable exploitation limits because of its current storage loss and depletion rate. Groundwater level stabilization requires a 25 to 30 percent reduction of extraction or a major increase in recharge through managed aquifer recharge.

5. Conclusion

The present study achieved its objective of measuring groundwater depletion in Patna District Bihar by combining three methods which included groundwater level monitoring and remote sensing data and GIS spatial mapping. The analysis of time showed that groundwater levels decreased from 6.2 meters in 2010 to 11.1 meters in 2024 which resulted in a total water loss of 4.9 meters and an average yearly decrease of about 0.35 meters. The volumetric water balance method estimated total groundwater storage loss at $2.35 \times 10^9 \text{ m}^3$ which demonstrates that aquifers experience high stress levels throughout areas with moderate agricultural activity.

The research demonstrated a strong connection between groundwater depletion and remote



sensing derived surface indicators. The agricultural expansion and increasing irrigation requirements caused the NDVI values to rise from 0.42 to 0.59, while the NDWI values declined from 0.21 to 0.10 which showed decreasing surface water resources and rising reliance on groundwater. The correlation analysis showed that groundwater decline strongly connects to vegetation intensity and water availability, while rainfall showed a weak link because human activities caused groundwater depletion more than climate change did. The GIS spatial analysis used to study different areas showed that agricultural zones experienced higher groundwater stress which proved that the integrated framework successfully detected specific depletion locations. The study results show that the selected method creates a strong system which can be expanded at low costs to assess groundwater resources in areas without data access. The findings demonstrate that even regions which use moderate irrigation systems face ongoing groundwater depletion, which creates an urgent need for sustainable practices to manage groundwater resources.

6. Limitations of the Study

The present study utilized district-scale groundwater and remote sensing datasets, which may not fully capture localized hydrogeological variability. Groundwater level analysis was based on secondary monitoring data, and seasonal groundwater fluctuations beyond the selected pre-monsoon period were not considered. Additionally, the study adopted a simplified water balance framework rather than a fully calibrated numerical groundwater model such as MODFLOW. Despite these limitations, the integrated methodology provides a reliable and scalable approach for regional groundwater assessment.

7. Policy Recommendations

The study results show that immediate policy actions are needed to stop groundwater depletion while maintaining water resources for future generations. The agricultural sector needs stricter groundwater extraction controls which should include both regulated pumping practices and groundwater monitoring technology. The implementation of water reduction programs through metered irrigation systems and water pricing models will help decrease water extraction rates.

The promotion of water-efficient irrigation systems, which include drip and sprinkler systems should be implemented as a method to decrease groundwater consumption. The agricultural sector can reduce aquifer stress through crop transition from water-intensive plants to less water-demanding agricultural methods. Managed aquifer recharge (MAR) systems through rainwater harvesting and recharge wells and check dams will improve groundwater replenishment during the monsoon season.

The institutional framework needs to support remote sensing and GIS technology integration for groundwater monitoring purposes. The tools enable organizations to assess groundwater conditions continuously at a low cost while they help decision-makers make evidence-based choices. Community involvement and public education programs form two vital components which help enforce sustainable water usage regulations and support successful policy implementation.

8. Future Scope

The current study shows how researchers can use their basic assessment method to evaluate groundwater depletion. Future studies can use advanced numerical models which include MODFLOW to study groundwater flow patterns and assess multiple management strategies. GRACE satellite data enables



scientists to study groundwater storage changes which occur across extensive regions. The use of higher-resolution remote sensing datasets together with time-series analysis enables better measurement of surface indicators which show seasonal changes in groundwater consumption. Groundwater dynamics can be better understood through the combination of socio-economic elements which include irrigation methods and population increases together with policy effects. Researchers can use Monte Carlo simulations as uncertainty analysis methods to determine storage estimate differences and make their models more trustworthy. The proposed framework enables researchers to investigate other regions which experience the same difficulties as existing sites because of their capacity to perform cross-regional comparisons that include different hydrogeological and climatic conditions. Generalized model development will be advanced through such studies while regional groundwater management strategies will receive support through these findings.

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