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Assessing Spatially Heterogeneous Impact of Land Use Land Cover Dynamics on Groundwater Quality Using Geostatistical Approach

Sanjib Das[1], Rijurekha Dasgupta[2], Sribas Kanji[3], Gourab Banerjee[4], Asis Mazumdar[5]
School of Water Resources Engineering, Jadavpur University

Abstract: Groundwater serves as a critical resource for domestic consumption, agriculture, and industrial applications worldwide. However, its quality is increasingly threatened by anthropogenic activities, especially land use and land cover (LULC) changes, which alter the quality status and affect aquifer vulnerability. Hence, it is important to understand the spatiotemporal pattern of this impact to develop sustainable land and water management plans. This study examines the spatial heterogeneity of the impact of LULC dynamics on groundwater quality in an anthropogenically affected zone using decadal dataset. A combination of remote sensing application and GIS-based spatial analysis was employed to evaluate eight key LULC transitions. These transition-maps were then overlaid with spatial nitrate-concentration data from groundwater samples to evaluate how different land-use changes affect groundwater quality across space. Results indicate that there is spatial heterogeneity in the impact of LULC transitions. Nitrate concentrations rose sharply in land areas converted to crop land and built-up zones, with the largest increases seen when fallow or waste lands were turned into crop land, where nitrate concentration (mg/l)changed from -30.384 to +92.751 and from -30.879 to +95.125 respectively. In contrast, changes were smaller where scrub forests were altered. Waterbody areas also showed increases, but not as strong as agricultural or urban shifts. The overall analysis regarding the impact of LULC transition does not exhibit the details of spatial distribution. It will guide the land and water management policy makers to develop more local-based planning to achieve sustainability aiding the cause of SDG 6.
Keywords: Groundwater quality, Nitrate contamination, Land use/land cover change, Remote sensing, GIS, Sustainable groundwater management, Aquifer vulnerability.

I. INTRODUCTION

Water is essential for life, with clean and mineral-rich water being crucial for human health (Ghosh et al., 2021). A major share of this water comes from underground aquifers, which supply about 34% of the world's freshwater and serve as a key resource for agriculture, industry, and households (Shekhar & Pandey, 2015). In developing countries like India, groundwater plays a crucial role, meeting about 85% of rural and approximately 50% of urban drinking water requirements, and supplying around 60-70% of irrigation water used in agriculture (Agarwal et al., 2013).

Rising population and growing commercial activity are intensifying pressure on freshwater supplies, particularly in arid, semi-arid, and rural regions where groundwater is vital for drinking, domestic use, and agriculture (Mukherjee et al., 2012). However, environmental changes and human activities are degrading groundwater quality, leading to contamination by harmful chemicals such as lead, chloride, ammonia, and nitrate (Rashid et al., 2021).

The intense groundwater irrigation which has started in Bengal since 80s led to the widespread adoption of high-yielding crop varieties, boosting food production but greatly increasing the demand for irrigation water (Schirmer et al., 2013). To meet this demand, farmers increasingly relied on groundwater, causing a rapid rise in its use across regions. Groundwater level fluctuations are influenced by factors such as agricultural output, land area under irrigation, water use in various sectors, and extraction methods. Many areas have experienced a steady groundwater decline, with drops of 1-2 meters per year reported in some locations (Prabhakar & Tiwari, 2015), raising serious concerns about long-term water security.

Groundwater depletion and quality deterioration are major concerns in many urban and peri-urban regions due to both natural hydrogeological conditions and intensified human activities (Thapa et al., 2018). Excessive groundwater abstraction lowers water levels and increases the concentration of dissolved ions, while land use/land cover (LULC) changes-such as agricultural expansion, urbanization, and industrial development-modify recharge processes and introduce contaminants.

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The extensive use of nitrogen and phosphate based fertilizers contributes to nitrate and sulfate enrichment in groundwater. High fluoride (>1.5 mg/l) causes dental fluorosis (Kaur et al., 2016), nitrate above 45 mg/l can lead to methemoglobinemia (Jain et al., 2010), and arsenic beyond 0.05 mg/l is linked to chronic diseases (Chakraborti et al., 2016). Hydrochemical and statistical analyses help distinguish geogenic and anthropogenic contamination sources (Viswanath et al., 2015), informing sustainable management.

LULC change assessments show clear impacts on groundwater: urbanization and industry reduce recharge and increase contaminants, while agricultural expansion raises nitrate and phosphate via fertilizer leaching (Dolui & Sarkar, 2023). Remote-sensing and hydrochemical studies report falling water tables and higher dissolved ions where natural cover converts to crops or built-up land (Choudhury et al., 2019). Research links fertilizer use to nitrate/sulfate increases and sewage or industrial discharge to metals and organics, underscoring the need for integrated LULC–groundwater management. GIS supports identifying suitable groundwater recharge zones, linking data with physical and socio-economic factors, and creating predictive groundwater maps (Ashtekar & Mohammed-Aslam, 2019).

Some studies have examined groundwater quality with emphasis on aquifer characteristics and general physicochemical parameters (Debnath & Mondal, 2013). However, a key research gap persists in understanding how land use and land cover (LULC) changes influence groundwater quality spatially. Previous studies indicate that the impact of land transitions is not uniform: for instance, agricultural-to-built-up conversion may lead to markedly different groundwater responses across regions due to variations in cropping practices, fertilizer application, irrigation intensity, and settlement expansion patterns (Viswanath et al., 2015). Even within a single study area, local-scale practices produce spatial heterogeneity in contamination levels. Addressing this gap, the present study examines how spatial variations in LULC transitions relate to groundwater nitrate contamination over time, employing an integrated methodological framework to capture these localized differences and their implications for groundwater quality.

The study adopts an integrated geospatial and hydro-chemical analysis framework. Multi-temporal satellite imagery (2005, 2015, and 2025) will be processed and classified using supervised classification techniques to generate LULC maps. LULC transition matrices and spatial change detection methods will be used to assess land use shifts and heterogeneity. Groundwater samples corresponding to the same time periods will be analyzed with a focus on nitrate concentration. Spatial interpolation techniques (e.g., IDW/Kriging) will be applied to map groundwater quality patterns. Finally, spatial overlay analysis will be conducted to examine the relationship between LULC transitions and nitrate contamination, enabling the identification of pollution hotspots and anthropogenic influence zones. The study is structured around the following specific objectives:

1) To systematically map and assess the patterns of Land Use/Land Cover (LULC) changes for the years 2005, 2015, and 2025 using geospatial techniques to understand decadal patterns.
2) To analyze temporal variations in groundwater quality, with emphasis on changes in nitrate concentrations across the same time periods.
3) To quantify the relationship between LULC changes and groundwater nitrate levels, identifying spatial hotspots and potential anthropogenic drivers.
4) To propose a scientifically grounded framework for sustainable groundwater management and pollution mitigation in the region.

II. MATERIALS AND METHODOLOGY

A. Study area

Birbhum, located in western West Bengal, is the northernmost district of the Burdwan Division with Suri as its administrative headquarters. It covers about 4,545 sq. km between 23°32′30″N-24°35′00″N and 87°05′25″E-88°01′40″E, bounded by Jamtara, Dumka, and Pakur of Jharkhand to the west and Murshidabad and Purba Bardhaman to the east and south respectively. The district comprises three subdivisions (Suri, Rampurhat, and Bolpur), along with 19 CD Blocks, 167 Gram Panchayats, six municipalities, and 2,242 villages. As per Census 2011, the population is 3,502,404 with a density of 771 persons/sq. km. Physiographically part of the "Rarhbanga" region, it shows Archean rocks in the west and northwest, Rajmahal basalt in the north, and older alluvium and recent floodplain deposits in the southeast (Mondal et al., 2014). The terrain is gently undulating, with a dry to moderately humid climate and annual rainfall of ~1,420 mm. Groundwater, the primary source of drinking and irrigation, flows west to east. Eastern tube wells (avg. 100 m depth. The district's annual groundwater draft is estimated at about 0.036 million ham, of which roughly 0.032 million ham (~89%) is withdrawn for irrigation while only about 0.0038 million ham serves domestic and industrial needs, indicating strong irrigation-dominated pressure on the resource. According to CGWB (2009), blocks like Murarai-II, Nalhati-II, Rampurhat-II, and Nanoor are semi-critical due to seasonal groundwater fluctuations. Nitrate exceeds 45 mg/l in 17% of shallow aquifer samples but only 0.6% in deeper aquifers, with Rampurhat-II samples mostly within safe limits.

Birbhum's present land-use/land-cover is dominantly agricultural, with roughly 3,329.05 km² area under cultivation (≈73.25%), reflecting that the vast majority of land and livelihoods remain tied to farming. Major LULC classes include extensive croplands (rice, legumes, potatoes, oilseeds), scattered forest patches (~159.3 km²), built-up and non-agricultural areas concentrated around towns, and fallow/uncultivated uplands in the western lateritic zone.

Agricultural productivity in Birbhum shows distinct spatial variation when evaluated using the Agricultural Productivity Index, which considers crop yield, cropping intensity, input usage, and land capability. Blocks with index values above 115, such as Mayureswar-II, Labpur, Nalhati-I, and Bolpur-Santiniketan, form the high productivity zone, benefiting from fertile loam–clay soils and favourable hydrological support from rivers like the Ajoy. Mohammad Bazar, Sainthia, and Mayureswar-I fall under moderate productivity (index 95–115), while Nalhati-II, Murarai-I/II, and Suri-II represent low productivity areas (index 75–95).Rampurhat-I, Rajnagar, and Khoyrasole lie in the very low productivity zone (index below 75), where lateritic soils and limited soil nutrients constrain agricultural growth. This pattern is similarly reflected in agricultural development levels, which are highest in the east, moderate in the north, lower in the south, and lowest toward the western plateau fringe.

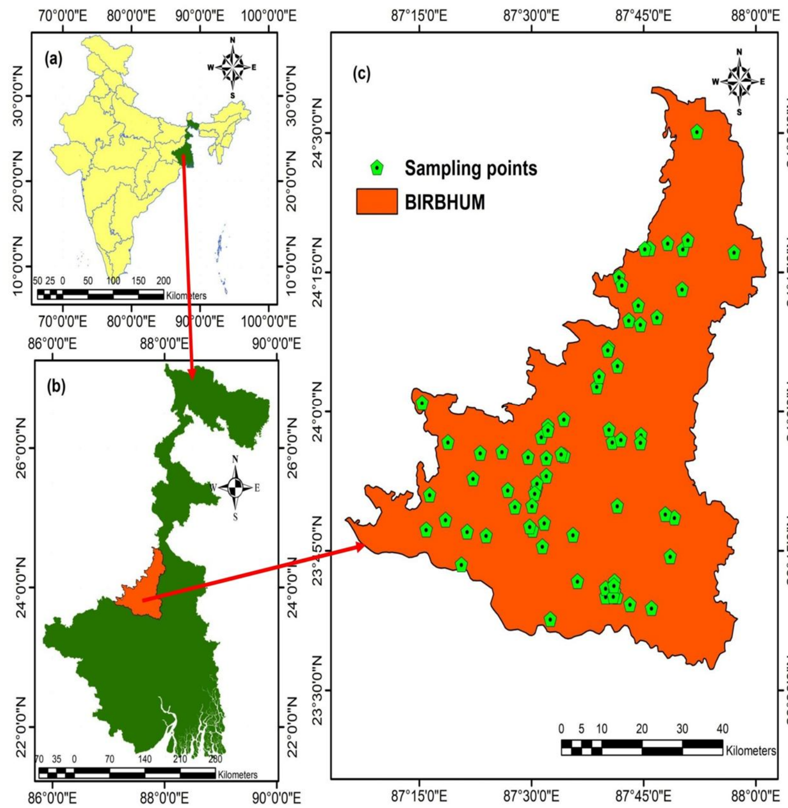


Fig. 1 Map and geographic location of the study area

III.OVERALL METHODOLOGY

This research adopts a multi-temporal, spatial analytical framework using geospatial technologies to assess LULC changes and groundwater quality dynamics at the local scale. By integrating remote sensing data, GIS-based change detection, and groundwater quality evaluation, the study identifies spatial and temporal trends while quantifying nitrate contamination levels. Particular emphasis is placed on capturing spatial heterogeneity, recognizing that land use transitions and groundwater responses vary across locations due to differences in agricultural practices, settlement expansion, and hydrogeological settings (Fig.2).The decadal variations of nitrate concentration are first evaluated with the help of spatial interpolation and mathematical operations. The variation of this nitrate concentration is then segregated into different LULC transition zones at different temporal periods to the spatial pattern of the role of various LULC transition zones across the geographical area. Finally, this study develops a basic framework for the policy makers and executives to identify potential critical zones of heavy anthropogenic load on groundwater and to explore the spatial heterogeneity found in the role of LULC transition zones in altering nitrate concentrations.

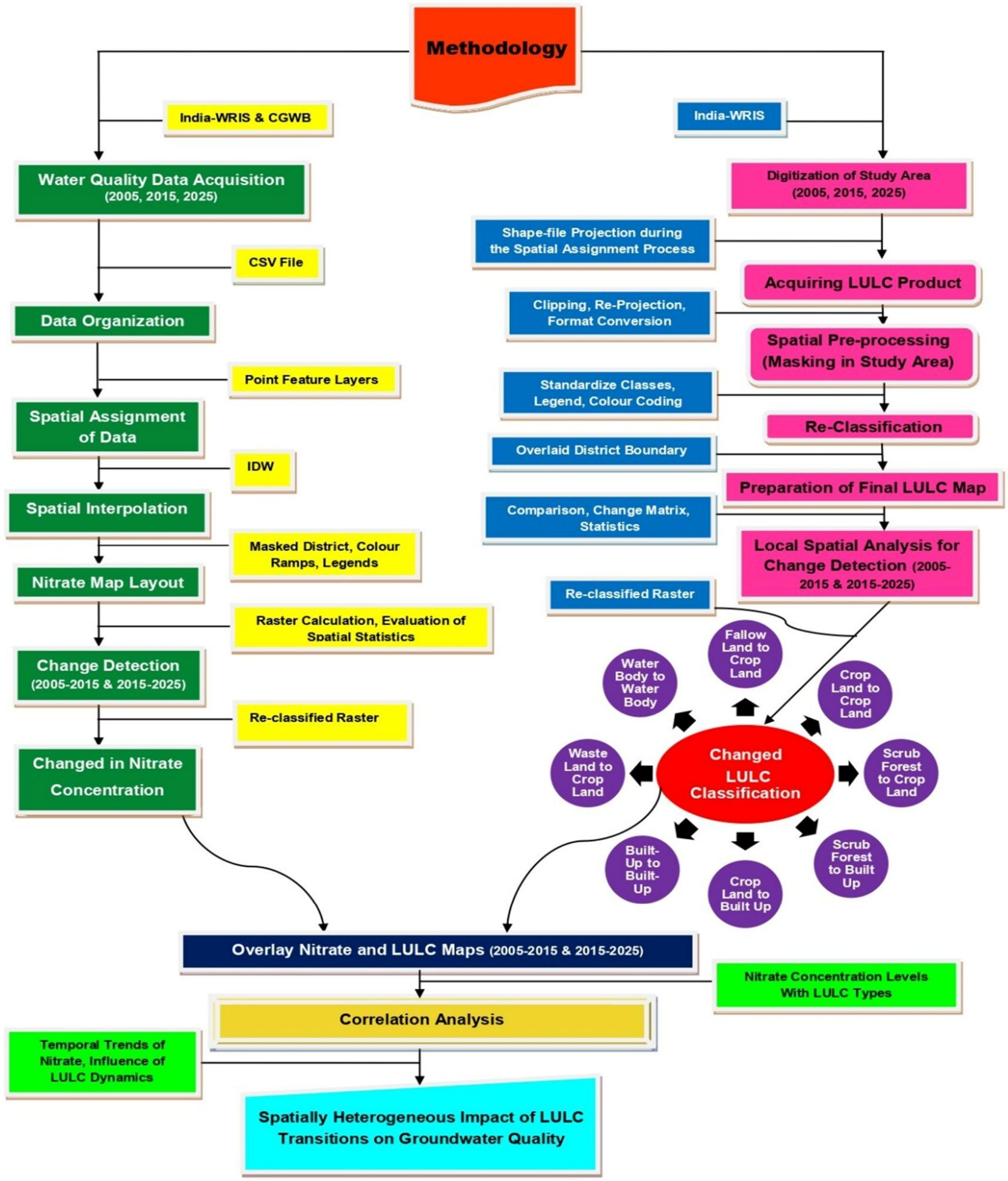


Fig. 2 Flowchart of the methodology adopted

B. Groundwater quality data

The foundation of this study is a dataset of groundwater quality parameters sourced from the CGWB and accessed through the India-WRIS public domain portal (https://indiawris.gov.in/wris). The data comprises geo-spatially referenced 72 dug-well monitoring stations located throughout the Birbhum district. To assess the quality status of groundwater in Birbhum district, fourteen standard water quality parameters were considered: pH, Electrical Conductivity (EC, µS/cm), Total Dissolved Solids (TDS, mg/l), Calcium (Ca^{2+}, mg/l), Magnesium (Mg^{2+}, mg/l), Sodium (Na^{+}, mg/l), Potassium (K^{+}, mg/l), Iron (Fe, mg/l), Bicarbonate (HCO_3^{-}, mg/l), Chloride (Cl^{-}, mg/l), Fluoride (F^{-}, mg/l), Sulphate (SO_4^{2-}, mg/l), Nitrate (NO_3^{-}, mg/l), and Total Hardness (TH, mg/l). Their selection aligns with standard practices for evaluating the suitability of groundwater for drinking and agricultural use.

C. LULC map preparation

The methodology for LULC map preparation was executed through a systematic multi-step process, ensuring accurate spatial representation and change analysis of land use over the period from 2005 to 2025. LULC raster and vector datasets for the years 2005, 2015, and 2025 were obtained from the India-WRIS portal, focusing explicitly on the boundary of study area. These datasets provided the foundational spatial information necessary for subsequent analysis. All datasets were then standardized to a common coordinate system, specifically WGS 84 / UTM Zone 45N, to ensure spatial consistency across different datasets. During the pre-processing phase, the LULC layers were clipped to the study area boundary, reprojected to a uniform coordinate system, and converted between raster and vector formats where required, facilitating seamless data analysis. Subsequently, the LULC data was reclassified to achieve a standardized set of land use categories. These included classes such as Fallow land, Crop Land, Deciduous Forest, Scrub Land, Scrub Forest, Plantation, Built-up, Waste Land, and Water Bodies.

The classification process involved harmonizing class codes and legends across the datasets from different years, thus allowing for accurate temporal comparison. Standard color coding was assigned to each class for visualization purposes. Map preparation involved generating thematic LULC maps for each of the selected years using ArcGIS. The maps were enhanced with cartographic elements including legends, north arrows, scale bars, and titles for clarity. Overlay layers, such as administrative boundaries, were incorporated to provide contextual understanding of land use patterns within the district. Change detection analysis was conducted by comparing the LULC maps across different time points, specifically between 2005-2015 and 2015-2025. This process included the creation of change matrices to quantify transitions such as a) Fallow land to Crop land, b) Crop land to Crop land, c) Scrub forest to Crop land, d) Scrub forest to Built-up, e) Crop land to Built-up, f) Built up to Built-up, g) Waste land to Crop land, and h) Waterbody to Waterbody. The selected LULC transitions are chosen because they exemplify meaningful changes in land function (agricultural intensification, urbanization, land reclamation) that are known drivers of nitrate mobilization and groundwater quality degradation; they allow comparative analysis of different change-pathways; and they align with the study area's dynamics and data availability. Area calculations in square kilometers were performed for each class and change, providing quantitative insights into land transformation over the two periods. The final outputs encompassed a set of detailed maps: three LULC maps for the years 2005, 2015, and 2025, and two change detection maps illustrating land use transitions for 2005–2015 and 2015–2025.These were supplemented with summary tables that detailed the extent of each land use class, along with percentage changes over time. All GIS-ready layers, including shapefiles and raster datasets, were prepared for further spatial analysis and decision-making purposes.

D. Nitrate map preparation

Nitrate concentration maps for Birbhum district of West Bengal were generated for the years 2005, 2015, and in GIS environment by applying the Inverse Distance Weighted (IDW) interpolation technique to georeferenced groundwater nitrate concentration data. The IDW method is a deterministic spatial interpolation approach that estimates values at the unknown points within the extent of known points by providing more importance on the nearby points compared to those farther away. This makes it particularly suitable for environmental applications such as groundwater quality mapping, where spatial variability plays a significant role in understanding the spatial distribution of contaminant concentration (Ambica et al., 2017). Groundwater nitrate data for the selected years were sourced from reliable secondary databases (https://indiawris.gov.in/wris/#/GWQuality). The datasets included georeferenced coordinates (latitude and longitude) along with corresponding nitrate concentration values in mg/l. Each set of nitrate sampling points was converted into point feature layers using latitude and longitude. Subsequently, the IDW interpolation is executed in GIS environment. The resultant rasters were clipped to the Birbhum district boundary to restrict the analysis within the study area.

E. Geostatistical operations

The geostatistical operations performed in this study have formed the foundation of capturing the spatial heterogeneity of the impact of LULC transition zones on groundwater nitrate concentrations. The geostatistical operations are executed using three different data layers such as- nitrate concentration change in groundwater (in raster form), the LULC transition zones (in raster form) and the village-level map of the study area (in vector form). Three major steps have been adopted to carry out the geostatistical operations in this study. First, the cell to cell combining has been implemented to evaluate the spatial distribution of nitrate concentration change in different LULC transition zones. At the end of this step, a raster layer is developed with two bands of nitrate concentration change and LULC transition zone (transformed from categorical to numerical). At the second step, the aforementioned raster is segregated using zonal extraction analysis where the village-wise impact of LULC transition zones on nitrate concentration change is obtained. At the last step, the segregated vector is merged and further rasterized.

This entire process is done for two decades that is from 2005-2015 and 2015-2025. This geostatistical operation provides advantages over the conventional change detection studies as because it doesn't exhibit an overall mean of nitrate concentration change in a particular LULC transition zone only but it evaluates the spatial heterogeneity of the impact. The details of this advantage are discussed in the discussion section later.

IV. RESULTS AND DISCUSSIONS

A. Statistical evaluation of groundwater quality

The present study revealed that the groundwater quality of Birbhum district has undergone notable temporal fluctuations in minimum, maximum, and mean values, reflecting varying degrees of contamination and natural variations during the years 2005, 2015, and 2025 (Table I).

Table I
Statistics of groundwater quality parameters of Birbhum district during 2005, 2015 and 2025.

Groundwater quality parameters & Unit	Year - 2005			Year - 2015			Year – 2025		
	Min	Max	Mean±Std.dev	Min	Max	Mean±Std.dev	Min	Max	Mean±Std.dev
pH	7.01	8.30	7.890±0.30	7.60	8.10	7.90±0.100	6.04	9.56	7.58±0.570
EC (μS/cm)	50	1900	510±378	176	3985	848±729	169	2166	629±397
TDS (mg/l)	34	1273	337±256	118	2670	568±489	113	1451	415±267
TH (mg/l)	20	583	154±102	60	1410	252±225	45	420	185±81
Ca^{2+} (mg/l)	06	76	29±16	12	332	48±42	10	130	44±25
Mg^{2+} (mg/l)	1.22	59.59	16.98±14.9	4.8	206	29.00±33.6	4.0	50	16.50±9.74
HCO_3^- (mg/l)	18	403	162.7±93.7	85	1196	290.2±196	31	537	206.9±111
Na^+ (mg/l)	01	330	48±54	17	370	77±73	08	274	52±50
K^+ (mg/l)	0.01	130	11±25	0.05	255	17.6±41.3	01	218	3.0±39.0
Fe (mg/l)	0.01	5.1	1.23±1.34	0	7.88	1.25±1.98	0.04	8.15	0.46±1.14
Cl^- (mg/l)	07	372	68±80	07	1163	121±186	14	255	76±64
F^- (mg/l)	0.07	11	0.76±1.37	0	02	0.63±0.46	0.04	8.15	0.46±1.14
SO_4^{2-} (mg/l)	01	194	24±39	0	282	24±39	0	89	14.58±20.6
NO_3^- (mg/l)	0	35.0	4.22±7.12	0	115	11.3±18.8	0	49	12.34±15.2

Nitrate concentrations in the groundwater show a clear increasing trend from 2005 to 2025, indicating a growing influence of anthropogenic activities on the aquifer system. In 2005, nitrate values ranged from 0 to 35 mg/L, increasing substantially by 2015 when the maximum concentration reached 115 mg/L, the highest recorded in the entire dataset. Although the peak value decreased to 49 mg/L in 2025, it still approached the WHO permissible limit for drinking water, suggesting continued nitrate stress in certain locations. The extremely high value observed in 2015 implies the presence of localized hotspot regions, likely associated with intensive agricultural practices involving nitrogen-rich fertilizers, leakage from domestic sewage systems, or areas with shallow groundwater tables that are more vulnerable to contamination. A notable feature of the nitrate data is that the standard deviation exceeds the mean in all three years of observation. This statistical pattern indicates a highly skewed distribution dominated by a few abnormally high nitrate concentrations. Such high outliers elevate the overall variability while most sampling sites continue to exhibit low or zero nitrate levels. The disparity reflects heterogeneous land-use patterns across the study area, where some locations remain relatively unaffected while others experience strong contamination inputs. The presence of these extreme values, therefore, explains the high standard deviation and underscores the uneven spatial distribution of nitrate pollution within the region.

The Mean ± Standard Deviation (Mean ± Std. dev) values offer a comprehensive understanding of the spatial and temporal variability of groundwater quality in Birbhum district across the years 2005, 2015, and 2025. The mean represents the average concentration of each parameter, reflecting the overall groundwater condition, while the standard deviation indicates the degree of variation among different sampling sites. A lower standard deviation suggests uniformity and stability in water quality, whereas a higher value denotes inconsistency and spatial heterogeneity, often linked to localized contamination or diverse geological conditions. In 2005, the groundwater exhibited relatively consistent quality, as seen in parameters such as pH (7.89 ± 0.30) and TDS (337 ± 256 mg/l). The low to moderate deviations imply that most sampling sites maintained similar water characteristics, influenced primarily by natural hydro-geochemical processes. By 2015, a significant increase in both mean and standard deviation values was observed for several parameters, marking a phase of intense anthropogenic influence. The Electrical Conductivity (848 ± 729 µS/cm), TDS (568 ± 489 mg/l), and Total Hardness (252 ± 225 mg/l) values reflect the rising concentration of dissolved ions, minerals, and hardness-inducing substances across the district. High deviations also found in HCO_3^- (±196.7 mg/l) and Cl^- (±186 mg/l). In 2025, the mean values of several parameters, including EC (629 ± 397 µS/cm), TDS (415 ± 267 mg/l), and TH (185 ± 81 mg/l), declined, indicating a partial recovery. However, persistently high standard deviations for Fe (0.46 ± 1.14 mg/l), F^- (0.46 ± 1.14 mg/l), and NO_3^- (12.34 ± 15.21 mg/l) reveal continued spatial inconsistency and the presence of localized contamination zones.

B. Nitrate maps and status

Groundwater quality can most simply be represented on a map by contouring the concentrations of a specific substance. In this study, spatial variations of nitrate influencing groundwater quality were examined. **Fig.3** illustrates the spatial distribution of nitrate in Birbhum district for the years 2005, 2015, and 2025. The nitrate concentration shows considerable variation across both space and time. The maps display several small clusters of high concentration. The study further discusses the spatial distribution of nitrate and the factors contributing to its occurrence.

The analysis shows that nitrate concentration in Birbhum district varies both spatially and temporally between 2005 and 2025. In 2005, elevated nitrate values were mainly found in the northern, southern, central, western, and southwestern parts of the district, while comparatively lower levels occurred in portions of the northern, eastern, and southeastern regions. By 2015, areas with high nitrate broadened, extending across much of the northern, southern, central, western, and southwestern zones. In contrast, low-nitrate regions became concentrated in certain northern, eastern, southeastern, and central sectors. Projections for 2025 indicate that high nitrate levels are likely to persist in parts of the northern, southern, central, and southwestern regions, whereas lower concentrations are expected in segments of the northern and southeastern zones. Overall, the shifting pattern suggests that nitrate contamination is not static but moves progressively across different geographical regions of Birbhum district over the study period.

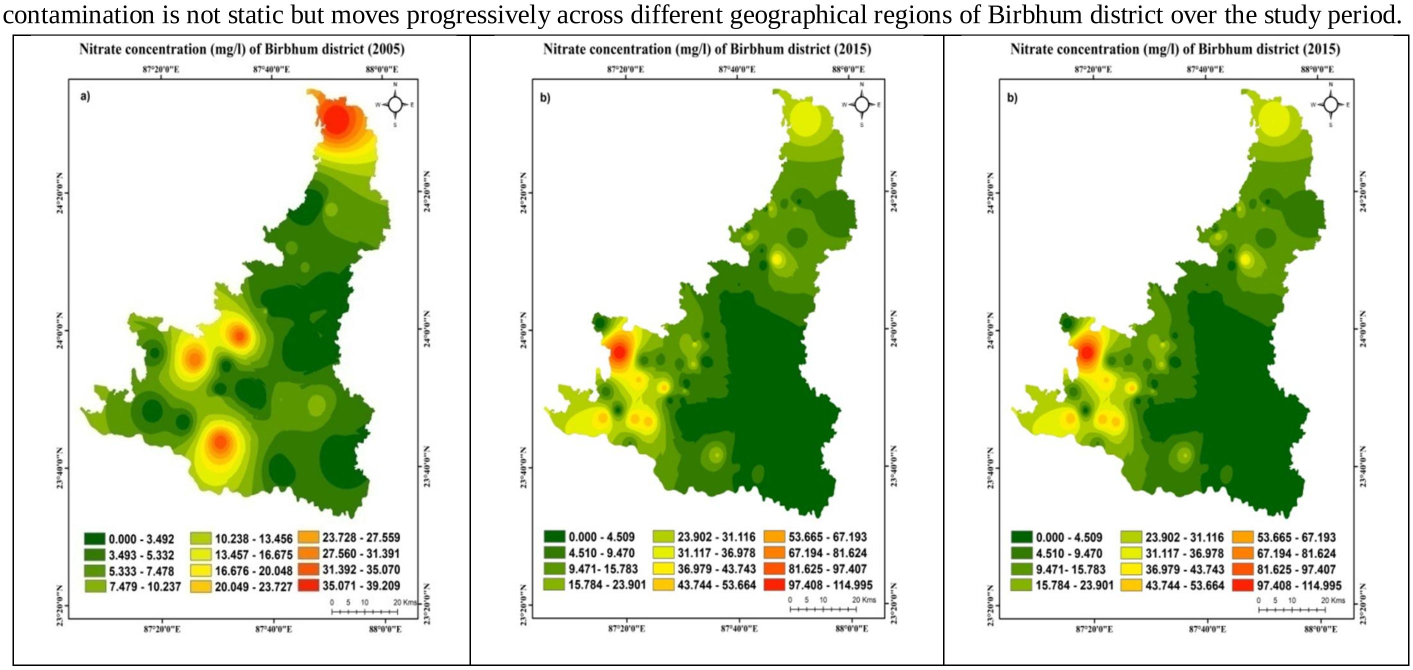


Fig. 3 Nitrate concentration of Birbhum district for 2005, 2015, and 2025.

C. Nitrate change detection analysis

The nitrate change detection analysis provides a comprehensive understanding of the shifting patterns of groundwater contamination of the Birbhum district over the two-decade period from 2005 to 2025. By analyzing and comparing the spatial distribution maps of nitrate concentration for the years 2005, 2015, and 2025 (Fig.4a-b), it becomes evident that there have been considerable changes in both the intensity and spatial extent of nitrate presence across the district.

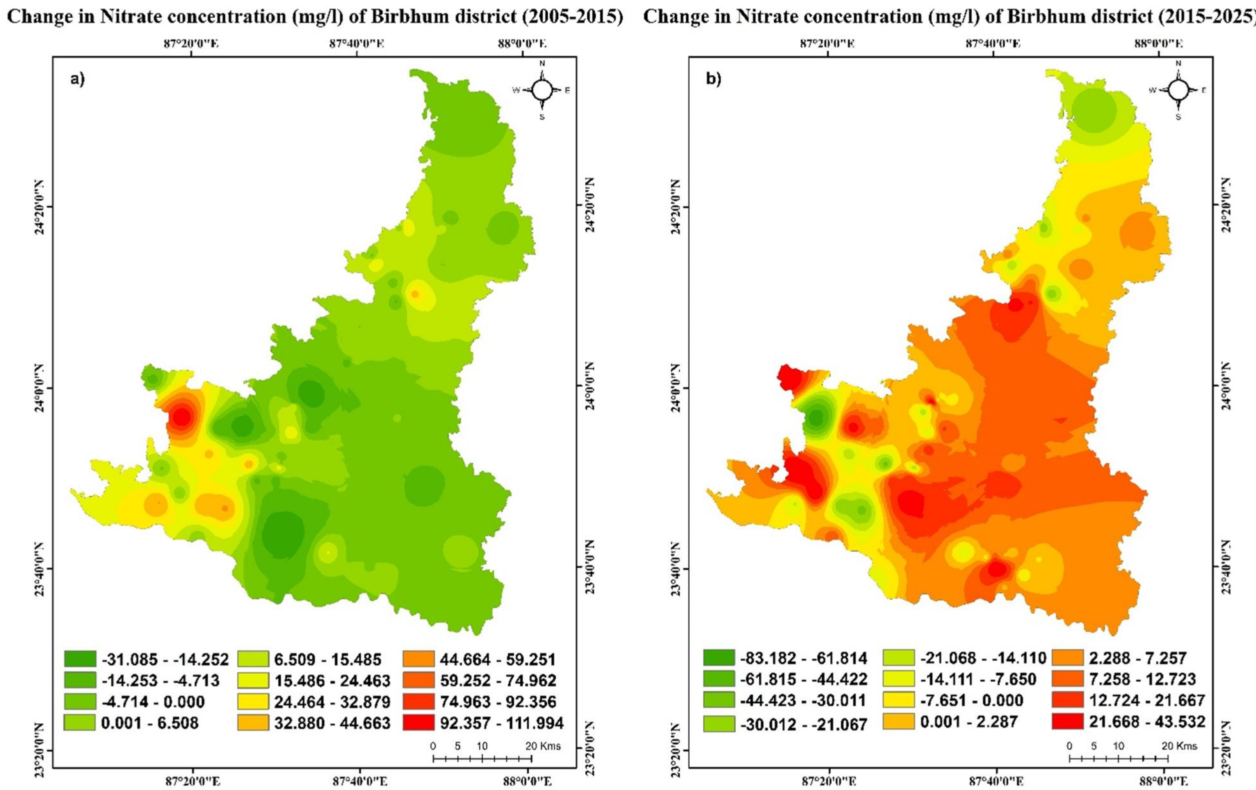


Fig.4 Nitrate change detection of Birbhum district for the years a) 2005-2015 and b) 2015-2025

The study highlights how different regions of the district have experienced either an increase or decrease in nitrate levels over time, reflecting the combined influence of agricultural practices, land use changes, and hydrogeological conditions.

During the 2005–2015 period, the strongest increases in nitrate concentration were mainly confined to the northern, central, and southwestern parts of Birbhum district, where agricultural intensification and growing population pressures were most evident. In the following decade, from 2015 to 2025, these high-increase zones did not remain limited to their earlier locations; instead, they expanded outward and began appearing across a broader portion of the district. The northern region continued to show marked increases, but new areas of rapid nitrate growth emerged toward the south and southeast, indicating that contamination pressures have spread into regions that were previously less affected. This change reflects a shift from localized hotspots to a more widespread pattern of nitrate enrichment, suggesting that contributing factors such as fertilizer use, wastewater infiltration, and land-use change have become more extensive across the district over time.

Between 2005 and 2015, the regions with declining nitrate levels were generally situated in the eastern and southeastern parts of Birbhum district, along with select pockets in the northern and central zones. These areas likely benefited from lower fertilizer application, less intensive land use, or more effective natural dilution processes. However, this pattern did not remain stable over time. Some of the regions that showed improvement in the first period, particularly portions of the central and southeastern zones experienced a shift in the following decade, with nitrate concentrations rising again from 2015 to 2025. This change indicates that the initial reductions were not sustained and that these areas later came under renewed pressure from agricultural expansion, changing land-use practices, or increased domestic wastewater inputs. Overall, while some parts of the district maintained decreasing trends, others transitioned from decline to increase, reflecting the dynamic nature of nitrate contamination across the region.

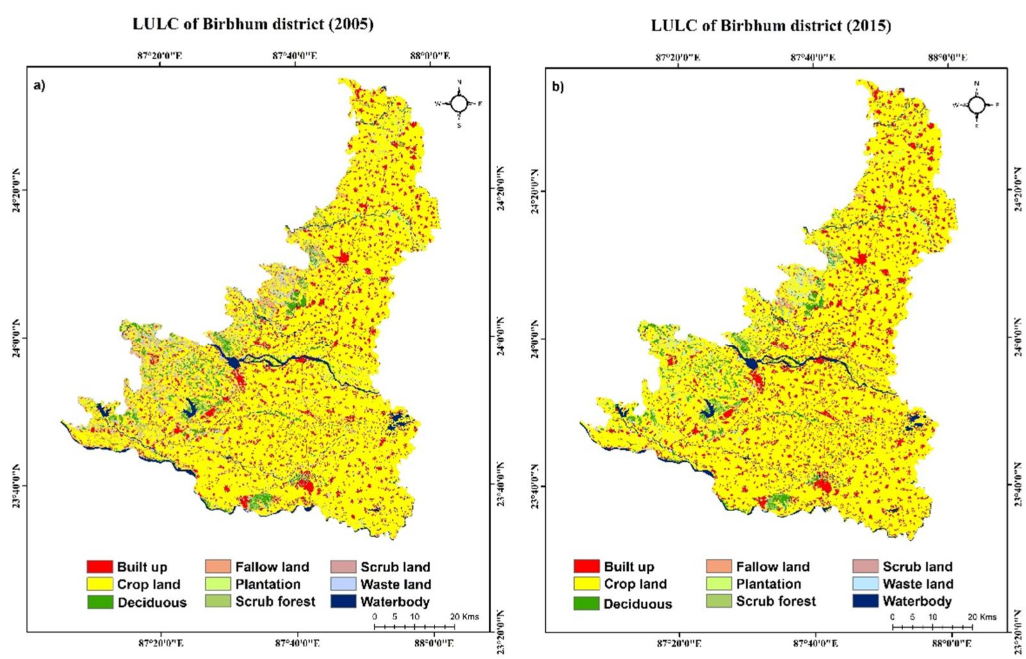
Across Birbhum district, the area showing increasing nitrate levels covers a substantial and growing share of the total district, expanding from roughly one-third of the region in 2005–2015 to nearly half by 2015–2025. In contrast, the zones with decreasing nitrate occupy a smaller and more localized portion of the district. These declining areas have not expanded significantly over time and remain limited compared to the widespread regions of increase. Overall, the district shows a clear dominance of nitrate-increasing zones over nitrate-decreasing ones, indicating a broadening contamination footprint.

D. LULC maps and status

Land Use /Land Cover (LULC) maps are drawn with the help of the data acquisition from the India-WRIS portal, using Arc GIS software. LULC data was classified and reclassified to achieve a standardized set of land use categories for the years 2005, 2015, and 2025(Fig.5). These included classes such as (a) Built up, (b) Crop land, (c) Deciduous, (d) Fallow land, (e) Plantation, (f) Scrub forest,(g) Scrub land,(h) Waste land, and (i) Waterbody.

From 2005 to 2025, Birbhum district has undergone gradual but noticeable changes in land use and land cover. Built-up areas have expanded primarily in the northern, central, and southern regions, while peripheral areas remain relatively sparsely urbanized. Cropland continues to dominate the southeastern and central zones, with minor reductions observed in the southwestern and some central areas. Deciduous forests and plantations are largely concentrated in the southwestern and central parts of the district, whereas the northern, eastern, and southeastern regions maintain sparse tree cover. Scrublands and degraded forests persist in the lateritic southwestern areas, while sandy stretches along riverbanks and degraded lands in the western and southwestern regions remain largely stable. Waste land is mainly located in the northern and southwestern regions, with slight extensions into the southern areas. Waterbodies, which support irrigation and local livelihoods, are concentrated in the southwestern, central, and northern parts of the district. Mining activity, particularly in the coal-rich southwestern region, has intensified, reflecting the balance between resource utilization and environmental management. Overall, the observed shifts in LULC illustrate the dynamic interplay between urbanization, agriculture, ecological conservation, and resource exploitation, resulting in gradual but regionally focused land transformation across the district.

Between 2005 and 2025, Birbhum district saw clear changes in land use. Built-up areas grew from 431.5 km² (9.45%) to 533.2 km² (11.67%) and cropland increased from 3275.8 km² (71.71%) to 3594.5 km² (78.69%). At the same time, deciduous forests, fallow land, plantations, and scrub forests decreased. Waste land and waterbodies stayed almost the same, showing that urban and farming areas expanded while natural areas shrank.



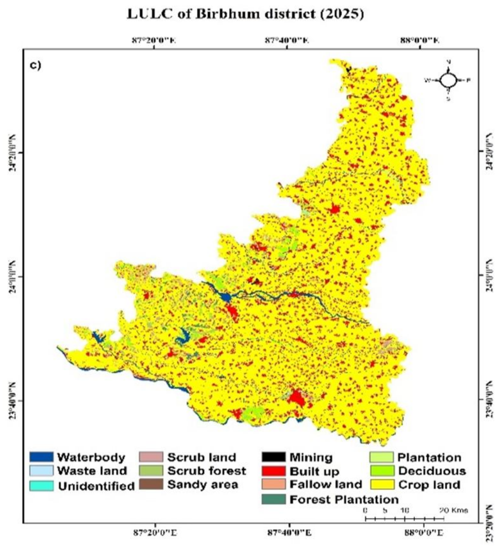


Fig. 5 LULC map for the years (a) 2005, (b) 2015, and (c) 2025 of Birbhum district.

E. LULC change Detection Analysis

The analysis reveals a clear temporal and spatial variation in LULC classes across Birbhum district from 2005 to 2025(Fig.6).During this period, Birbhum district experienced noticeable changes in land use and land cover. Built-up areas gradually expanded in northern, central, and southern blocks, reflecting urban growth, while peripheral areas remained sparsely developed. Cropland remained concentrated in southeastern and central blocks, with slight reductions in southwestern and some central regions. Deciduous forests and plantations persisted mainly in southwestern and central areas, supporting ecological stability. Scrublands, waste land, and sandy areas continued to occupy degraded and lateritic zones with minimal spatial shifts. Overall, the LULC pattern indicates a combination of urban expansion, stable agriculture, persistent forests, and relatively stable degraded lands.

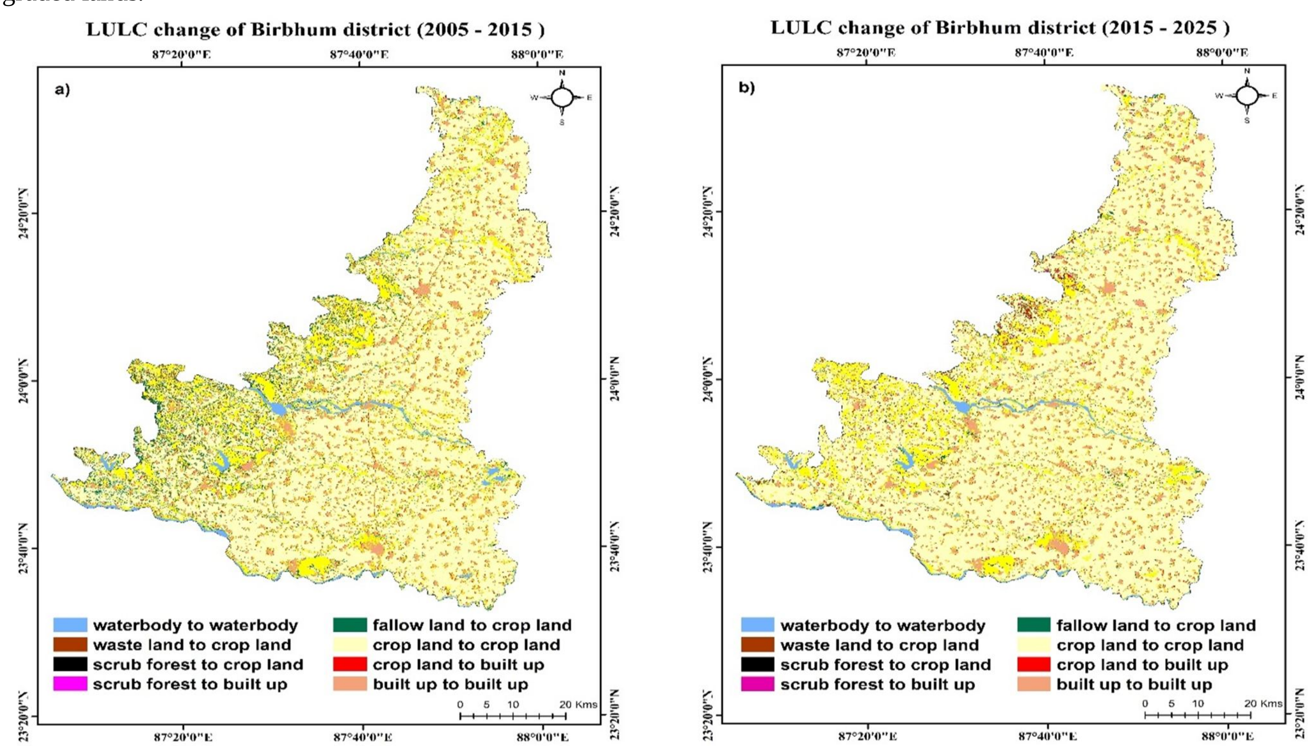


Fig. 6 LULC change detection of Birbhum district for the years a) 2005-2015 and b) 2015-2025

The analysis of Land Use and Land Cover (LULC) changes in Birbhum district between 2005-2015, and 2015-2025 reveals dynamic transformations influenced by agricultural expansion, urbanization, and environmental changes. Cropland continues to dominate the landscape, increasing steadily from 71.71% (3275.82 km²) in 2005 to 76.10% (3476.05 km²) in 2015 and further to 78.69% (3470.20 km²) in 2025, reflecting intensified agricultural practices and the conversion of fallow and forested areas into cultivable land. Built-up areas, the second-largest LULC category, show consistent growth, rising from 9.45% (431.49 km²) in 2005 to 10.78% (492.26 km²) in 2015, and reaching 11.67% (533.23 km²) by 2025, indicating ongoing urban and infrastructural expansion.

Fallow land (including Sandy area, Mining, and Barren rocky area), on the other hand, exhibits a sharp decline from 5.37% (245.18 km²) in 2005 to 2.12% (96.64 km²) in 2015 and only 0.37% (16.69 km²) in 2025, suggesting that previously unused lands are being brought under active cultivation or construction. Waste land decreased from 4.25% (193.94 km²) in 2005 to 2.12% (100.33 km²) in 2015 but slightly increased to 2.62% (119.65 km²) in 2025, likely due to degradation of marginal lands or unregulated mining activities. Waterbodies experienced a gradual decline from 3.30% (150.37 km²) in 2005 to 2.94% (134.17 km²) in 2015 and 2.87% (131.31 km²) in 2025, possibly due to sedimentation, urban encroachment, and changing hydrological conditions. Vegetation-related classes also show a declining trend. Deciduous forests reduced from 2.70% (123.30 km²) in 2005 to 2.68% (122.44 km²) in 2015 and further to 2.12% (96.98 km²) in 2025, while scrub forests declined from 1.63% (74.28 km²) in 2005 to 1.61% (73.62 km²) in 2015 and then to 1.02% (46.44 km²) in 2025. Plantation (considering Forest Plantation as well as General Plantation) areas followed a similar path, decreasing from 1.62% (73.90 km²) in 2005 to 1.59% (72.44 km²) in 2015 and significantly reducing to 0.63% (28.70 km²) in 2025. Scrub land remained negligible throughout the study period, with a minor reduction from 0.0004% (0.02 km²) in 2005 to 0.0002% (0.01 km²) in 2015, followed by a slight increase to 0.02% (0.82 km²) in 2025.

The study showed that the LULC pattern of Birbhum district underwent notable transformations between 2005-2015 and 2015-2025 (Table II). The two decades represent distinct phases; the first marked by rapid agricultural expansion and land reclamation, and the second by intensifying urban growth and forest degradation. Built-up land expanded by 23.58%, covering an additional 2.23% of the district's total area, showing rapid growth around Suri, Bolpur, and Rampurhat. Cropland increased by 9.73%, accounting for 6.98% of total area, mainly by converting fallow and waste lands into cultivable fields. Deciduous forest declined by 21.35% (0.58% of total area) as mining and settlements expanded. Fallow land recorded a drastic 93.19% decrease (5.00% of total area), reflecting the loss of traditional agricultural cycles. Plantation areas reduced by 61.16% (0.99% of total area), while scrub forest fell by 37.48% (0.61% of total area), both showing vegetation degradation. Scrub land, though minimal, surged by 4000% (0.02% of total area), representing transitional degraded zones. Waste land declined by 38.31% (1.63% of total area) with minor recovery in the later decade. Waterbody reduced by 12.68% (0.42% of total area) due to siltation and encroachment.

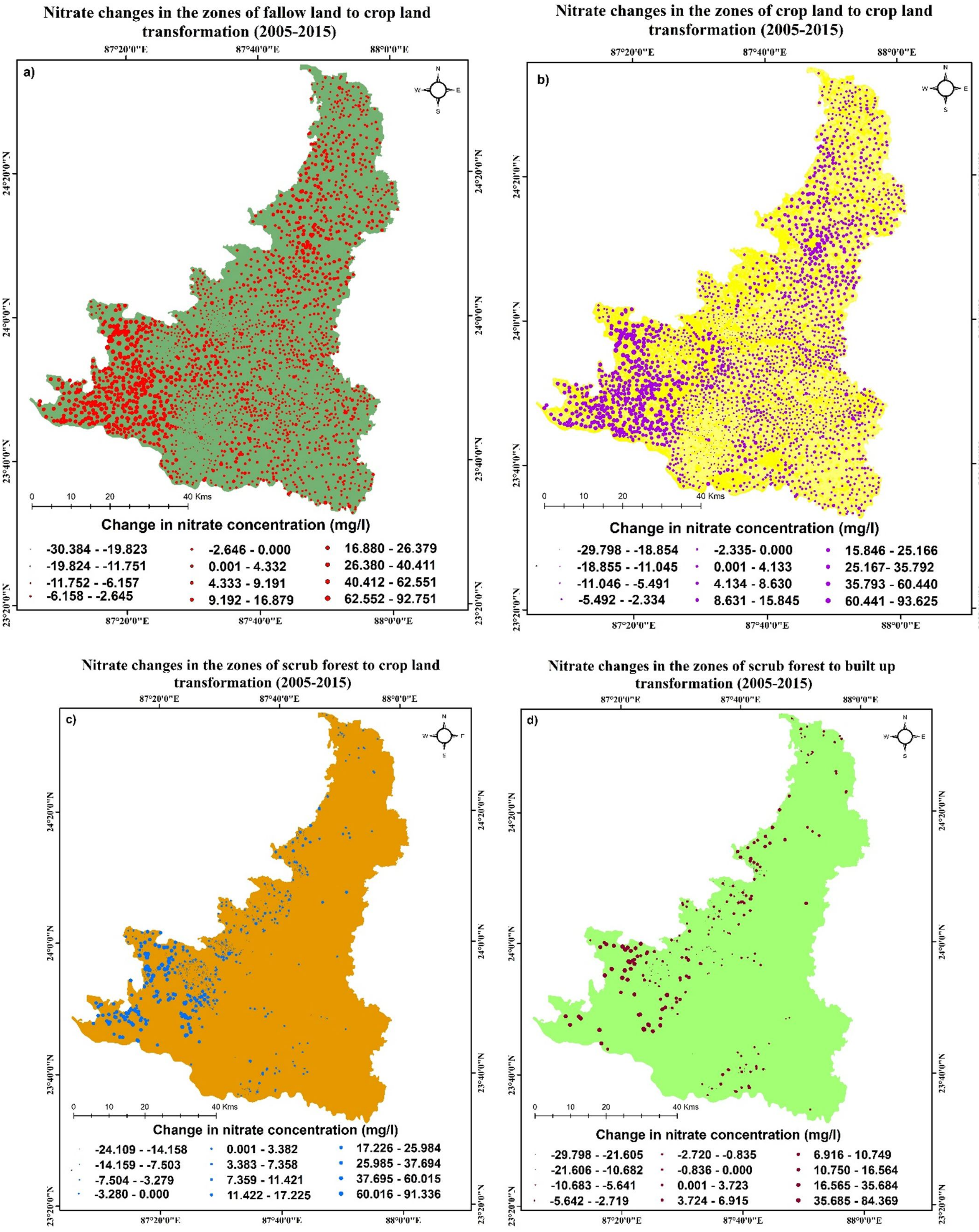
Table II
Land Use and Land Cover (LULC) dynamics in Birbhum District: 2005–2025

Sl. No.	LULC classes	2005-2015		2015-2025		2005-2025		2005-2025
		Area in km^2	% of changes	Area in km^2	% of changes	Area in km^2	% of changes	% of changes over total area
1	Built up	431.49	+14.08	492.26	+8.32	533.23	+23.58	+2.23
2	Crop land	3275.82	+6.11	3476.05	+3.41	3594.47	+9.73	+6.98
3	Deciduous forest	123.30	-0.70	122.44	-20.79	96.98	-21.35	-0.58
4	Fallow land	245.18	-60.58	96.64	-82.73	16.69	-93.19	-5.00
5	Plantation	73.90	-1.98	72.44	-60.38	28.70	-61.16	-0.99
6	Scrub forest	74.28	-0.89	73.62	-36.92	46.44	-37.48	-0.61
7	Scrub land	0.02	-50.00	0.01	+8100.00	0.82	+4000.00	+0.02
8	Waste land	193.94	-48.27	100.33	+19.26	119.65	-38.31	-1.63
9	Waterbody	150.37	-10.77	134.17	-2.13	131.31	-12.68	-0.42

F. Changes in nitrate levels across LULC alteration classes

Over the two decades from 2005 to 2025, changes in nitrate levels have offered a detailed insight into how groundwater contamination patterns have evolved in relation to land use and land cover (LULC) changes across 2,242 villages, spanning 167 Gram Panchayats and 6 municipal areas within 19 CD blocks of the Birbhum district(Fig.7 & Fig.8).Eight key LULC transitions (Fallow land to Crop land, Crop land to Crop land, Scrub forest to Crop land, Scrub forest to Built-up, Crop land to Built-up, Built up to Built-up, Waste land to Crop land, and Waterbody to Waterbody) were examined and the analysis revealed the following findings:

1) Fallow land to cropland transitions: Between 2005 and 2015, nitrate concentrations ranged from -30.38 mg/L to +92.75 mg/L. Positive changes were observed mainly in the southwestern and northern regions, while declines occurred in parts of the northern and eastern areas. This suggests that agricultural intensification increased fertilizer application in some regions, elevating nitrate levels, whereas limited cultivation or better land management in others reduced them. During 2015–2025, nitrate changes ranged from -57.37 mg/L to +36.10 mg/L, with widespread increases across nearly all regions, especially in the eastern, southeastern, and central zones, reflecting continued agricultural expansion. Decreases were limited to parts of the southwestern and northern regions, likely due to reduced cultivation or improved groundwater recharge.
2) Cropland to cropland transitions: From 2005 to 2015, nitrate ranged from -29.80 mg/L to +93.63 mg/L. Positive changes were observed in the southwestern and northern regions, while nearby areas showed declines, reflecting differences in cropping intensity, fertilizer management, and local recharge conditions. During 2015–2025, nitrate concentrations ranged from -62.18 mg/L to +41.25 mg/L. Most regions experienced increases, particularly in southwestern, western, and central areas, while decreases occurred in limited northern and southwestern zones, likely due to better land and water management.
3) Scrub forest to cropland transitions: Between 2005 and 2015, nitrate changes ranged from -24.11 mg/L to +91.34 mg/L, with increases in southwestern areas where scrublands were converted to cropland, and declines in nearby villages, reflecting variations in cultivation and soil-water conditions. From 2015 to 2025, concentrations ranged from -54.04 mg/L to +37.46 mg/L. Most regions exhibited rising nitrate, particularly in southwestern, western, central, and northern areas, with decreases limited to parts of the southwestern and northern regions due to lower cropping intensity or improved land management.
4) Scrub forest to built-up transitions: During 2005–2015, nitrate ranged from -29.80 mg/L to +84.37 mg/L. Positive changes occurred mainly in southwestern villages, while declines were observed in southern, central, and western regions. In 2015–2025, nitrate ranged from -54.05 mg/L to +41.25 mg/L, with increases across southern, southwestern, western, central, and northern regions, and declines in some southwestern and northern areas, likely due to reduced cultivation or improved recharge.
5) Cropland to built-up transitions: From 2005 to 2015, nitrate ranged from -29.72 mg/L to +93.63 mg/L. Areas transitioning from cropland to built-up generally showed increases in southwestern and northern regions, likely due to residual nitrate from previous agriculture. Decreases were observed in central, eastern, southeastern, and northern zones, reflecting soil sealing, reduced fertilizer input, or improved drainage. During 2015–2025, nitrate ranged from -59.41 mg/L to +41.25 mg/L, with increases across central, southern, eastern, and southeastern regions, while northern areas showed declines due to better urban planning and groundwater recharge.
6) Built-up to built-up transitions: Between 2005 and 2015, nitrate ranged from -29.80 mg/L to +93.63 mg/L, with increases in southwestern and northern regions and decreases in eastern, southeastern, central, and northern areas, reflecting variations in land use intensity and nutrient management. From 2015–2025, nitrate ranged from -59.41 mg/L to +41.25 mg/L, with widespread increases in central, southern, eastern, and southeastern regions, while limited northern areas showed decreases.
7) Waste land to cropland transitions: Between 2005 and 2015, nitrate ranged from -29.80 mg/L to +93.63 mg/L. Increases occurred in southwestern and northern regions, while decreases were observed in northern, central, and eastern areas. During 2015–2025, nitrate ranged from -62.18 mg/L to +41.25 mg/L, with widespread increases across southwestern, western, central, and northern regions, and declines limited to eastern and northern zones, reflecting intensified agriculture and localized improvements in land management
8) Waterbody to waterbody transitions**:** From 2005–2015, nitrate ranged from -29.80 mg/L to +93.63 mg/L. Increases were concentrated in the southwestern region, while declines occurred in northern, central, eastern, southern, and southeastern zones. During 2015–2025, nitrate ranged from -62.18 mg/L to +41.25 mg/L, with increases across western, central, eastern, southern, and southeastern regions, while northern areas experienced decreases, likely influenced by variations in nutrient input, catchment characteristics, and water management practices.


Nitrate changes in the zones of fallow land to crop land transformation (2005-2015)
a)
Change in nitrate concentration (mg/l)
-30.384 - -19.823
-19.824 - -11.751
-11.752 - -6.157
-6.158 - -2.645
-2.646 - 0.000
0.001 - 4.332
4.333 - 9.191
9.192 - 16.879
16.880 - 26.379
26.380 - 40.411
40.412 - 62.551
62.552 - 92.751
Nitrate changes in the zones of crop land to crop land transformation (2005-2015)
b)
Change in nitrate concentration (mg/l)
-29.798 - -18.854
-18.855 - -11.045
-11.046 - -5.491
-5.492 - -2.334
-2.335- 0.000
0.001 - 4.133
4.134 - 8.630
8.631 - 15.845
15.846 - 25.166
25.167- 35.792
35.793 - 60.440
60.441 - 93.625
Nitrate changes in the zones of scrub forest to crop land transformation (2005-2015)
c)
Change in nitrate concentration (mg/l)
-24.109 - -14.158
-14.159 - -7.503
-7.504 - -3.279
-3.280 - 0.000
0.001 - 3.382
3.383 - 7.358
7.359 - 11.421
11.422 - 17.225
17.226 - 25.984
25.985 - 37.694
37.695 - 60.015
60.016 - 91.336
Nitrate changes in the zones of scrub forest to built up transformation (2005-2015)
d)
Change in nitrate concentration (mg/l)
-29.798 - -21.605
-21.606 - -10.682
-10.683 - -5.641
-5.642 - -2.719
-2.720 - -0.835
-0.836 - 0.000
0.001 - 3.723
3.724 - 6.915
6.916 - 10.749
10.750 - 16.564
16.565 - 35.684
35.685 - 84.369
0 10 20 40 Kms
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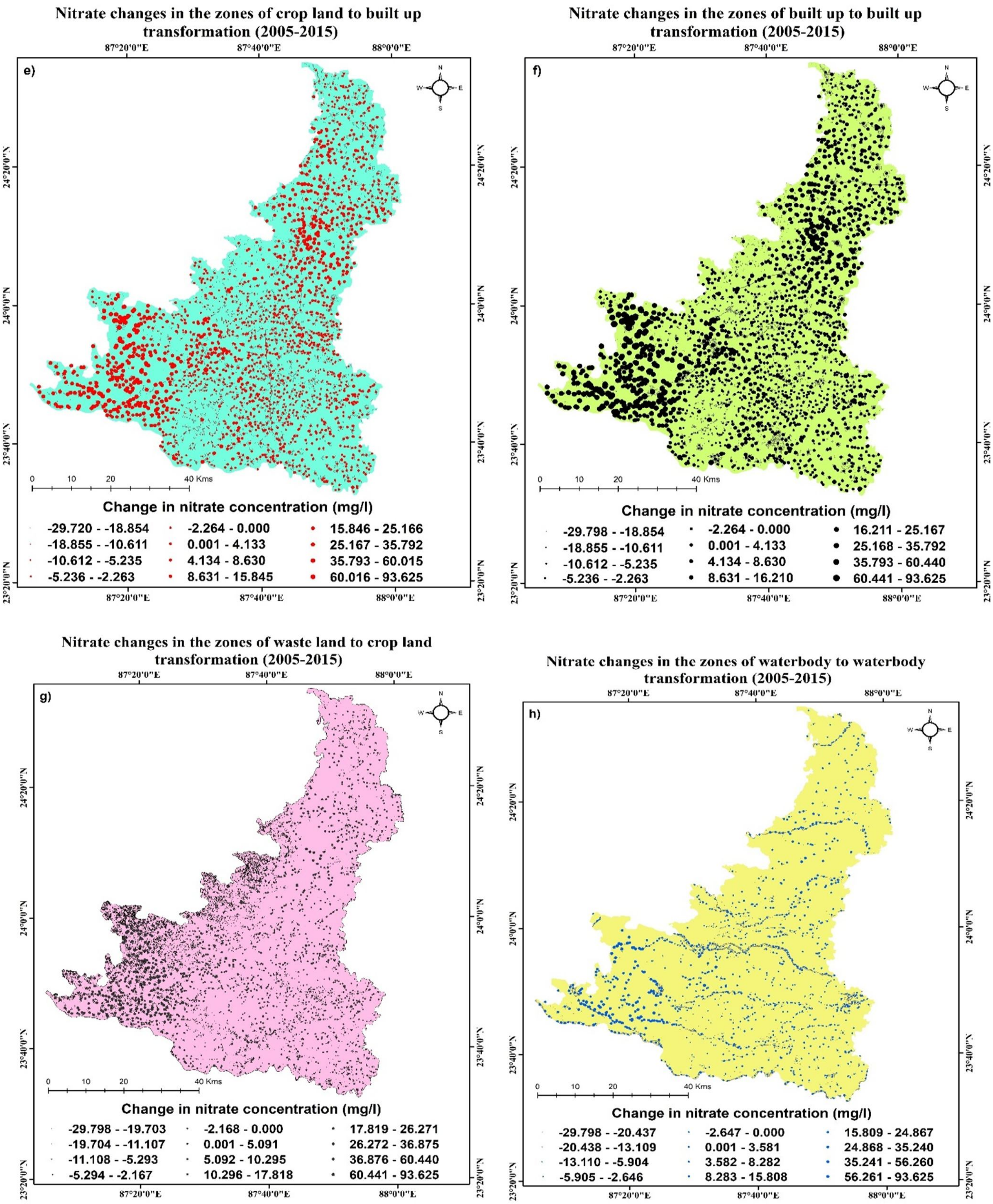
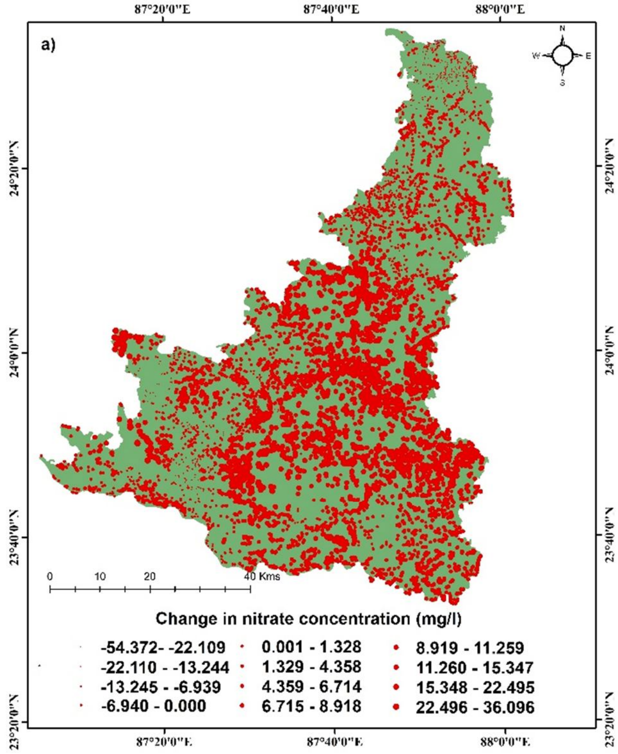
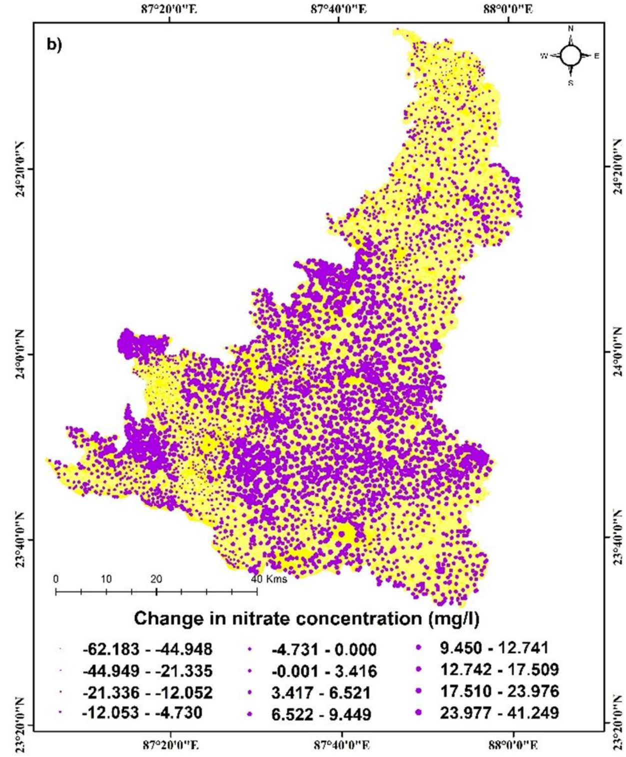


Fig. 7 Nitrate concentration changes in the zones a) Fallow land to Crop land, b) Crop land to Crop land, c) Scrub forest to Crop land, d) Scrub forest to Built-up, e) Crop land to Built-up, f) Built-up to Built-up, g) Waste land to Crop land, and h) Waterbody to Waterbody during 2005-2015

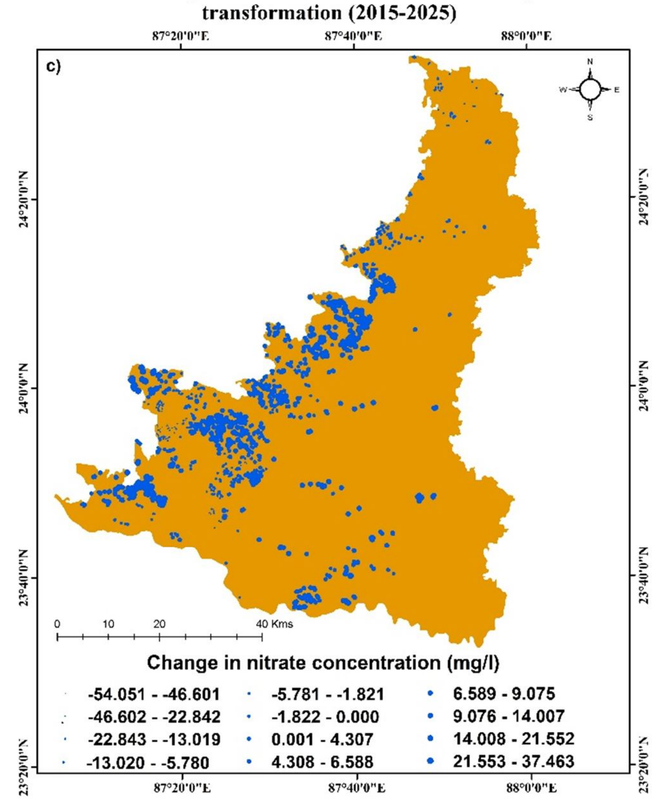
Nitrate changes in the zones of fallow land to crop land transformation (2015-2025)



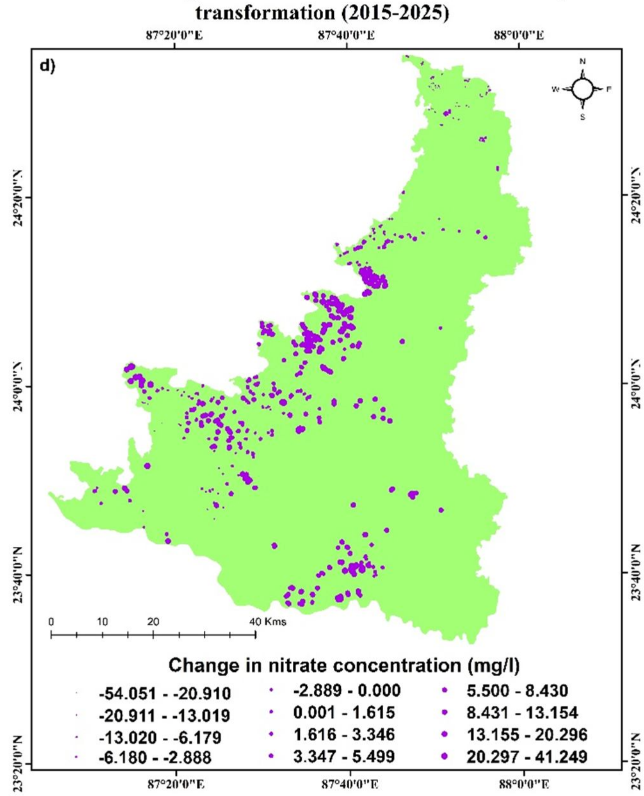
Nitrate changes in the zones of crop land to crop land transformation (2015-2025)



Nitrate changes in the zones of scrub forest to crop land transformation (2015-2025)



Nitrate changes in the zones of scrub forest to built up transformation (2015-2025)



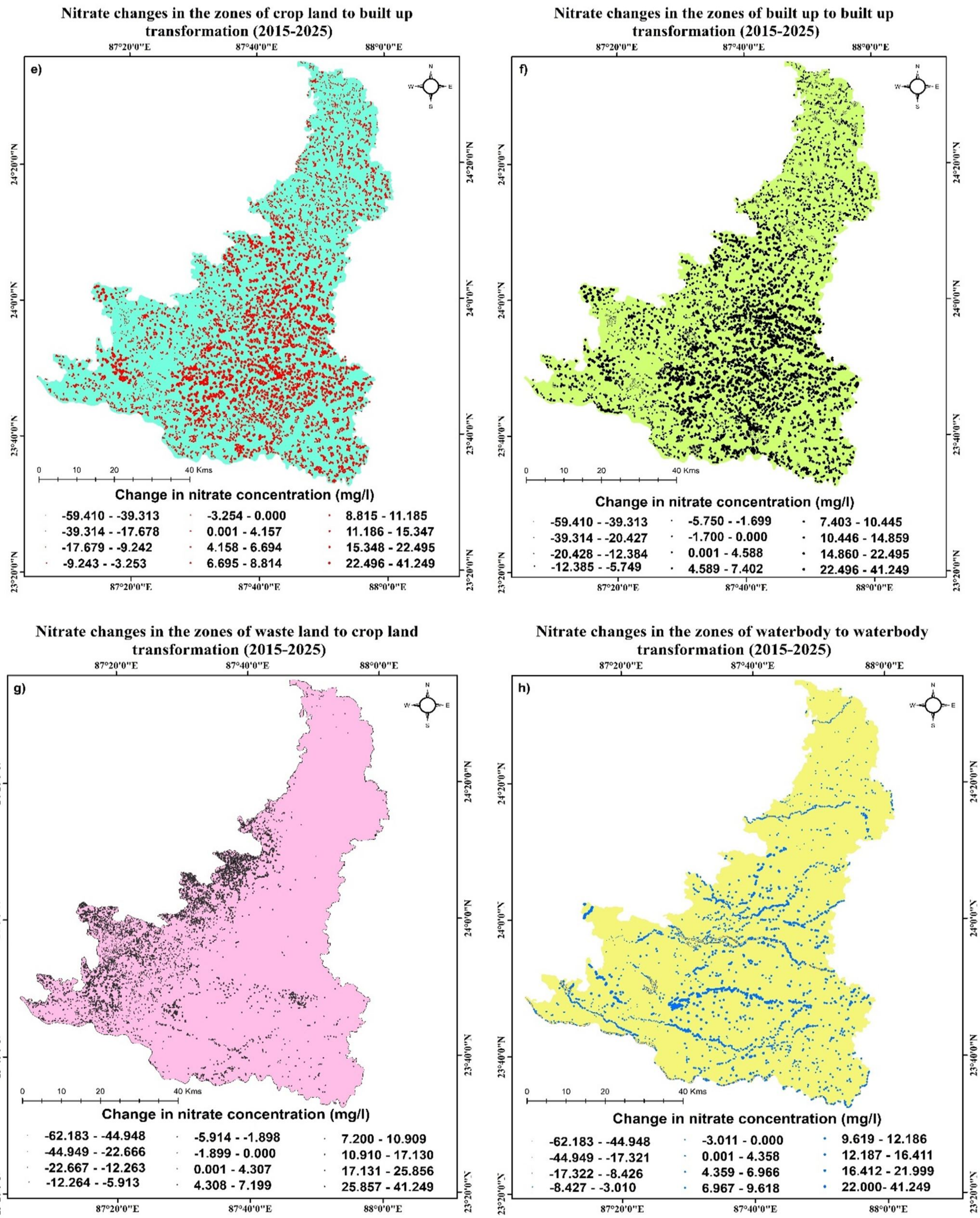


Fig. 8 Nitrate concentration changes in the zones a) Fallow land to Crop land, b) Crop land to Crop land, c) Scrub forest to Crop land, d) Scrub forest to Built-up, e) Crop land to Built-up, f) Built-up to Built-up, g) Waste land to Crop land, and h) Waterbody to Waterbody during 2015-2025

The discussion part of this study and is mainly comprised of two parts. Firstly, the conventional studies have been confined in evaluating an overall mean change in nitrate concentration in a particular LULC transition zone.This study is an attempt to assess the spatial heterogeneity of the impact of LULC transitions. As elaboration, it may happen the scrub land to crop land transition is not affecting the nitrate concentration uniformly over the entire study area. The methodology of this study has allowed to configure the specific regions as a subset of the total area where a particular LULC transition zone is affecting the groundwater quality in a detrimental way. Many studies on this topic also do not emphasize or capture the deterioration of groundwater quality in the zones where no LULC transition took place. But, the methodology of this study has shown even when the LULC is not altered, it may affect the groundwater quality because of the change of practices in a particular LULC class. For example- crop land to crop land has increased the nitrate concentration, remained still and also decreased in different subset of the study area. The places where the concentration has increased indicates the fact that the agricultural practices (like- intensive use of fertilizers) have paved the path of increase in nitrate concentration.The methodology provides a spatially detailed analysis, allowing the mapping of land use changes and their direct relationship with nitrate contamination across Birbhum district. Comparing LULC and groundwater data from 2005, 2015, and 2025 enables detection of temporal trends and variations in nitrate levels. It also helps identify hotspots where specific land use transitions, such as cropland expansion or urban growth, contribute most to groundwater contamination. By integrating multi-temporal dataset, the approach offers a comprehensive understanding of human-environment interactions and provides valuable insights for policy making and management including targeted fertilizer regulation, urban planning and groundwater protection strategies.

Secondly, despite its strengths, the methodology has limitations. The resolution of LULC and groundwater data may not capture fine-scale variations and reclassification of land use can oversimplify heterogeneous landscapes. Establishing direct causal links between land use changes and nitrate levels is complex as other factors like soil type, rainfall, and hydrogeology also influence groundwater quality. Temporal gaps between datasets may overlook short-term fluctuations and handling large spatial datasets requires significant technical expertise, time and resources.

V. CONCLUSION

The groundwater quality in Birbhum district exhibited notable spatial and temporal variations between 2005 and 2025, influenced by both natural factors and human activities. Key parameters such as pH, Electrical Conductivity (EC), Total Dissolved Solids (TDS), and ions including nitrate, chloride, calcium, magnesium, and sodium showed significant changes over time. Interpolated maps using the IDW method indicated higher EC, TDS, and nitrate levels in regions with intensive agriculture and expanding urban areas. Nitrate concentrations, in particular, increased, with high-value clusters appearing in southern and central regions due to excessive fertilizer use and inadequate waste management. Lower nitrate levels were observed in forested or minimally disturbed areas, while rapid land use transitions, such as conversion of fallow or forest land to cropland or built-up zones, corresponded to rising nitrate. The study highlights agricultural intensification and urbanization as key drivers of contamination and underscores the need for sustainable land and water management to protect groundwater resources.

Future studies should monitor groundwater over long periods to track nitrate and other contaminants and use models to predict changes. Land use, population growth, agriculture, and climate impacts should be considered to manage water sustainably. Research should cover different regions and identify vulnerable areas. Tools like GIS, remote sensing, and AI can help track pollution and detect hotspots. Studies should also look at other contaminants and test solutions like managed aquifer recharge, constructed wetlands, and careful fertilizer use. Collaboration with government, communities, and NGOs is important to promote sustainable practices and protect groundwater.

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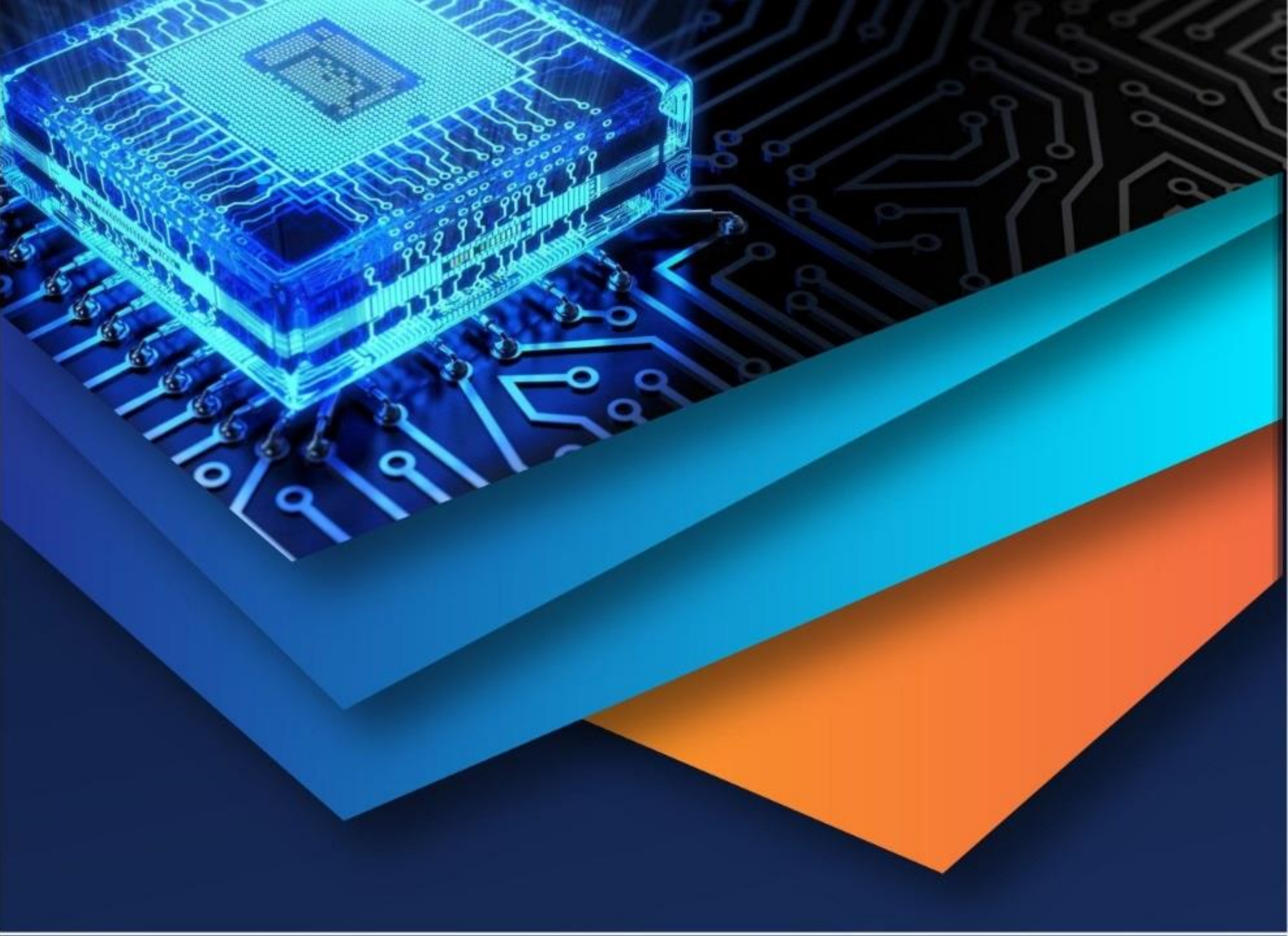

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