Integrated Geospatial Assessment of Groundwater Quality, Rainfall Variability, and Horticultural Plantation Suitability in Semi-Arid Regions: A Case Study of Bhiwani and Charkhi Dadri, Haryana (India)

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Abstract
Sustainable agricultural development in semi-arid regions is increasingly constrained by declining groundwater resources, deteriorating water quality, and erratic rainfall patterns. This study presents an integrated geospatial assessment of groundwater quality, rainfall variability, land use/land cover (LULC), and vegetation dynamics for evaluating horticultural plantation suitability in Bhiwani and Charkhi Dadri districts of Haryana, India. Multi-source datasets including Landsat-derived NDVI, supervised LULC classification, rainfall interpolation (2024), and groundwater quality parameters (EC, TDS, Fluoride, Sodium, etc.) were analyzed using GIS and remote sensing techniques. The results indicate severe groundwater stress, with all blocks categorized as over-exploited except Siwani. High salinity (EC and TDS) dominates northern and southwestern regions, while alkalinity (high bicarbonate and pH) affects agricultural sustainability. Rainfall analysis shows peak precipitation during July–August (400–503 mm), but overall annual variability remains high, limiting recharge. LULC analysis reveals dominance of fallow land (46.55%), followed by agricultural land (23.39%), while horticultural plantations occupy only 5.12% of the area. NDVI analysis confirms sparse vegetation cover, with limited high-value zones corresponding to horticulture clusters. The study demonstrates that horticultural expansion is feasible only in localized zones with moderate groundwater quality and vegetation density. The integration of geospatial techniques provides a robust framework for sustainable land and water resource planning. Policy recommendations include micro-irrigation, groundwater recharge structures, and crop diversification towards less water-intensive horticulture.

Keywords: Groundwater Quality, NDVI, LULC, Rainfall Variability, Horticulture

1. Introduction

Water resources and agricultural sustainability have emerged as major global concerns in the twenty-first century due to increasing population pressure, climate variability, urbanization, and unsustainable exploitation of natural resources (Panda et al., 2010). Agriculture consumes nearly 70% of global freshwater resources, and the rising demand for food production has intensified pressure on groundwater systems, especially in arid and semi-arid regions (Kumar, 2018). According to the United Nations and FAO reports, many countries are experiencing severe groundwater depletion, declining water quality, and land degradation, which threaten food security and ecological sustainability. Climate change further aggravates this crisis through erratic rainfall patterns, prolonged droughts, rising temperatures, and increased evapotranspiration. As a result, sustainable agricultural planning based on scientific assessment of land and water resources has become an urgent necessity at global, national, and regional scales (Kumar et al, 2021).

Globally, horticulture has gained importance as an economically viable and resource-efficient agricultural practice. Compared to traditional cereal-based agriculture, horticultural crops such as fruits, vegetables, floriculture, and plantation crops provide higher income, employment generation, nutritional security, and export potential (Sharma, et al., 2007). However, horticulture is highly sensitive to environmental conditions, particularly water quality, soil salinity, groundwater availability, and climatic variability. Therefore, identifying suitable areas for horticultural plantation through geospatial technologies has become a major research priority worldwide.

In many developing countries, particularly India, groundwater serves as the backbone of agricultural irrigation. India is the largest user of groundwater in the world, accounting for approximately one-fourth of global groundwater extraction (Singh et al., 2017). Excessive dependence on tube wells, subsidized electricity, and expansion of irrigated agriculture have accelerated groundwater depletion in several states, including Haryana, Punjab, Rajasthan, and Gujarat. In northwestern India, the semi-arid regions are witnessing rapid decline in groundwater levels along with deterioration in water quality due to salinity, alkalinity, and excessive dissolved salts. Such conditions adversely affect soil fertility, vegetation growth, and long-term agricultural productivity (Kumar, 2018).

Haryana, one of the agriculturally developed states of India, has experienced remarkable agricultural transformation after the Green Revolution. However, continuous cultivation of water-intensive crops, excessive groundwater extraction, and changing climatic conditions have resulted in severe hydro-environmental stress in many districts (Sihag et al., 2021). The western and southwestern districts of Haryana, particularly Bhiwani and Charkhi Dadri, are among the most vulnerable regions facing groundwater scarcity, salinity hazards, and land degradation. These districts fall within the semi-arid agro-climatic zone characterized by low and erratic rainfall, high evapotranspiration, sandy soils, and poor natural recharge conditions. The study area exhibits significant spatial variability in groundwater quality parameters such as Electrical Conductivity (EC), Total Dissolved Solids (TDS), Sodium (Na), Chloride (Cl), Bicarbonate (HCO_3), and pH. (Kumar, 2018). High salinity and sodicity conditions are increasingly affecting agricultural land, resulting in declining crop productivity and expansion of fallow land. Simultaneously, groundwater extraction rates in several blocks have exceeded recharge capacity, leading to over-exploited aquifer conditions. According to groundwater assessment reports, blocks such as Bahal, Loharu, Tosham, and Bhiwani fall under critical or over-exploited categories, indicating unsustainable groundwater use patterns (Dahiya, et al. 2022). Despite these environmental constraints, horticultural plantations are emerging as a potential alternative for sustainable agricultural diversification in the region. Horticulture requires comparatively less water than conventional crops and provides higher economic returns per unit area. However, the success of horticultural development depends upon careful assessment of environmental suitability, including vegetation condition, groundwater quality, rainfall availability, and land use characteristics. Inappropriate site selection may lead to crop failure, soil degradation, and

economic losses. Therefore, there is a pressing need to identify scientifically suitable zones for horticultural plantation using advanced geospatial techniques (Dulam et al. 2025).
Remote Sensing (RS) and Geographic Information System (GIS) technologies provide an effective framework for integrated analysis of natural resources (Kumar and Singh, 2025). Satellite-based vegetation indices such as Normalized Difference Vegetation Index (NDVI) help in assessing vegetation health and crop vigor, while Land Use/Land Cover (LULC) mapping provides information regarding agricultural and non-agricultural land distribution. Similarly, GIS-based interpolation and spatial modeling enable analysis of groundwater quality, rainfall distribution, and environmental suitability (Manjula et al. 2022). The integration of these datasets through Multi-Criteria Evaluation (MCE) and machine learning approaches offers powerful tools for agricultural planning and resource management. Several studies across the world have demonstrated the effectiveness of GIS and remote sensing techniques in land suitability assessment (Kumar et al., 2008). However, most previous studies have focused either on groundwater quality or vegetation analysis separately. Limited research has been conducted integrating groundwater quality, rainfall variability, NDVI, LULC, and groundwater extraction together for horticultural suitability assessment in semi-arid regions of Haryana. Furthermore, there is insufficient understanding of how hydro-chemical stress and groundwater over-exploitation influence vegetation dynamics and horticultural potential in the study area (Kumar, 2018).
The present study attempts to fill this research gap by conducting an integrated geospatial assessment of groundwater quality, rainfall variability, vegetation condition, and land use characteristics in Bhiwani and Charkhi Dadri districts. The study employs satellite data, groundwater quality parameters, NDVI analysis, supervised classification, weighted overlay analysis, and machine learning techniques to identify suitable zones for horticultural plantation development. The research not only contributes to scientific understanding of hydro-environmental stress in semi-arid regions but also provides practical insights for sustainable agricultural planning and groundwater management. The central problem addressed in this research is the increasing mismatch between groundwater availability, water quality, and agricultural expansion in semi-arid regions. Excessive groundwater extraction, coupled with poor recharge and deteriorating water quality, has created severe constraints for sustainable agriculture in the study area. Large portions of agricultural land are becoming fallow due to salinity, sodicity, and water scarcity. Under such conditions, identifying environmentally suitable and economically viable horticultural zones becomes essential for improving land productivity, conserving groundwater resources, and enhancing farmers' livelihoods. Therefore, the present study seeks to answer the key questions: How do groundwater quality and rainfall variability influence horticultural suitability in the study area?

2. Study Area

The research region (Bhiwani and Charkhi Dadri district) is located in the western part of Haryana state, spanning an area of 4802 square kilometers. Its geographic range spans from 28°25'N to 29°29'N latitude and from 75°26'E to 76°28'E longitude. The research location is situated in the Indo-Gangetic plains (Alluvial plain, Aeolian plain, and dunes alongside the Aravali hills). The geological study area is situated in a younger quaternary alluvial formation. The slope of the study region varies from 210 to 680 m. The region has a semi-arid and tropical steppe climate with temperatures ranging from 25 °C to 47 °C and receiving 20-40 mm of rainfall. The study area lacks a perennial river. The soil in this region is composed of loamy, sandy, and fine loamy types. Groundwater levels and quality are decreasing in numerous locations within the study area. Fig. 1 shows the map indicating the location of the study area.

3. Methods and Methodology

The research was rigorously validated and relied upon by combining primary and secondary data. NDVI analysis, and LULC categorization all employ Landsat 8 images. The site appropriateness analysis for the research region was conducted using data on groundwater quality, and rainfall data. Georeferencing, rectification, and radiometric correction are applied to acquired images. The horticulture planation in the research region is evaluated by supervised image classification. The research area's horticulture plantings are identified using NDVI thresholding. With the help of the integration of both the data, horticultural planation suitability map is prepared. IDW (Inverse Distance Weightage) method was used to generate monthly rainfall maps. Groundwater quality analysis using various parameters as EC, TDS, Fluoride, Sodium, Magnesium etc. was using spatial interpolation methods. Suitability analysis was analyzed by combing NDVI, LULC, groundwater quality and rainfall distribution. Fig. 2 is showing the detailed methodology for the study. Following equations were used for various purposes:

$$NDVI = \frac{NIR-RED}{NIR+RED}$$ ……………………(Rouse, et al. 1974)

$$Z_0 = \frac{\sum_{i=1}^{n} d_i^{-p} Z_i}{\sum_{i=1}^{n} d_i^{-p}}$$

IDW

Here:

Z(x) = predicted rainfall

Zi = observed rainfall

di= distance

p= power parameter

Water Quality Index= $\sum(w_i \times Q_i)$

Here:

Wi = weight of parameter (EC, TDS, Na, etc.)

Qi = normalized quality rating

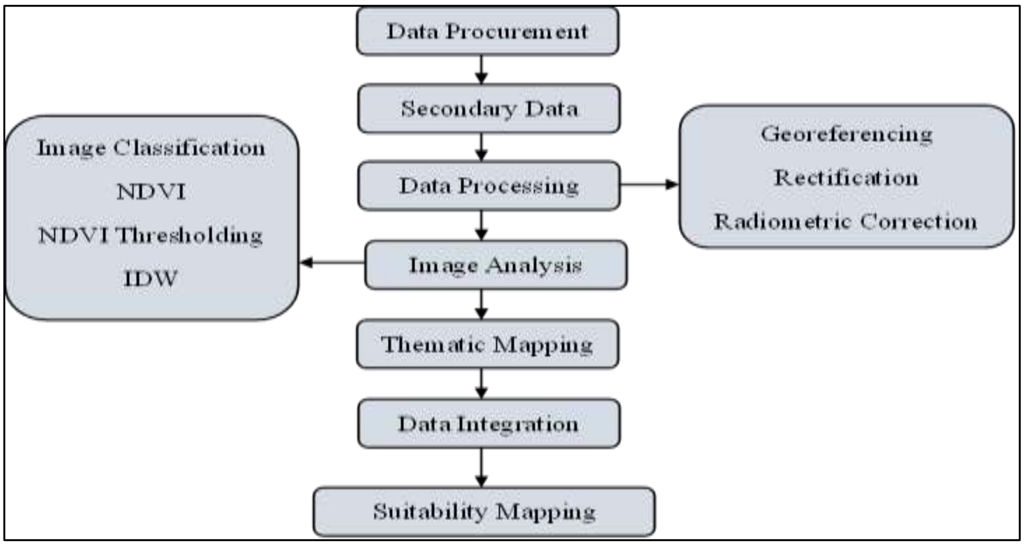

Fig. 2: Detailed Methodology

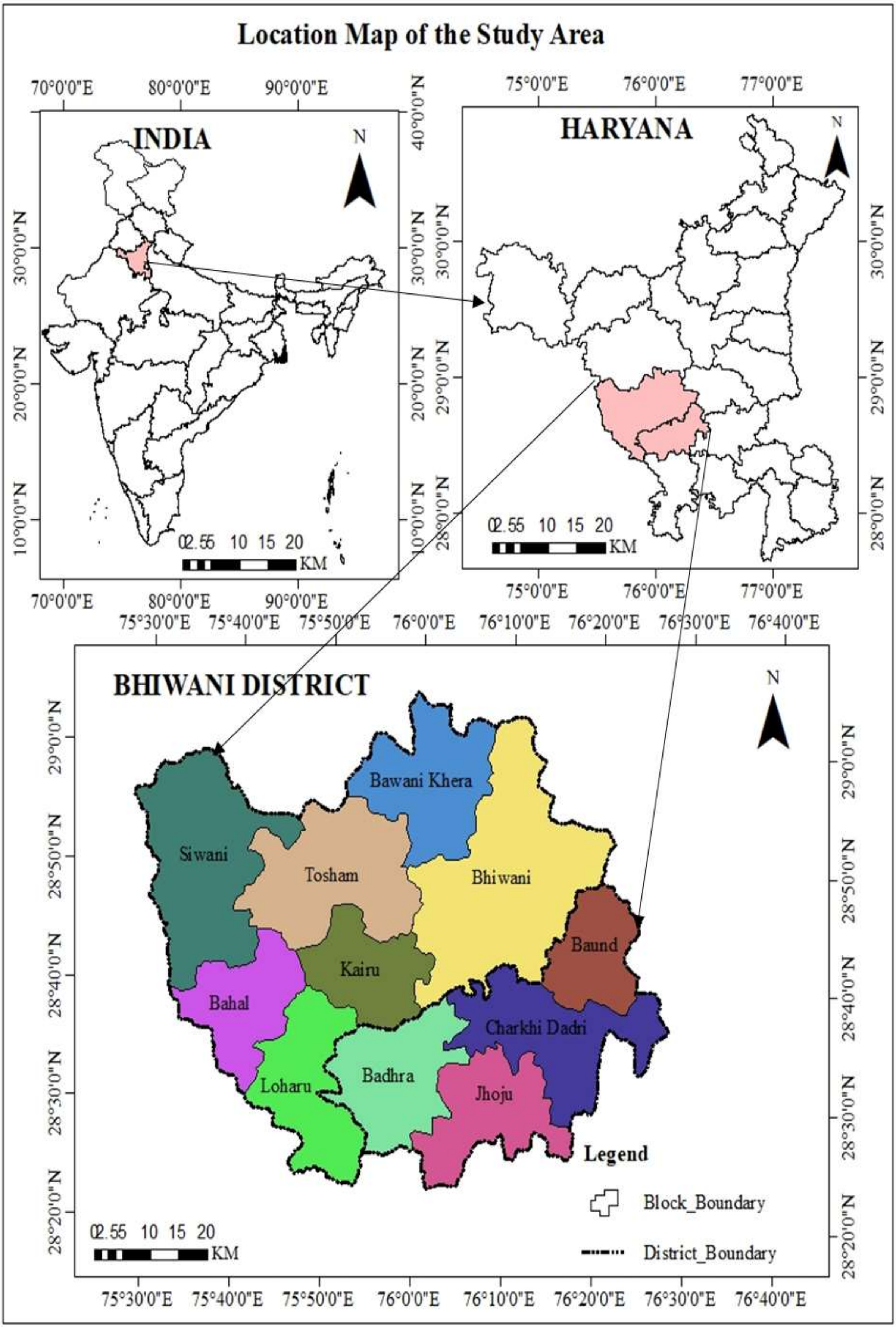

Fig. 1: Location map of the study area

4. Result and Discussion

Horticultural planation suitability was analysed by integration of both primary and secondary data. Detailed results are discussed below:

4.1 Rainfall variability analysis

Monthly rainfall data for the year of 2024 was collected and analyzed. The data analysis is showing strong seasonal concentration with peak rainfall in August as 503 mm and minimum in December 201 mm. Fig. 3 is showing the rainfall distribution in the study area.

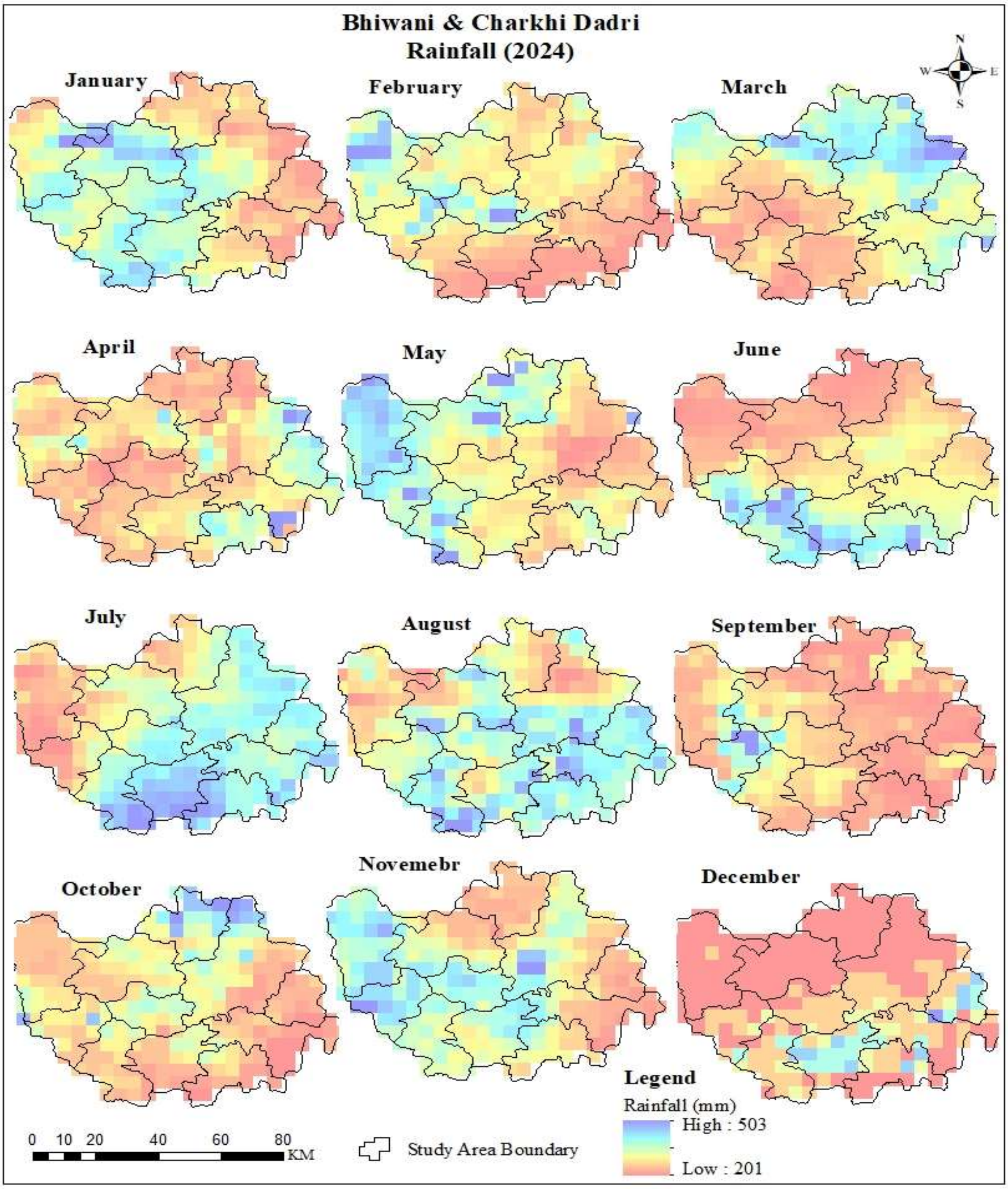

Fig. 3: Rainfall distribution

The Fig. 3 is showing the analysis of rainfall distribution in the Bhiwani and Charkhi Dadri District of Haryana. Coefficient of variation is high which indicating rainfall instability in the study area. Monsoon contributes approximately 55-60 % of the total rainfall in the area. pre monsoon period of rainfall in conventional driven and spatially uneven in Bhiwani and Charkhi Dadri districts. The monthly data is indicating that the precipitation is largely concentrated in Monsoon months. Northern and central blocks of the study area receive relatively higher rainfall and southwestern regions is showing rain shadow effect. The spatial analysis reveals highly seasonal and uneven distribution pattern characteristics of semi-arid climates. The rainfall trend is showing that gradual increasing from January to March followed by a slight decline in April and then a steady rise leading up to monsoon. The post-monsoon period shows that rainfall is declining in that season. The spatial disparity of the rainfall in the study area is attributed by regional climate and rain shadow effects. Overall, recharge potential is very low due to high evaporation and low rainfall. Thus, short monsoon duration is showing low recharge efficiency and high runoff losses reduced the groundwater replenishment.

4.2 Land use and land cover mapping

Supervised image classification is done to analyse the land use and land cover mapping in the study area. The entire study area is classified into six classes as built-up area, fallow land, horticultural-planation, waterbody, vegetation and agricultural land. Fig.4, Table 1 and Fig. 5 are showing the land use and land cover mapping of the study area.

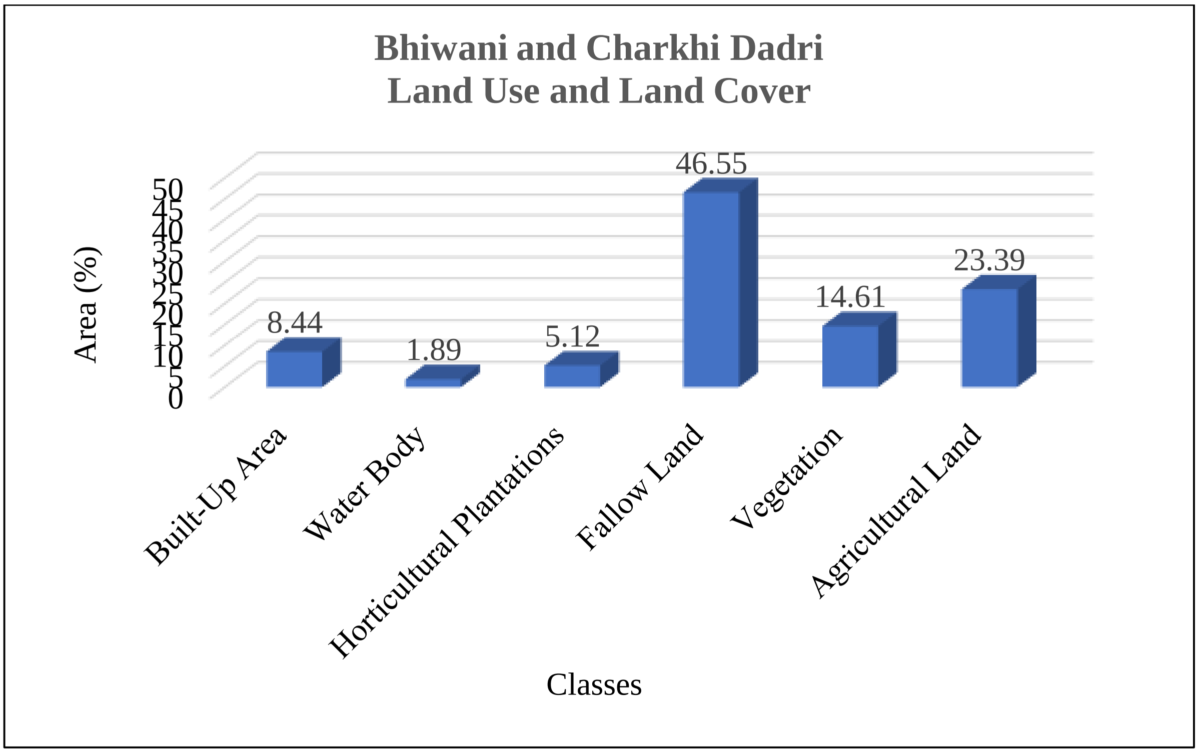

Fig. 4: Area under various LULC classes

Table 1: LULU analysis

Years		Built-Up Area	Water Body	Horticultural Plantations	Fallow Land	Vegetation	Agricultural Land
	Area (ha)	40536	9096	24568	223542	70142	112316

2024	% of Area	8.44	1.89	5.12	46.55	14.61	23.39

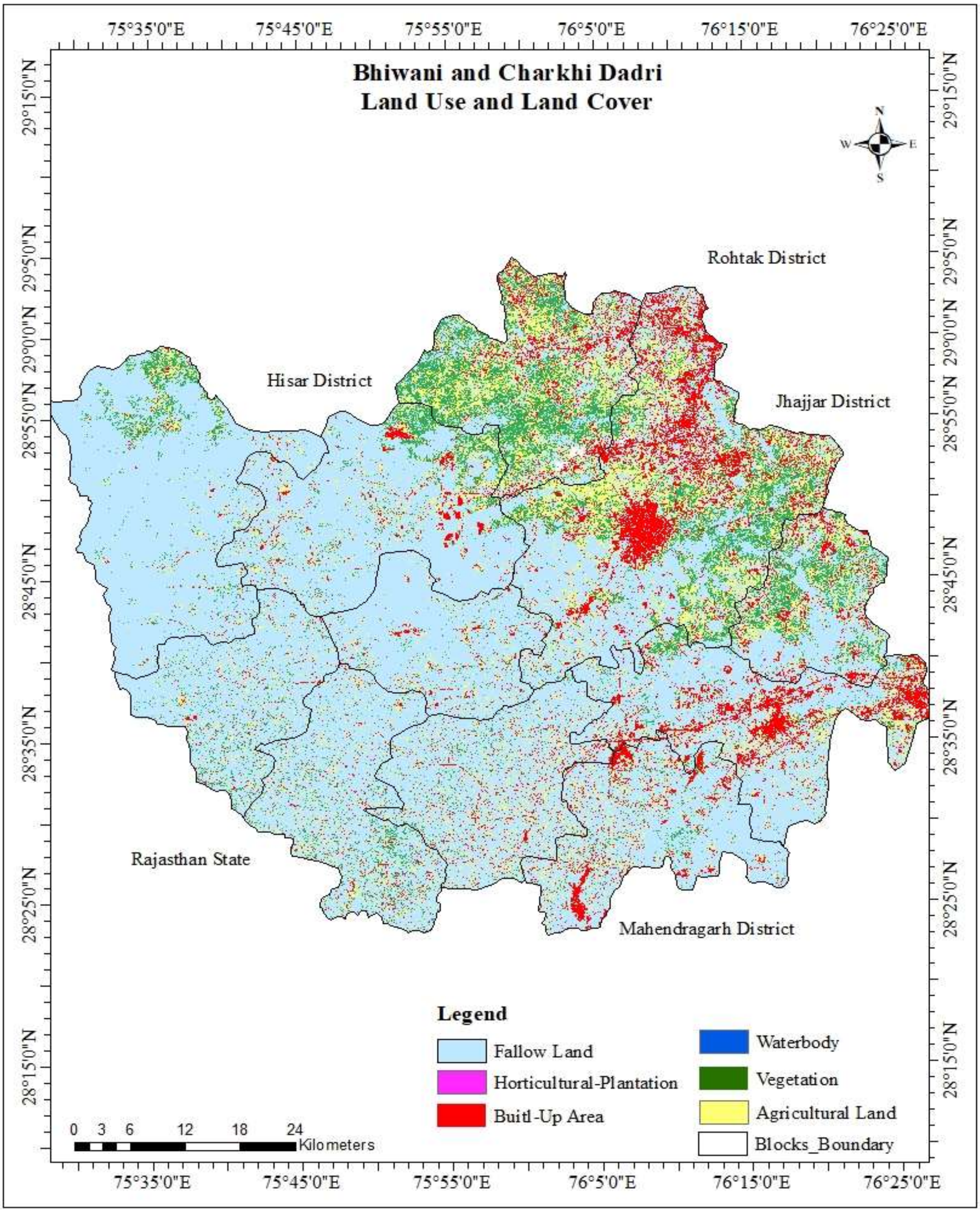

Fig. 5: LULC map

Fig. 4, Table 1 and Fig. 5 is showing the land use and land cover analysis of the study area. The LULC analysis reveals that fallow land dominates the study area, accounting for 46.55% of the total area of the study area. Agricultural land constitutes 23.39%, while vegetation covers 14.61%. Built-up areas account for 8.44%, and horticultural plantations occupy only 5.12% of the area. The high proportion of fallow land indicates underutilization of available land resources, likely due to poor soil quality, water scarcity, and salinity issues. The limited extent of horticultural plantations suggests that environmental constraints restrict their expansion. The spatial distribution shows that agricultural and horticultural activities are concentrated in areas with relatively better groundwater quality and vegetation density.

4.3 NDVI thresholding

The NDVI analysis indicates values ranging from -0.41 to 0.50, reflecting varying vegetation conditions across the study area. Most areas fall within the range of 0.1 to 0.3, indicating sparse to moderate vegetation. Table 2, Fig. 6 and Fig. 7 are showing the NDVI analysis of the study area.

Table 2: NDVI thresholding calculation

Years	NDVI area other than Horticultural Plantation	NDVI Thresholding Area	Area in %
2024	451202	28998	6.04

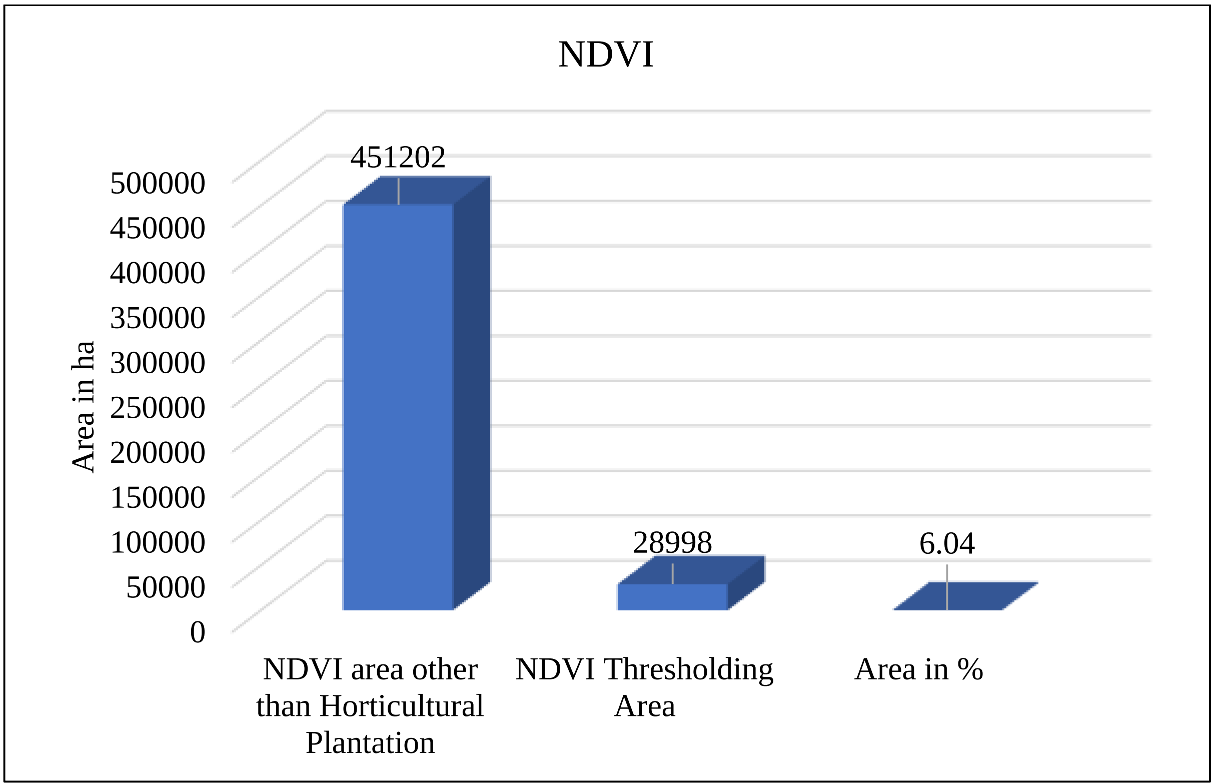

Fig. 6: NDVI analysis

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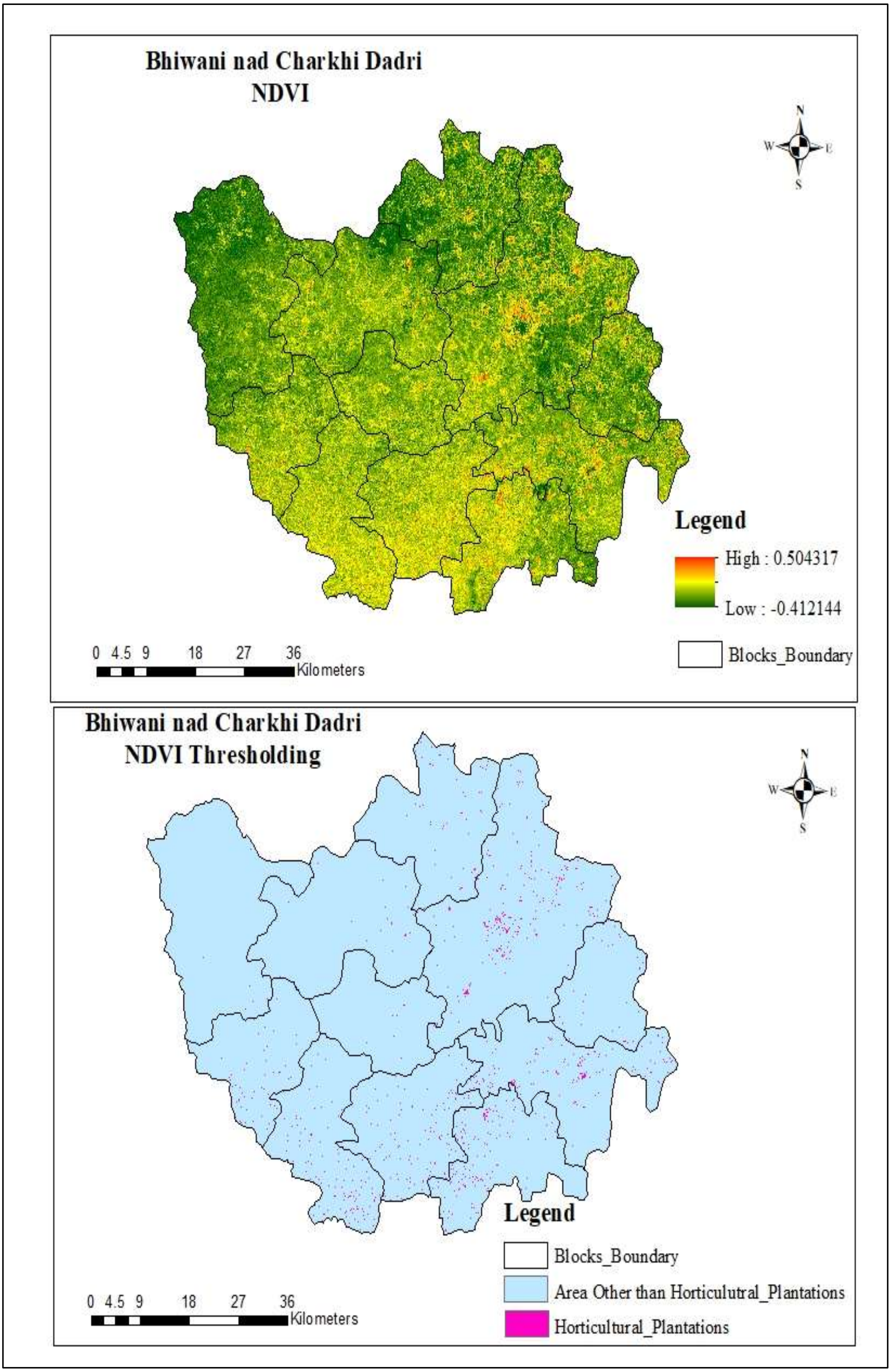

Fig. 7: NDVI thresholding

Table 2, Fig. 6 and Fig. 7 are showing the NDVI thresholding analysis of the study area. Higher NDVI values are observed in localized regions corresponding to irrigated agriculture and horticultural plantations. The NDVI thresholding results confirm that only 5.12% of the area is under horticulture. The low NDVI values in large parts of the study area highlight poor vegetation health, which can be attributed to water scarcity, soil degradation, and salinity issues.

4.4 Groundwater quality analysis

Secondary data was used to analyze the groundwater quality of the study area. Various parameters were discussed and presented by Fig. 8.

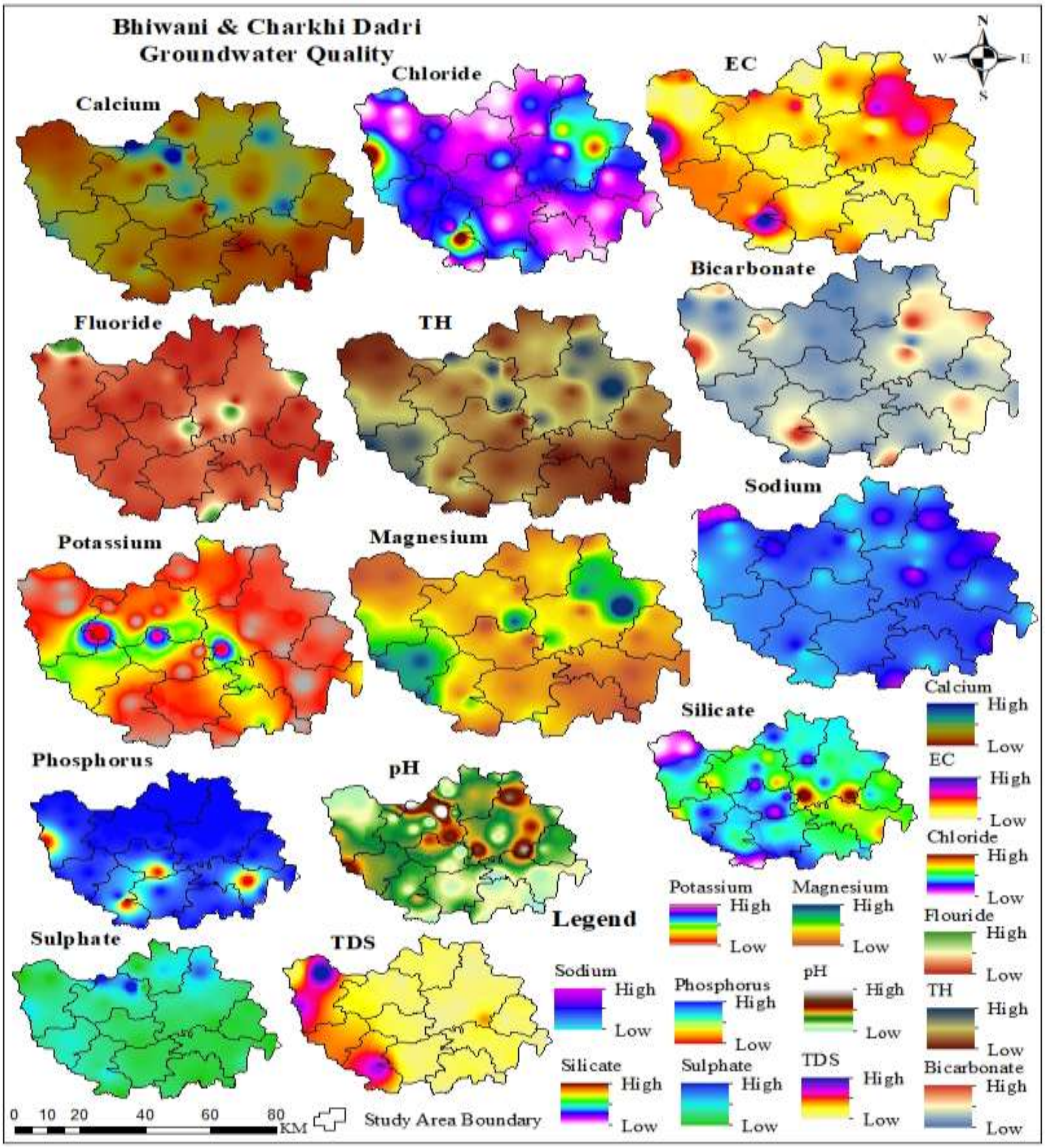

Fig. 8: Groundwater quality map

Fig. 8 is showing the analysis of groundwater quality in the study area. The spatial distribution of Electrical Conductivity (EC) indicates significant salinity variations across the study area. High EC values are predominantly observed in the northern, southwestern, and central-eastern parts of the region. These elevated EC levels suggest the presence of high soluble salt concentrations in groundwater, rendering it unsuitable for irrigation in affected areas. Conversely, central regions exhibit relatively lower EC values, indicating comparatively better water quality. The high salinity levels can be attributed to factors such as excessive groundwater extraction, poor drainage conditions, and evaporation-induced salt accumulation. Prolonged use of such saline water for irrigation may lead to soil salinization, reduced crop productivity, and long-term land degradation. The TDS distribution closely follows the pattern observed for EC, with higher concentrations in the southwestern and northern regions. Elevated TDS levels indicate the presence of dissolved inorganic salts, making the water brackish in nature. Such water is unsuitable for sensitive crops and can adversely affect soil structure and permeability. The correlation between EC and TDS suggests that salinity is a dominant hadrochemical characteristic in the region. The presence of high TDS values further confirms the limited suitability of groundwater for irrigation purposes in large parts of the study area. Fluoride concentration is generally within safe limits across most of the study area, with localized pockets of higher values observed in Bhiwani, Siwani, and Jhojhu blocks. These elevated fluoride levels are likely associated with geological formations containing fluoride-bearing minerals. While fluoride primarily poses health risks in drinking water, its agricultural impact is relatively limited. However, prolonged exposure may indirectly affect soil and plant systems. The localized nature of high fluoride zones suggests the need for targeted monitoring and mitigation strategies.

Calcium distribution shows moderate concentrations across the study area, with higher values observed in Tosham and parts of Bhiwani. Calcium is an essential nutrient for plant growth and plays a crucial role in maintaining soil structure. The presence of adequate calcium levels can help mitigate the adverse effects of sodium by improving soil permeability and aggregation. Therefore, regions with moderate calcium concentrations are relatively more suitable for agricultural and horticultural activities. High chloride concentrations are observed in Siwani and Loharu regions, while lower levels are recorded in Tosham, Jhojhu, and Bawani Khera. Elevated chloride levels in irrigation water can lead to toxicity in plants, particularly in chloride-sensitive crops such as fruits and vegetables. The spatial distribution of chloride suggests that southwestern regions are more vulnerable to salinity-related stress, which may limit the expansion of horticultural plantations in these areas. Total hardness is significantly high in Bahal, Tosham, and Bhiwani regions, indicating the presence of high concentrations of calcium and magnesium ions. Hard water can affect soil permeability and reduce infiltration rates, thereby impacting irrigation efficiency. Although hardness is not directly harmful to crops, its indirect effects on soil structure and water movement can influence agricultural productivity. High bicarbonate concentrations are observed in Siwani, Loharu, and parts of Bhiwani. Elevated bicarbonate levels contribute to soil alkalinity, which can adversely affect nutrient availability and plant growth. High bicarbonate water may lead to the precipitation of calcium and magnesium, resulting in sodium dominance and increased soil sodicity. This process further exacerbates soil degradation. Potassium distribution indicates higher concentrations in Siwani, Bahal, Tosham, and Bhiwani regions. As an essential macronutrient, potassium plays a vital role in plant metabolism, photosynthesis, and stress resistance. The presence of adequate potassium levels in these regions is favourable for horticultural crops, provided other limiting factors such as salinity and water availability are addressed. Magnesium levels are higher in southern Siwani, Bahal, and southeastern Tosham. While magnesium is an essential nutrient, excessive concentrations may lead to soil imbalance and reduced calcium availability. High magnesium levels can also contribute to soil dispersion, particularly when combined with high sodium concentrations. Sodium concentration is relatively high in northern Siwani and parts of Bhiwani. Elevated sodium levels are a major concern as they lead to soil sodicity, which reduces soil permeability and aeration. High sodium adsorption ratio (SAR) conditions can severely affect crop growth and reduce agricultural productivity. This makes large portions of the study area unsuitable for intensive agriculture without proper soil management practices. Phosphorus is generally abundant across the study area, indicating nutrient-rich soil conditions. However, excessive phosphorus may lead to nutrient imbalance and environmental concerns such as eutrophication. The widespread availability of phosphorus supports agricultural productivity, particularly for horticultural crops that require balanced nutrient supply. Sulphate levels are moderately distributed across the region, with no significant spatial constraints. Sulphate is an essential nutrient for plant growth and contributes to protein synthesis. The absence of extreme sulphate concentrations indicates that it does not pose a major limitation for agriculture in the study area. The pH values indicate alkaline conditions in Tosham, Kairu, Bhiwani, and northwestern Bahal regions. High pH levels reduce the availability of micronutrients such as iron, zinc, and manganese, leading to nutrient deficiencies in crops. The alkaline nature of soil and water is a critical factor limiting agricultural productivity in the region. Silicate distribution shows scattered variations across the study area. Although silicate plays a minor role in plant growth, it can enhance resistance to pests and environmental stress. Its overall impact on agricultural suitability is limited compared to other parameters.

4.5 Site suitability analysis

Site suitability map for horticultural plantation from all the datasets (rainfall, groundwater quality, NDVI, and LULC), was prepared to convert all parameters into a common suitability scale, assign weights, and perform a weighted overlay analysis. The integration of rainfall, groundwater quality, NDVI, and LULC data reveals a strong interrelationship between water availability, soil conditions, and vegetation health. Areas with moderate rainfall, low salinity, and higher NDVI values are more suitable for horticultural development. The entire study area was classified into three classes is low suitability, moderate suitability and high suitability of horticultural planation in Bhiwani and Charkhi Dadri districts of Haryana. Fig. 9 and Fig. 10 are showing the site suitability map of the study area. Table 3, 4,and 5 are showing the role of various parameters, weight assignment and area of for site suitability.

Table 3: Parameters role in site suitability

Parameters	Role	Parameters	Role
NDVI	Vegetation Health	TDS	Water quality
LULC	Land Variability	Sodium	Sodicity
Rainfall	Water Input	pH	Alkalinity
EC	Salinity	Groundwater Extraction	Sustainability

Table 4: Weight assignment analysis

Parameters	Weight	Reason
NDVI	18	Indicator of vegetation health
LULC	16	Suitability for land use
Rainfall	16	Input source of water
EC	15	Salinization impact
TDS	12	Usability of water
Sodium	10	Degradation of soil

pH	7	Availability of nutrient
Extraction	6	Sustaiblity

Table 5: Site suitability area calculation

Class	**Low**	**Moderate**	**High**
Area in ha	79604	153265	247331
Area in %	16.56	31.93	51.51

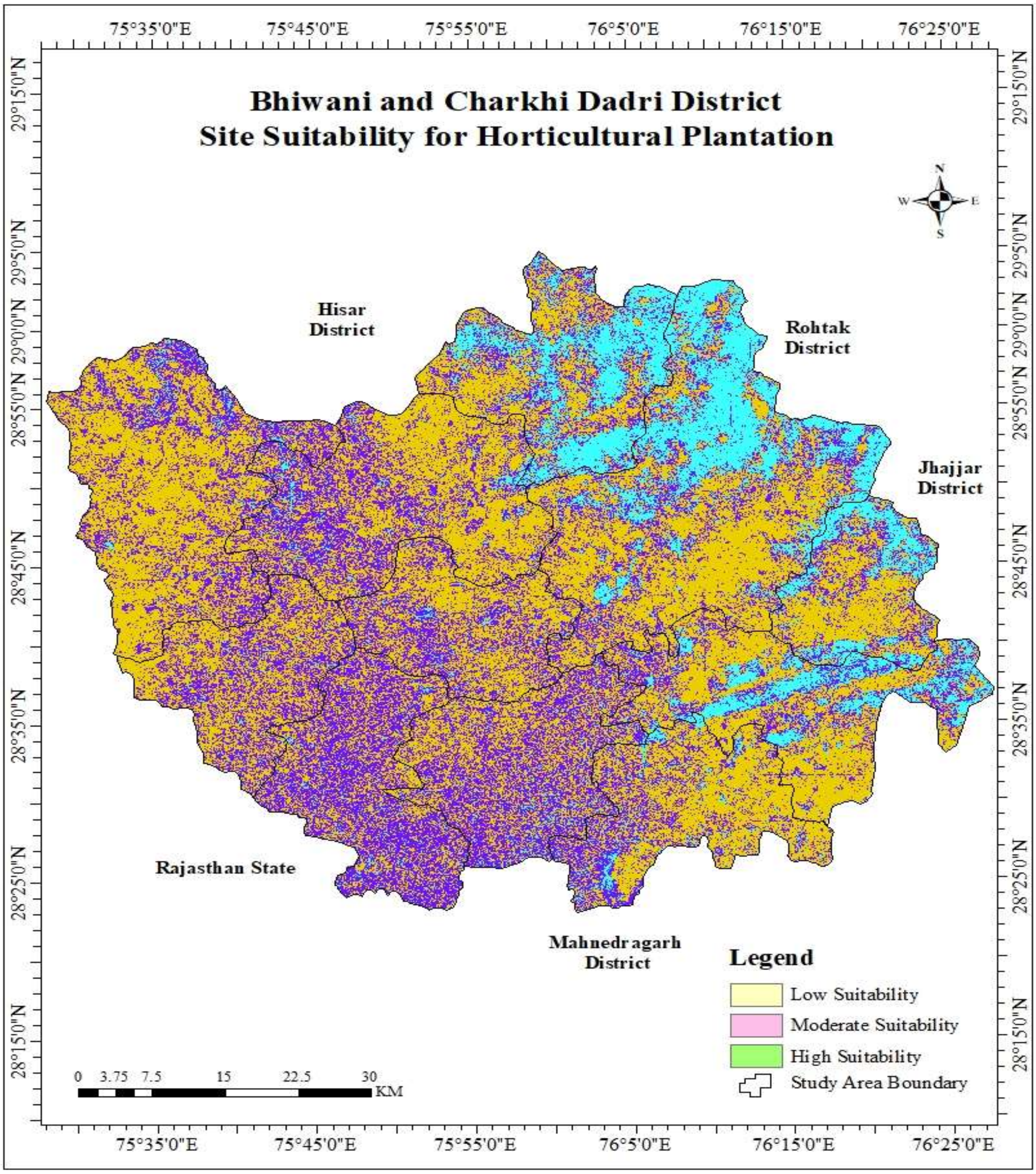

Fig. 9: Site suitability map

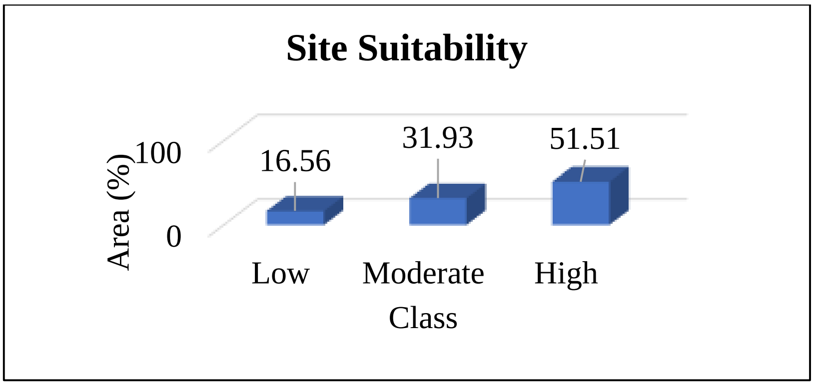

Fig. 10: Land Suitability

Table 5, Fig. 9 and Fig. 10 are showing the site suitability analysis in the study area. The results classified the study area into three suitability categories: High, Moderate, and Low suitability. The analysis revealed that 51.51% of the total area falls under the High Suitability category, indicating favourable conditions for horticultural plantation. These areas are mainly distributed in the central, eastern, and northeastern parts of Bhiwani and Charkhi Dadri districts, where groundwater quality is relatively better and vegetation density is higher. The Moderate Suitability category covers 31.93% of the area, representing regions with moderate environmental conditions that can support horticulture through proper management practices such as drip irrigation and soil amendments. The Low Suitability class occupies only 16.56% of the total area and is concentrated mainly in the western and southwestern parts, particularly around Loharu, Bahal, and Siwani blocks. These areas are constrained by high salinity, elevated TDS, sodium hazards, poor vegetation cover, and excessive groundwater extraction. The spatial pattern indicates that groundwater quality plays a crucial role in determining horticultural suitability. The results further demonstrate that nearly 83.44% of the study area falls under high and moderate suitability classes, suggesting considerable potential for horticultural expansion. Therefore, horticultural plantation can be promoted as a sustainable land-use option in suitable areas, while groundwater conservation and salinity management measures are required in low suitability zones to improve agricultural productivity and resource sustainability.

Conclusion

The present study demonstrates the effectiveness of integrating Remote Sensing and GIS techniques for assessing horticultural plantation suitability in the semi-arid districts of Bhiwani and Charkhi Dadri. The analysis revealed significant spatial variations in rainfall, groundwater quality, vegetation condition, and land use patterns across the study area. Groundwater quality parameters such as EC, TDS, sodium, and pH emerged as major factors influencing agricultural suitability. The site suitability analysis showed that 51.51% of the area is highly suitable, 31.93% moderately suitable, and 16.56% low suitable for horticultural plantation development. High suitability zones are mainly concentrated in central and eastern parts of the study area, whereas western regions are constrained by salinity and groundwater over-exploitation. NDVI and LULC analysis further confirmed the potential for expanding horticultural activities in suitable areas. The study highlights that sustainable horticultural development can improve land productivity and farmers' income while reducing pressure on conventional agriculture. Therefore, efficient groundwater management, micro-irrigation practices, and scientific land-use planning are essential for achieving long-term agricultural sustainability in the region.

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