GEO-SPATIAL TECHNIQUES AND MACHINE LEARNING-BASED ASSESSMENT OF GROUNDWATER SUSTAINABILITY IN THE RAJSHAHI REGION, BANGLADESH

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ABSTRACT

Excessive use of groundwater across different sectors led to groundwater depletion in the northwest region of Bangladesh. Planning for the sustainable use of Groundwater is very much needed. Not only agricultural consumption but also unplanned urban growth are among the main contributors to the groundwater shortage during the dry season. Historical trends of the five-year duration (weekly) maximum and minimum depths of groundwater tables (GWTs) indicate the sustainability status of groundwater resources, food security, and risk zones. In this study, groundwater potential risk zones are delineated by combining spatiotemporal analysis with machine learning (ML) techniques in the Rajshahi district of Bangladesh. Assessment of long-term groundwater trend from 1995 to 2024 of GWTs of 8 monitoring wells located in Sadar Upazila and their impacts on the condition of groundwater table rise and fall in response to urban growth, different thematic layers, including slope, elevation, geology, land use, lineament, drainage, and soil rainfall are considered. Based on the current trend of the groundwater table, potential future groundwater risk zones are identified. Water table (m) prediction was undertaken using CatBoost Classifier, and the results show that CatBoost Classifier performs best with 88.47% accuracy, 88.70% precision, 88.70% recall, and 88.47% of F1-Score. Our study successfully determined changes in groundwater levels in the Rajshahi region of Bangladesh from 1995 to 2024 and predicted a potential groundwater crisis from 2025 to 2040 due to rapid urbanization, increased industrial water demand, and climate change. Therefore, the study identifies probable future risk zones in Rajshahi district, where the implementation of artificial aquifer recharge and water-saving technologies is urgently needed to ensure sustainable groundwater consumption.

Keywords: *Groundwater sustainability, Groundwater potential risk zone, Spatio-temporal analysis, Machine learning (ML), Groundwater recharge.*

1. INTRODUCTION

Groundwater is one of the fundamental sources of fresh water in the Rajshahi region. It is necessary for industry, household consumption, and farming. Mainly, tube and deep wells supply the majority of the drinking water for the entire town and its neighbouring areas(Dey et al., 2017; Janardhanan et al., 2023). The water resources crisis in developing countries, including Bangladesh, is getting progressively worse due to factors such as uncontrolled groundwater overexploitation, urbanisation, industrialisation, and a changing climate(Mojid et al., 2019; Taylor et al., 2013). Approximately two billion people in developing nations will face a water shortage at some point, according to research(Dhakal et al., 2022). According to research, treatment of wastewater and reuse are becoming more and more essential for sustainable water management, especially in view of the global shortage of water and rising urbanization(Silva, 2023). The country's use of groundwater started to increase mainly after 1995. This has contributed to a serious shortage of water in the districts of Chapainawabganj, Rajshahi, and Naogaon(Shahid & Hazarika, 2010). The highest record drop in the level of groundwater in Bangladesh's northwest took place in Rajshahi district, where it dropped by 4 to 12 meters between 1981 and 2014(A. T. M. S. Rahman et al., 2016). According to research, the Rajshahi region's groundwater decrease rate is steadily rising. About 0.8 meters are lost every ten years on average(Salam et al., 2020). The Rajshahi region's yearly precipitation dropped by around 25% during that time, which naturally lowered groundwater recharge(Mamun et al., 2021). Through the last three decades, the level of groundwater has been rapidly dropping in the Rajshahi region districts that include Bogura and Pabna, with an average drop of 2-6 meters; in some areas, the drop has risen to 10-13 meters(Hasanuzzaman et al., 2017; Salam et al., 2020). In the past several decades, there has also been significant groundwater depletion in the other three districts of the Rajshahi region: Joypurhat, Sirajganj, and Natore. In this region, investigations have convincingly shown the depth and pace of water table decline; in Joypurhat, for instance, the level of groundwater has dropped by roughly 0.104 to 0.159 meters(Ahmed et al., 2021; Rashid et al., 2021). GIS, remote sensing, and MCDM (such as the process of analytical hierarchy, or AHP) are all frequently utilized to find potential groundwater zones(Arulbalaji et al., 2019; Fatema et al., 2023). To ensure long-term water management, well installation, artificial recharge, and conserving water, legislators, farmers, and water administrators can all benefit significantly from this type of mapping(Doke et al., 2021). Although the use of groundwater and sustainability in Bangladesh is the subject of much research, there is currently still a lack of Integrated geospatial analysis and machine learning (ML) based forecasting that is focused on groundwater sustainability in the northwest region, especially Rajshahi, under the influence of growing urbanisation, industrialisation, and climate change. Meanwhile, inadequate focus has been paid to the use of machine learning algorithms (ML)and geographic information systems (GIS) in evaluating the impacts of urbanisation and determining vulnerable areas. The main objective of this research is to evaluate the long-term conditions and changes in Bangladesh's Rajshahi region between 1995 and 2024. Through integrating rainfall, thematic layers including urbanisation, geological situations, and changes in land use, it also attempts to determine potential groundwater zones. Finally, machine learning (ML)techniques, particularly the CatBoost classifier model, are employed to make accurate predictions to assess future vulnerability for the years 2025-2040.

2. METHODOLOGY

There are multiple techniques for predicting Groundwater, and a few of these methods may be reliable for probabilistic prediction of future groundwater levels on a meter (m) scale. Machine learning techniques are one of the interesting methods for Future groundwater level prediction. A long-term probabilistic prediction can be possible by using multiple Machine Learning algorithms and the application of geospatial techniques. The overall methodology covers some sequential steps.

- BWDB: To investigate historical fluctuations and trends, groundwater level data were collected from the Bangladesh Water Development Board (BWDB) for the period 1995 to 2024.
- World Clim: Rainfall-associated climate data were collected to determine that rainfall impacts groundwater recharge.

- GEE and USGS to support geospatial and spatial analyses, data on land use land cover (LULC), soil, geology, and digital elevation models (DEM) have been collected.

2.1 Description of the Study Area

This study focuses on the Rajshahi region specifically, between latitudes 23°48'N to 25°16' N and longitudes 88°01'E to 89°48'E. Rajshahi region in northwestern Bangladesh is a low-lying alluvial plain with the slightly more elevated and drought-prone Barind Tract, making it one of the country's anhydrous regions. Annual rainfall is relatively low (roughly 1500–2200 mm), strongly concentrated in the monsoon season (especially June–July), and a pronounced dry period from November to March. A total of eight observation wells (including well ids GT8549005, GT8878016,GT1020005,GT7066005,GT6963011,GT7655022, ,GT6460015,GT3847001) in the Rajshahi region, were used in this study, which mainly elaborates on the status of groundwater levels in the urban area.As per the 2022 census report, this region's total population is 2,03,53,116 with a population density of 1,121/km², where the urban population is 4840396 (23.78%) (Population and Housing Census 2022, National Report (volume I)). This region covers 18,174.4 km², which is shown in Figure 1.

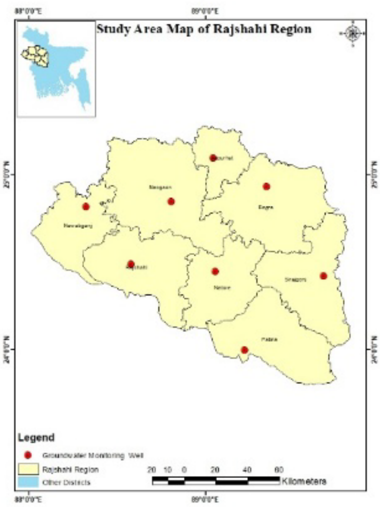

Figure 1: Study area map.

3. RESULTS AND DISCUSSION

3.1 Land Use and Land Cover

The land use and land cover map of the Rajshahi region,1995 to 2025 shown in Figure 2. From the analysis, urban areas increased gradually from 1995 to 2025. In 1995, the Rajshahi region was predominantly covered by agriculture (light green) with scattered vegetation patches and relatively small urban areas, covering approximately 2228.98 km2, but in 2025, it covered approximately 3346.64 km2.

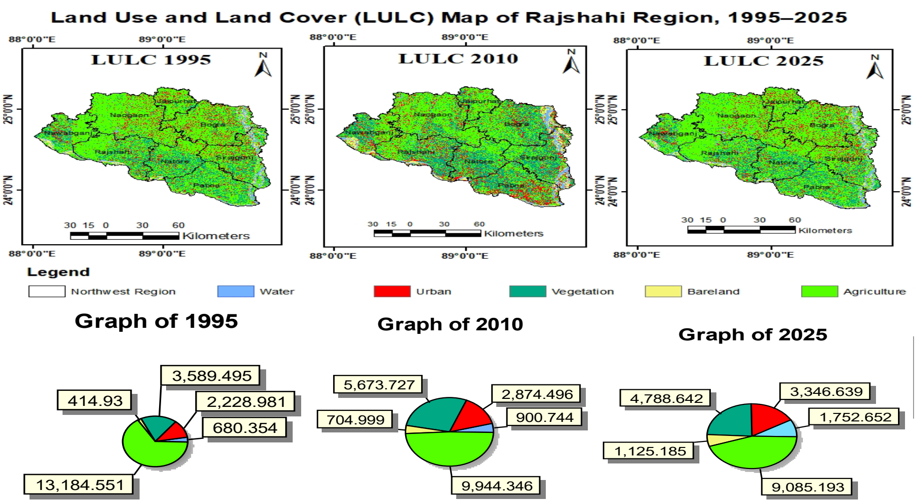

Figure 2: Land use and land cover map of the Rajshahi region,1995 to 2025.

Due to the better lifestyle, available income sources pull people towards the urban areas. Rapid growth of urbanization has its negative impacts on water, vegetation, bare land, and agriculture, too, as shown in Figure 2.

3.2 Rainfall

In Bangladesh, the highest rainfall occurs during the monsoon, especially between June and September. Among these, July usually records the highest average rainfall throughout the country. Worldclim historical precipitation data was processed to produce the monsoon seasonal rainfall distribution, especially in July, for the Rajshahi region in 1995,2005,2015, and 2024, as is shown in Figure 3. Based on this map, we observed that Nawabganj, Pabna, some parts of Rajshahi, and Naogaon have experienced comparatively lower seasonal rainfall, ranging from 220 mm to 260 mm. However, Bogra, Jaipurhat, and some parts of Rajshahi have experienced comparatively higher rainfall. Due to the lowest seasonal rainfall, the groundwater table in those areas is not fully recovering to its previous state, which has a significant impact on the food security of the local people.

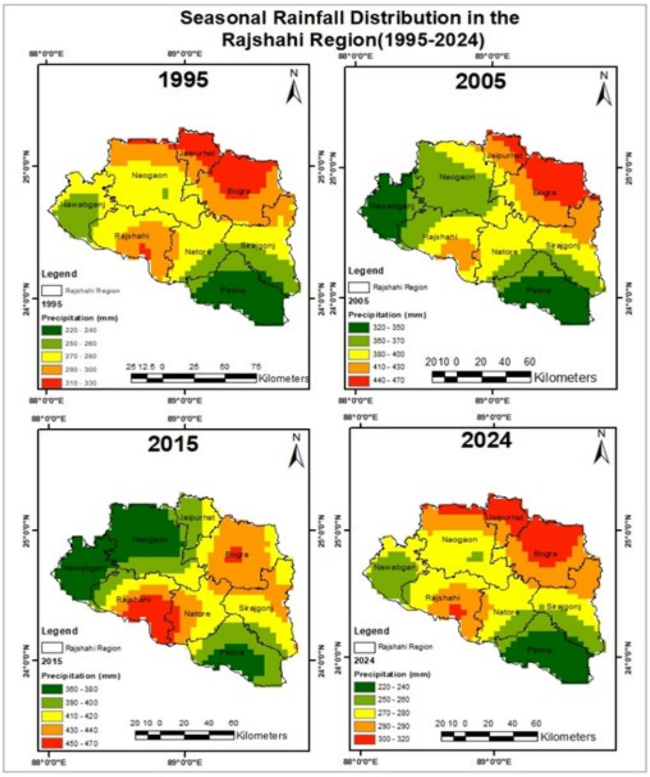

Figure 3: Seasonal rainfall distribution of Rajshahi region from 1995 to 2024.

3.3 DEM

The Digital Elevation Model (DEM) of the Rajshahi region was generated using SRTM (30 m resolution) data obtained from the USGS Earth Explorer. DEM shown in Figure 4, illustrates elevation differences across the study area, with higher elevations in the northwest parts, mainly Nawabganj, parts of Rajshahi, Naogaon, Jaipurhat, and Bogra, which have an elevation range between 22m and 86m, and lower elevations towards the southeast, including Pabna and Sirajganj, with an elevation range between -32 m and 21 m.

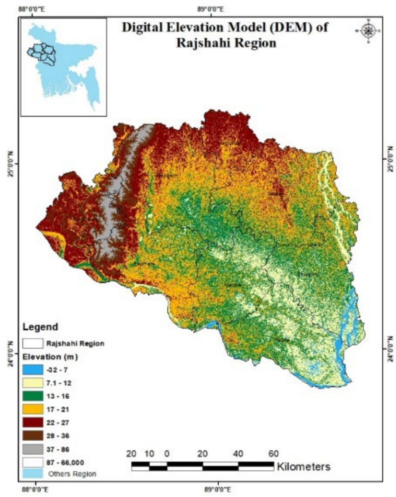

Figure 4: Digital Elevation Model (DEM) of the Rajshahi region.

3.4 Soil

Infiltration of Water is highly dependent on the soil type and texture. The spatial distribution of Soil is shown in Figure 5, which was collected from the USGS.

Bangladesh, the largest deltaic island, and for this reason, most parts of the country are formed by floodplain soil. The soil classification map of the Rajshahi region indicates that this area is largely composed of non-calcareous grey floodplain soil. Another soil includes acid sulphate soil, calcareous grey floodplain soil, and calcareous dark grey floodplain soil, which are also found here(Islam et al., 2017). However, non-calcareous dark grey floodplain soil and red-brown terrace soil are comparatively less dominant. Based on their infiltration rate of water, the sequence is “Red-brown terrace soil >

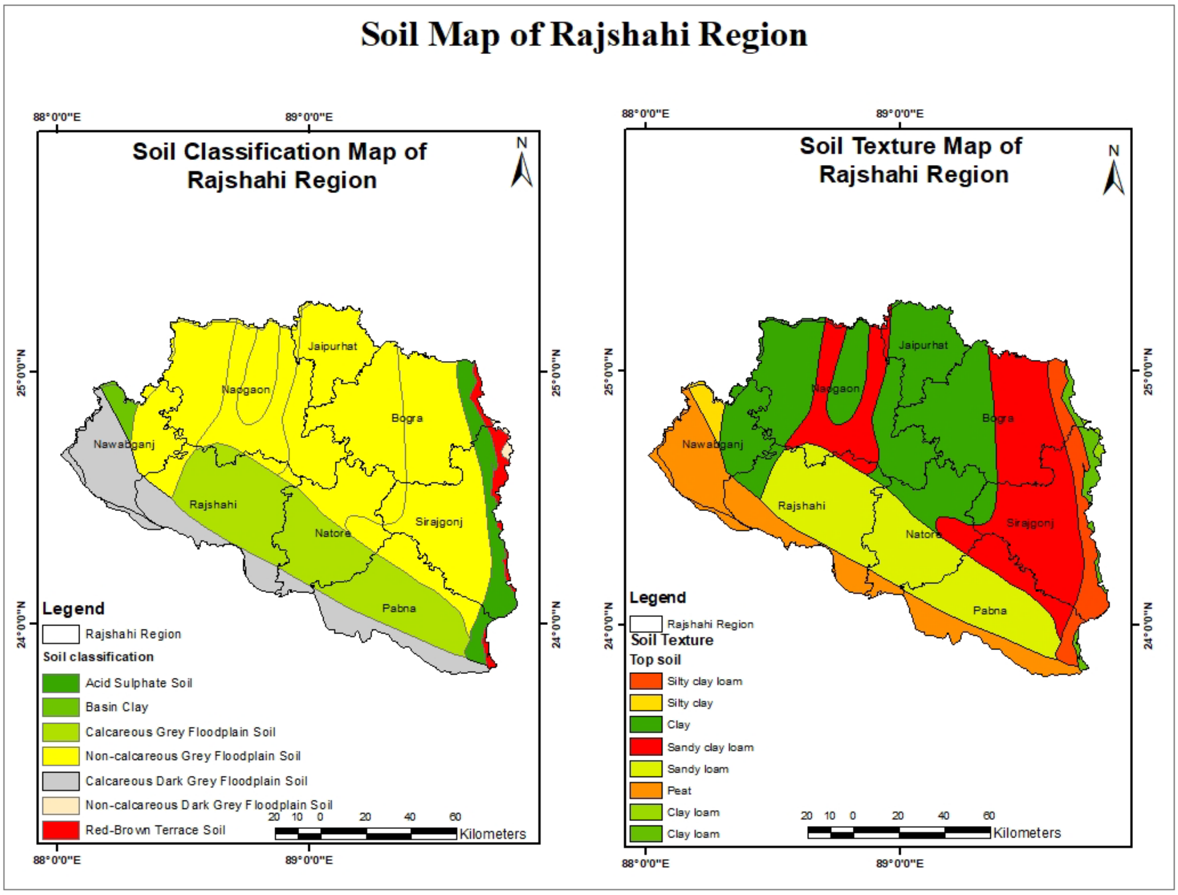

Figure 5: Soil map of the Rajshahi region, Bangladesh.

Non-calcareous grey floodplain soil > Calcareous dark grey floodplain soil >Acid sulphate soil”. Based on the soil texture, the maximum area covered with clay soil, which has the lowest infiltration of water infiltration capability, but loamy soil has the highest water infiltration capability. Based on this region’s soil textures and water infiltration capabilities, the following sequences include: Sandy loam > Sandy clay > Peat > Clay loam > Silty clay loam > Silty clay > Clay, which clarifies the main reason behind the groundwater level decreases.

3.5 Geology

Geology is also an interesting factor that affects groundwater recharge in a region. The Geological map of the Rajshahi region is shown in Figure 6 (a), which was collected from the USGS. Due to the geographic location of Bangladesh, the highest portion is formed through alluvium. Geo-Spatial analysis of our study area represents that Alluvial silt and Barind clay residuum, Alluvial silt and clay, Alluvial sand, and Marsh clay and peat are in the highest proportion, and others like Deltaic sand are relatively low. Barind clay residuum has the lowest water infiltration capabilities, so there is a significant impact on some parts of Nawabganj, Naogaon, and Rajshahi. But others have relatively low infiltration of water capability.

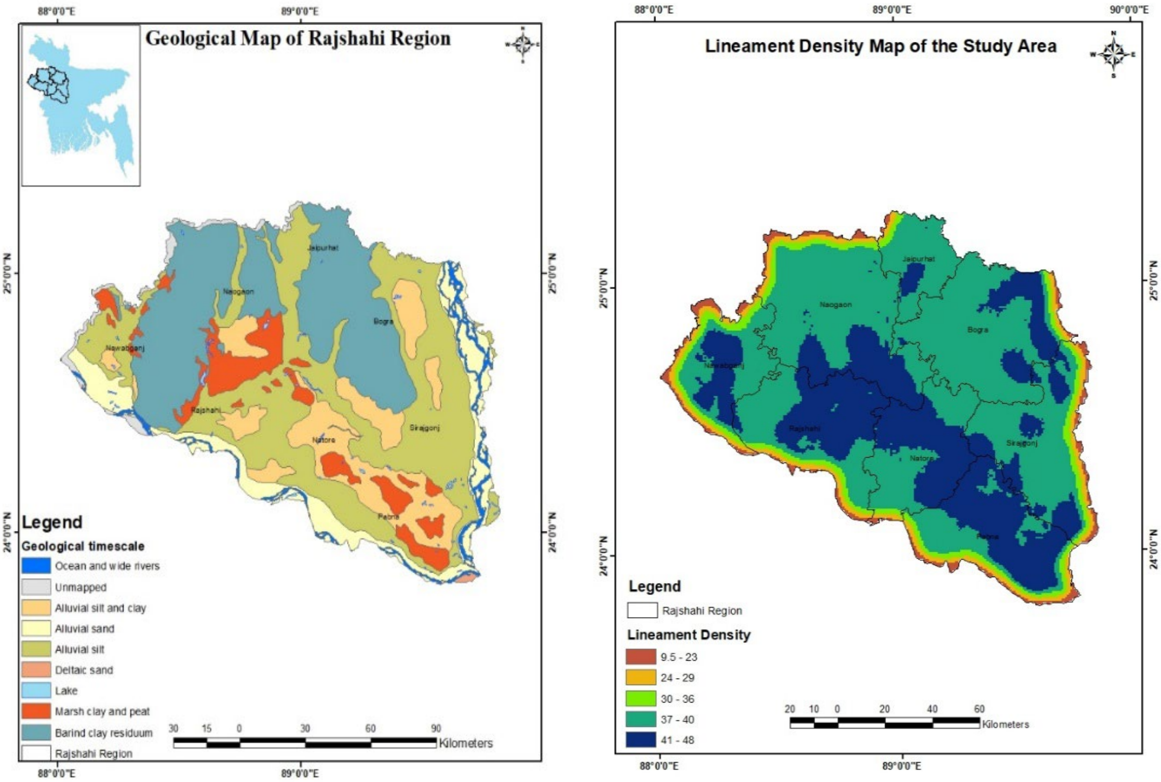

Figure 6: (a) Geological map of Rajshahi region. (b)Lineament density map.

3.6 Lineament Density

The map shown in Figure-6(b) represents the lineament density of the Rajshahi Region in Bangladesh. Different colors of the map show the density values ranging from low (9.5–23) in brown to high (41–48) in dark blue. The zones of High lineament density, mainly in the central and southeastern areas, indicate regions with greater fracture and fault networks that can enhance the capability of groundwater recharge by allowing easier infiltration of rainwater. But, low lineament density areas along the boundaries have reduced groundwater recharge potential and may experience lower groundwater levels.

3.7 Ground Water Level

Historical Groundwater level data (1995 to 2024) was collected from BWDB, which mainly focuses on the major urban areas' groundwater level status, and further application of machine learning techniques helps us to predict the future groundwater level.
A Long Short-Term Memory (LSTM) neural network is an interesting method that was developed for each district to capture the temporal trends of groundwater level fluctuations. Each model used historical groundwater level data to predict the next year's groundwater level for the following year, trained using the Adam optimizer and mean squared error (MSE) loss function for 200 epochs.
Future groundwater levels for the years 2025 to 2040 were predicted iteratively, where each prediction served as input for the next. The output values were inverse-scaled to their original range and adjusted within realistic limits. Historical and predicted trends were visualized for each district, and projected 2040 groundwater levels were reported for the regional groundwater level comparison and identifying the future risk zone shown in Figure 7.

Based on the analysis of historical groundwater levels, it is observed that the water level is deepest in Nawabganj, parts of Naogaon, and Rajshahi, ranging between 11m and 28m, while Sirajganj and Pabna have the shallowest levels, ranging between 2.9m and 8.1m. The Barid area's level of groundwater declined in 2010 mainly as a consequence of too much extraction for agricultural purposes (Boro rice)

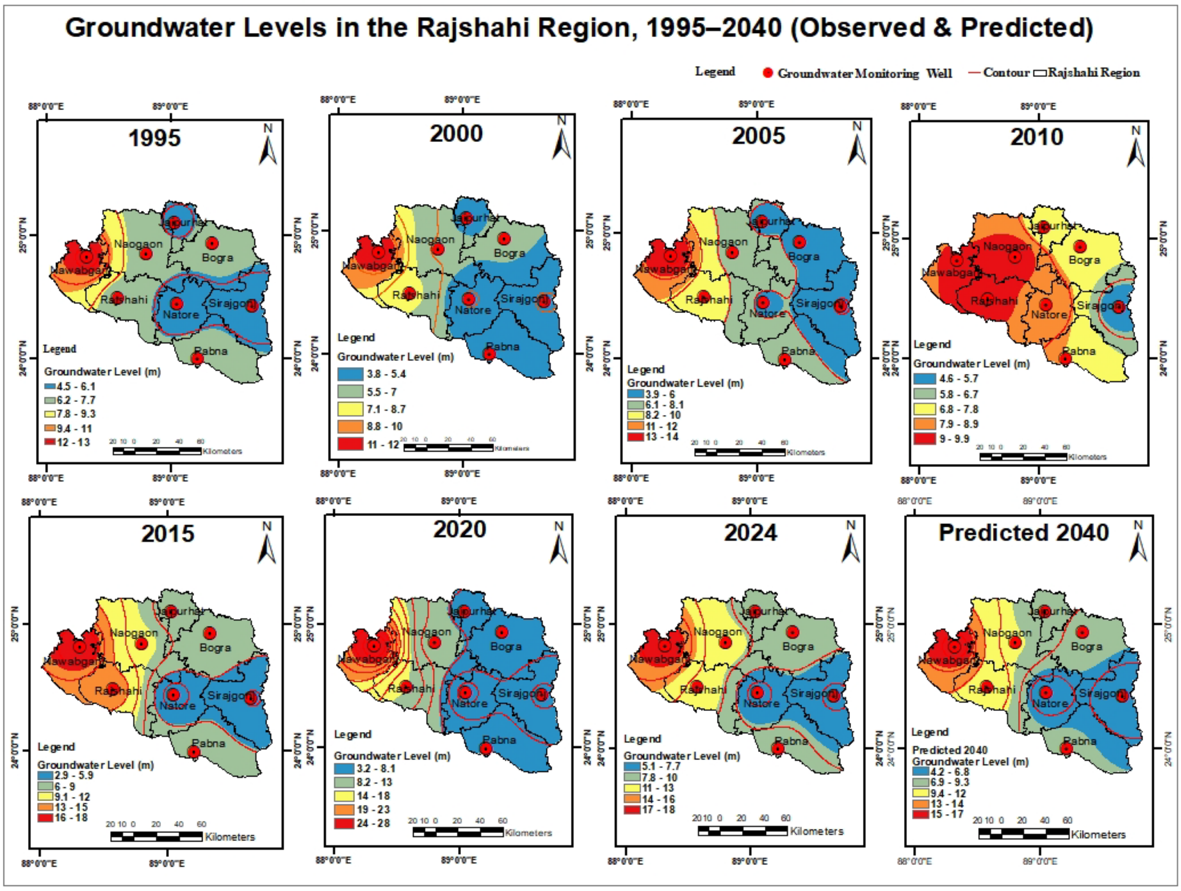

Figure 7: Potential risk zone prediction based on historical groundwater level.

and reduced recharging caused by inadequate Precipitation(Md. M. Rahman & Mahbub, 2012). By applying machine learning techniques, we predicted the future groundwater level in 2040 and the future highest risk zone, which is Nawabganj, but others are relatively low-risk zones.

3.8 Machine Learning Model Evaluation

In this study, the CatBoost classifier machine learning algorithm was employed, which is able to predict categorical features. We mainly focus on the performance of accuracy, generalizability, and interpretability to ensure that the method can be used in practice for hydological problems. By that means, as it can be observed from Table 2, CatBoost achieved its accurate performance with a mean of 88.47% and a standard deviation in the value of 1.53, and the AUC score at the mean point was 0.9641 with a standard deviation of 0.0072.

Table 1: Validation Metrics for the CatBoost classifier.

	Accuracy	AUC	Recall	Prec.	F1	Kappa	MCC
Mean	0.8847	0.9641	0.8847	0.887	0.8847	0.8096	0.8109

Table 2: Comparative performance of machine learning classifiers.

Model	Classifier	Accuracy	AUC	Recall	Prec.	F1	Kappa	MCC
Catboost	CatBoost Classifier	0.8847	0.9641	0.8847	0.887	0.8847	0.8096	0.8109
lightgbm	Light Gradient Boosting Machine	0.8831	0.9635	0.8831	0.8831	0.8831	0.805	0.8058
xgboost	Extreme Gradient Boosting	0.8816	0.9623	0.8816	0.883	0.8818	0.802	0.8027
rf	Random Forest Classifier	0.8638	0.9545	0.8638	0.8653	0.8632	0.7734	0.7747
dt	Decision Tree Classifier	0.8528	0.873	0.8528	0.8538	0.8526	0.7525	0.7565
gbc	Gradient Boosting Classifier	0.8481	0.9609	0.8481	0.8495	0.8476	0.7425	0.7448
et	Extra Trees Classifier	0.8393	0.9409	0.8393	0.8403	0.8385	0.7325	0.7337
knn	K Neighbors Classifier	0.7541	0.8902	0.7541	0.7684	0.7541	0.6091	0.6163
nb	Naive Bayes	0.5611	0.7916	05611	0.6431	0.5399	0.3756	0.4281

3.9 Graphical Performance Analysis:

Figure 8 shows a Precision-Recall (PR) curve of Cat-Boost. The average precision of the model was 0.95, especially important in the imbalanced case. This almost-horizontal trend of precision with different levels of recall indicates that the model is very strong in terms of high predictive reliability of the model at all the operating levels. This means that Cat-Boost reduces false positives without reducing sensitivity, which is important in groundwater classification since misclassification can translate to incorrect water management measures.

Figure 9 plots the ROC curves of both classes. The model had scores of 0.99, 0.96, and 0.98 on classes 0, 1, and 2, respectively, and both micro and macro averages of 0.98. These findings demonstrate that the classifier has a high true positive rate and a low false positive rate at all levels, which once again demonstrates its discriminative capacity.

The confusion matrix is displayed in Figure 10. The classifier was able to classify 160 out of 175 shallow examples (91.4), 400 out of 445 medium examples (89.9), and 173 out of 202 deep examples (85.6%) correctly. The cases of misclassifications were mainly between the Medium and Deep categories, which is understandable since there is a gradual shift in the depth of water.

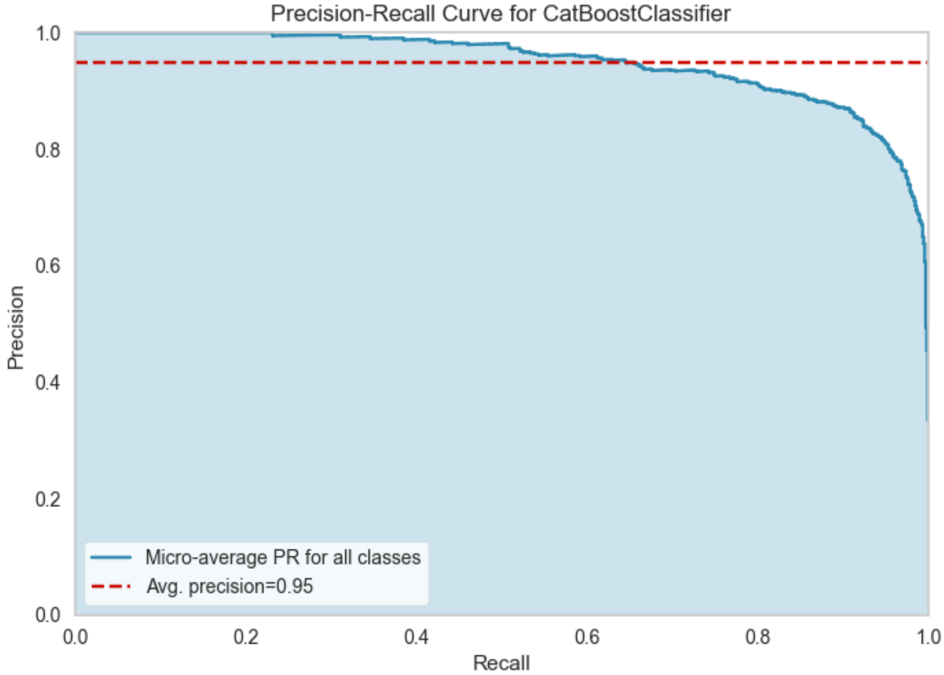

Figure 8: Precision -Recall curve for CatBoost Classifier.

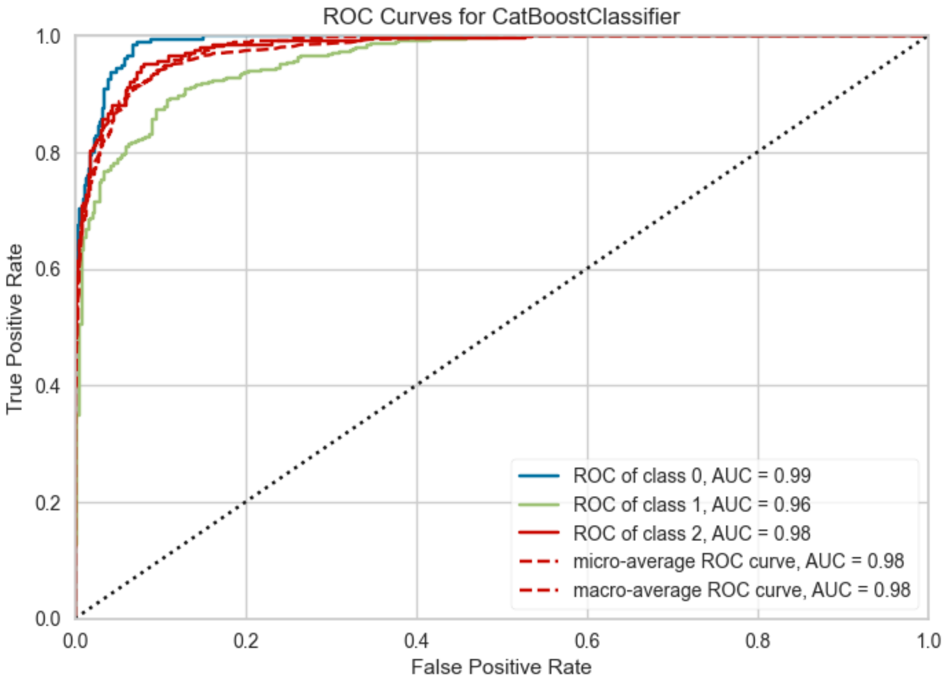

Figure 9: ROC curves for the CatBoost Classifier.

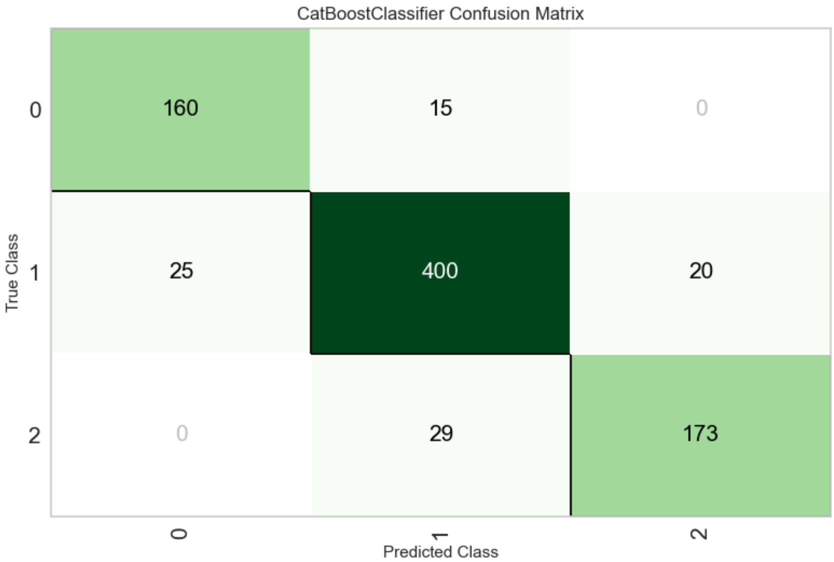

Figure 10: Confusion matrix of the CatBoost Classifier

4. CONCLUSIONS

The current research utilized Integrated geospatial and machine learning techniques to investigate the challenges around the sustainability and variation level of groundwater in the Rajshahi region. On the basis of groundwater level reports (1995-2024) studies, the above three districts experiencing extreme depletion of water would be Rajshahi, Naogaon, and Chapainawabganj. The predictive power is further guaranteed by the high prediction capability of the CatBoost model used, whose accuracy and AUC score were 88.47% and 0.9641. Yet, despite the great performance obtained in terms of different error indices by the model framework based on CatBoost, one has to consider some uncertainty, which is inherent in the complex and nonlinear character of a groundwater system. Cross-validation (10-fold) was performed so as not to overfit the models and to attain some measure of stability across folds. However, the extent to which those models are accurate will depend on the hydrogeological context and available data. Therefore, the predictions are applicable for the Rajshahi locality and require local calibration and validation in other areas. If the current levels of groundwater abstraction and natural rainfall persist, agricultural production in Rajshahi, as well as water security in the region, and the provision of urban water, will be seriously compromised by 2040.

If current trends in land conversion and use persist, groundwater depletion is projected to escalate by 2040. To minimize depletion, immediate solutions, including collecting rainwater, efficient irrigation strategies, and artificial replenishment, are essential. The findings of the research provide an insightful framework for the future sustainability of water and climate change resilience in the Rajshahi region through sustainable groundwater management and policy planning.

Further study will be conducted using a high-resolution groundwater table study using with additional monitoring wells. Advanced hybrid machine learning models (climate impact- based) can be integrated to enhance the prediction of long-term groundwater and analysis. Furthermore, the efficiency of water-saving technologies and artificial aquifer recharge can be assessed to plan sustainable groundwater management schemes.

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Declaration of Use of AI:
The authors state that they used Artificial Intelligence (AI) tools, Grammarly to improve the language, clarity of English expression, and coherence of the manuscript.

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