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PREDICTIVE MODELING OF INLAND GROUNDWATER BEHAVIOR AND ITS MANAGEMENT APPROACHES IN SYLHET, BANGLADESH

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ABSTRACT

The aquifer in Bangladesh's Sylhet District, essential for local irrigation and drinking water, has experienced a sustained decline in groundwater levels. As a result, the primary goal of this research work was to analyze the hydrodynamic fluctuations behavior of aquifers and anticipate the behavior of groundwater future trends, specifically in terms of estimating water table (WT) depth scenarios in the Sylhet region of Bangladesh. The hydrodynamic behavior of groundwater was analyzed using secondary data and a thick confining layer beneath the surface was found in the study region according to aquifer composition and stratification analysis by Rockworks15 software. MAKESENS modelling was used to analyze the previous groundwater fluctuation and generate the present and future trends of groundwater table. Across the study region, the WT depths showed a decreasing trend which indicated that rainfall had less influence on the WT depth and the worst conditions observed in Fenchuganj, Balaganj, Bishwanath, and some parts of Dakshin Surma upazila. The predicted values of WT depth yielded the same results about the worst-case scenarios. In particular cases, considering the current values the depth would be approximately doubled by the year 2050. The overall mean values of maximum and minimum WT depth were 7.55 m and 5.71 m, respectively, reflecting a long-term declining trend of WT depth throughout the study area as the depths (<8 m) were below the suction limit. The simulated values (by ArcGIS 10.5) also explored that groundwater usage would be less feasible in the same regions as those found in the previous analysis. In order to identify areas for improvement, the study also looked at Bangladesh's groundwater policies. The investigation focused at current groundwater-related laws and regulations in order to identify any shortcomings of existing policies. The current study concludes with policy recommendations for functional groundwater resource management after discussing the prospects for sustainable groundwater management to support irrigated agriculture in Bangladesh. This research will also enhance the existing body of expertise, facilitating more efficient management of the increasing constraints on groundwater resources.

Keywords: Groundwater, Water Table Trend, MAKESENS, ArcGIS 10.5, Groundwater Depletion

1. INTRODUCTION

Global groundwater withdrawal is on average 648 km^3 a year, with 50% for agriculture, 34.5% for domestic consumption and 15.5% for industrial consumption (Nazari et al., 2025). This resource is extremely important in Bangladesh, where more than 90% of the rural 73.09% of irrigated agriculture depends on aquifer extraction, and the population depends on groundwater for drinking needs (Parvin et al., 2022; BADC, 2020). With extraction rates exceeding natural recharge capacities, the agricultural sector's excessive groundwater exploitation, especially for dry-season Boro rice farming, has caused significant aquifer depletion statewide (Mainuddin et al., 2020; Taylor, 2022).

A multifaceted hydrogeological can be found in the Sylhet region of northeastern part of Bangladesh. Sylhet receives an average of 4,180 mm of rainfall annually (Ria et al., 2021). But, groundwater recharge potential has been impacted by variability of rainfall and modification of land use and land cover (LULC) (Talukdar et al., 2025). A formation consists of fine sand, silt, and combinations of sand and gravel and has considerable variation in soil characteristics that influence its ability to store ground water (Anzuman et al., 2025). The northern part of Sylhet shows higher potential for recharge, while the southern and eastern regions are more stressed (Talukdar et al., 2025). Prior research has mostly concentrated on mapping potential zones (Dey et al., 2023; Hasan et al., 2021) and assessing groundwater quality (Islam et al., 2017), but rigorous prediction modeling of long-term groundwater behavior is still noticeably lacking in the literature.

Growing agricultural demand, the effects of climate variability on recharge patterns, and the hydrogeological limitations of the Sylhet basin all highlight the need for predictive modeling. Although they offer historical perspectives, traditional groundwater evaluation methods are not very useful for proactive resource management. The development of reliable predictive models that can guide sustainable governance solutions is required to fill this research gap. The key objectives of this study are to: (i) develop and validate predictive models for water table dynamics using statistical and geospatial techniques; (ii) characterize the hydrodynamic properties of aquifers in southwestern Sylhet through thorough lithological and trend analysis; and (iii) develop scientifically supported management strategies based on predictive scenarios for sustainable groundwater governance.

2. METHODOLOGY

2.1 Study Area Characterization

The southern portion of the Sylhet district is selected for this study, which is roughly 12,298.4 km² and lies between 23°58′ and 25°12′ N and 90°56′ and 92°30′ E (Figure 1). The area is a part of the Sylhet sub-basin of the Bengal Basin, a tectonically active depression with the Tripura Bend Belt to the east and the Shillong Plateau to the north (Johnson & Alam, 1991).

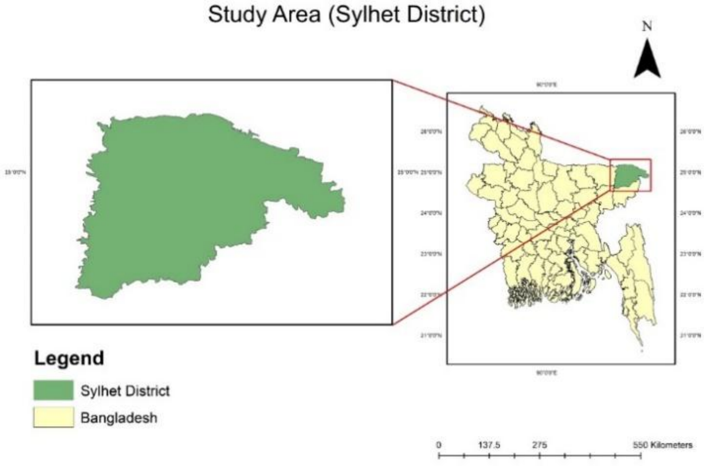


Figure 1: Study Area Map

Hydrogeology: The Dupi Tila Formation (Pliocene-Pleistocene) and Chandina Formation (Holocene) make up the region's multi-layered aquifer system. Vertical recharge is severely hampered by the thick clay layer (3-8 m) covering the semi-confined to restricted upper aquifer (JICA, 2002).

Climate Profile: The area has a humid subtropical monsoon climate, with an average annual rainfall of 4,200 mm, of which 65-69% falls between June and September. Wintertime temperatures are 14.7°C, whereas summer temperatures are 33.6°C (BBS, 2023).

Agricultural Land Use: Rice-based farming systems cover the majority of the area. During the dry season, about 68% of irrigation is used for boro rice, which is produced mainly using groundwater from shallow and deep tube wells.

2.2 Data Acquisition and Processing

A multi-source data acquisition plan was employed to ensure comprehensive analysis:

Observation well data: Monthly water table depth data were collected from the Bangladesh Water Development Board (BWDB) between 1990 and 2017. Five upazilas such as Balaganj, Bishwanath, Fenchuganj, Golapganj, and Dakshin Surma are covered geographically by the observation well network (Table 1).

Table 1. Geographical characteristics of observation wells under different upazilas of Sylhet district

Upazila	Well ID	Lat (°)	Long(°)	Upazila	Well ID	Lat (°)	Long (°)
Balaganj	SY72	24.68	91.80	Dakshin Surma	SY55	24.86	91.93
Balaganj	SY82	24.74	91.76	Dakshin Surma	SY56	24.98	91.94
Balaganj	SY83	24.73	91.82	Dakshin Surma	SY57	24.96	91.98
Bishwanath	SY84	24.81	91.74	Dakshin Surma	SY71	24.94	91.75
Fenchuganj	SY30	24.68	91.98	Dakshin Surma	SY85	24.88	91.83
Golapganj	SY53	24.79	92.05	Dakshin Surma	SY111	24.91	91.89

Rainfall Data: Daily rainfall records (1990-2015) were acquired from the Bangladesh Meteorological Department (BMD). Missing values were filled in using spatial interpolation and quality control techniques.

Irrigation Equipment Data: The Bangladesh Agricultural Development Corporation (BADC) Minor Irrigation Survey reports were used to compile the number of shallow tube well (STW) and deep tube well (DTW) distributions and command areas (2010-2018).

Lithological Data: For subsurface characterization, borehole logs from 42 sites, including stratigraphic descriptions and grain size distributions were collected from BWDB.

2.3 Analytical Framework

2.3.1 Trend Analysis and Predictive Modeling

The MAKESENS (Mann-Kendall Test for Trend and Sen's Slope Estimator) software package was used for non-parametric trend detection and slope estimation (Salmi et al., 2002). The details methodology is stated below:

Mann-Kendall Test: Monotonic trends in water table time series, with the test statistic S was computed as:

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} sgn\left(x_j - x_i\right) \tag{1}$$

Where x_i and x_j are sequential data values, n is the dataset length, and sgn is the signum function. The standardized test statistic Z was computed to determine trend significance at $\alpha = 0.05$, 0.01, and 0.001 levels.

Sen's Slope Estimator: The magnitude of trends was quantified using Sen's non-parametric method:

$$Q_i = \frac{x_i - x_k}{j-k} \quad \text{for } i = 1,2,\ldots,N \tag{2}$$

Where, x_j and x_k are data values at times j and k $(j > k)$, respectively. The median of N values of Q_i represents Sen's slope estimator.

***Future Projection*:** Water table depths for 2030, 2040, and 2050 were projected using the linear regression model:

$$WT_{future} = B + Q \times (T_{future} - T_{base}) \tag{3}$$

Where B is the intercept, Q is Sen's slope (m/year), and T represents time.

2.3.2 Geospatial Analysis

Spatial interpolation of water table depths was performed using Inverse Distance Weighting (IDW) in ArcGIS 10.5:

$$Z_0 = \frac{\sum_{i=1}^{n} \frac{Z_i}{d_i^p}}{\sum_{i=1}^{n} \frac{1}{d_i^p}} \tag{4}$$

Where, Z_0 is the estimated value at unsampled location, Z_i is the known value, d_i is the distance between locations, and p is the power parameter (optimized to 2 through cross-validation).

2.3.3 Lithological Modeling

Two-dimensional lithological cross-section was prepared using RockWorks 15 software, integrating borehole data to characterize spatial variability of hydro-stratigraphic units and confining layers

2.3.4 Statistical Correlation Analysis

Pearson correlation coefficients were computed between rainfall and water table depths to quantify recharge effectiveness, with significance testing at α = 0.05.

3. RESULTS AND DISCUSSION

3.1 Aquifer Characteristics

As part of the current investigation, the two-dimensional lithological cross-section shown in Figure 2 was created using RockWorks 15 software. Grain size data and comprehensive stratigraphic descriptions were included in 42 drill logs that were gathered from the BWDB. The model was created over a transect from southwest to northeast in order to represent the spatial heterogeneity of confining layers and aquifer units. Lithological modeling revealed a complex multi-layer aquifer system dominated by heterogeneous sedimentary sequences (Figure 2). The upper 100 m consists of -

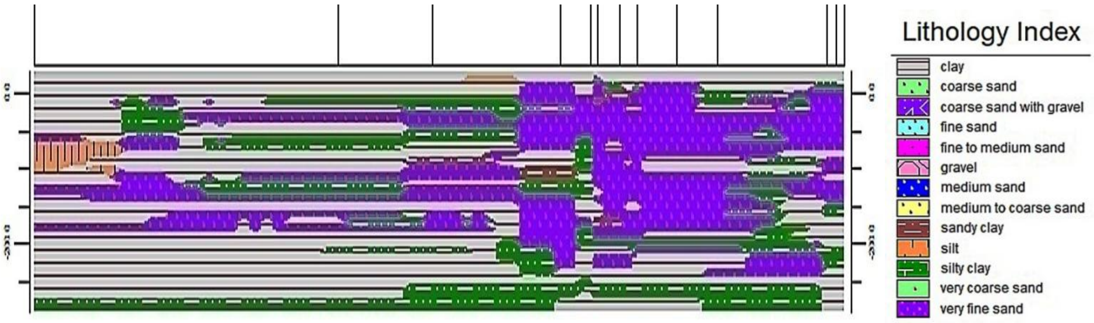


Figure 2: 2-D Lithological cross-section of the study area

Surface Layer: The continuous layer of clay and silty clay, which is between 2-8 meters thick, serves as an upper confining unit and greatly restricts vertical infiltration.

Upper Aquifer: The Chandina Formation's weathered alluvial sands (15-35 m depth) with semi-confined behavior, fine to medium grain size, and random clay lenses.

Lower Aquifer: The main restricted aquifer with a larger production potential is the Dupi Tila Formation (40-90 m depth), which is composed of coarse to extremely coarse sands with layers of gravel.

Aquifer thickness in the study area varies from 15-65 m, exhibits notable spatial heterogeneity that directly influences groundwater flow and recharge. The research area's subsurface composition varied, according to two-dimensional lithological modeling with RockWorks 15 (Figure 2). Clay, coarse sand with gravel, very fine sand, very coarse sand, silt, and silty clay are among the predominant elements depicted in the model, which runs from southwest to northeast. Materials from aquifers were found beneath the main layer of clay. The presence of clay beds at the surface is a notable feature that suggests a thick confining layer beneath that severely limits vertical groundwater transport and recharge, a crucial element governing groundwater dynamics in the area. The confining layer restricts rainfall infiltration capacity regardless of precipitation volumes, which explains the observed low correlation between rainfall and groundwater levels. This geological limitation essentially influences the behavior of the predictive model.

3.2 Groundwater Extraction Patterns and Demand Analysis

Model validation and calibration depend on an understanding of current extraction trends. During the dry season, groundwater is used for 58% irrigation, 41% fishing and navigation, and less than 1% household and industrial purposes. Groundwater exploitation patterns have undergone significant alterations, according to an analysis of irrigation infrastructure data (Table 2). There is a discernible regional difference in groundwater irrigation in the study area using shallow tubewells (STW) and deep tubewells (DTW). For example, DTW areas showed a growing tendency between 2010 and 2018, while STW-irrigated fields varied from 20 to 760 hectares (ha) among various upazilas.

Table 2: Irrigated Areas in Sylhet Upazilas (Source: BADC and BWDB)

Upazila	STW Area (ha) 2010	STW Area (ha) 2018	DTW Area (ha) 2010	DTW Area (ha) 2018
Fenchuganj	200	250	30	150
Balaganj	760	800	130	310
Dakshin Surma	49	60	20	50
Bishwanath	200	240	25	100
Others	Varies	Varies	Varies	Varies

Shallow Tube Wells (STWs): The command area increased by 240-670% in various upazilas, with Bishwanath experiencing the most growth (90-760 ha).

Deep Tube Wells (DTWs): Results showed even more significant growth, especially in Dakshin Surma (0 to 70 ha) and Bishwanath (0 to 105 ha), suggesting a deliberate move to deeper aquifers as shallow resources ran out.

This intensification is directly linked to the region's agricultural modernization and the increasing predominance of water-intensive Boro rice production, which utilizes around 1,086 L per kg of yield (Mainuddin et al., 2020).

3.3 Rainfall-Groundwater Dynamics and Recharge Limitations

As shown in Figure 3, there was little connection ($R^2 = 0.007$) between rainfall and WT depth despite an increase in annual rainfall (4200-5000 mm). The poor correlation ($R^2 = 0.007$) suggests that rainfall does not significantly impact groundwater level changes in the studied area. As a result, future groundwater forecasts did not include rainfall as a predictive variable. Since groundwater dynamics are mostly controlled by lithological confinement and extraction pressure rather than direct recharge from precipitation, trend-based statistical modeling utilizing Sen's slope was deemed more acceptable. Because of the confining layer and low aquifer permeability, seasonal hydrographs further demonstrated that rainfall has little effect on groundwater recharging. This inconsistent relationship results from a number of hydrogeological limitations: (i) Confining Layer Efficacy: With an estimated vertical hydraulic conductivity of 10^{-2} to 10^{-2} cm/s, the thick surface clay layer greatly reduces infiltration. (ii) Monsoon Depth: There is a temporal mismatch between supply and demand during the monsoon months of June through September, when evapotranspiration rates are at their peak and irrigation demand is at its lowest. (iii) Runoff Dominance: In outlying areas, steep topographic gradients encourage quick runoff instead of infiltration, which further lowers recharge efficiency.

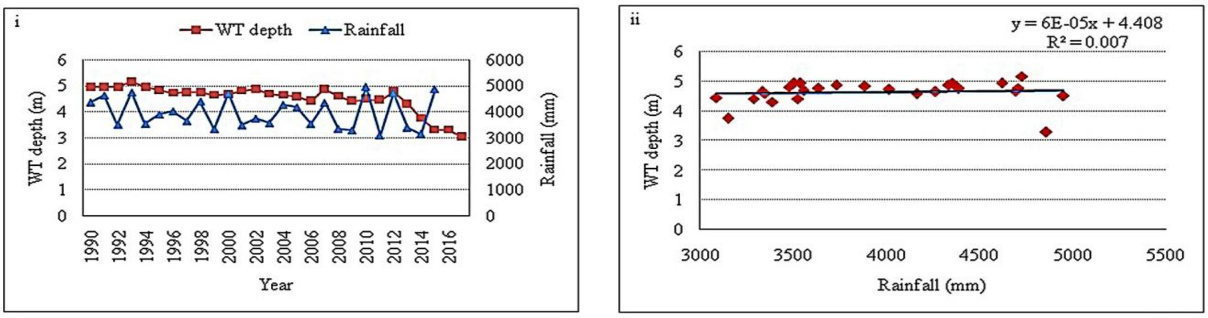
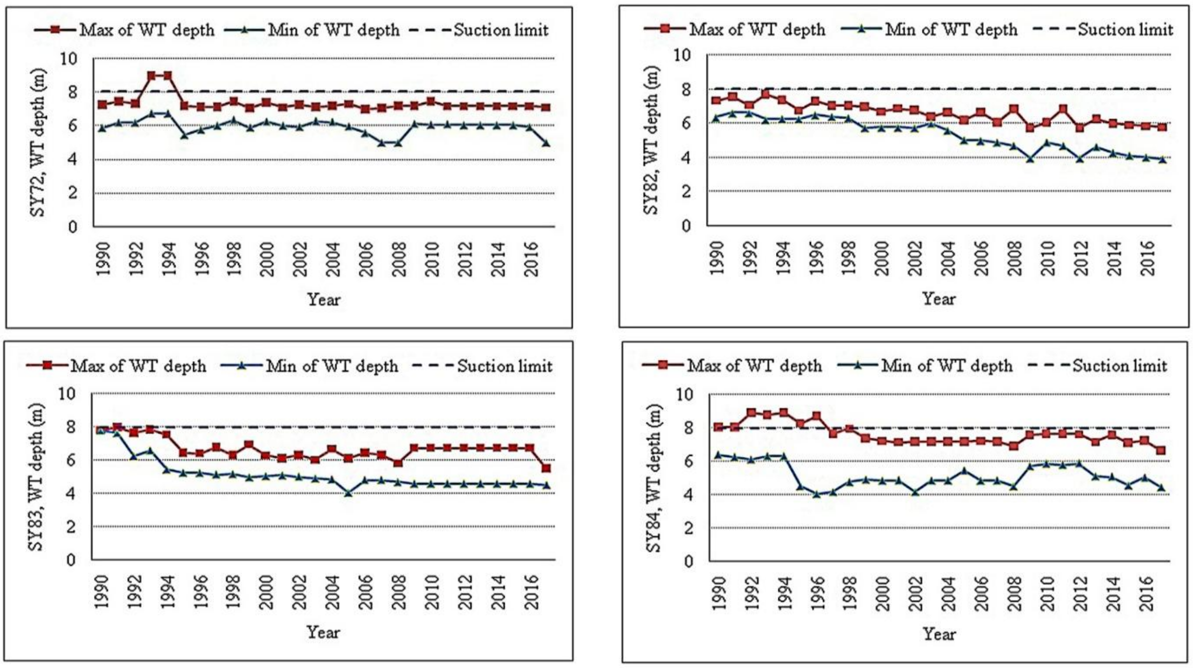


Figure 3: Relationship of Rainfall and Water Table Fluctuations

These results highlight the necessity of regulated aquifer recharge procedures and cast doubt on accepted theories regarding rainfall-recharge correlations in clay-dominated aquifers.

3.4 Historical Water Table Dynamics (1990-2017)

A thorough trend analysis shows alarming patterns of groundwater loss throughout the monitoring network (Figure 4). Sen's slope values range from -0.007 to -0.174 m/year, and 10 out of 12 monitoring wells show statistically significant dropping trends ($\alpha < 0.05$). Dakshin Surma (SY111: -3.63 m maximum, -4.11 m minimum over 28 years) and Balaganj (SY82: -1.57 m maximum, -2.46 m minimum) showed the worst depletion. Ten wells showed minimum water table depths below the 8 m suction limit for traditional pumps, suggesting possible obsolescence of irrigation infrastructure. Comprehensive trend analysis reveals concerning groundwater depletion patterns across the monitoring network (Figure 4).



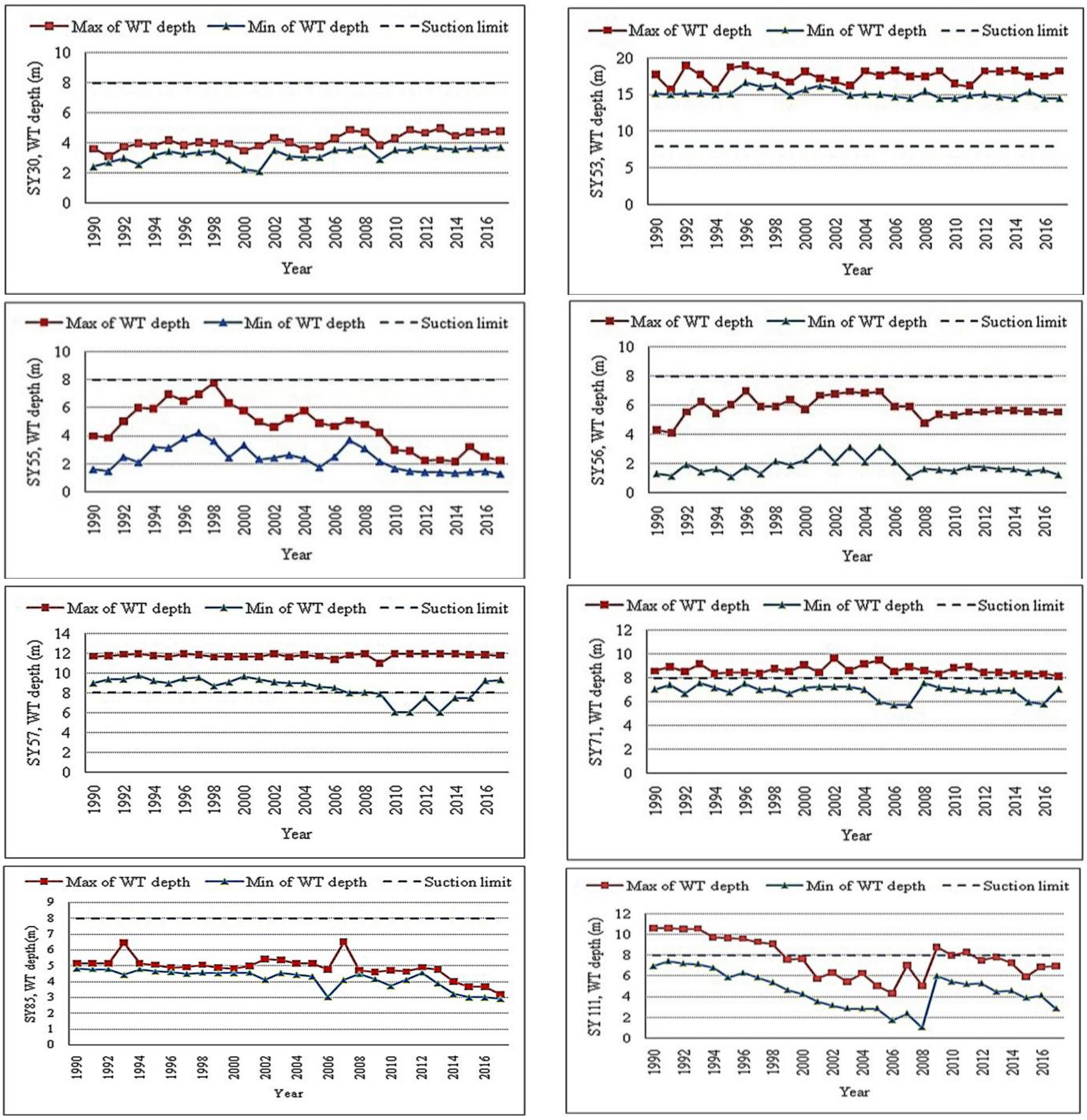


Figure 4: Trend of Water Table Hydrograph

Spatiotemporal analysis (Figure 4) demonstrates progressive expansion of depletion zones, particularly in central and southern sectors of the study area.

3.5 Predictive Model Results and Future Predictions

Maximum and minimum water table fluctuations (Tables 3 and Table 4) shown declining depths in most areas. Well SY111 (Dakshin Surma) showed worst conditions since maximum depth decreased 3.63 m (10.59 to 6.96 m), minimum depth decreased 4.11 m (6.97 to 2.86 m) over 28 years.

MAKESENS (Equation 3) forecasts for 2030, 2040, and 2050 showed that the decline will continue. Between 1990 and 2050, Well SY55 displayed an exceptional maximum depth decline of 10.59 m to -3.21 m. The extreme minimum depth decline in Well SY111 was 6.97 m to -2.51 m. Water tables would drop in wells SY56, SY71, SY82, and SY83 (Dakshin Surma, Balaganj). Trends were statistically significant ($\alpha < 0.001$ to 0.1), except for the well SY53, SY56, SY57, SY71, SY83 (Table 3) and SY56, SY71, SY72 (Table 4), where the null hypothesis was accepted. The greatest depth of groundwater level (Q) was -0.174 to 0.044 m/year, and the minimum depth was -0.16 to 0.032

m/year. With the exception of SY30, all locations saw declining trends; nonetheless, even SY30's trend limits stayed below the suction limit.

Golapganj and minor Dakshin Surma portions maintained the highest depths (excellent circumstances) in the spatial simulation using IDW (Table 5) for 2030, 2040, and 2050, while the majority of Dakshin Surma, Bishwanath, Balaganj, and Fenchuganj parts showed the lowest values (bad conditions). The average maximum depths for 2030, 2040, and 2050 are 6.67 m, 6.24 m, and 5.81 m; the average minimum depths are 4.56 m, 4.12 m, and 3.67 m, all of which are below the suction limit of 8 m, suggesting that suction pumps will fail in the majority of locations. The validated MAKESENS model projects continued groundwater depletion through 2050 (Tables 3, 4).

Table 3: Future projection of maximum WT depth using MAKESENS

Well	Upazila	Observed (m) 1990/2017	Fluctuation (m)	Q (m/yr)	Predicted Min WT (m)			Trend (α)
					2030	2040	2050	
SY72	Balaganj	7.27/7.09	-0.18	-0.007	7.04	6.97	6.90	*
SY82	Balaganj	7.35/5.78	-1.57	-0.067	4.91	4.24	3.57	***
SY83	Balaganj	7.81/5.49	-2.32	-0.036	5.77	5.41	5.05	+
SY84	Bishwanath	8.04/6.61	-1.43	-0.048	6.23	5.75	5.27	***
SY30	Fenchuganj	3.60/4.79	+1.19	0.044	5.36	5.80	6.24	***
SY53	Golapganj	17.69/18.22	+0.53	0.000	17.66	17.66	17.66	-
SY55	D. Surma	3.97/2.20	-1.77	-0.174	0.27	-1.47	-3.21	***
SY56	D. Surma	4.34/5.55	+1.21	-0.008	5.54	5.46	5.38	-
SY57	D. Surma	11.70/11.79	+0.09	0.002	11.84	11.86	11.88	-
SY71	D. Surma	8.57/8.14	-0.43	-0.009	8.29	8.20	8.11	+
SY85	D. Surma	5.13/3.20	-1.93	-0.034	3.92	3.58	3.24	***
SY111	D. Surma	10.59/6.96	-3.63	-0.150	4.46	2.99	1.52	***

Note: +α=0.1, *α=0.05, **α=0.01, ***α=0.001, -no significant trend

Table 4: Future projection of minimum WT depth using MAKESENS

Well	Upazila	Observed (m) 1990/2017	Fluctuation (m)	Q (m/yr)	Predicted Min WT (m)			Trend (α)
					2030	2040	2050	
SY72	Balaganj	5.86/4.99	-0.87	-0.014	5.66	5.52	5.38	-
SY82	Balaganj	6.34/3.88	-2.46	-0.108	2.47	1.39	0.31	***
SY83	Balaganj	7.75/4.47	-3.28	-0.044	3.72	3.28	2.84	***
SY84	Bishwanath	6.36/4.43	-1.93	-0.014	4.49	4.35	4.21	-
SY30	Fenchuganj	2.41/3.71	+1.30	0.032	4.14	4.46	4.78	***
SY53	Golapganj	15.15/14.53	-0.62	-0.026	14.22	13.96	13.70	**
SY55	D. Surma	1.57/1.23	-0.34	-0.060	0.57	-0.03	-0.63	**
SY56	D. Surma	1.32/1.23	-0.09	-0.002	1.60	1.58	1.56	-
SY57	D. Surma	8.98/9.32	+0.34	-0.084	6.22	5.38	4.54	***
SY71	D. Surma	7.02/7.03	+0.01	-0.017	6.59	6.42	6.25	+
SY85	D. Surma	4.83/2.90	-1.93	-0.047	3.02	2.55	2.08	***
SY111	D. Surma	6.97/2.86	-4.11	-0.160	0.70	-0.91	-2.51	***

There were identified 3 critical forecasts:
Regional Average: With minimum depths predicted at 4.56 m, 4.12 m, and 3.67 m, respectively, the mean maximum water table depth is predicted to decrease to 6.67 m (2030), 6.24 m (2040), and 5.81 m (2050).
Severe Situations: A number of places are getting close to critical thresholds; SY55 (Dakshin Surma) is expected to reach -3.21 m by 2050, indicating possible dangers of land subsidence and aquifer compression.

When the infrastructure implications are considered, it is evident that by 2040, approximately 78% of the study area will exceed suction lift limits. This means we'll need to transition to submersible pumping systems, which will come with both energy and financial impacts.

These predictions really underscore how unsustainable our current extraction patterns are and highlight the urgent need for action. A summary of the results from the IDW method is presented below:

Table 5: Spatial simulation (IDW)

Year	Max WT (m)	Min WT (m)
Current	7.55	5.71
2030	6.67	4.56
2040	6.24	4.12
2050	5.81	3.67

The data shows that when the suction limit drops below 8 meters, standard pumps just won't cut it in this region. This means we'll need to dig deeper wells and invest in more powerful systems, which is going to drive up costs significantly. There's also a clear difference in groundwater conditions across the area. For instance, Golapganj and a small part of Dakshin Surma are classified as good or stable zones, indicating relatively balanced groundwater levels. In contrast, most of Dakshin Surma, along with Bishwanath, Balaganj, and parts of Fenchuganj, are in critical zones where groundwater levels have dropped significantly. To restore balance and ensure the sustainability of our groundwater supplies, we need to take immediate management actions in these severely affected areas.

4. DISCUSSION

The agricultural economy in Asia, particularly Bangladesh's quest for rice self-sufficiency, heavily relies on groundwater (UNESCO, 2003; Earthscan, 2007). Unfortunately, the overuse of this resource leads to both depletion and quality issues (Qureshi et al., 2014). Our predictive modeling indicates that the aquifer's lithology allows only limited rainfall to seep in, resulting in a minimal impact on groundwater recharge ($R^2 = 0.007$) (Belhassan, 2011). The low recharge rates can be attributed to the loose tertiary and Pleistocene sediments found in the area (Rashid, 1991). This decline is evident, as average depths have dropped from 7.55 m to 5.71 m. The situation is exacerbated by irrigation demands, seasonal shortages, and limited resource potential, aligning with the trends of declining groundwater levels observed across Bangladesh (Sarkar and Ali, 2009; Shamsudduha et al., 2009; Jahan et al., 2010; Shahid and Hazarika, 2010; Kutub, 2015; Hasanuzzaman et al., 2017; Mojid et al., 2019; Mainuddin et al., 2020).

Predictive models suggest that by 2050, average depths could fall to 5.81 m and even 3.67 m below the suction limit (8 m), rendering traditional pumps ineffective. Some boreholes (SY55, SY111) may even show negative depths, indicating a serious depletion that requires immediate attention. The extraction rates are outpacing recharge, as evidenced by declining trends in 75% of wells (Q: -0.174 to 0.044 m/year). The spatial variability highlights the significant influence of human activities and localized geological factors on these dynamics. To prevent irreversible damage, timely action is essential. Improving irrigation efficiency, which is currently lacking in Bangladesh (Qureshi et al., 2014), could help reduce water loss. It's vital to raise awareness and build capacity to promote responsible water use among stakeholders, farmers, lawmakers, and consumers. Groundwater availability, quality, demand, and governance are shaped by a mix of hydrological, hydrogeological, geographic, political, social, and economic factors (Walton and McLane, 2013).

5. POLICY FRAMEWORK AND MANAGEMENT OPTIONS

5.1 Review of Existing Policies

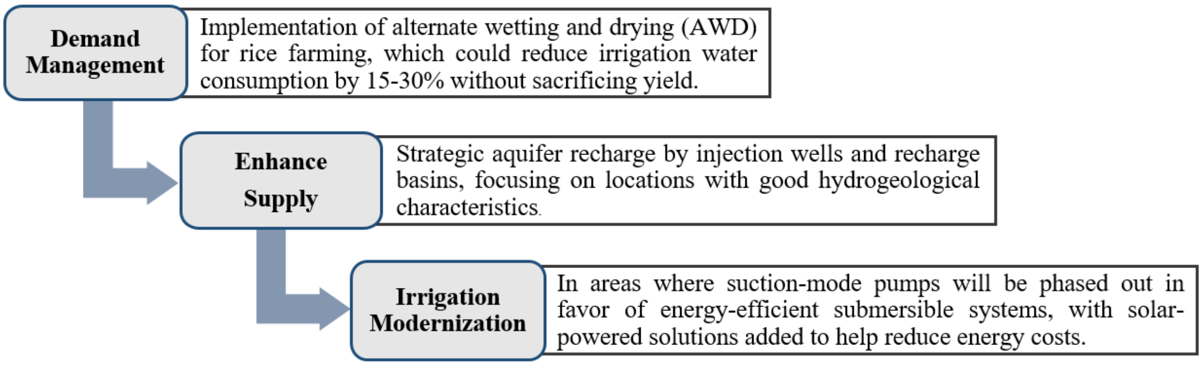
Bangladesh focused on surface irrigation, which accounted for 7% of its irrigable land, up until the 1970s (Dey et al., 2013). In the 1980s, the development of groundwater gained traction, largely due to the introduction of high-yielding rice varieties (Qureshi et al., 2014). The "Ground Water

Management Ordinance, 1985" was the first step in regulating groundwater use, placing restrictions on private tube wells in areas facing decline (Qureshi et al., 2014). Some key policy takeaways include: (i) the National Water Policy (1999), which encourages community education and minor irrigation; (ii) the New Agricultural Extension Policy (1996), which highlights the importance of efficient land and water use; (iii) the National Agricultural Policy (1999), which gives priority to surface irrigation and conjunctive use; (iv) the National Irrigation Water Resources Policy (2006), which acknowledges the significance of irrigation; and (v) the Bangladesh Water Act (2013), which aims to integrate water resources management. However, several policy shortcomings were identified, such as unclear institutional roles, ineffective enforcement with weak penalties, a lack of response to the depletion of boro rice irrigation, no guidelines for promoting alternative crops, limited involvement from stakeholders, and insufficient capacity building.

5.2 Management Considerations and Policy Integration

5.2.1 Technical Approaches

Based on predictive modeling, a tiered technical plan of action is suggested below:



Implementation of alternate wetting and drying (AWD) for rice farming, which could reduce irrigation water consumption by 15-30% without sacrificing yield.

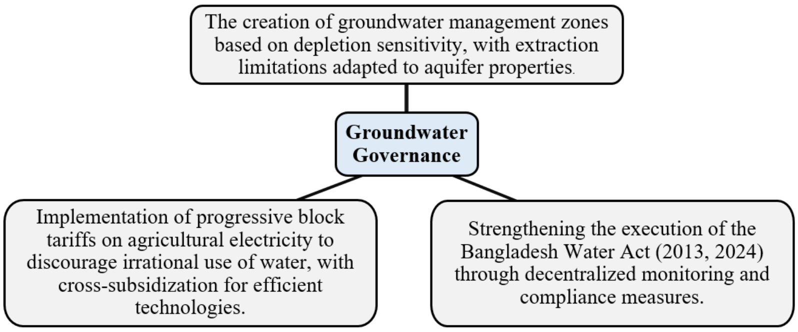
Strategic aquifer recharge by injection wells and recharge basins, focusing on locations with good hydrogeological characteristics.

In areas where suction-mode pumps will be phased out in favor of energy-efficient submersible systems, with solar-powered solutions added to help reduce energy costs.

Figure 4: Tiered Technical Approach

5.2.2 Suggested Policy Reform Plan

Review of existing policies and field studies indicates that groundwater governance in Bangladesh necessitates significant institutional restructuring, including groundwater zone mapping, providing subsidies for water use, and strengthening the existing rules and regulations described in Figure 6.



The creation of groundwater management zones based on depletion sensitivity, with extraction limitations adapted to aquifer properties.

Implementation of progressive block tariffs on agricultural electricity to discourage irrational use of water, with cross-subsidization for efficient technologies.

Strengthening the execution of the Bangladesh Water Act (2013, 2024) through decentralized monitoring and compliance measures.

Figure 6: Suggested plan for policy reform

5.2.3 Agricultural adaptation.

Crop diversity is a critical adaptation strategy, which suggests water-efficient crops. Raise awareness of cultivation of pulses, oilseeds, and maize during the dry season reduces irrigation requirement by 40-60% when compared to Boro rice. Also integrating aquaculture and agriculture systems may be adopted to improve water production and farm profitability**.**

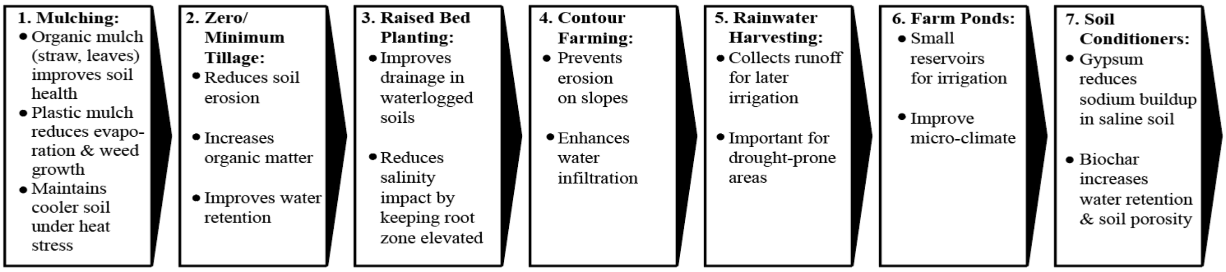


Figure 7: Proposed agricultural adaptation practices from local people

6. CONCLUSIONS

This study highlights the critical role of predictive modeling in managing groundwater resources. Our approach included 3D lithological modeling, MAKESENS statistical trend analysis, geographical interpolation, and policy analysis. Our thorough investigation reveals:

i. The Sylhet aquifer system is facing systematic depletion, with current extraction rates in vulnerable areas being 25-40% higher than natural recharge.
ii. The potential for rainwater recharge is significantly hampered by hydrogeological restrictions.
iii. Predictive modeling suggests that by 2040-2050, a significant portion of the study area will be nearing critical thresholds due to unsustainable trends.
iv. An all-encompassing management framework that combines technological, policy, and agricultural changes offers a pathway to sustainable groundwater governance.

This approach and its findings provide valuable insights for managing groundwater in similar hydrogeological settings worldwide, particularly in South Asian alluvial basins facing issues of resource depletion and intensified agriculture.

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