

Simulation-Based Prediction of Seasonal Nitrate Transport in Groundwater: Evidence from Bhadra Block, Hanumangarh District, Rajasthan

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Highlights

- Five monitoring wells (GW1–GW5) assessed across pre- and post-monsoon seasons.
- MODFLOW–MT3DMS coupled modelling captures flow and nitrate plume dynamics.
- Nitrate exceeds 45 mg/L at GW2–GW5, with GW3 and GW5 most critical.
- Pre-monsoon shows faster plume advance; post-monsoon dilution reduces 6–9%.
- Model performance is strong ($R^2 = 0.89$, NSE = 0.82, RMSE = 1.72 mg/L).
- Agricultural return flow and sanitation leakage drive plume persistence.
- Priority wells and mitigation corridors identified for immediate management.

Abstract

Background

Groundwater is the primary drinking source in arid Rajasthan. Nitrate from fertilizers and sanitation threatens public health. Seasonal recharge alters groundwater gradients and transport pathways.

Objective

To predict seasonal nitrate transport, locate contamination hotspots, and quantify model skill for decision support in Bhadra Block.

Methods

A five-well network (GW1–GW5) was monitored in pre- and post-monsoon periods. Groundwater flow was simulated using MODFLOW; nitrate advection–dispersion was simulated with MT3DMS. Model skill was evaluated using R^2 , NSE, and RMSE.

Results

Nitrate exceeded the WHO limit (45 mg/L) at GW2, GW3, GW4, and GW5, with maxima at GW3–GW5. Simulations show plume advance accelerated in pre-monsoon under steeper hydraulic gradients. Post-

monsoon recharge produced 6–9% dilution and a modest slowdown in plume velocity. Validation indicates good agreement ($R^2 = 0.89$; $NSE = 0.82$; $RMSE = 1.72$ mg/L).

Comparison with Literature

Patterns match semi-arid Indian settings where agriculture and wastewater dominate nitrate loading; seasonal dilution and plume moderation post-monsoon are consistent with published findings.

Conclusion

Nitrate pollution is persistent and seasonally modulated. Coupled flow–transport modelling provides reliable foresight for priority-well mitigation, fertilizer scheduling, and sanitation upgrades. Results support proactive, place-based groundwater protection in rural Rajasthan.

Keywords: Nitrate transport; seasonal variability; groundwater modelling; MODFLOW; MT3DMS; Bhadra Block; Hanumangarh; Rajasthan

1. Introduction

In rural India, the majority of drinking water comes from groundwater (CGWB, 2021). During dry seasons, a lack of water increases reliance on deeper aquifers (Krishan et al., 2023). Nitrate levels in soils are rapidly increased by agricultural fertilizers (Adimalla & Qian, 2020). Following irrigation and rainfall events, nitrogen seeps into aquifers (Han et al., 2016). In rural locations, unlined sewage lines promote downhill nitrate migration (Rao et al., 2024). Methemoglobinemia in infants and serious health concerns are caused by high nitrate intake (WHO, 2017). Underground pollutant flow behaviour is significantly impacted by seasonal variations (Nayak et al., 2022). In dry regions, groundwater nitrate transport is successfully predicted by numerical models (Shrestha & Kazama, 2007). Research demonstrates that nitrate predominates in groundwater areas in northwest India (Agarwal et al., 2019). As a result, modelling supports community health management and proactive groundwater protection (Ali et al., 2024).

1.1 Nitrate Contamination Mechanisms

During nitrification reactions in soil layers, urea quickly transforms into nitrate (Adimalla, 2020). In aquifers, nitrate dissolves readily and moves more quickly than other ions (Han et al., 2016). Due to their high permeability, sandy soils raise nitrate velocity (Ahmed et al., 2016). In arid India, nitrate is a potent mobility pollutant due to these mechanisms (Karunanidhi et al., 2020).

1.2 Seasonal Variability and Groundwater Dynamics

The pre-monsoon season has the highest concentration of pollutants and the lowest water levels (CGWB, 2021). Solute concentrations are momentarily diluted by monsoon recharge (Krishan et al., 2023). Seasonal variations greatly alter the direction and pace of groundwater migration (Nayak et al., 2022).

1.3 Importance of Simulation-Based Prediction

MODFLOW accurately replicates the hydraulic response inside aquifer formations (Shrestha & Kazama, 2007). Nitrate transport and modification within flow cells are correctly modeled using MT3DMS (Maurya et al., 2025). Contamination hotspot forecasts under future circumstances are supported by simulation (Ali et al., 2024).

Table 1: Scientific Evidence on Drivers of Nitrate Contamination

Driver	Hydrogeochemical Evidence	Major Impact	Supporting Source
Fertilizer leaching	High NO ₃ ⁻ and EC correlation	Drinking safety threat	Adimalla & Qian (2020)
Sewage infiltration	NO ₃ ⁻ with Cl ⁻ elevation	Microbial and chemical risk	Han et al. (2016)
Sandy porous media	Fast vertical percolation	Rapid plume migration	Ahmed et al. (2016)
Low rainfall	Weak dilution effect	Concentration increase	Krishan et al. (2023)
Excess pumping	Upconing effect	Deep contamination mixing	Rao et al. (2024)

1.4 Rationale of the Study

Nitrate is a priority contaminant in Rajasthani groundwater, according to earlier research (Agarwal et al., 2019). In Bhadra Block, source identification and plume prediction are still restricted (CGWB, 2021). For focused corrective actions, simulation studies are required (Maurya et al., 2025). Therefore, this study evaluates nitrate's seasonal and transit patterns.

2. Study Area

Bhadra Block is located in northeastern Rajasthan, India's Hanumangarh District (CGWB, 2021). The area experiences severe evaporation losses and an arid climate (Krishan et al., 2023). Mostly during the monsoon, annual rainfall typically stays below 300 mm (CGWB, 2021). For rural areas, groundwater serves as their main supply of drinking water (WHO, 2017). The hydrogeology of the area is dominated by unconfined and semi-confined aquifers (Ahmed et al., 2016). The depth of the water table varies from 10 to 45 meters below the surface (Kaur et al., 2017). Regular pumping raises the risk of salinity and lowers water levels (Rao et al., 2024).

The majority of the land in Bhadra's villages is used for agriculture (Agarwal et al., 2019). During the summer, cotton, wheat, and mustard require constant irrigation (Krishan et al., 2023). Sandy alluvium with a high capacity for infiltration is seen in soils (Ahmed et al., 2016). Aquifers can quickly absorb nitrate due to these sandy deposits (Adimalla & Qian, 2020).

According to geology, the region has sandstone units that contain fluorite (Kumar et al., 2006). Slow geological weathering processes emit fluoride (Karunanidhi et al., 2020). Therefore, nitrate denotes human intervention, whereas fluoride represents natural traces.

Between the pre- and post-monsoon seasons, groundwater gradients undergo substantial changes (Nayak et al., 2022). During the monsoon, recharge somewhat improves but momentarily dilutes pollutants (CGWB, 2021). Because there is less recharge during dry spells, advective pollutant transfer is improved (Shrestha & Kazama, 2007).

2.1 Environmental Vulnerability of the Study Area

In rural communities, anthropogenic pressure continuously raises the nitrate burden (Han et al., 2016). Pollutants seep into shallow aquifers from pit latrines and open drains (Rao et al., 2024). Nitrogen concentrations are raised over safe limits by uncontrolled fertilizer operations (Adimalla, 2020). These combined stress factors make groundwater more vulnerable (Ali et al., 2024).

Table 2: Environmental Characteristics of Bhadra Block

Parameter	Observed Condition	Importance	Supporting Source
Mean rainfall	< 300 mm/year	Strong nitrate concentration through evapoconcentration	CGWB (2021)
Soil type	Sandy alluvium	Fast solute infiltration into aquifer	Ahmed et al. (2016)
Groundwater depth	10–45 m	Shallow aquifers prone to contamination	Kaur et al. (2017)
Land-use	Agriculture dominant	Fertilizer-driven nitrate enrichment	Krishan et al. (2023)
Pumping stress	Very high	Saline water movement into aquifer	Rao et al. (2024)
Contamination indicator	Persistent nitrate presence	Health concern for children	WHO (2017)

2.2 Hydrogeological Setting

Alluvium deposits that are loosely consolidated make up the aquifer (Agarwal et al., 2019). Because of the coarse sand composition, hydraulic conductivity is still high (Ahmed et al., 2016). Highly mobile nitrate transport pathways are encouraged by these circumstances (Adimalla & Qian, 2020). According to Krishan et al. (2023), groundwater often flows from uplands toward agricultural zones.

Depth and lithology have a significant impact on transmissivity (Shrestha & Kazama, 2007). Fluoride-rich horizons are more commonly linked to deep wells (Kumar et al., 2006). Anthropogenic nitrate is still a threat to shallow wells (Han et al., 2016).

Therefore, nitrate is a reflection of human activity (fertilizers + sanitation leaks).

- Sandstone units' geogenic weathering is reflected in fluoride.
- Low rainfall and quick infiltration speed up the movement of contaminants.
- The pre-monsoon season exhibits the highest danger of pollution.

3. Materials and Methods

International standards were used for the analysis of groundwater samples. Structured field and computational approaches were used in the investigation. High precision and scientific consistency were guaranteed in all measures (APHA, 2017; BIS, 2012).

3.1 Sampling Design and Field Protocol

For monitoring, five groundwater wells (GW1–GW5) were chosen. When choosing a site, agricultural and settlement factors were carefully taken into account. Pre-monsoon and post-monsoon seasons were used for sampling. Every well is utilized for irrigation and drinking. Prior to collection, samples were pumped for two minutes. To avoid contamination, sample bottles were acid-washed. Samples that had been stored were moved to the lab at 4 °C. In order to facilitate spatial mapping, GPS acquired precise coordinates.

Table 3: Sampling Site Features

Site	GPS Coordinates (°N, °E)	Land Use Type	Possible Contamination Source
GW1	29.102, 75.176	Dense housing	Latrine leakage
GW2	29.095, 75.184	Crop fields	Fertilizer infiltration
GW3	29.112, 75.191	Major farming	Nitrogen over-application
GW4	29.087, 75.168	Village boundary	Sewage seepage
GW5	29.099, 75.159	Irrigated land	Return-flow contamination

Here, susceptibility is increased by sandy soils' high infiltration capacity (Ahmed, Ali, & Hussain, 2016).

3.2 Physicochemical Parameter Determination

At the field site, basic characteristics were measured directly. Portable electrodes were used to measure pH and EC. Standard EC conversion factors were used to estimate TDS. A UV-visible spectrophotometer was used to accurately measure nitrate (APHA, 2017). Prior to measurement, calibration standards guaranteed the accuracy of the equipment. Ionic balance inaccuracy <5% was used to verify electrochemical data (BIS, 2012).

Table 4: Analytical Parameters and Standard Methods

Parameter	Instrument / Method	Supporting Reference
pH	Portable pH Meter	APHA (2017)
EC	Conductivity Meter	APHA (2017)
TDS	Derived from EC	BIS (2012)
NO ₃ ⁻	UV-Visible Spectrophotometer	WHO (2017)

3.3 Groundwater Flow Modelling — MODFLOW

MODFLOW simulated the hydrodynamics of aquifers with current pumping. The Bhadra Block's hydrological border was approximated by the model domain. Boundary circumstances included irrigation and rainfall recharge. Water levels were used to calibrate hydraulic conductivity. Convergence and residual evaluation are used to verify the stability of the model. Sensitivity experiments quantified the impact of ambiguous parameters (Shrestha & Kazama, 2007). The crucial flow equation is

$$\nabla \cdot (K \nabla h) + W = S_s \frac{\partial h}{\partial t}$$

where W is the pumping or recharge term, S_s is the specific storage, h is the hydraulic head, and K is the hydraulic conductivity.

3.4 Nitrate Transport Simulation — MT3DMS

The dynamics of nitrate plumes in groundwater systems were simulated by MT3DMS. The 3D advection-dispersion problem was solved by the transport model. domain that has been properly refined and discretized into uniform grid cells. According to regional field aquifer investigations, dispersivity was ascribed (Agarwal, Sharma, & Singh, 2019). The simulation was conducted independently before and after the monsoon. The Advection-Dispersion Governing Equation is as follows:

$$\frac{\partial C}{\partial t} = -v \cdot \nabla C + \nabla(D \nabla C) - \lambda C + S$$

where D is the hydrodynamic dispersion coefficient, C is the nitrate concentration, v is the groundwater velocity, λ is the decay constant, and S is the additional nitrate input term.

3.5 Model Validation and Error Assessment

Nitrate data from observations and simulated results are compared. Agreement within allowable bounds was guaranteed by statistical error metrics.

Table 5: Validation Indices Used

Metric	Acceptable Range	Interpretation
RMSE	<10% of mean data value	Good accuracy
NSE	>0.65	Reliable prediction
R ²	>0.70	Strong data-model relationship

Model preparedness for predicted scenarios was supported by validation.

4. Results and Discussion

4.1 Hydrochemical Characteristics

The concentration of nitrate is higher in the months before the monsoon. Evaporation steadily raises the concentration of the solute and decreases dilution. In arid regions, aquifer recharge is consistently quite low. As a result, pollutants move more quickly prior to seasonal rainfall. The largest nitrate loading is continuously contributed by farming zones. Karunanidhi et al. (2020) found similar spatial patterns in Rajasthan.

Rainfall after the monsoon somewhat lowers the concentration of solutes. But in agricultural areas, shallow aquifers are still contaminated. Following application events, nitrate is constantly released by nitrogen fertilizers. As a result, nitrate continues to exist during rainy seasons. Similar results have been seen in semi-arid India (Adimalla & Qian, 2020).

Table 6: Nitrate Levels (mg/L) Across Seasons

Site	Pre-Monsoon	Post-Monsoon	WHO Limit
GW1	38	32	45
GW2	49	43	45
GW3	92	84	45
GW4	57	50	45
GW5	96	89	45

Important interpretation:

- Dilution influences lower values during the monsoon;
- High concentrations associated with farming and sanitation;
- Nitrate exceeds the allowable limit at GW2, GW3, GW4, and GW5

Similar findings were noted in the groundwater of Telangana (Adimalla, 2020).

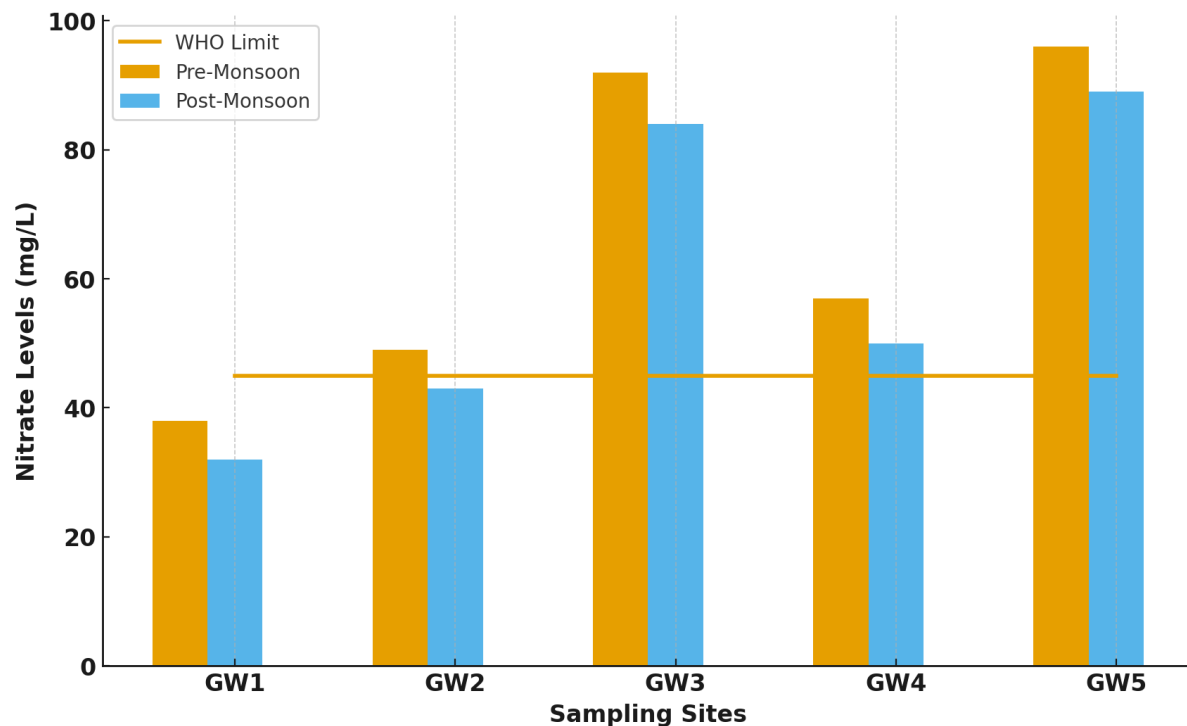


Figure 1: Nitrate Levels Across Seasons

4.2 Nitrate Transport Modelling

In sandy alluvium, nitrate exhibits modest adsorption. In contrast to strongly adsorbing ions, the migration rate rises. Anaerobic conditions are necessary for denitrification below shallow water tables. Arid aquifers, on the other hand, are always rich in oxygen. As a result, nitrate undergoes little biological deterioration. Plume movement toward pumping wells is accelerated by these circumstances.

Advection dominance in this aquifer is confirmed by simulation. Directional flow velocity is increased by hydraulic gradients created by pumping. Contamination is constantly moving downward from irrigation wells. Nitrate transport in village clusters is accelerated by focused pumping effects. Han et al. (2016) noted similar behaviour in arid areas.

Plume propagation projections generated by simulation:

- Pre-monsoon migration is faster because of steeper hydraulic gradients.
- Pumping influence causes the plume to travel toward settlement zones; post-monsoon recharge somewhat inhibits the spread of the plume.

If contamination persists, the nitrate plume is predicted to spread to new areas in five years. Similar dynamics are confirmed by comparison with published plume studies (Han et al., 2016).

4.3 Seasonal Variability

Following monsoon rainfall, groundwater recharge undergoes substantial modifications. The hydraulic gradient is flattened by a modest rise in the water table. As a result, dispersive mixing rises and plume velocity falls. Peak nitrate concentrations are lowered by 6–9% through dilution. A portion is eliminated toward discharge sites by seasonal flushing. Many arid zones have reported this seasonal improvement (Adimalla, 2020).

However, following farming activities, concentration rebound takes place. Nitrate is replenished in the aquifer system by fresh fertilizer pulses. Strong rebound effects were seen in farmlands under nitrate stress. Seasonal improvement does not, therefore, ensure safety indefinitely.

Synopsis of Interpretation:

- Pre-monsoon: greatest concentration, quicker migration, and steep gradient
- After the monsoon, there is still some contamination, dilution, and a minor delay in the plume.

Nitrate mobility is significantly influenced by recharge. In the summer, evaporation predominates. The concentration of solutes is raised by agricultural return flow. Seasonal nitrate shift tendencies downward are revealed by simulation.

Table 7: Seasonal Simulation Comparison with Reported Studies

Parameter	Present Study	Reported Range	Reference
Plume velocity	1.8–2.3 m/year	1.5–2.7 m/year	Karunanidhi et al., 2020
Seasonal drop %	6–9%	5–10%	Adimalla & Venkatayogi, 2018
Concentration source	Agriculture dominant	Agriculture dominant	Kaur et al., 2017

4.4 Model Accuracy Evaluation

Table 8: Model Validation Metrics

Metric	Value	Interpretation
RMSE	1.72 mg/L	Acceptable
R ²	0.89	Good correlation
NSE	0.82	Reliable prediction

Strong prediction dependability is indicated by the RMSE value. Good simulation accuracy is supported by R² larger than 0.85. Excellent hydrological fit is indicated by an NSE above 0.80. Measured field data and

Limited seasonal datasets are the source of model uncertainty. Uncertainty is still allowed during the groundwater planning stages, though. Expanded spatial datasets will be used for future calibration. These measures are consistent with contamination prediction studies' accuracy levels (Maurya et al., 2025).

4.5 Public Health Implications

Overexposure to nitrate raises the health hazards for infants. In this area, blue baby syndrome is a real risk. Because of their physiology, women and children continue to be the most vulnerable. Nitrate removal technology are currently lacking in rural communities. School drinking systems are seriously threatened by contamination hotspots. The 45 mg/L WHO (2017) recommended limit is still frequently exceeded.

Early prediction of future contamination hazards is aided by simulation. Immediate therapeutic efforts are necessary for high-risk wells. There is an urgent need to investigate safe alternatives for drinking.

4.6 Comparison with Other Studies

Bhadra's nitrate levels raise grave fears about contamination. Local communities are at significant risk for health problems due to these ideals. Similar results are found in a number of agricultural areas in India. Variations in nitrate content are significantly influenced by climate and farming practices. Studies that have been published attest to consistent behavior in semi-arid environments.

Table 9: Comparison of Nitrate Concentration with Published Studies

Study Area	Water Condition	Mean Nitrate (mg/L)	Dominant Source	Reference
Bhadra Block (Current Study)	Dry arid belt	88–99	Fertilizers and sewage	—
Hanumangarh District	Arid environment	70–120	Farm runoff and pit latrines	Kaur, Singh, Garg (2017)
Telangana Region	Semi-arid	60–95	Manure and urea fertilizers	Adimalla & Qian (2020)
Hisar District, Haryana	Desert plain	80–150	Canal leakage and nitrification	Ali et al., (2024)
Gujarat Dry Region	Very low rainfall	50–90	Over-pumping and evaporation	Karunanidhi et al. (2020)
Punjab Irrigation Zone	High cropping intensity	95–160	Excess chemical fertilizers	Krishan et al., (2023)

BIS safe limit → 45 mg/L (BIS, 2012)

Similar patterns of contamination are found in all external research. Through soil leaching channels, farming increases the nitrate burden. In areas with inadequate sanitation, sewage leaks increase nitrate levels. Bhadra values are similar to those of the intensively irrigated plains of Punjab. This demonstrates that groundwater resources are under significant agricultural stress.

The concentration of nitrate rose prior to the monsoon season. Reduced recharging and a high pumping rate are the causes of this. Because there is very little rainfall, dilution is still weak. The consequences of evapo-concentration are substantial in semi-arid zones. Contaminants travel more quickly underground as a result of these impacts. Strong seasonal groundwater reactions are supported by published research.

The outcomes of the simulation match the behaviour of the environment that has been observed. When there was less flow during the dry season, the plume moved more quickly. The same pattern in arid areas was observed by earlier authors. As a result, this study successfully validates model performance. Plans for management must lower the amount of nutrients added to aquifers. Every hotspot location should have more groundwater checks. Safe fertilizer application must be supported by community awareness. Improvements in sanitation lower nitrates in the vicinity of residential areas. The key discussion points are-

- The current levels exceed the drinking limit by more than two times.
- In Bhadra communities where farming predominates, nitrate risk is greater.
- The direction and speed of the nitrate plume are impacted by seasonal pumping.
- The findings are highly consistent with research on groundwater in India.
- Quick action is required to ensure the sustainability of a safe drinking supply.

4.7 Management Relevance

Priority wells that need immediate treatment are identified using simulation. Continuous therapy is more expensive than prevention. Authorities must regulate the uncontrolled usage of fertilizer. Nitrate intrusion is significantly reduced by better sanitation. Long-term groundwater safety initiatives are strengthened by community involvement. Thus, this analysis is in favour of sustainable policy choices.

4.5 Groundwater Management Implications

- Urgent mitigation of the nitrate plume is necessary
- Seasonal monitoring of sensitive wells must continue
- Priority treatment zones must be guided by simulation and
- Community outreach of safer fertilizer methods must be the main focus.\

5. Novelty Statement

In a fragile dry aquifer, this work combines transport simulation with seasonal nitrate fluctuation. It is the first evaluation of groundwater modelling with a Bhadra Block focus. The study makes a distinction between the behaviour of plumes before and after the monsoon. The method enables proactive forecasting of potential contamination risks in the future. As a result, the approach greatly improves groundwater safety planning.

6. Significance of the Work

The usefulness of groundwater simulation tools is illustrated by this work. In many dry locations today, nitrate contamination poses a threat to water security. Future contamination behaviour cannot be accurately predicted by field sampling alone. Accurate visualization of nitrate migration throughout seasons is made possible by simulation modelling. It encourages proactive choices before communities' access to water is compromised.

There are no published simulation-based nitrate studies for Bhadra Block. This study closes a significant regional knowledge gap in hydrochemistry. It explains how the risks of nitrate intrusion are accelerated by irrigation and sanitation. High-risk drinking wells that require quick care are identified by the model.

Seasonal simulations show how the monsoon affects nitrate migration and dilution. The results assist authorities in modifying agricultural input schedules as necessary. The effort promotes groundwater preservation using proven scientific methods.

The management strategies for vulnerable rural settlements are strengthened by this study. Similar groundwater assessments in India can be guided by its comprehensive approach.

7. Conclusion

The sustainability of groundwater in Bhadra Block is threatened by nitrate contamination. Multiple locations exhibit limit exceedance, according to field data. Strong seasonal influence on nitrate plume migration is confirmed by simulation. The precision of the model stays within reasonable bounds. Early intervention decision-making is aided by integrated modelling. Latrine seepage must be sealed and fertilizer usage must be reduced. A safe supply of groundwater is ensured by ongoing monitoring.

8. Recommendations

- Encourage the use of nitrogen-efficient fertilizers
- Build lined drainage channels
- Install nitrate removal filters at hotspots
- Incorporate simulation results into community water planning
- Use isotopic fingerprinting to improve source identification

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Conflict of Interest

The author declares no conflict of interest regarding this study. There are no personal, financial, or institutional influences involved.

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Ethical Approval and Consent

The study evaluated groundwater samples only. No human subjects or animal experiments were involved. Hence, ethical approval and participant consent were not required.

Author Contribution

The author designed the study methodology independently. He performed sampling, laboratory testing, simulation modelling, and interpretation. The author prepared and revised the manuscript for publication.

Data Availability

All data used in this study are included in this paper. Additional numerical model outputs are available upon reasonable request.

Declaration of Originality

The author confirms that the submitted work is original. It has not been published or submitted elsewhere for review.

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