

Microbial Safety and Nitrate Transport in Shallow Aquifers of Rural Haryana: A Geochemical and Public-Health Assessment

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Abstract

Rural areas of Haryana rely on handpumps and tubewells to draw water from shallow alluvial aquifers, which are already under significant abstraction stress due to the nitrogen and fecal loads that come from agriculture and community sanitation. This article assesses the health risk, microbial attenuation, and published monitoring data while also developing a transparent screening-level model of nitrate leaching and transport. Out of 879 samples taken in Haryana in 2024, 128 (or 14.56% of the total) tested positive for nitrate levels higher than the 45 mg/L limit set by IS 10500:2012. Under the above conditions, a mass-balance calculation yields the following results: a recharge concentration of 62.8 mg NO₃⁻/L, a trip time to a 10 m water table of 7.1 years, and an infant hazard quotient of 1.33. Bacterial indicators may be suppressed within meters in slow natural flow, but they can travel hundreds of meters in pumping-induced gradients, and viruses can go around five times further, according to first-order decay simulations. The paper highlights the importance of paired chemical-microbial monitoring, the limitations of screening techniques, and uncertainty.

Keywords: nitrate; groundwater; Haryana; advection–dispersion; denitrification; faecal indicator bacteria.

1. Introduction

The Indian state of Haryana relies on groundwater for both drinking water and irrigated farming in its rural areas. Particularly concerning in shallow aquifers (water table usually within tens of meters) are nitrate and faecal microbial pollution, two quality concerns characterized by being chemically stable and highly mobile, respectively. Despite having a same progenitor, the subsurface behaviours of fertilizer, animal dung, septic effluent, and leaking sewers are remarkably different. In contrast to viruses and protozoan cysts, which can remain for longer periods of time, nitrate is very sparing in oxygen aquifers and can persist for decades. The majority of enteric bacteria are destroyed within a few days to a few weeks. In some states, including Haryana, nitrate levels rose between 2017 and 2023. Nearly 20% of the samples taken across the country exceeded the 45 mg/L nitrate limit, as reported in the CGWB Annual Groundwater Quality Report 2024. Haryana is no different from other states in that it uses more groundwater than it can replace. In order to understand how these hydrological variables control microbial risk, it is necessary to provide a chemically accurate account of the nitrate production, transport, and attenuation processes.

Here are the objectives: (i) to summarize the monitoring evidence for Haryana in a concise manner; (ii) to calculate nitrate loading, transport, and attenuation in an accurate and repeatable manner; (iii) to evaluate the possible effects of attenuation on microorganisms and their exposure risk; and (iv) to fairly assess the current management options and their limitations. Tables 1 and 2 display the published figures. I just wanted to say a little thing about the data. Since Tables 3–8's model calculations are not site-specific but rather based on specified assumptions characteristic of loamy-sand alluvium, you are free to re-run them using field data.

2. Study Setting: Hydrogeology and Ground water Stress

With an average annual rainfall of 615 mm, heavily concentrated during the monsoon, Haryana receives a lot of rain for its 44,212 km² of land area. Based on the CGWB state profile, the state is divided into zones according to aquifer-yield. In the southern districts (Ambala, Kurukshetra, Karnal, Sonapat), the alluvial aquifers are the most productive, while in the northern districts (Siswa, Hisar, Bhiwani, Mahendragarh, and Jind) the tubewells produce modest discharges. The majority of the state is located on the Indo-Gangetic alluvial plain,

which means that the soils are mostly sand and loam. This type of soil allows soluble anions to travel quickly vertically.

Table1.Groundwater resource status of Haryana (CGWB state profile, 2011 assessment)

Parameter	Value
Annual replenishable groundwater resource	10.78 BCM
Net annual groundwater availability	9.79 BCM
Annual groundwater draft	13.05 BCM
Stage of ground water development(draft/availability×100)	133.3% (13.05 /9.79 ×100)
Blocks: over-exploited/critical/semi-critical	71 /15 /7

Source: CGWB, Groundwater Scenario of Haryana.

Abstraction surpasses the annual extractable resource when the stage of development is greater than 100%. There are two chemical effects of falling water tables. The first step is to vertically and laterally draw water into the pumped zone, which is typically older and of lower quality. In addition, they deepen the unsaturated zone, which allows for the downward flow of nitrate from the vadose zone due to previous fertilizer applications as a result of increased irrigation or recharge. Section 9 discusses the uncertainties, one of which is the non-monotonic relationship between water-table decline and nitrate concentration.

Table2.Ground water quality exceed andesine Haryana, CGWB monitoring 2024

Parameter	Samples	Limit (mg/L)	Samples above limit	%above limit
Nitrate (NO ₃ ⁻)	879	45	128	14.56
Fluoride(F ⁻)	879	1.5	208	23.66

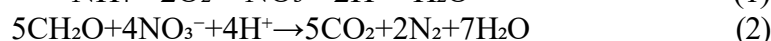
Source: CGWB, Groundwater Quality of Haryana, 2024. Percentages recomputed: 128/879×100=14.56%; 208/879 × 100 = 23.66%.

There should be two points of equilibrium. The nitrate exceedance rate in Haryana (14.6%) is lower than the national average of approximately 20%, hence the state does not stand out in this regard. From 2017 to 2023, there was a growing trend in nitrate exceedances reported by CGWB in a number of districts, including Bhiwani, Faridabad, Fatehabad, Gurugram, Hisar, Jhajjar, Jind, Kaithal, and Karnal. Nitrogen concentrations in tubewell water ranged from 56.19 to 91.36 mg/L, with concentrations exceeding 45 mg/L in every sample, in a loamy sand profile up to 15 meters deep, according to a case study of two adjacent villages in Haryana conducted by Prem and Jhorar. This finding supports the idea that district averages can mask serious hotspots. Because monitoring networks are typically deeper and less densely distributed than village handpumps, they can either exaggerate or understate a household's exposure.

3. Nitrate Geochemistry

3.1 Sources and transformations

There are four main sources of nitrate in shallow groundwater: (i) agriculture manure and soil nitrogen that has been mineralized from it; (ii) human waste from septic tanks, pit latrines, and unsewered drains; and (iii) naturally occurring soil nitrogen, which includes nitrate that has accumulated in the unsaturated zone of semi-arid soils. Often overlooked is the fourth source: high nitrate levels do not conclusively show anthropogenic pollution in dry and semi-arid environments, where they accumulate over extended periods of time in the vadose zone. Using tracers such nitrate's dual stable isotopes ($\delta^{15}\text{N}$ and $\delta^{18}\text{O}$), chloride/bromide ratios, and boron is necessary for isolating these sources. Important redox reactions include ammonium nitrification, which makes soil acidic and releases nitrate into the soil, and heterotrophic denitrification, which eliminates nitrate in environments with low oxygen levels and an accessible electron donor:



Organic carbon (or, in certain aquifers, pyrite or Fe(II)) and anoxic conditions are necessary

for reaction (2). Natural denitrification is not widespread in Haryana's shallow alluvial aquifers since these aquifers are typically oxygen-rich and contain little organic carbon. Denitrification does happen, but it is often in isolated areas, such clay-rich or organic-rich lenses. Characteristic isotopic ranges widely cited from Kendall (1998) are approximately -3 to $+3\text{‰}$ $\delta^{15}\text{N}$ for fertilizer nitrate, $+3$ to $+8\text{‰}$ for soil organic nitrogen and $+8$ to $+20\text{‰}$ for manure and septic effluent, with denitrification ricing there si dual nitrate in both $\delta^{15}\text{N}$ and $\delta^{18}\text{O}$. The ranges overlap, so isotopes are best used together with hadrochemical data.

3.2 Units and regulatory limits

It is common for researchers to make mistakes when comparing studies that describe nitrate as NO_3^- or as $\text{NO}_3\text{-N}$, because the two terms are often confused. From the molar masses, we may deduce the conversion factors as follows: ($\text{NO}_3^- = 62.004$ g/mol; $\text{N} = 14.007$ g/mol): 1 mg/L $\text{NO}_3\text{-N} = 4.427$ mg/L NO_3^- , and 1 mg/L $\text{NO}_3^- = 0.2259$ mg/L $\text{NO}_3\text{-N}$.

Table 3. Nitrate limit expressed in common units

Standard	mg/L as NO_3^-	mg/L as $\text{NO}_3\text{-N}$	mmol/L (= meq/L)
BIS IS 10500:2012 (acceptable)	45.0	10.17	0.726
WHO guideline value	50.0	11.30	0.806
USEPAMCL (as N)	44.3	10.00	0.714

Calculated from molar masses. IS 10500:2012 gives 45 mg/L as the acceptable limit with no relaxation in the absence of an alternative source; the WHO value of 50 mg/L is a short-term guideline protecting bottle-fed infants from methemoglobinemia; the US EPA limit is 10 mg/L as N.

In addition, the World Health Organization has set a temporary limit of 3 mg/L for nitrite, and in cases where both are present, the total of the ratios of the two concentrations to this limit must not be more than one: $C(\text{NO}_3^-)/50 + C(\text{NO}_2^-)/3 \leq 1$. Even though each ion is below its own value, a solution containing 40 mg/L nitrate and 1 mg/L nitrite fails the combined criterion because the result is 1.13 ($40/50 + 1/3$).

4. Nitrate Transport: Theory and Worked Calculations

4.1 Governing equation

One-dimensional vertical transport of a solute through the unsaturated zone and into the aquifer is described by the advection–dispersion–reaction equation:

$$\frac{\partial C}{\partial t} = D \frac{\partial^2 C}{\partial z^2} - v \frac{\partial C}{\partial z} - \lambda C \quad (3)$$

where C is the concentration in milligrams per liter, v is the average pore-water velocity in meters per year, D is the longitudinal dispersion coefficient in millimetres per year, and λ is the first-order decay constant in yr^{-1} . $V = R_{\text{net}}/\theta$ is the velocity, where R_{set} is the net deep percolation in meters per year and θ is the volumetric water content. The formula $D = \alpha_1 v + D^* \tau$ incorporates both mechanical dispersion (dispersity α_1) and effective molecular diffusion. Since nitrate is anionic, it repels soil with a negative charge and does not absorb much, hence we assume that $R = 1$.

4.2 Nitrate loading from a mass balance

By dividing the mass of leached nitrogen by the volume of percolating water, we may determine the concentration of nitrate in water that is exiting the root zone. The outcome in milligrams of $\text{NO}_3\text{-N}$ /liter is, given a nitrogen application rate in kg/ha, a leached fraction f_l , and a net percolation rate in millimetres ($1 \text{ mm} = 10 \text{ m}^3/\text{ha} = 10^4 \text{ L/ha}$):

$$C(\text{N}) = 100 \cdot f_l \cdot N / R_{\text{net}} \quad (4)$$

Worked example. Assume $N = 150$ kg N/ha/yr, $f_l = 20\%$, rainfall 615 mm with 10% recharge (61.5 mm) and 150 mm of deep percolation from irrigation, so $R_{\text{net}} = 61.5 + 150 = 211.5$ mm. Leached $N = 0.20 \times 150 = 30$ kg/ha. Then $C(\text{N}) = 100 \times 30 / 211.5 = 14.18$ mg $\text{NO}_3\text{-N/L}$, equivalent to 62.8 mg NO_3^-/L ($\times 4.427$). This is 1.4 times the 45 mg/L limit and lies within the same order as values reported for Haryana tubewells, although agreement should not be read as validation, because the inputs are assumed.

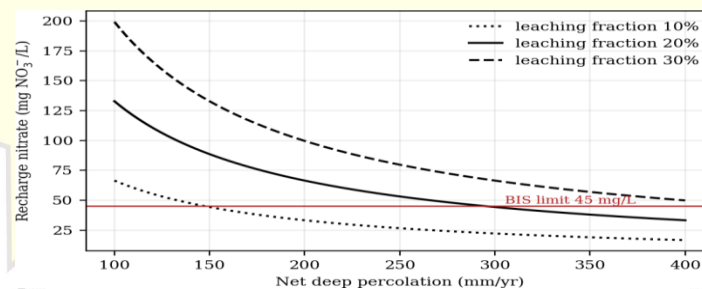
Table 4. Sensitivity of recharge nitrate ($\text{mg NO}_3^-/\text{L}$) to leaching fraction and net percolation ($\text{N applied} = 150 \text{ kg N/ha/yr}$)

Leached fraction f_l	$R_{\text{net}}=150\text{mm}$	$R_{\text{net}}=211.5\text{mm}$	$R_{\text{net}}=300\text{mm}$
10%	44.3	31.4	22.1
20%	88.5	62.8	44.3
30%	132.8	94.2	66.4

Computed from Eq. (4) and converted with the factor 4.427. Values above 45 mg/L exceed the BIS limit.

More water dilutes the same nitrogen load, as seen in Table 4, which is an inverse relation with percolation. In water management, this is an actual trade-off. Although more water lowers the concentration, it increases the overall mass flux of nitrate to the aquifer, which means that heavy irrigation tends to elevate the leached proportion itself. Improving nitrogen-use efficiency is more successful than depending on dilution, as only the 10% leaching row and the 20% row at 300 mm remain below the BIS limit in the grid, regardless of the percolation rate.

Figure 1. Recharge nitrate as a function of net percolation for three leaching fractions ($\text{N}=150 \text{ kg}$



N/ha/yr), from Eq. (4).

Travel time and breakthrough

Assume a volumetric water content of $\theta = 0.15$ in the loamy-sand profile. The vertical pore velocity is $v = 0.2115 \text{ m/yr} \div 0.15 = 1.41 \text{ m/yr}$. For a water table at 10 m, the advective travel time is $t = 10/1.41 = 7.1$ years. If only natural rainfall recharge applied (61.5 mm/yr), v would be 0.41 m/yr and $t = 24.4$ years. Irrigation therefore shortens the lag between surface practice and groundwater impact from about 24 years to about seven years, which has an important management implication: the effect reduced fertiliser use on the water table will be delayed, and nitrate currently entering the aquifer reflects practices of earlier years.

The concentration at depth x can be determined using the Ogata-Banks solution to Eq. (3) with $\lambda = 0$, in the case of a continuous step source at the top of the profile:

$$C/C_0 = \frac{1}{2} \left[\text{erfc}((x-vt)/(2\sqrt{Dt})) + \exp(vx/D) \cdot \text{erfc}((x+vt)/(2\sqrt{Dt})) \right] \quad (5)$$

With $\alpha_i = 0.5 \text{ m}$ (an assumed value), $D = 1.9 \times 10^{-9} \text{ m}^2/\text{s}$, tortuosity 0.5 ($D\tau = 0.030 \text{ m}^2/\text{yr}$) the dispersion coefficients $D = 0.5 \times 1.41 + 0.030 = 0.735 \text{ m}^2/\text{yr}$. The Péclet number $Pe = vx/D = 19.2$ indicates advection-dominated transport.

Table 5. Predicted relative nitrate concentration C/C_0 at $x = 10 \text{ m}$ ($v = 1.41 \text{ m/yr}$, $D = 0.735 \text{ m}^2/\text{yr}$)

Times in source on set (yr)	C/C_0
3.0	0.004
5.0	0.173
7.1 (=x/v)	0.563
10.0	0.893
15.0	0.995
20.0	1.000

Calculated from Eq. (5). The value at $t = x/v$ is slightly above 0.5 because the second ($\exp \cdot \text{erfc}$) term of Eq. (5) adds a positive contribution at that time.

There is a clear trend in the data: after three years with low nitrate levels ($C/C_0 = 0.004$), the water table reaches 90% of its source concentration after ten years, and after fifteen years, it is practically at source strength. Since the aquifer volume already contains the earlier load, the nitrate in a handpump can vary rapidly once the front arrives, but it does not decline quickly once source reductions begin. This is a practical consequence.

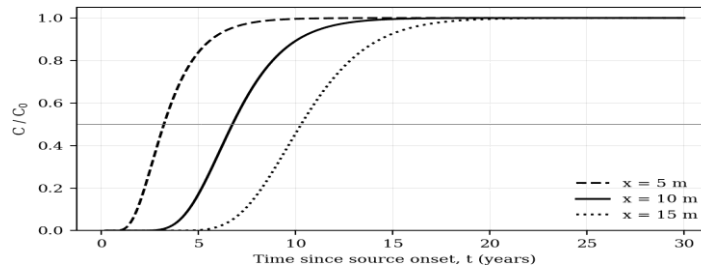


Figure2. Breakthrough curves from the Ogata-Banks solution (Eq.5) at three depths ($v=1.41\text{m/yr}$, $D=0.735\text{ m}^2\text{/yr}$).

Attenuation by denitrification

According to Eq. 6, where λ is equal to $\ln 2/t_{1/2}$, the proportion that remains after travel time t , assuming denitrification does take place, is $C/C_0 = \exp(-\lambda t) = 0.5^{(t/t_{1/2})}$. Table 6 shows the degree to which an unmeasured parameter affects the solution using the same 7.1-year journey time as in the previous section.

Table 6. Nitrate removal over a 7.1-year travel time for assumed denitrification half-lives

Half-life $t_{1/2}$ (yr)	λ (yr^{-1})	Fraction remaining	Removed (%)
2	0.347	0.086	91.4
10	0.069	0.612	38.8
50	0.014	0.906	9.4

Calculated as $0.5^{(7.09/t_{1/2})}$. Half-lives are scenario values, not measurements.

Two years' half-life would eliminate 91% of the nitrate, whereas fifty years' half-life would remove only 9%. You should look at denitrification as a benefit rather than a drawback because the half-life in oxic Haryana aquifers is not well controlled. Prior to any credit being granted, field evidence such as $\text{NO}_3^-/\text{Cl}^-$ ratios, dissolved O_2 , $\delta^{15}\text{N}$ - $\delta^{18}\text{O}$ enrichment, and excess N_2 as determined by dissolved-gas analysis is required.

5. Microbial Safety

5.1 Indicators, pathways and hazards

Both the International Standard 10500:2012 and the World Health Organization's guidelines stipulate that a 100 mL sample of drinking water must not include any thermotolerant coliforms or *Escherichia coli* in order to evaluate the water's microbiological quality. While indicator organisms do communicate a fecal route, they do not directly test infections. A number of pathogenic bacteria and viruses can cause problems in the digestive tract, including cryptosporidium and giardia, as well as rotavirus, hepatitis A and E, Shigella, *Vibrio cholerae*, and *E. coli*. Viruses are smaller and more persistent, thus the absence of signs does not necessarily mean that there are no viruses. There are four main channels in rural Haryana that sewage can travel through: (i) handpumps themselves; (ii) village ponds that recharge shallow aquifers and collect sewage and livestock waste; (iii) waterlogging and flooding during the monsoons, which can carry surface contamination to poorly sealed wellheads; and (iv) the handpump itself. A positive sample might not necessarily represent the aquifer, but rather the pump and priming water, since research by Ferguson and colleagues demonstrated that components of hand pumps retain total coliforms and *E. coli* and release them into pumped water over time. Chaudhuri and Roy pointed out that the combined impact of quality and

depletion is mainly felt by rural households that utilize handpumps, which draw from shallow groundwater.

5.2 Attenuation and set-back distance: a first -order model

To a first approximation, the log₁₀ reduction after travel time t is $\lambda t / \ln 10$, and the distance for an n -log reduction at pore velocity v is:

$$L_n = n \cdot \ln 10 \cdot v / \lambda \quad (6)$$

We take $\lambda = 0.10 \text{ d}^{-1}$ for *E. coli* ($T_{90} = \ln 10 / \lambda = 23.0 \text{ d}$) and $\lambda = 0.02 \text{ d}^{-1}$ for an enteric virus ($T_{90} = 115.1 \text{ d}$). These are illustrative values within the range reported in the literature (see Pang 2009; Jin and Flury 2002), and real decay depends on temperature, soil, sorption and the organism. Velocities are 0.024 m/d (natural gradient, from Darcy: $v = K_i / n_e = 3 \times 0.002 / 0.25$), and 0.5 and 2.0 m/d to represent flow towards a pumping well.

Table 7. Distance for 4-log(99.99%) removal by first-order in activation alone

Organism	$\lambda (\text{d}^{-1})$	$T_{90} (\text{d})$	$t(4\text{-log})(\text{d})$	$v = 0.024 \text{ m/d}$ (m)	$v = 0.5 \text{ m/d}$ (m)
<i>E. coli</i> (bacterial indicator)	0.10	23.0	92.1	2.2	46
Enteric virus (e.g. rotavirus)	0.02	115.1	460.5	11.1	230

At $v = 2.0 \text{ m/d}$ the 4-log distances are 184 m (*E. coli*) and 921 m (virus). Calculated from Eq.(6); $t(4\text{-log}) = 4 \times \ln 10 / \lambda$.

Consistent with the conventional rule of thumb that moderate set-back distances guard against bacteria, *E. coli* would be inactivated within around 2 m under natural-gradient flow. At a distance of 184 meters , the identical organism could pass through a four-log filter; at 921 meters , it could infect a virus. But the model is intentionally pessimistic in one area and hopeful in another. Filtration and attachment remove organisms without inactivating them, and it disregards preferential flow through root channels, fissures, poorly sealed borehole annuli, and abandoned wells—all of which can carry bacteria significantly faster than the matrix velocity. The right thing to do is to have wells sanitary-completed (with a concrete apron, sealed annulus, and drainage away from the pad) and to have set-back regulations in place.

5.3 Co-occurrence of nitrate and microbial contamination

Since both high nitrate and faecal markers can be attributed to sanitation, they are typically thought to be related. The data are more complex. The fields are a major source of nitrate since they use fertilizer, which kills germs but leaves behind nitrate. This means that *E. coli* can be present in a well with high nitrate levels, or vice versa, especially during monsoons. In comparison to nitrate on its own, the presence of chloride, boron, or sodium in conjunction with a positive indication provides more compelling evidence of a sewage source. Because of this, nitrate should not be used as a stand-in for microbiological safety; rather, the two should be tested independently.

6. Health Risk Assessment

In infants, the conversion of nitrate to nitrite in the intestines causes haemoglobin to be oxidized to methaemoglobin, a condition known as infant methemoglobinemia ("blue-baby syndrome"). There have been reports of longer-term associations with thyroid disease, colorectal cancer, and adverse birth outcomes. However, according to Ward et al. (2018), the epidemiological evidence is suggestive in some cases but inconsistent in others. Therefore, it is most defensible to take a purely regulatory view based on the infant endpoint. The hazard quotient, which is the screening risk, is calculated as follows: $HQ = ADD / RfD$, where ADD is the average daily dosage, C is the concentration in mg/L , IR is the intake in L/day , and BW is the body weight in kg . The nitrate reference dose set by the US EPA IRIS is $1.6 \text{ mg NO}_3\text{-N/kg/day}$, which is 1.6 multiplied by 4.427 , or $7.08 \text{ mg NO}_3\text{-N/kg/day}$. In Section 4.2, we find that $C = 62.8 \text{ mg/L}$:

Table 8. Hazard quotients for nitrate at 62.8 mg NO₃⁻/L (RfD= 7.08 mg NO₃⁻/kg/day)

Group	IR (L/d)	BW (kg)	ADD(mg/kg/d)	HQ
Infant(formula-fed)	0.75	5	9.42	1.33
Child (6 y)	1.00	20	3.14	0.44
Adult	2.00	60	2.09	0.30

Intake rates and bodyweights are assumed screening values. Example: adult $ADD = 62.8 \times 2.0 / 60 = 2.09 \text{ mg/kg/d}$; $HQ = 2.09 / 7.08 = 0.30$.

A formula-fed baby, with an HQ of 1.33, drinks about four times as much water than an adult does per kilogram of body weight. At the precise 45 mg/L BIS limit, the infant HQ is 0.95, which is slightly less than one, indicating that there is little room for newborns at this limit and that water over this level should not be used for infant formula. Since the RfD incorporates uncertainty factors and the exposure implies continued drinking of the same water, an HQ above 1 indicates management action rather than a disease prognosis. The converse is true for microbiological dangers; infants younger than five are at a higher acute risk if their HQ is less than 1.

7. Analytical Methods and Monitoring Designs

A reasonable amount of sampling points is necessary for a monitoring program to be defensible. The equation for calculating the likelihood of an event occurring within a certain margin d , with a 95% confidence level, is $n = ZZp(1 - p)/dZ$ (Eq. 7), where $Z = 1.96$. With the CGWB nitrate exceedance fraction $p = 0.1456$ and $d = 0.05$, the number of independent wells needed is 191.2, calculated as $3.8416 \times 0.1456 \times 0.8544 / 0.0025$. It takes 531 wells to tighten the gap to $d = 0.03$. With no background data, the cautious $p = 0.5$ and $d = 0.05$ yields $n = 385$ wells for microbial prevalence. Prior to and after the monsoon, stratify the samples by district, well depth, land use, and distance to sanitation. Inflate the sample size to account for clustering within villages (design effect). Nitrogen nitrate measurements can be quickly and accurately taken using UV spectrophotometry at 220 nm with a 275 nm correction for dissolved organic matter. For low-organic groundwater, ion chromatography is the method of choice because it can measure NO₃⁻, NO₂⁻, Cl⁻, SO₄Z⁻, and F⁻ all at once. Another option is cadmium or vanadium (III) reduction colorimetry. Report blanks, duplicates, and spiking recoveries in addition to the ion balance (cations vs. anions in meq/L, typically within $\pm 5\%$). Field H₂S presence-absence tests are helpful for screening, although they are not as specific as membrane filtration or the chromogenic most-probable-number procedures for total coliforms and E. coli (APHA Standard procedures). Collect samples in sterile containers, refrigerate them to 4 °C, and analyze them within 6-8 hours. If you want to distinguish between contamination in the wellhead and contamination in the aquifer, you should purge the well, burn it or disinfect it at the spout, and take samples at the first draw and after steady pumping.

8. Management and Treatment Options

No one solution tackles nitrate and microbiological risk simultaneously; source substitution, treatment, and source control all have their advantages and disadvantages. Table 9 provides a qualitative comparison of the primary choices.

Table 9. Qualitative comparison of household and community interventions

Option	Nitrate removal	Microbial control	Chemical or practical considerations
Boiling	None	Effective	Evaporation raises nitrate concentration; risk if used for infant formula
Chlorination	None	Effective (residual)	Does not remove nitrate; disinfection by-products where organic matter is present
Reverse osmosis	High	High	Brine disposal, loss of minerals, water wastage, maintenance

Nitrate-selective anion exchange	High	None	Competing sulphate and bicarbonate; regenerant brine; needs post-disinfection
Electrodialysis	Moderate-high	Partial	Energy and membrane cost; suited to community scale
Biological denitrification	High	Requires polishing	Needs carbon source; control fresh dual organics and bacteria
Alternative or blended source (canal, piped)	Dilution	Depends on source	Reliable if network is protected; cost and institutional capacity
Nitrogen management (4R: right source, rate, time, place)	Prevents loading	Not applicable	Long lag before benefit (Section 4.3); changes farmer cost and yield risk

Qualitative synthesis from general water. - Treatment; practice; performance; depends; on; feedwater; composition; and; operation.

The lengthy travel times mentioned in Section 4.3 suggest that treatment and source control work with rather than against each other. Current methods safeguard future recharge, while treatment or source substitution safeguards consumers today. In terms of microbial safety, the most cost-effective measures include sanitary well completion, latrine and soakpit relocation, handpump platform drainage, and household chlorination with residual testing.

9. Limitations

Certain limitations should be considered when interpreting the results of this study. Because they assume uniform and unidimensional transport, the screening models used in Sections 4-6 only give rough estimates rather than site-specific predictions. However, the soil and groundwater systems in Haryana could be multi-layered, subject to factors like preferential flow, recharge that varies across space, and falling groundwater levels. Parameters like the leached fraction, net percolation, and denitrification rate—which cannot be precisely predicted without field-based measurements—strongly influence uncertainty, according to the sensitivity analyses shown in Tables 4 and 6. Because CGWB samples are taken from certain monitoring wells at specific periods, and because a single pre-monsoon observation might not be enough to depict yearly circumstances or individual home exposure, there are limitations to the monitoring data as well. Another difficulty is determining where the nitrates in the water came from; different areas may have different proportions of agricultural fertilizers, wastewater, and naturally occurring soil nitrogen. Thus, techniques for management should not zero in on just agricultural or sanitation-related issues. Improving fertilizer timing, fertigation, and nutrient recommendations based on soil tests are preferable than blanket reductions in nitrogen fertilizer use, but this approach has the potential to reduce crop output and farmers' income. Lastly, there are additional contaminants that might affect the quality of Haryana's groundwater besides nitrate. Fluoride, uranium, salinity, and arsenic are some of the other possible contaminants. Therefore, the full pollutant profile, not just nitrate, should be considered when making decisions about groundwater treatment and management. It is important to think about the cost, water recovery efficiency, waste disposal requirements, and resource implications of technologies like reverse osmosis, even if they can handle multiple contaminants at once.

10. Conclusion

While the percentage of Haryana groundwater samples with nitrate levels above the 45 mg/L standard is lower than the national average, it is on the rise, and there are local hotspots where levels are much higher, according to published CGWB statistics (14.56%). The recharge concentrations range from 22 to 133 mg $\text{NO}_3^- \cdot \text{L}^{-1}$, according to a transparent mass-balance, when considering several realistic leaching and percolation scenarios (Table 4). Irrigation reduces the time it takes for surface practices to affect groundwater levels to approximately seven years, assuming a water table of 10 meters. Reductions at the source will take some time to manifest because nitrate is conservative in oxic aquifers. Attenuation by inactivation works well at natural gradients but is easily negated by pumping-induced flow, favored routes, and inadequate wellhead cleanliness, which are governed by distinct physical principles and impact microbial contamination. When it comes to nitrate (HQ 1.33 at 62.8 mg/L) and microbiological

risks, infants and children under the age of five are at the biggest danger. Here are some practical suggestions: (i) combine nitrate and microbial indicator monitoring using a stratified design with 192 wells per stratum to estimate nitrate prevalence; (ii) pair source control with household treatment and sanitary well completion; (iv) replace the assumed parameters in this paper with measured K , θ , recharge, decay, and leaching values for the study villages; and (v) use dual isotopes and ion ratios to attribute sources before targeting interventions. Bringing the current screening framework up to date in this way would make it an ideal calibrated site model for a PhD field study.

Works Cited

1. APHA, AWWA, WEF (2017). Standard Methods for the Examination of Water and Wastewater, 23rd ed.
2. American Public Health Association, Washington, DC.
3. BIS (2012). IS 10500:2012 Drinking Water – Specification (Second Revision). Bureau of Indian Standards, New Delhi.
4. Central Ground Water Board (2024). Ground Water Quality of Haryana, 2024. CGWB, Faridabad. <https://cgwb.gov.in>
5. Central Ground Water Board. Ground Water Scenario of Haryana (State Profile). CGWB, Faridabad.
6. Chaudhuri, S., Roy, M. (2016). Reflections on groundwater quality and urban–rural disparity in drinking water sources in the state of Haryana, India. *International Journal for Scientific Research and Development*, 4(4), 837–843.
7. Ferguson, A. S., et al. (2011). *Hand-pumps as reservoirs for microbial contamination of well water*. **Journal of Water and Health**, 9(4), 708–717.
8. *Journal of Water and Health*, 9(4), 708–717.
9. Freeze, R. A., & Cherry, J. A. (1979). *Groundwater*. Prentice-Hall, Englewood Cliffs, NJ.
10. Jin, Y., & Flury, M. (2002). Fate and transport of viruses in porous media. *Advances in Agronomy*, 77, 39–102.
11. Kendall, C. (1998). Tracing nitrogen sources and cycling in catchments. In C. Kendall & J. J. McDonnell (Eds.), *Isotope Tracers in Catchment Hydrology* (pp. 519–576). Elsevier, Amsterdam.
12. Ogata, A., & Banks, R. B. (1961). *A solution of the differential equation of longitudinal dispersion in porous media*. US Geological Survey Professional Paper 411-A.
13. Pang, L. (2009). Microbial removal rates in subsurface media estimated from published studies of field experiments and large intact soil cores. *Journal of Environmental Quality*, 38(4), 1531–1559.
14. USEPA. Nitrate (CASRN 14797-55-8), *IRIS Chemical Assessment Summary*. Integrated Risk Information System.
15. Ward, M. H., et al. (2018). Drinking water nitrate and human health: An updated review. *International Journal of Environmental Research and Public Health*, 15(7), 1557.
16. WHO (2022). *Guidelines for Drinking-water Quality: Fourth Edition Incorporating the First and Second Addenda*. World Health Organization, Geneva.