

Groundwater Contamination Sources, Pathways, Health Risks, Monitoring and Management

Pappu Kumar*

Assistant Professor, Department of Civil Engineering, Sandip University, Sijoul, Madhubani, Bihar 847235.

*Corresponding author email ID: pappusobh@gmail.com

HIGHLIGHTS

- Groundwater contamination is a persistent threat to drinking water, agriculture, and public health.
- Both geogenic and anthropogenic pollutants shape groundwater quality across regions.
- Hydrogeology strongly controls contaminant mobility, persistence, and exposure risk.
- Prevention-first monitoring and aquifer protection are more effective than delayed remediation.

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ABSTRACT

Groundwater is a vital source of drinking water, irrigation, and industrial supply, but its quality is increasingly threatened by both natural and human-induced contamination. Because aquifers are hidden and often slow to flush, pollutants can remain undetected and persist for long periods. This review examines the major sources, transport mechanisms, impacts, monitoring approaches, remediation options, and governance challenges associated with groundwater contamination. It covers geogenic contaminants such as arsenic, fluoride, salinity, and uranium; anthropogenic pollutants from agriculture, sanitation, mining, and industry; and emerging contaminants including per- and polyfluoroalkyl substances (PFAS), pharmaceuticals, and microplastics. The review shows that contamination is strongly shaped by hydrogeology, recharge, redox conditions, and land use, making it a complex multi-contaminant problem. Effective management requires prevention-first governance, risk-based monitoring, source control, targeted treatment, and long-term aquifer protection.

1. INTRODUCTION

Groundwater supports domestic water security, irrigated agriculture, industry, and drought buffering in both humid and arid regions. Because it is buffered from short-term evaporation losses and can be stored underground for long periods, it is often treated as a strategic reserve during periods of climatic variability. The 2022 United Nations World Water

Development Report emphasized that groundwater constitutes the largest volume of unfrozen freshwater available to society and remains fundamental to drinking-water supplies and food production in many countries (UNESCO, 2022). However, the same "invisible" nature of aquifers that makes them societally valuable also encourages chronic underinvestment in quality surveillance, source control, and aquifer protection. Contamination

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usually does not present as a dramatic event. Instead, it often appears as a slow, spatially heterogeneous process that is discovered only after users have already been exposed.

This delayed visibility creates several practical problems. First, contamination can migrate and age in the subsurface long before a monitoring system detects it. Second, the affected water may appear physically clean and acceptable, even when dissolved contaminants are present at concentrations of toxicological concern. Third, once a contaminant reaches a low-permeability aquifer or a fractured-rock system with complex flow paths, remediation is usually slower and costlier than preventing release in the first place. WHO has repeatedly stressed that chemical and microbial hazards in drinking water continue to be major public-health concerns, and groundwater is a particularly important route of exposure for naturally occurring arsenic and fluoride as well as human-derived pollutants where wastewater and agricultural wastes are poorly managed (WHO, 2022; WHO, 2023).

Groundwater contamination should not be understood as a single issue. It sits at the intersection of hydrogeology, geochemistry, public health, land-use planning, industrial regulation, and social inequality. In many locations the problem is not a single contaminant but a combined burden of nitrate, salinity, pathogens, heavy metals, and geogenic toxicants. Aquifer users are also heterogeneous: deep municipal wells, shallow rural hand pumps, private domestic wells, irrigation wells, and peri-urban boreholes face different exposure profiles. A risk-based interpretation must therefore consider not only contaminant concentration, but also well depth, treatment status, patterns of consumption, user vulnerability, and the feasibility of switching to safer sources (Xie et al., 2023).

The literature increasingly shows that groundwater quality deterioration is linked to broader development pathways. Agricultural intensification increases nitrogen loading and pesticide pressure. Urban growth adds sewage leakage, septic-system failure, landfill leachate, and construction-related disturbances. Industrialization contributes metals, solvents, hydrocarbons, and complex chemical mixtures. Mining can alter hydrochemistry and mobilize acid-generating or metal-bearing contaminants. Climate variability modifies recharge timing, redox conditions, and salinity gradients, which in turn influence contaminant transport and geogenic mobilization. Over-abstraction further compounds the problem by lowering water tables, changing hydraulic gradients, and sometimes

drawing poor-quality water from deeper or more saline zones (UNESCO, 2022; Ravindiran et al., 2023).

The groundwater contamination problem is particularly severe in countries where dependence on untreated or minimally treated groundwater is high. In India, for example, quality problems include widespread fluoride, arsenic, nitrate, iron, manganese, salinity, and increasingly recognized uranium hotspots. Official sources from the Central Ground Water Board have documented both geogenic and anthropogenic contamination in isolated pockets across many states, highlighting that groundwater quality must be treated as a dynamic management issue rather than a fixed background condition (CGWB, 2014; CGWB, 2025). Similar patterns are observed across South Asia, parts of sub-Saharan Africa, North China, and Latin America, though the dominant contaminant suite varies with geology, sanitation infrastructure, irrigation intensity, and regulatory enforcement.

The scientific challenge is not simply to detect contaminants. It is to understand source–pathway–receptor relationships in a heterogeneous subsurface environment. Pollutants move through recharge zones, soils, fractures, conduits, and porous media under the influence of advection, dispersion, diffusion, sorption, biotransformation, mineral dissolution, redox reactions, and density-driven flow. The same contaminant can behave very differently in two neighboring aquifers because the controlling conditions differ. Nitrate, for example, is highly mobile under oxic conditions but may be attenuated by denitrification in reducing environments. Arsenic may remain adsorbed to iron oxides in one hydrochemical setting but be mobilized under strongly reducing conditions in another. PFAS and other emerging contaminants raise additional challenges because persistence, co-occurrence, and monitoring capabilities are still evolving (Mukherjee et al., 2024; Tokranov et al., 2024).

This review is designed as a structured synthesis for researchers, policy practitioners, and manuscript preparation. First, it classifies the major sources and classes of groundwater contaminants. Second, it explains the hydrogeologic and geochemical pathways that determine contaminant fate and transport. Third, it summarizes the principal health and environmental risks associated with contaminated groundwater. Fourth, it reviews current monitoring and assessment approaches, including the strengths and limitations of common indices and risk models. Fifth, it evaluates management and remediation options, distinguishing between source control, exposure reduction, and aquifer restoration. Sixth, it identifies policy and research gaps, with

particular attention to prevention-first governance and integrated quality–quantity management.

The paper adopts a review logic rather than a narrow contaminant-specific approach because fragmentation is itself one of the reasons groundwater policies underperforms. Water managers often treat arsenic, nitrate, salinity, microbes, and industrial pollutants as separate silos handled by separate programs, even though communities experience them through the same wells. The more defensible framing is that groundwater contamination is a coupled system problem involving hydrogeology, exposure, and institutions. In that sense, the review argues for a shift from reactive water testing toward anticipatory groundwater stewardship built on hazard mapping, routine surveillance, strong source regulation, and long-term aquifer protection (WHO, 2022; UNESCO, 2022; Xie et al., 2023).

2. HYDROGEOLOGIC BASIS OF GROUNDWATER CONTAMINATION

Any serious treatment of groundwater contamination must begin with hydrogeology. Contaminants do not move through the subsurface as they move through a river channel or a pipe. Instead, they travel through complex media whose hydraulic conductivity, porosity, fracture architecture, mineralogy, and geochemical state vary over space and depth. This matters because contamination risk is not determined solely by the amount of pollutant released at the surface. It is also determined by whether the hydrogeologic setting permits rapid recharge, storage, mixing, attenuation, or bypass flow (Table 1).

Aquifer type is a first-order control. Unconfined aquifers are generally more vulnerable to surface-derived contamination because recharge moves more directly from the land surface into the saturated zone. Confined aquifers may appear protected, but they are not immune; leakage through confining beds, poorly sealed wells, faults, fractures, or abandoned boreholes can provide entry routes. Karst aquifers are especially vulnerable because conduits and enlarged fractures can transmit water and contaminants rapidly with little filtration. Fractured hard-rock aquifers may also exhibit preferential pathways that are difficult to predict from surface inspection alone. In contrast, thick clay-rich vadose zones can attenuate some microbial and sorbing contaminants, although they do not guarantee protection against dissolved and persistent chemicals (USGS, 2018; Al-Hashimi et al., 2021).

Recharge regime strongly affects contamination. Areas with intense irrigation return flow, canal seepage, flood recharge, leaking water networks, or concentrated urban runoff may experience enhanced downward transport of dissolved contaminants. Recharge also controls

oxygen availability and redox evolution in aquifers, which in turn shapes contaminant chemistry. Nitrate tends to persist in oxic zones but may be reduced under anoxic conditions if electron donors are available. Arsenic mobilization, by contrast, is often associated with reducing conditions that dissolve iron oxyhydroxides and release sorbed arsenic. Fluoride concentrations are influenced by residence time, pH, alkalinity, evaporative concentration, and mineral equilibrium conditions. Thus, the same hydroclimatic change that increases recharge in one setting may dilute contamination, while in another setting it may accelerate pollutant flushing from the surface to the aquifer (Mukherjee et al., 2024; Herath et al., 2016).

The vadose zone is frequently underestimated in management discussions. It is not just a layer that contaminants must pass through; it is a dynamic reactor. Sorption, volatilization, biodegradation, filtration, and retardation may occur there. The thickness and composition of the unsaturated zone influence whether pollutants are delayed, transformed, or transmitted. Yet preferential flow through root channels, desiccation cracks, coarse lenses, or poorly grouted well annuli can bypass much of this attenuation capacity. This is why sanitation-related contamination may still reach groundwater even where the soil profile appears thick enough to provide protection. Field evidence summarized in systematic reviews of microbial groundwater contamination shows that sanitation density, animal loading, rainfall, and hydrogeologic shortcuts interact strongly, and broad assumptions based on soil type alone are often misleading (Bagordo et al., 2024).

Groundwater age and residence time are equally important. Long residence times can increase the water–rock interaction that produces geogenic contamination, such as fluoride enrichment, iron and manganese release, or salinity buildup. But old groundwater is not always safer from anthropogenic contamination. In some systems, downward migration from decades of legacy fertilizer uses or historical industrial disposal is only now reaching deeper supply wells. Therefore, monitoring data must be interpreted in light of lag times. A low nitrate concentration today does not necessarily mean a low future risk if the catchment has accumulated nitrogen and hydraulic travel times are long. This “legacy contamination” problem is one reason why groundwater policy requires a long planning horizon (Abascal et al., 2022; Xie et al., 2023).

Pumping changes contaminant behavior in ways practitioners often underestimate. Heavy abstraction can induce vertical leakage, capture contaminated plumes, cause seawater intrusion in coastal aquifers, and alter the oxidation state of aquifer materials. In some arsenic-prone regions, pumping changes residence time and geochemical gradients; in coastal settings, over-pumping can

reverse freshwater heads and pull saline water inland. Pumping can also create inter-aquifer transfer through defective well construction, effectively turning wells into conduits for contamination. The governance implication is straightforward: groundwater quality cannot be managed separately from groundwater quantity. Allocation decisions, irrigation pumping, and urban wellfield design can create or worsen contamination risk even when no new pollutant sources are added (UNESCO, 2022).

Subsurface heterogeneity further complicates monitoring. Contaminant concentration at one well is not automatically representative of the surrounding aquifer. Small-scale heterogeneity in lithology, redox state, fracture connectivity, or recharge can generate sharp concentration differences between neighboring wells. A monitoring network that is too sparse or too shallow may therefore underestimate risk. This is particularly problematic for contaminants that occur in localized geologic pockets or that enter through point sources such as leaking lagoons, industrial spills, or burial sites. Multi-depth monitoring, well-construction data, and hydro stratigraphic interpretation are essential for defensible conclusions (Al-Hashimi et al., 2021; Ravindiran et al., 2023).

Groundwater contamination is also a temporal problem. Concentrations vary seasonally with recharge, irrigation cycles, pumping intensity, and dilution. In monsoon climates, shallow aquifers may show post-rainfall microbial pulses, while geogenic solutes may become more concentrated during dry periods when evaporation and residence time increase. Long-term trend assessment is therefore more useful than one-time sampling campaigns. The CGWB annual quality reporting approach in India reflects this logic by moving toward standardized, repeated groundwater-quality monitoring and hotspot assessment rather than one-off surveys (CGWB, 2025).

Hydrogeology determines what prevention, monitoring, and remediation will work. A management plan that ignores the local aquifer setting is unlikely to succeed. Pump-and-treat may be ineffective in strongly sorbing low-permeability formations; denitrification barriers may not suit every aquifer; blanket assumptions about “safe depth” can fail where deep aquifers are hydraulically connected to contaminated shallow units. For this reason, hydrogeologic characterization should be treated as an operational prerequisite, not a luxury add-on, in any groundwater contamination program (Table 2).

Table 1. Major groundwater contaminants, dominant sources, and principal health concerns

Contaminant / group	Typical dominant source	Main concern	Illustrative references
Arsenic	Geogenic mobilization in reducing aquifers; mining in some settings	Carcinogenicity, skin lesions, chronic systemic toxicity	Shankar et al., 2014; Mukherjee et al., 2024
Fluoride	Geogenic dissolution in alkaline, long-residence groundwater	Dental and skeletal fluorosis	WHO, 2022; Mukherjee et al., 2024; CGWB, 2025
Nitrate	Fertilizer, manure, sewage, septic leakage	Infant methaemoglobinaemia risk; broader chronic-risk concern; indicator of diffuse pollution	Abascal et al., 2022; WHO, 2022
Iron / manganese	Geogenic release under reducing conditions	Aesthetic problems, operational issues, neurological concern for Mn at elevated exposure	WHO, 2022; Xie et al., 2023
Chromium, lead, cadmium and other metals	Industry, mining, waste disposal	Neurotoxicity, carcinogenicity, renal and developmental harm	Ravindiran et al., 2023; Xie et al., 2023
Microbial pathogens	Sewage leakage, pit latrines, septic systems, manure	Acute gastrointestinal and other infectious disease risk	Bagordo et al., 2024; Natishah et al., 2025
PFAS and other emerging organics	Industrial use, landfills, wastewater, firefighting foams	Persistence, chronic low-dose exposure concern, difficult removal	McMahon et al., 2022; Tokranov et al., 2024; Roy et al., 2025
Salinity / chloride	Seawater intrusion, irrigation return flow, sewage, evaporative concentration	Taste, corrosion, soil degradation, indirect crop and livelihood impacts	UNESCO, 2022; CGWB, 2025

Table 2. Monitoring and management options by contamination context

Context	Priority monitoring focus	Immediate user protection	Longer-term management
Geogenic arsenic / fluoride hotspot	Well-specific testing, depth profiling, hydrochemistry	Alternative safe source, blending, adsorption/RO where feasible	Safe aquifer targeting, hazard zoning, long-term surveillance
Nitrate-vulnerable agricultural aquifer	Nitrate, chloride, seasonal sampling, land-use diagnostics	Alternative source for infants and high-risk households; treatment where needed	Nutrient management, irrigation efficiency, denitrification opportunities
Peri-urban sanitation stress	Microbial indicators, nitrogen species, sanitary inspection, rainfall-linked sampling	Disinfection, boil/chlorinate where applicable, advisories, source substitution	Sewer repair, septic regulation, fecal sludge management, protected wellheads
Industrial / mining plume	Contaminant-specific chemistry, plume delineation, sentinel wells	Restrict use, alternative supply, point-of-entry treatment if necessary	Source removal, containment, PRB or other site-specific remediation
Emerging contaminants / PFAS risk zone	Targeted advanced analytics, source inventory, vulnerable receptor mapping	Blending or advanced treatment, exposure advisories	Chemical stewardship, landfill and industrial controls, long-term monitoring

3. SOURCES AND MAJOR CLASSES OF GROUNDWATER CONTAMINANTS

Groundwater contaminants are commonly grouped into geogenic, agricultural, urban-sanitation, industrial-mining, and emerging categories. This classification is analytically useful, but in practice the categories often overlap. A peri-urban aquifer, for example, may contain nitrate from fertilizer, chloride from sewage, pathogens from onsite sanitation, chromium from tanneries, and fluoride from background geology. The central management challenge is therefore not merely identifying a contaminant but diagnosing the dominant source mix and pathways.

3.1 Geogenic contaminants

Geogenic contamination refers to contaminants derived primarily from aquifer materials and natural geochemical conditions rather than direct human discharge. Arsenic, fluoride, selenium, uranium, iron, manganese, salinity, and some radionuclides fall into this category. Geogenic does not mean harmless or unavoidable in policy terms. It means that the contaminant is mobilized

from natural materials by hydrochemical processes. The scientific literature on arsenic is especially mature. Reviews show that arsenic release is controlled by sediment source, iron mineralogy, redox reactions, pH, competitive ion exchange, and groundwater age, with severe human exposure documented in many deltaic and alluvial regions (Shankar et al., 2014; Herath et al., 2016; Mukherjee et al., 2024). Fluoride enrichment is associated with prolonged water-rock interaction, alkaline conditions, and dissolution or desorption from fluoride-bearing minerals. Uranium occurrence is increasingly documented in hard-rock and alluvial settings where oxidizing conditions and carbonate chemistry favor mobility (Mukherjee et al., 2024; CGWB, 2025).

India provides a clear example of the geogenic problem. Official sources identify widespread fluoride and arsenic hotspots, with localized uranium, iron, salinity, and manganese concerns. Parliament responses and CGWB reports have repeatedly noted that fluoride and arsenic contamination occur in isolated pockets across many districts and states, while other geogenic contaminants are more spatially specific (PIB, 2022; CGWB, 2014; CGWB, 2025). Similar

geogenic challenges are found in Bangladesh, Pakistan, parts of China, East Africa, and the Americas. The key point is that source control alone cannot eliminate geogenic contamination because the source is the aquifer matrix itself; therefore, prevention must focus on well siting, safe aquifer targeting, blending, alternative supply, and treatment rather than solely on surface pollution control.

3.2 Agricultural contamination

Agriculture is the dominant diffuse source of nitrate in groundwater globally. Because nitrate is highly soluble and weakly sorbed under oxic conditions, it leaches readily from fertilized fields, manure-amended soils, animal production systems, and irrigation return flows. The global review by Abascal et al. (2022) described nitrate as the most widespread anthropogenic groundwater pollutant, reflecting its mobility, persistence in oxic aquifers, and the scale of agricultural nitrogen loading. Groundwater nitrate contamination is not only a fertilizer issue. It is also shaped by cropping intensity, timing of applications, soil texture, depth to water table, irrigation method, drainage, and the mismatch between nitrogen supply and plant uptake. In intensively farmed regions, legacy nitrogen stored in soils and unsaturated zones can continue to contaminate groundwater long after best management practices are introduced.

Agriculture also contributes pesticides, veterinary pharmaceuticals, pathogens, salinity, and trace metals associated with some agrochemicals. Pesticide behavior varies markedly by compound because sorption, degradation, and leaching potential depend on molecular properties and soil conditions. Persistent compounds and degradates may move into groundwater even where the parent pesticide is no longer in widespread use. In irrigated drylands, evapoconcentration and salt return flows can increase salinity and mobilize trace elements. Livestock operations increased risk through manure storage, land application, and pathogen loading, especially where vulnerable wells are located downgradient.

3.3 Urban and sanitation-related contamination

Urban groundwater pollution is often underestimated because city water management is institutionally fragmented. Leaking sewers, septic systems, pit latrines, stormwater infiltration, landfill leachate, fuel stations, informal dumps, construction debris, and broken water pipes all interact with aquifers. A 2025 review focused on the Indian urban context highlighted that rapid and poorly planned

urbanization exposes groundwater to nitrogen species, microbial contamination, heavy metals, chlorides, organic pollutants, and emerging contaminants, especially where onsite sanitation and waste management lag behind built-up expansion (Sridhar & Parimalarenganayaki, 2025). These risks are amplified in dense settlements where groundwater is shallow and private borewells are common.

Sanitation-related contamination is not limited to conventional sewer failure. In many low- and middle-income settings the main sources are onsite systems, open drains, wastewater ponds, and fecal contamination from human or animal waste entering the recharge zone. Microbial pollution is a major concern because contaminated groundwater may be consumed without disinfection. Field-scale synthesis shows that proximity to sanitation systems, rainfall events, aquifer vulnerability, and well construction quality are recurrent determinants of microbial contamination (Bagordo et al., 2024). This is operationally important because microbiological contamination can fluctuate rapidly and may be missed by infrequent sampling.

3.4 Industrial and mining contamination

Industrial activities create some of the most toxic groundwater contamination problems because releases may involve solvents, hydrocarbons, acids, dyes, heavy metals, cyanide, chlorinated compounds, and other persistent mixtures. Typical sources include lagoons, unlined waste dumps, industrial estates, chemical storage, accidental spills, ash ponds, metal finishing, tanning, electroplating, petrochemical operations, and pharmaceutical manufacturing. In mining districts, acid mine drainage and oxidation of sulfide-bearing wastes can mobilize iron, sulfate, arsenic, lead, cadmium, and other metals. The resulting plumes may remain active for long periods if source zones are not removed. Compared with diffuse nitrate contamination, industrial plumes often demand site-specific hydrogeologic delineation and containment.

The risk is not confined to large formal industry. Small and medium enterprises in peri-urban areas may lack proper effluent treatment or secure disposal, leading to cumulative aquifer stress. Informal recycling clusters and artisanal processing can also be important sources of metals and organic chemicals. Reviews of groundwater contamination management consistently note that industrial pollution is difficult to reverse once dense non-aqueous or strongly sorbing pollutants enter the

subsurface, which is why source removal and strict pre-release controls are far more cost-effective than downstream remediation (Al-Hashimi et al., 2021; Ravindiran et al., 2023).

3.5 Emerging contaminants

Emerging contaminants include PFAS, pharmaceuticals and personal care products, endocrine-disrupting compounds, microplastics, disinfection by-product precursors, and other chemicals that are increasingly detected but incompletely regulated. The PFAS issue is especially important because these compounds are persistent, mobile, and difficult to remove once they enter groundwater. U.S. studies have shown widespread PFAS occurrence in groundwater used for drinking-water supply, and predictive modeling suggests that the footprint of contamination at supply depths may continue to expand as contaminated recharge migrates through aquifer systems (McMahon et al., 2022; Tokranov et al., 2024). More recent review literature has expanded attention to PFAS in drinking water generally, emphasizing persistence, mixture

complexity, and regulatory transition (Al-Maqtari et al., 2025).

Emerging contaminants matter for three reasons. First, they challenge conventional monitoring because many standard groundwater programs were designed for nitrate, metals, salinity, and coliforms, not trace organic chemicals. Second, they often co-occur with legacy pollutants, complicating risk interpretation. Third, some removal technologies that work for pathogens or metals are ineffective for persistent organics. Reviews on groundwater emerging contaminants indicate that pharmaceuticals, personal care products, and plastic-associated pollutants are likely to grow in policy importance as analytical methods and regulatory thresholds evolve (Roy et al., 2025).

Taken together, these categories show why groundwater contamination is no longer well described by a simple dichotomy between “natural” and “human-made” pollution. Contemporary groundwater systems increasingly experience mixed loads, long lag times, and interacting exposures. Any serious monitoring or remediation program must therefore be diagnostic rather than generic.

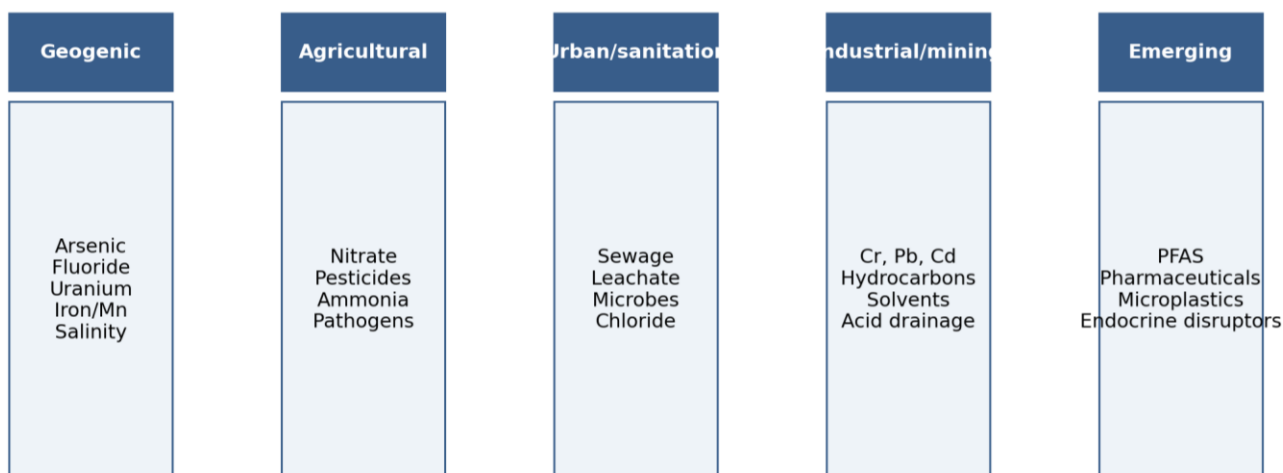


Figure 2. Major classes of groundwater contaminants and their typical source domains.

Groundwater contamination is increasingly multi-source and multi-contaminant, requiring integrated surveillance rather than contaminant-specific silos. Source: author-developed synthesis from Ravindiran et al. (2023), CGWB (2025), and Roy et al. (2025).

4. TRANSPORT, TRANSFORMATION, AND PERSISTENCE IN THE SUBSURFACE

Contaminants do not merely enter groundwater; they evolve within it. Their movement and persistence depend on physical transport,

geochemical reactions, and biological processes. Understanding these controls is essential because identical surface releases can yield very different contamination patterns depending on the aquifer environment.

Advection is the fundamental transport process: contaminants move with flowing groundwater along hydraulic gradients. Dispersion spreads the plume longitudinally and laterally, while diffusion enables movement into and out of low-permeability zones. In heterogeneous aquifers, these processes generate complex plumes rather than

smooth fronts. Preferential pathways in fractures, karst conduits, or coarse sand lenses can produce rapid transport with limited attenuation. Conversely, matrix diffusion can store contaminants in low-permeability materials and sustain long tailing even after the primary source is removed. This is one reason chlorinated-solvent sites and some industrial contamination problems remain active for years or decades after visible releases have stopped (Al-Hashimi et al., 2021).

Sorption is a major control on many inorganic and organic contaminants. Metals and metalloids may adsorb to iron oxides, clay surfaces, organic matter, or carbonate minerals, slowing migration. But sorption is not permanent. Changes in pH, ionic strength, competitive ions, or redox conditions can remobilize previously retained contaminants. Arsenic is the classic example: strong sorption under some conditions can give way to release when reductive dissolution of iron minerals occurs. Fluoride, too, is influenced by mineral equilibria and adsorption-desorption behavior. Organic contaminants vary widely: some hydrocarbons sorb modestly and biodegrade under favorable conditions, whereas PFAS exhibit persistence and complex partitioning behavior that complicates conventional assumptions about attenuation (Mukherjee et al., 2024; Tokranov et al., 2024).

Redox state is one of the most important but poorly communicated controls in groundwater contamination. Oxidation-reduction conditions determine whether nitrogen species remain as nitrate, are reduced to nitrogen gases, or are converted to ammonium. They influence the solubility of iron and manganese, the release of arsenic, the precipitation of sulfides, and the degradation potential for many organic contaminants. Aquifer redox evolution is shaped by recharge chemistry, availability of organic carbon, residence time, and microbial processes. Therefore, field measurements such as dissolved oxygen, oxidation-reduction potential, Fe, Mn, sulfate, alkalinity, and dissolved organic carbon are often more informative than contaminant concentration alone when diagnosing why a plume behaves as it does (Xie et al., 2023).

Biological transformation can reduce risk for some contaminants, but practitioners should avoid assuming that “natural attenuation” is always protective. Denitrification can lower nitrate where suitable electron donors and reducing conditions exist, yet incomplete denitrification or spatial variability may leave unsafe concentrations in supply wells. Hydrocarbon degradation can be effective

under aerobic or anaerobic conditions depending on compound class, but chlorinated solvents may form toxic intermediates during incomplete dechlorination. Microbial die-off may reduce pathogen concentrations, yet viruses and protozoa can remain problematic depending on temperature, subsurface retention, and travel times. Natural attenuation should therefore be treated as a measurable process requiring evidence, not as an optimistic default assumption.

Persistence is especially problematic in groundwater because turnover is often slow. In rivers, pollutant loads may be flushed or diluted relatively quickly. In aquifers, contaminants may remain for years, decades, or longer depending on recharge and pumping. This persistence changes the economics of management. Source control yields delayed benefits, while failure to act creates long-term liabilities. The persistence issue is particularly obvious for nitrate, arsenic exposure from longstanding well use, salinity buildup, and PFAS contamination. Once persistent contaminants are distributed through a regional aquifer, the options narrow to blending, treatment, source substitution, or very long recovery timelines (Abascal et al., 2022; McMahan et al., 2022).

Climate variability and land-use change modify transport dynamics in ways that merit more attention. Intense rainfall can mobilize pathogens and solutes through preferential pathways. Drought may increase concentration through reduced dilution and higher dependence on deeper, older groundwater. Managed aquifer recharge can improve quantity security but may also introduce contaminants if source water quality and pretreatment are inadequate. Sea-level rise and coastal pumping intensify salinity intrusion, changing density-driven flow and geochemical mixing patterns. Thus, contamination should be understood as a moving hydro-environmental target rather than a static water-quality condition (UNESCO, 2022; Ravindiran et al., 2023).

A final operational issue is that contaminant transformation can produce misleading signals if monitoring design is weak. For example, low nitrate in a reducing aquifer may be interpreted as safety even when ammonium or geogenic arsenic becomes more likely under the same conditions. Likewise, a pathogen-negative sample does not guarantee safety where episodic contamination follows rainfall. Monitoring must therefore be tailored to process understanding. This is a critical point for manuscript framing as well: groundwater contamination studies are stronger when they move beyond reporting concentration tables and instead explain the

hydrogeochemical mechanisms responsible for contaminant occurrence.

5. HUMAN HEALTH, LIVELIHOOD, AND ENVIRONMENTAL RISKS

The health significance of groundwater contamination depends on contaminant type, concentration, route of exposure, duration of exposure, user vulnerability, and whether any treatment occurs before consumption. Unlike surface-water pollution episodes that may trigger immediate alarms, groundwater exposure is often chronic. Families may consume the same contaminated well water for years, leading to cumulative health impacts that are difficult to attribute clinically without environmental testing.

Arsenic remains one of the best documented groundwater-related public-health hazards. Long-term exposure to inorganic arsenic in drinking water is associated with skin lesions, cardiovascular disease, diabetes, adverse pregnancy outcomes, and increased risks of skin, lung, bladder, and other cancers. The classic review by Shankar et al. (2014) remains foundational on prevalence and health risks, while more recent synthesis has situated arsenic within the broader category of geogenic groundwater contaminants affecting hundreds of millions of people globally (Mukherjee et al., 2024). What makes arsenic particularly dangerous is that contaminated groundwater may be colorless, tasteless, and socially normalized, especially where tube wells are otherwise perceived as safer than microbially contaminated surface water.

Fluoride is another major groundwater hazard. At low concentrations fluoride can be beneficial for dental health, but chronic high exposure through drinking water is associated with dental fluorosis and, at higher or prolonged exposure, skeletal fluorosis and associated musculoskeletal impacts. Fluoride contamination is strongly associated with hard-rock and arid to semi-arid hydrogeologic settings, where long residence times and alkaline geochemistry can enhance dissolution. The social burden is often underestimated because fluorosis is sometimes treated as a purely medical problem when in fact it is a water-supply and aquifer-governance problem. Where rural communities depend on untreated borewell water, exposure can become intergenerational.

Nitrate contamination is linked most classically to methaemoglobinaemia risk in infants, but current literature also discusses broader potential health implications and co-exposure concerns. WHO

guidelines emphasize prevention of nitrate contamination through appropriate management of agricultural practices and sanitation systems, especially for private wells and small supplies (WHO, 2022). The key management point is that nitrate often signals broader pollution pressure. A nitrate-affected aquifer may also be vulnerable to pathogens, salinity, or agrochemical residues. Chronic health risk assessments in regional studies increasingly show that children are more vulnerable than adults because of higher intake relative to body mass and developmental sensitivity (Abascal et al., 2022).

Heavy metals and trace elements such as chromium, lead, cadmium, manganese, and uranium create additional concern. Health effects range from neurotoxicity and kidney damage to carcinogenicity and developmental harm, depending on the contaminant and oxidation state. For chromium, for example, speciation matters because Cr(VI) is significantly more toxic and mobile than Cr(III). Risk-assessment studies from mining, industrial, and landfill-affected regions repeatedly demonstrate that children tend to face higher non-carcinogenic risk indices than adults for the same water source because of body-weight normalization. This is one reason why health-risk sections in groundwater manuscripts should avoid simplistic statements that a water source is “safe” merely because an aggregated water quality index seems acceptable (Xie et al., 2023).

Microbial contamination poses a more immediate but highly variable risk. Fecal bacteria, enteric viruses, protozoa, and related indicators may enter groundwater from sanitation systems, wastewater irrigation, leaking sewers, or manure applications. Even where the hydrogeologic setting provides some attenuation, intense rainfall or preferential flow can trigger contamination events. Systematic review evidence indicates that microbial contamination is strongly influenced by sanitation density, well protection, aquifer vulnerability, and rainfall conditions (Bagordo et al., 2024). The public-health implication is substantial for small and decentralized supplies because households often consume groundwater without disinfection, assuming that subsurface filtration ensures safety.

Emerging contaminants add a layer of uncertainty and policy difficulty. PFAS are associated with immune, developmental, metabolic, and other health concerns, and their persistence means that even low-level chronic exposure can become a regulatory concern. Pharmaceuticals and endocrine-disrupting compounds raise questions about long-term low-dose and mixture effects, especially where wastewater

reuse or sanitation leakage contributes to recharge. The science is evolving, but uncertainty is not a justification for inaction. In environmental-health terms, persistent and mobile contaminants with long aquifer residence times warrant precautionary monitoring and source control even before every toxicological question is resolved (McMahon et al., 2022; Al-Maqtari et al., 2025; Roy et al., 2025).

Livelihood impacts are also significant. Contaminated groundwater affects irrigation quality, soil salinity, crop choice, livestock health, and labor productivity. Farmers using saline or nitrate-rich groundwater may face declining soil quality or indirect contamination concerns. Communities depending on untreated groundwater often incur hidden costs through illness, reduced work capacity, medical expenditure, and time spent sourcing alternative water. Environmental risks extend beyond humans: contaminated baseflow can affect connected rivers, springs, wetlands, and groundwater-dependent ecosystems. Thus, groundwater contamination is not only a household drinking-water issue; it is a rural-development and ecosystem issue as well (UNESCO, 2022).

An important methodological caution is that risk assessment should not be reduced to deterministic hazard quotients alone. Real-world risk depends on exposure variability, well switching behavior, treatment use, cumulative contaminant mixtures, and socio-economic vulnerability. A contaminant concentration slightly below a guideline value is not necessarily risk-free if users are exposed to multiple contaminants or if monitoring is infrequent. Conversely, a contaminated aquifer may pose lower actual risk where reliable treatment and source substitution are already in place. Good groundwater scholarship therefore distinguishes hazard from realized exposure and recognizes uncertainty explicitly.

6. MONITORING, ASSESSMENT, AND INTERPRETATION

Monitoring is the operational backbone of groundwater contamination management, yet it is often the weakest component in practice. Many jurisdictions rely on infrequent sampling, a small number of public wells, and limited analyte lists. This creates a misleading sense of security, especially where private wells, seasonal variability, or contaminant heterogeneity are substantial. A technically credible monitoring system should answer four questions: what contaminants are present, where

they occur, how concentrations change over time, and which users are exposed.

Sampling design is more important than many published studies acknowledge. A single sample from a single well is almost never enough to characterize an aquifer. Monitoring design should consider well depth, screen interval, aquifer unit, land use, hydrogeologic vulnerability, and potential upgradient sources. Sentinel wells in recharge areas can provide early warning, while nested or multi-depth wells help distinguish shallow contamination from deeper supply risk. Standard field measurements such as pH, electrical conductivity, temperature, dissolved oxygen, and redox indicators should accompany laboratory analyses because they provide essential context for interpreting contaminant mobility. Without hydrochemical context, concentration data can become a descriptive list rather than an explanatory assessment (Xie et al., 2023; Ravindiran et al., 2023).

Parameters must be matched to the contamination hypothesis. In agricultural settings, nitrate, ammonium, chloride, pesticides, and isotopic tools may be appropriate. In geogenic zones, arsenic, fluoride, iron, manganese, uranium, major ions, and redox indicators matter more. In peri-urban environments, microbial indicators, chloride, nitrogen species, emerging organic contaminants, and selected heavy metals may be necessary. Industrial areas may require volatile organic compounds, solvents, hydrocarbons, chromium, lead, cadmium, or contaminant-specific panels. One of the most common mistakes in groundwater-quality reporting is to apply a generic suite to every setting regardless of source logic.

Water quality indices are widely used because they condense many variables into a single number. They are useful for broad communication and mapping, but they have limitations. Aggregation can obscure the fact that one toxic contaminant dominates health risk even if the overall index suggests acceptable quality. Indices also depend heavily on variable selection, weighting, and the standard used for comparison. Therefore, a water quality index should not replace contaminant-specific interpretation, especially for arsenic, fluoride, PFAS, pathogens, or carcinogenic metals. A manuscript that relies on indices without discussing contaminants of primary concern is often scientifically weak.

Health risk assessment has become standard in many regional groundwater studies, usually through deterministic non-carcinogenic hazard quotients and carcinogenic risk estimates. These tools

are useful, but they are frequently misapplied. Assumptions about water intake, exposure duration, body weight, and contaminant speciation are often copied without local justification. Children's vulnerability is sometimes acknowledged but not operationalized in discussion. More robust assessment can incorporate uncertainty, mixture considerations, and separate scenarios for households using untreated groundwater versus treated or blended supplies. The best studies also distinguish ingestion from dermal exposure realistically rather than mechanically calculating every pathway regardless of relevance.

Microbial assessment requires additional care because contamination can be episodic and indicator organisms may not fully represent viral or protozoan risk. Reviews recommend integrating sanitary inspection, rainfall context, well-construction assessment, and repeated sampling rather than relying only on a one-time coliform result (Bagordo et al., 2024; Natishah et al., 2025). For decentralized rural systems, simple field risk screening combined with periodic laboratory confirmation can be more useful than complex but unsustainable surveillance designs. Emerging-contaminant monitoring is constrained by cost, analytical sensitivity, and regulatory uncertainty. PFAS measurement, for instance, requires specialized methods and careful attention to sample handling to avoid contamination. Yet the growing evidence base suggests that groundwater programs designed only around conventional parameters are increasingly incomplete. A pragmatic approach is tiered monitoring: routine baseline panels for all high-use aquifers, followed by targeted advanced analytics in vulnerable industrial, peri-urban, or landfill-influenced zones.

Spatial analysis and digital tools have improved groundwater assessment. Geographic information systems, vulnerability mapping, machine learning classifiers, and geostatistical interpolation can help identify hotspots and prioritize monitoring. However, predictive tools are not a substitute for measured data. Models trained on sparse or biased well datasets can produce false confidence. Tokranov et al. (2024), for example, show the value of predictive modeling for PFAS occurrence, but such models remain dependent on high-quality observed data. The correct use of predictive analytics in groundwater contamination is therefore as a decision-support layer, not as a replacement for field hydrogeology and laboratory verification.

Interpretation should be action-oriented. Monitoring data should trigger decisions about public

advisories, retesting frequency, treatment needs, well replacement, source investigation, or remediation. Too many groundwater-quality reports end with maps and statistics but no operational pathway. A stronger monitoring framework ties thresholds to management response: for example, repeat sampling after extreme rainfall, immediate confirmatory analysis when arsenic exceeds a trigger, sanitary inspection where microbial indicators are positive, or source tracing when nitrate and chloride rise together. In short, groundwater monitoring is valuable only when it is designed to support intervention rather than merely description.

7. PREVENTION, TREATMENT, AND REMEDIATION

The hierarchy of groundwater contamination management should be explicit: prevent pollutant entry wherever possible, reduce exposure quickly when contamination is detected, and remediate the aquifer or source zone where technically and economically feasible. Programs fail when they start with the hardest and most expensive step - subsurface cleanup - instead of controlling releases and protecting users.

Prevention is the most cost-effective strategy. For agricultural contamination this means nutrient budgeting, split fertilizer application, controlled-release inputs where appropriate, irrigation efficiency, lined manure storage, timing applications away from intense rainfall, and protecting high-vulnerability recharge zones. For urban and peri-urban contamination it means sewer maintenance, septic-system regulation, safe fecal sludge management, landfill leachate control, zoning around wellfields, and rigorous construction standards for wells and boreholes. For industrial contamination the essentials are stricter effluent compliance, secure chemical storage, lined waste facilities, groundwater monitoring around high-risk sites, and rapid response to spills. Prevention is not glamorous, but it determines whether an aquifer remains manageable decades later (WHO, 2022; Ravindiran et al., 2023).

Exposure reduction is the immediate priority once contaminated groundwater is identified. Options include switching to a safer source, deepening or relocating wells where hydrogeologically justified, blending with low-contaminant water, point-of-use treatment, centralized treatment, and community risk communication. The correct choice depends on contaminant type and local logistics. Arsenic and fluoride can often be addressed through adsorption, coagulation-based units, activated alumina, reverse

osmosis, or selective media, but performance depends on chemistry, maintenance, and sludge handling. Nitrate can be managed through ion exchange, reverse osmosis, biological denitrification, or source substitution, but household-scale options are not always easy to maintain. Microbial contamination requires disinfection and improved sanitary protection. PFAS and some organics may require advanced treatment such as activated carbon, ion exchange, high-pressure membranes, or other specialized systems (WHO, 2022; Al-Maqtari et al., 2025).

Aquifer remediation is technically more difficult. Pump-and-treat remains widely used for plume containment and hydraulic control, but it is often slow and expensive, especially where contaminants are strongly sorbed, present in low-permeability matrices, or continuously re-released from source zones. Nevertheless, pump-and-treat can still be appropriate for plume management, barrier creation, and protecting sensitive receptors when combined with source control. In situ remediation offers alternatives that may be more sustainable in certain settings. These include permeable reactive barriers, bioremediation, monitored natural attenuation where justified, in situ chemical reduction or oxidation, electrokinetic approaches in selected

media, and amendments that immobilize or transform contaminants (Al-Hashimi et al., 2021; CLU-IN, 2024).

Permeable reactive barriers (PRBs) are particularly important in the groundwater-remediation literature because they can intercept plumes passively if designed well. Zero-valent iron, activated carbon, apatite, biochar, organic substrates, and other reactive materials have been evaluated depending on contaminant type. The key constraints are hydrogeologic compatibility, hydraulic capture, media longevity, clogging risk, and performance monitoring. PRBs are not universal solutions, but they can be effective for certain metals, nitrates, chlorinated compounds, and mixed plumes when site conditions are favorable. The literature increasingly emphasizes that remediation technology choice must follow site conceptualization, not precede it.

Natural attenuation deserves a cautious but legitimate place in the management hierarchy. For petroleum hydrocarbons or nitrate in some systems, intrinsic biodegradation or denitrification can reduce contaminant mass or hazard. But the burden of proof is on the practitioner. Evidence should include trend data, geochemical indicators, plume stability, and receptor protection. Invoking natural attenuation without demonstrating these conditions is not good groundwater management; it is wishful thinking.

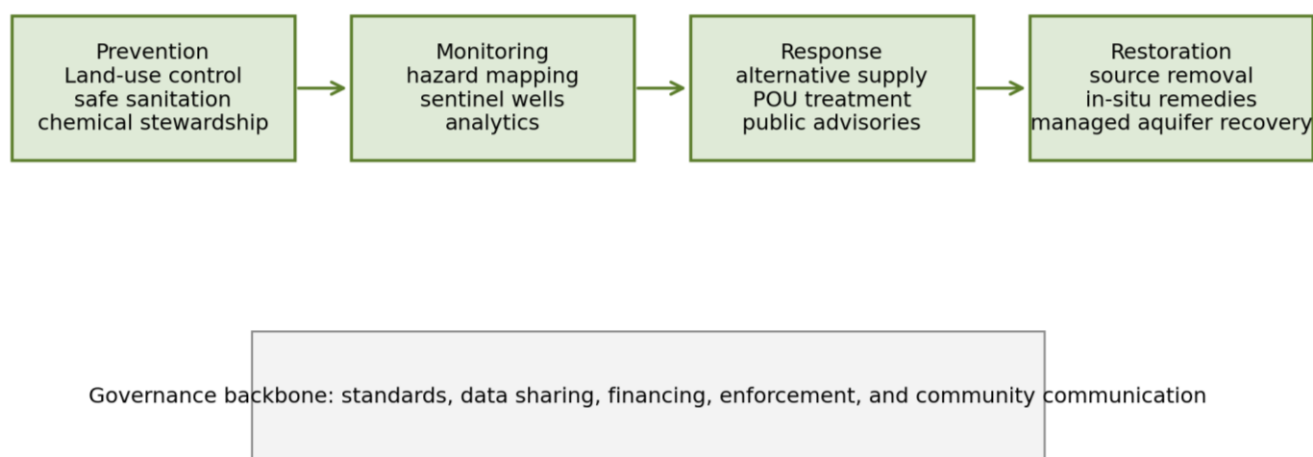


Figure 3. Multi-barrier management framework for groundwater contamination.

Managed aquifer recharge (MAR) occupies an interesting position because it can be either a solution or a new contamination pathway. Recharge with properly treated water can improve groundwater quantity, dilute salinity, and support aquifer restoration. Recharge with inadequately treated wastewater, stormwater, or surface water can introduce pathogens, nutrients, trace organics, and

clogging problems. Therefore, MAR should be considered a controlled hydrogeologic intervention that requires source-water standards, pretreatment, vadose-zone assessment, monitoring, and operational safeguards rather than a simple recharge technique.

Community-level success depends on institutions as much as on technology. Point-of-use arsenic filters fail when media replacement is

neglected. Fluoride-removal plants fail when sludge management is ignored. Centralized nitrate treatment fails where electricity, operator capacity, or revenue recovery is weak. Thus, the best remediation option is not merely the one with the highest theoretical removal efficiency; it is the one that fits the contamination type, hydrogeologic setting, maintenance capacity, and governance reality of the affected area.

A final point deserves blunt emphasis: no technology compensates for chronic regulatory failure. If industry continues releasing solvents, if sewer networks continue leaking, or if vulnerable recharge zones continue receiving unmanaged waste, treatment systems become an endless downstream subsidy for upstream negligence. The durable strategy is therefore multi-barrier management: source control, protected well design, monitoring, treatment where required, and long-term land-use governance.

A prevention-first sequence links source control, monitoring, response, and restoration, all supported by governance, financing, and communication. Source: author-developed framework based on WHO (2022), UNESCO (2022), and CLU-IN (2024).

8. POLICY, GOVERNANCE, AND THE INDIA CONTEXT

Groundwater contamination is often treated as a technical issue, but most persistent failures are institutional. The problem commonly arises from fragmented authority: one agency manages groundwater quantity, another drinking-water quality, another sanitation, another industrial regulation, and another agriculture. Contaminants move across these administrative boundaries even when budgets and accountability do not. As UNESCO (2022) argued, groundwater governance suffers globally from invisibility, weak data systems, and policy under-prioritization relative to surface water.

A governance system for groundwater contamination requires at least five elements. First, clear standards and trigger values for contaminants of concern. Second, routine and transparent monitoring across public and private supplies. Third, enforceable source-control mechanisms covering agriculture, sanitation, landfills, and industry. Fourth, risk communication that reaches users quickly and credibly. Fifth, sustained financing for both surveillance and remediation. Most underperforming systems fail not because the science is unknown but because these elements are incomplete or disconnected.

The India context illustrates both the scale of the challenge and the need for integration. Official statements and CGWB publications document the occurrence of fluoride, arsenic, nitrate, iron, heavy metals, salinity, manganese, and uranium in isolated pockets across multiple states. A 2022 government release noted fluoride contamination beyond permissible limits in isolated pockets of 370 districts across 23 states and arsenic contamination in 152 districts across 21 states (PIB, 2022). More recent national reporting indicates that nitrate remains a major concern: the Annual Ground Water Quality Report 2025 reported that 19.8% of tested samples exceeded the permissible limit for nitrate, while 9.04% exceeded the limit for fluoride and 3.1% for arsenic in the assessed sample set (CGWB, 2025). These figures matter because they show that the groundwater-quality problem is neither narrow nor static. It is multi-contaminant and still evolving.

Indian groundwater policy has historically prioritized resource development and extraction because groundwater underpins both irrigation and rural drinking-water access. That legacy has consequences. In many regions, the pressure to expand groundwater use outpaced attention to aquifer protection, wastewater management, and monitoring density. In hard-rock regions, drilling deeper was often treated as the default solution to both scarcity and quality, even though deeper abstraction can sometimes encounter fluoride, salinity, or uranium. In floodplain settings, widespread reliance on shallow tube wells reduced microbial risk compared with some surface sources but introduced geogenic arsenic exposure. These trade-offs show why groundwater governance cannot rely on simplistic narratives of “groundwater = safe.”

There are, however, important institutional improvements. National and state programs increasingly recognize groundwater quality as a recurring surveillance issue. The CGWB’s standardized quality monitoring and hotspot assessment frameworks represent movement toward a more systematic baseline and annual alerting approach (CGWB, 2025). Drinking-water programs such as Jal Jeevan Mission have expanded the policy conversation around source sustainability and safe supply, although implementation quality varies. The larger lesson is that groundwater quality improvement requires coordination between public-health agencies, rural water-supply departments, hydrogeologists, agricultural extension systems, and pollution-control boards.

For India, five governance priorities stand out. First, map quality hazards alongside quantity stress, rather than in separate planning exercises. Over-exploited blocks with known geogenic or nitrate problems should receive targeted surveillance and risk communication. Second, integrate private and decentralized sources into monitoring systems. Many of the highest-risk users rely on household or community borewells outside formal treatment networks. Third, improve source protection around peri-urban and rural sanitation systems, especially where onsite sanitation density is high and groundwater is shallow. Fourth, establish contaminant-specific response pathways: arsenic and fluoride need different operational solutions than nitrate or microbial contamination. Fifth, build long-term public data platforms so researchers and local governments can analyze trends rather than isolated observations.

The policy literature also suggests that groundwater contamination is an equity issue. Poorer households are more likely to rely on untreated local groundwater, less able to afford testing and treatment, and more exposed to the consequences of delayed regulation. Therefore, a rights-based perspective on safe drinking water aligns closely with a prevention-first groundwater agenda. Communities should not bear the burden of discovering contamination only after health impacts accumulate.

A recurring governance mistake is to conflate “scheme coverage” with “risk reduction.” Installing pipelines, borewells, or treatment units is not enough if contaminant surveillance, maintenance, and communication are weak. Another mistake is treating contamination as purely local when the drivers are regional - for example, basin-scale fertilizer intensity, regional geology, or urban wastewater growth. Stronger governance therefore requires scale matching: local response for exposure reduction, regional planning for land use and aquifer management, and national standards and financing for sustained monitoring.

Overall, the India case demonstrates that groundwater contamination is not a marginal issue affecting a few exceptional hotspots. It is a structural water-security problem that touches public health, agriculture, environmental regulation, and rural development. Any review paper aimed at contemporary relevance should frame groundwater quality not as a technical appendix to groundwater development but as a core component of water governance itself.

9. RESEARCH GAPS AND FUTURE DIRECTIONS

Despite a large and expanding literature, several research and practice gaps continue to limit effective groundwater contamination management. The first is the persistence of contaminant-specific silos. Arsenic researchers, nitrate modelers, PFAS analysts, and microbial-risk specialists often work in parallel rather than in integrated frameworks. Yet users experience water from one well, not from disciplinary compartments. Future research should place greater emphasis on multi-contaminant exposure, cumulative risk, and decision frameworks that prioritize communities facing several overlapping hazards.

The second gap is monitoring design. Many published regional studies remain cross-sectional, based on one or two sampling rounds, and therefore weak on temporal dynamics. This limits causal interpretation and policy utility. More long-term sentinel monitoring is needed, especially across monsoon transitions, drought periods, and high-intensity recharge events. Seasonal and trend-aware monitoring is particularly important for microbial contamination, nitrate flushing, salinity shifts, and redox-sensitive geogenic contaminants. Studies that integrate hydrographs, pumping regimes, and geochemical indicators with contaminant measurements are likely to be more informative than concentration mapping alone.

Third, there is still insufficient linkage between hydrogeology and policy design. Vulnerability maps often remain academic outputs without operational integration into sanitation planning, industrial siting, fertilizer regulation, or public-health surveillance. Future work should convert vulnerability assessment into governance tools - for example, delineating no-discharge recharge zones, prioritizing testing in shallow alluvial settings, or linking agricultural advisories to nitrate-vulnerable aquifers. This requires more collaboration between hydrogeologists, environmental-health researchers, and policy implementers.

Fourth, emerging contaminants need stronger groundwater-focused evidence outside a few well-studied countries. PFAS, pharmaceuticals, and microplastics are increasingly discussed in review literature, but routine groundwater monitoring in many regions remains limited. There is a risk that regulatory systems will repeat the historical pattern seen with arsenic and nitrate: exposure occurring for years before surveillance catches up. A preventive stance would expand targeted monitoring in industrial corridors, peri-urban recharge zones,

landfill-influenced areas, and wastewater-reuse settings (McMahon et al., 2022; Roy et al., 2025).

Fifth, treatment research should pay more attention to operational durability. Too much literature still emphasizes laboratory removal efficiency without addressing media replacement, sludge disposal, energy demand, operator skill, seasonal feed-water variability, and cost recovery. For field deployment, robustness often matters more than peak removal performance under ideal conditions. Comparative evaluations should therefore include maintenance burden, resilience to power interruptions, waste generation, and acceptability to users.

Sixth, health-risk assessment needs to move beyond deterministic single-contaminant models. Future studies should account for co-exposure, uncertainty, and vulnerability gradients such as age, nutrition status, pregnancy, and socio-economic constraints on switching sources. More work is also needed on the indirect impacts of contaminated groundwater through irrigation, food systems, and ecosystem services.

Seventh, there is a communication gap. Technical groundwater reports often use language and formats inaccessible to communities or local administrators. Risk communication research should therefore address how to convey spatial uncertainty, intermittent contamination, and treatment guidance without undermining trust. The challenge is particularly acute where wells are culturally embedded and alternatives are scarce. Simply telling users a well is “unsafe” is not enough if no practical alternative exists.

Finally, climate change and groundwater contamination must be studied together rather than separately. Changing recharge regimes, drought intensification, sea-level rise, flood pulses, and temperature shifts will alter contaminant transport and exposure patterns. Managed aquifer recharge, wastewater reuse, and groundwater banking may expand under climate adaptation agendas, but these interventions require strong water-quality safeguards. Future groundwater research should therefore evaluate not only contamination status but contamination futures under changing hydrologic and land-use conditions.

In synthesis, the next generation of groundwater contamination research should be more integrated, more time-aware, and more decision-oriented. The goal should not merely be to describe contaminated aquifers better. It should be to reduce

exposure faster and protect aquifers before contamination becomes entrenched.

10. CONCLUSION

Groundwater contamination is a slow-moving but high-consequence threat to water security. It undermines the reliability of the world's largest accessible freshwater reserve and directly affects health, agriculture, ecosystem integrity, and social equity. The evidence reviewed here shows that contamination arises from a combination of geogenic conditions, agricultural intensification, urban sanitation failures, industrial releases, mining impacts, and emerging contaminants whose regulation is still evolving. Because aquifers respond slowly and heterogeneously, contamination can persist for years or decades and remain invisible until exposure is already widespread. Three conclusions are especially important. First, groundwater quality must be managed together with groundwater quantity. Pumping, recharge alteration, and land-use change influence contamination just as strongly as pollutant loading does. Second, prevention is more effective and cheaper than restoration. Once contaminants are distributed through an aquifer, technical options narrow and social costs escalate. Third, groundwater contamination is increasingly a multi-contaminant governance problem, not a sequence of isolated chemical incidents. This requires integrated monitoring, source control, hydrogeologic characterization, targeted treatment, and transparent communication. The defensible strategy is a multi-barrier approach: protect recharge zones, regulate pollutant sources, monitor systematically, respond rapidly when thresholds are exceeded, and restore aquifers where feasible using site-specific remediation. For scholarship, stronger papers are those that connect concentration data to process understanding, exposure pathways, and realistic management implications rather than presenting groundwater quality as a static descriptive dataset. Groundwater protection should be treated as essential public infrastructure. Safe aquifers do not persist by accident. They persist when societies invest in prevention, science, institutions, and accountability.

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