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# Human Health Risk Assessment of Heavy Metal Contaminated Groundwater: Implications for Drinking Water Treatment and Policy Design

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# تقييم مخاطر تلوث المياه الجوفية بالمعادن الثقيلة على صحة الإنسان: الآثار المترتبة على معالجة مياه الشرب وتصميم السياسات

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## Abstract

Groundwater provides drinking water to billions of people around the world. However, in many areas, the resource is quietly poisoned. Heavy metals such as arsenic (As), lead (Pb), cadmium (Cd), chromium (Cr), and mercury (Hg) enter water bodies through natural geological weather, mining operations, industrial emissions, and unregulated agricultural inputs. The consequences are severe and often irreversible. This paper provides a systematic assessment of the human health risks (HHRA) of groundwater contaminated with heavy metals, using the U.S. Environmental Protection Agency's (USEPA) four-step framework as a methodology. We evaluate carcinogenic and non-carcinogenic risks through food, urine absorption, and respiratory tracts. Based on field studies and experimental datasets from South Asia, Sub-Saharan Africa, and Southeast Asia, the analysis shows that hazard ratio (HQ) and cancer risk (CR) values in affected communities are routinely above acceptable ranges. We evaluate the performance of traditional and modern drinking water treatment techniques such as freezing, absorption, membrane filtration, and electrocogulation, especially in terms of extraction efficiency, cost, and contextual application. Finally, we examine the governance landscape related to groundwater quality and identify critical gaps in monitoring, regulation, and justice. Six evidence-based policy recommendations have been made to bridge the gap between scientific knowledge and preventive measures. The findings confirm that heavy metal contamination in drinking water is not just a technical challenge but a profound structural and ethical challenge, requiring an urgent and coordinated response from governments, engineers, scientists, and communities.

**Keywords:** Groundwater Contamination, Heavy Metals, Human Health Risk Assessment, Arsenic, Lead, Cadmium, Chromium, Drinking Water Treatment, USEPA Framework, Risk of Causing Cancer, Risk Scale, Water Policy.

## الملخص

تُعد المياه الجوفية مصدرًا رئيسيًا لمياه الشرب لمليارات الأشخاص حول العالم. غير أنّ هذا المورد يتعرض في كثير من المناطق لتلوث صامت وخطير. إذ تدخل المعادن الثقيلة، مثل الزرنيخ(As) ، والرصاص(Pb) ، والكادميوم(Cd) ، والكروم(Cr) ، والزئبق (Hg)، إلى المسطحات والموارد المائية عبر عدة مصادر، من بينها التجوية الجيولوجية الطبيعية، وأنشطة التعدين، والانبعاثات الصناعية، والاستخدام غير المنظم للمدخلات الزراعية. وتترتب على هذا التلوث آثار صحية وبيئية جسيمة، غالبًا ما تكون طويلة الأمد أو غير قابلة للعكس.

تقدم هذه الورقة تقييمًا منهجيًا لمخاطر صحة الإنسان الناتجة عن تلوث المياه الجوفية بالمعادن الثقيلة، وذلك بالاعتماد على الإطار المنهجي ذي الخطوات الأربع لوكالة حماية البيئة الأمريكية (USEPA). كما تقيّم الدراسة المخاطر السرطانية وغير السرطانية من خلال مسارات التعرض الرئيسة، وهي: الابتلاع، والامتصاص الجلدي، والاستنشاق.

واستنادًا إلى دراسات ميدانية ومجموعات بيانات تجريبية من جنوب آسيا، وأفريقيا جنوب الصحراء الكبرى، وجنوب شرق آسيا، تُظهر نتائج التحليل أنّ قيم معامل الخطورة (HQ) ومخاطر الإصابة بالسرطان (CR) في المجتمعات المتأثرة غالبًا ما تتجاوز الحدود المقبولة. كما تقيّم الورقة كفاءة تقنيات معالجة مياه الشرب التقليدية والحديثة، مثل التجميد، والامتزاز، والترشيح الغشائي، والتخثير الكهربي، وذلك من حيث كفاءة إزالة الملوثات، والتكلفة، ومدى ملاءمة التطبيق في السياقات المختلفة.

وأخيرًا، تبحث الدراسة في الإطار الحوكمي المرتبط بجودة المياه الجوفية، وتحدد الفجوات الحرجة في مجالات الرصد، والتنظيم، والعدالة البيئية. وبناءً على الأدلة المتاحة، تقترح الورقة ست توصيات سياسية تهدف إلى سد الفجوة بين المعرفة العلمية والإجراءات الوقائية. وتؤكد النتائج أنّ تلوث مياه الشرب بالمعادن الثقيلة لا يمثل تحديًا تقنيًا فحسب، بل يشكل أيضًا تحديًا بنيويًا وأخلاقيًا عميقًا، يتطلب استجابة عاجلة ومنسقة من الحكومات، والمهندسين، والعلماء، والمجتمعات المحلية.

**الكلمات المفتاحية:** تلوث المياه الجوفية، المعادن الثقيلة، تقييم المخاطر على صحة الإنسان، الزرنيخ، الرصاص، الكادميوم، الكروم، معالجة مياه الشرب، إطار عمل وكالة حماية البيئة الأمريكية، خطر الإصابة بالسرطان، مقياس المخاطر، سياسة المياه.

## 1. Introduction

Water is life. It's said so many times that its meaning is almost gone. But when you look at the data carefully it's hard to ignore the immediateness of it. About 2.5 billion people use groundwater as their primary source of drinking water (WHO, 2022 ; Lamma et al., 2018). In rural areas of Asia, Africa, and Latin America, a local tubular well or hand pump is often the only option. There is no substitute for bottled water. There is no municipal supply where to move. What comes out of the earth is what people drink.

In many places, what comes out of the ground is poisonous. Not dramatically and visually-not in any unpleasant smell or discoloration - but quietly, in the dissolved heavy metals that accumulate in the body over months and years. Arsenic causes skin lesions and cancers that appear a decade after exposure begins. The pills break the child's brain before the damage is apparent. Cadmium silently destroys kidney functions. These are not hypothetical hazards derived from laboratory animals. These are documented and measurable harms that affect millions of real people (IARC, 2012; Environmental Protection Agency (USEPA, 2023).

Human Health Risk Assessment (HHRA) is a methodology used to convert chemical contamination data into meaningful estimates of damage. When done well, it generates data (cost of risk, cancer risk estimates) that policymakers, engineers, and communities can take action on. When they are ignored, people are left exposed and no one clearly understands how serious the situation is or who is responsible for fixing it. (Lamma, 2021; Lamma & Swamy, 2015).

This paper examines the entire risk chain. The second part examines the sources and pathways of heavy metal pollution. Section 3 examines the effects of documented health. Section IV details the U.S. Environmental Protection Agency's four-stage risk assessment framework, including the hypothetical formulas and parameters used in practice. Section V presents the findings of important studies and field experiments. Section 6 examines drinking water treatment techniques (Lamma, 2021; Lamma & Swamy, 2015). Section 7 analyses the global political scenario, and Section 8 makes concrete recommendations. The global evidence is based on peer-reviewed literature and publicly available regulatory guidance. (Lamma & Swamy, 2018; Lamma et al., 2018).

The goal is to create something really useful a clear, evidence-based narrative of a serious problem, with direct consequences of how to solve it.

## 2. Sources and pathways of heavy metal contamination in groundwater

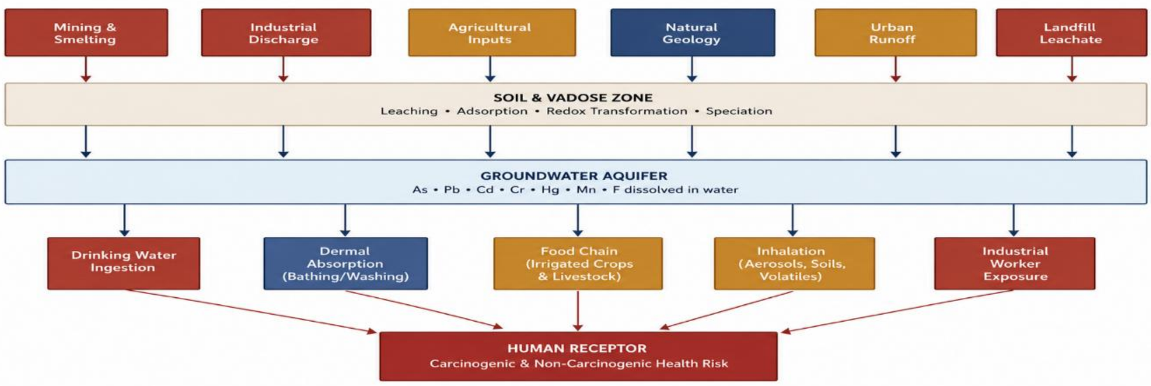


**Figure 1**: Pathways from source of heavy metal contamination to human exposure, showing geogenetic and anthropogenic impacts through the soil and vidus area, and through food, inhalation, and food chains from reservoirs to human receptors.

### 2.1 Natural geological resources

Not every pollution is man-made. In the Bengal Basin which includes Bangladesh and eastern India arsenic enters shallow aquifers through the natural dissolution of arsenic-rich iron hydroxide minerals contained in Holocene silt deposits. Under anaerobic reduction conditions arising in shallow aquifers, these minerals discharge Arnichok As(III) into groundwater. Smith et al. (2000) estimated that 35 to 77 million people in Bangladesh alone are exposed to amounts of arsenic in excess of 50 µg/L through this natural geochemical mechanism—which is the national standard. In some areas, the maximum dose exceeds 1000 µg/L, which is 100 times higher than the WHO guidance of 10 µg/L.

Fluoride, manganese and chromium also naturally enter groundwater in specific geological environments. Erosionized chromite-based supermafia rocks in groundwater systems in Greece, Cuba, and parts of India can produce amounts of Cr(VI) well above the safe limit without proximate industrial activity. This is important because it complicates the political narrative that there is a human culprit for every pollution. Sometimes, geology itself is a threat, and it requires a different kind of response, one that focuses on treating water and alternative sources rather than controlling resources.

### 2.2 Human resources

Human activities are responsible for pollution in large areas of the world. Mining is one of the most impactful sources. The acid mine emitted from the processing of sulfide mines especially in gold and copper mining produces a filter that carries out amounts of arsenic, cadmium, lead, and zinc thousands of times higher than normal background levels. Armah et al. (2010) documented widespread groundwater contamination within 30 km of active gold mines in Ghana's Oboasi region, where arsenic levels in residential wells reached 0.21 mg/L.

Industrial emissions from tanneries, electroplating facilities, battery manufacturing, and chemical plants inject chromium VI, cadmium, nickel, and mercury directly into soil and aquifers from where groundwater is recharged. In Dhaka's Hazaribagh tanning area, Ahmad et al. (2016) found total chromium levels in nearby residential wells up to 718 micrograms per litre - fourteen times higher than the World Health Organization guidelines. Agricultural inputs, especially phosphate fertilizers that are naturally contaminated with cadmium, and irrigation from contaminated surface water, provide a wide but important loading channel. Even urban plumbing infrastructure contributes to this: old lead service lines continue to leak even after the original contamination source has been resolved at $Pb^{2+}$ size.

### 2.3 Metal composition and movement

The shape of the metal in the solution its composition determines both its toxicity and its ease of extraction. Arsenic exists as Arsenite As(III) or Arsenate As(V). Arsenic is more active, more toxic, and harder to extract from conventional freezing. Chromium as Cr(III) Cr(VI) is far less dangerous, which is a proven carcinogen and easily penetrates biological membranes. Lead-specific chlorination is highly dependent on pH and carbonate chemistry; at a lower pH value that is common in acidic regions, $Pb^{2+}$ is more flexible and biovalent.

The geochemistry of soil and groundwater pH, redox potential, amount of organic matter, competing anion quantity all influence the composition of species. That's why field measurements can't be replaced by simple concentration data alone. For accurate risk assessment, it is important to know not only the amount of minerals present but also their shape.

## 3. Effects on the health of continuous exposure to heavy metals through drinking water

Before interacting with models and risk data, it's helpful to know what's actually being measured: the harm to people. The following table summarizes the critical health impacts of the six most critical minerals in groundwater, as well as the WHO guidance values.

**Table 1** Impact on the World Health Organization and Health Impacts and Values of the Drinking Water Guidelines for Critical Heavy Metals. Sources: WHO (2022), IARC (2012), and U.S. Environmental Protection Agency (2023).

| Heavy Metal | Main Track | Target Members | Health Effects | WHO guidelines (µg/L) |
|---|---|---|---|---|
| Arsenic (AS) | we swallowed | Skin, bladder, liver, lungs | Hyperkeratosis, skin cancer, bladder cancer, lung cancer, peripheral neuropathy | 10 |
| Commander (PIN) | we swallowed | Brain, kidneys, blood | Cognitive impairment in children, anemia, nephropathy — no safe surface for children | 10 |
| Cadmium (CD) | we swallowed | Kidneys, bone | Kidney tubule disorders, ET-ETI disease, bone sterilization, high blood pressure | 3 |
| Chromium Cr(VI) | Swallow + Skin | Lungs, stomach, liver | Carcinogen confirmation (IARC group 1); liver damage, gastrointestinal ulcers, dermatitis | 50 |
| Mercury (Hg) | Swallow (inorganic) | Brain, kidney | Tremors, mental retardation, kidney failure, nerve damage | 6 |
| Manganese (Minnesota) | we swallowed | Nose, Liver | Songa (movement disorder), developmental neurotoxicity in children | 400 (Tentative) |

Arsenic deserves special attention because of its high exposure to severe effects and long delays. Arsenic a clinical syndrome caused by chronic arsenic use first appears in the skin as melanosis and cornea, usually five to ten years after effects of more than 100 micrograms per liter. Cancers of the bladder, lungs, and liver continue to develop for decades. The IARC (2012) has classified inorganic arsenic as a Group I carcinogenic substance for humans based on ample evidence from human epidemiological studies and animal experiments.

Exposure to lead in young children triggers a different type of emergency. The U.S. Environmental Protection Agency and the World Health Organization now acknowledge that there is no documented safe level of lead in the blood of children. Even at pre-acceptable amounts—less than 10 µg/dL in the blood—measurable decreases in IQ and an increase in behavioral problems have been documented in large combined epidemiological studies (Lanveer et al., 2005). Children absorb five times more lead per unit of body weight than adults, and the nerve damage is mostly irreversible. It places the safety of children at the heart of any groundwater risk management framework.

Cadmium accumulates in a tube near the kidneys and damages its ability to reabsorb proteins, glucose, and amino acids. Long-term exposure leads to gradual kidney failure, and since the biological half-life of cadmium in humans is 10-30 years, the damage persists even after exposure ends. The Itai-Itai epidemic in Japan caused by cadmium contamination in rice irrigation water from a zinc mine is the most widely studied incident involving cadmium in large-scale toxic pollution, and its lessons are still directly relevant to contaminated groundwater systems today.

## 4- Human Health Risk Assessment Framework

The U.S. Environmental Protection Agency's four-stage risk assessment framework has been the global standard for assessing environmental health risks since the publication of the National Academy of Sciences' landmark report "Risk Assessment in the Federal Government" (1983). It has been continuously improved and is the systematic backbone of most national and international regulatory risk assessments. Figure 2 illustrates the four-step process.

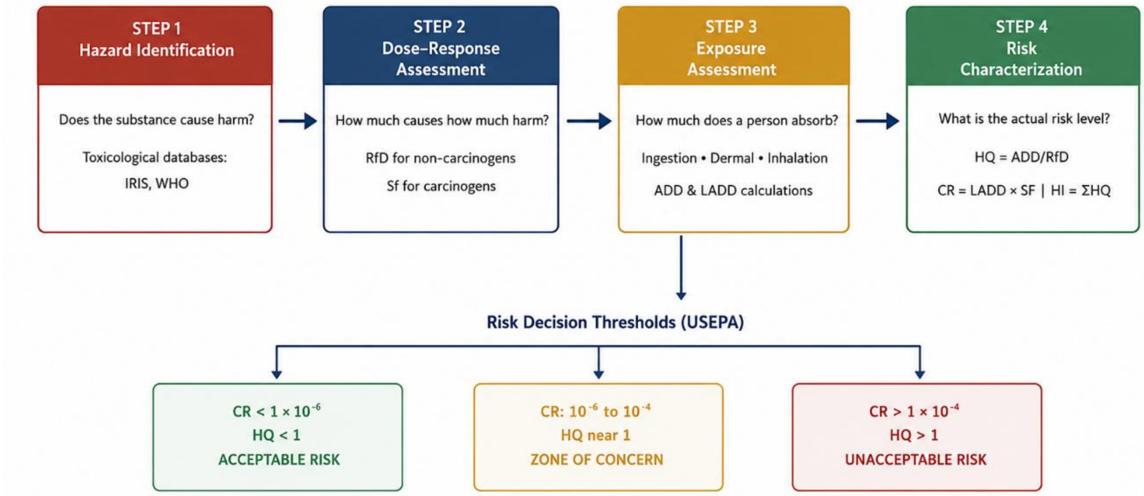


**Figure 2:** USEPA illustrates the four stages of the Human Health Risk Assessment Framework, Risk Identification, Dose-Response Assessment, Exposure Assessment, and Risk Characteristics phases with relevant decision-making limitations.

### 4.1 Identification of hazards

The first step raises a fundamental question: Does this substance cause harm? Regarding common heavy metals in groundwater, this question has been finally solved through decades of toxicology and epidemiological research. The USEPA and WHO Integrated Hazard Information System (IRIS) guidelines maintain toxicity profiles for each metal, explaining the nature of the risks carcinogenic versus non-carcinogenic and the robustness of the evidence. This step is relatively easy for the minerals discussed in this research.

### 4.2 Dosage review and response

The second stage determines how much substances a person absorbs and what the relationship is between the resulting health effects. For non-cancer-causing drugs, the reference dose (RfD) is the key parameter that is, as the level of daily intake or less, in terms of expected lifelong side effects. RfD values are expressed daily in mg/kg body weight. For carcinogenic substances, Cancer Propanesticity Factor (SF) or Cancer Strength Factor per unit indicates an increased likelihood of cancer in chronic daily amounts: units $(mg/kg/day)^{-1}$.

The main dose-response values of the U.S. Environmental Protection Agency's Rapid Arthritis Index include: liquid oral garnish = 1.5 $(mg/kg/day)^{-1}$; Oral analysis of arsenic = 0.0003 mg/kg/day; oral Cr(VI) SF = 0.5 $(mg/kg/day)^{-1}$. These values force digital outputs to fully calculate risk, so their accuracy and application are crucial.

### 4.3 Overview of the exhibition

Exposure assessment determines how much pollution a person absorbs over time. The standard model used by the U.S. Environmental Protection Agency (2011) calculates the average daily dose (ADD) of non-cancer-causing drugs and the lifetime average daily dose (LADD) of cancer-causing drugs. The general formula for food is: ADD = (C × IR × EF × ED) / (weight × AT), where C = amount of contamination in water (mg/L); IR = swallowing rate (L/day); EF = Frequency of Exposure (Day/Year); ED = Duration of Exposure (Year); Excess Weight = Body Weight (kg); AT = Average Time (Day). For early cancer risk, AT = 70 years × 365 days per year = 25,550 days, whatever the actual exposure duration, reflecting the average age tradition.

USEPA (2011) hypothetical parameter values that adults encounter in residence are: IR = 2 L/day; Overweight = 70 kg; EF = 365 days/year; ED = 30 years; AT (non-cancer) = ED × 365. For children: IR = 1 liter per day; overweight = 15 kg; EF = 350 days/year; ED = 6 years. These default defaults are intentionally conservative they are designed to protect rather than represent an individual's behavior.

The absorption of the skin is calculated separately by the specific absorption factor (AF) for each metal. For arsenic, the U.S. recommends EPA AF = 0.03 (i.e., 3% of the skin contact dose is absorbed). The breathing pattern of VPs is an analogous model that uses respiratory rate and volatile agents. In most groundwater use scenarios, the swallow path dominates total exposure, accounting for 85-95% of the total dose of most heavy metals.

### 4.4 Risk characteristics

The final step develops risk measurements by combining dose estimates with dose-response relationships. For non-cancer producer: HQ = ADD/RfD. HQ < 1 indicates an acceptable risk. HQ > 1 shows the potential for adverse health effects. When considering multiple metals or pathways, the risk index uses the following: HI = Σ HQi, and aggregates HQ values on all supporting minerals or pathways.

For carcinogenic substances: CR = LADD × SF. The acceptable risk range set by the U.S. Environmental Protection Agency ranges from $1\times10^{-6}$ (one in 1 million additional cancer cases) to $1\times10^{-4}$ (one in 10,000). Less than $1\times10^{-6}$ is generally considered unforgettable. Number above $1\times10^{-4}$ is unacceptable and requires formalization. Between these two borders, there is an area for which it is necessary to examine each case.

**Table 2:** Determination of Hazard Characteristics as a Result of Large Field Studies in Groundwater Contaminated Areas. CR = Lifetime Risk of Cancer; HI = Risk Index. Sources: Reference Studies.

| Area/Study | Metal (metal) | Concentration (µg/L) | Headquarters or Centre | Category of Danger |
|---|---|---|---|---|
| Bangladesh (Mukherjee et (al., 2006 | K | 1,000-50 | CR: $1.1\times10^{-3}$ | unacceptable |
| Ghana, Obuasi (Armah et (al., 2010 | Pb، CD، As | AS: 210; Index: 25; CD: 5 | Hello: 3.4 | unacceptable |
| India, West Bengal (Chakraborty, etc., 2016) | K | 200-10 | CR: $3.5\times10^{-4}$ | Zone of Concern |
| Vietnam, Red River Delta (Berg, etc., 2001) | K | 100-3,000 | CR: $>1\times10^{-3}$ | unacceptable |
| Pakistan, Punjab (Abid, etc., (2016 | Pb، Cr(VI) | Required Number: 18; Cr: 8 | Hello: 2.1 | unacceptable |
| Bangladesh, Dhaka (Ahmed (et al., 2016 | Cr(VI) | Up to 718 | CR: $4.9\times10^{-3}$ | unacceptable |
| China, Inner Mongolia (Guo, etc., 2014) | A، F، Mn | AS: 75 | CR: $2.8\times10^{-4}$ | Zone of Concern |

## 5. Evidence from studies and field experiments

### 5.1 Arsenic crisis in Bangladesh: the world's largest mass poisoning

The arsenic crisis in Bangladesh is, by most measures, the largest poisoning event in human history. In the 1970s and 1980s, international organizations promoted tube wells as a solution to surface water contamination and water-borne diarrhoeal diseases. The initiative worked: the death rate from diarrhoea dropped sharply. But wells in arsenic-rich holocene deposits were drilled without any chemical tests, and by the 1990s the arsenic epidemic had begun. This is invisible as it mimicked other situations and the affected communities were rural and politically marginalized.

Mukherjee et al. (2006) analyzed 3,534 groundwater samples from 24 districts and found that 51% of Bangladesh's standards exceeded 50 µg/L and 28% exceeded 100 µg/L. The risk of lifelong cancer through the EPA's swallowing model ranged from $2.6\times10^{-3}$ to $1.4\times10^{-3}$ square, both of which were significantly higher than the EPA's upper limit of $1\times10^{-4}$. These values mean that in the most affected villages, 1 in 400 to 1 in 70 residents alone increases the risk of lifelong cancer due to arsenic in drinking water. These figures are not admissible under any regulatory framework.

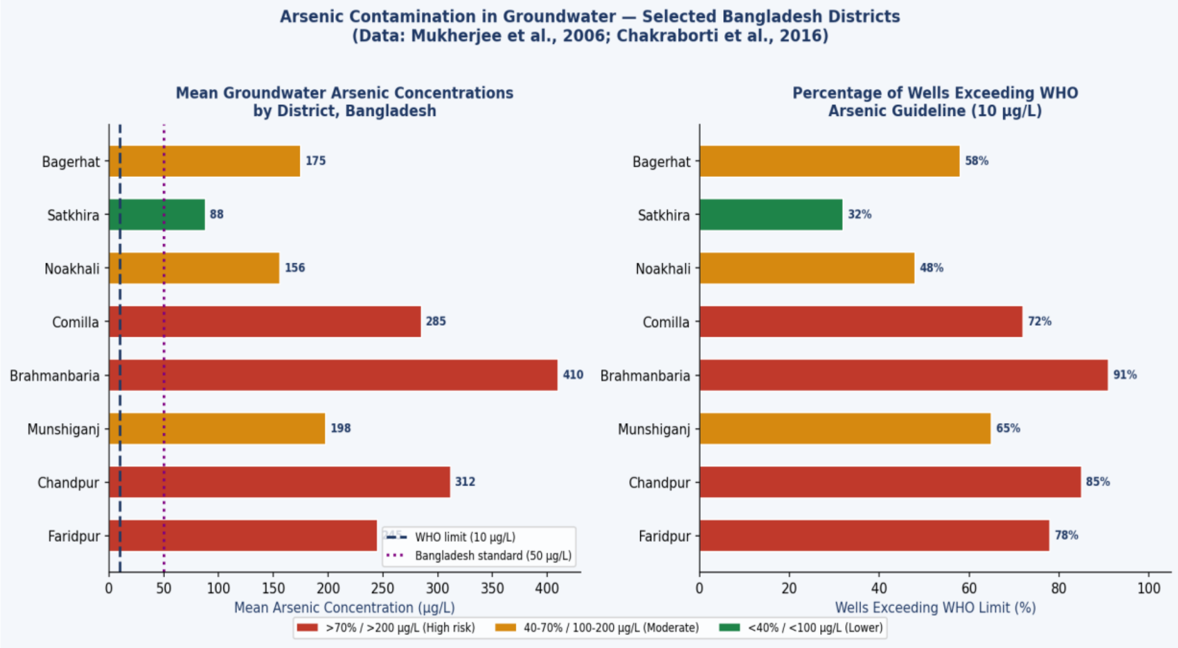


**Figure 3** Average amount of arsenic in groundwater in selected areas of Bangladesh and proportion of wells exceeding WHO guidelines (10 µg/L). The data is taken from Mukherjee et al. (2006) and Chakraborty et al. (2016).

## 5.2 Mining Affected Underground in Ghana

Armah et al. (2010) assessed a comprehensive health risk in Ghana's Oboasi gold mining area, which is one of the world's largest gold mines in terms of historical production. They took samples from 32 groundwater sites and found arsenic in some wells at a rate of 0.21 milligrams per liter 21 times higher than the World Health Organization's guidelines. Lead exceeded the WHO limit of 10 µg/L in 68% of locations, and cadmium increased by 44%. The calculated risk index for adults was 3.4, indicating that overall non-cancerogenic exposure is more than three times the safe limit.

One of the key methodologies of this study was that the skin and respiratory tract were incorporated with food. People don't just drink contaminated groundwater they bathe in it, cook with it, wash food. The authors found that increased skin pathways increased the overall risk index for adults by 12-18% and 20-25% for children under five years of age, a significant increase. Studies that ignore no-swallow routes systematically underestimate actual human contact, which can lead to risky and unpreventable risk management decisions.

## 5.3 Chromium contamination from tanneries in Bangladesh

The Hazratbagh tanning area in central Dhaka processes about 90% of Bangladesh's leather exports. Ahmed et al. (2016) measured total and hexavalent chromium in 45 groundwater samples from nearby residential areas. Of these, 34 met the WHO's total chromium guidance of more than 50 micrograms per liter. Importantly, Cr(VI) which is the carcinogenic part makes up 40-70% of the total chromium in most samples, while individual values reach 718 µg/L. The lifetime risk of additional cancer ranged from $6.8\times10^{-4}$ to $4.9\times10^{-3}$.

In this context, chromium contamination is almost entirely man-made. Tanneries discharge chromium-rich waste water into drainage pathways that recharge the shallow aquifer. The case is notable because it can legally be extended to specific industries, but enforcement of laws has been inadequate for decades. Society is at risk of cancer while the economic benefits of the leather industry are distributed elsewhere. (Lamma, Abubaker, & Lamma, 2015; Lamma, 2024)

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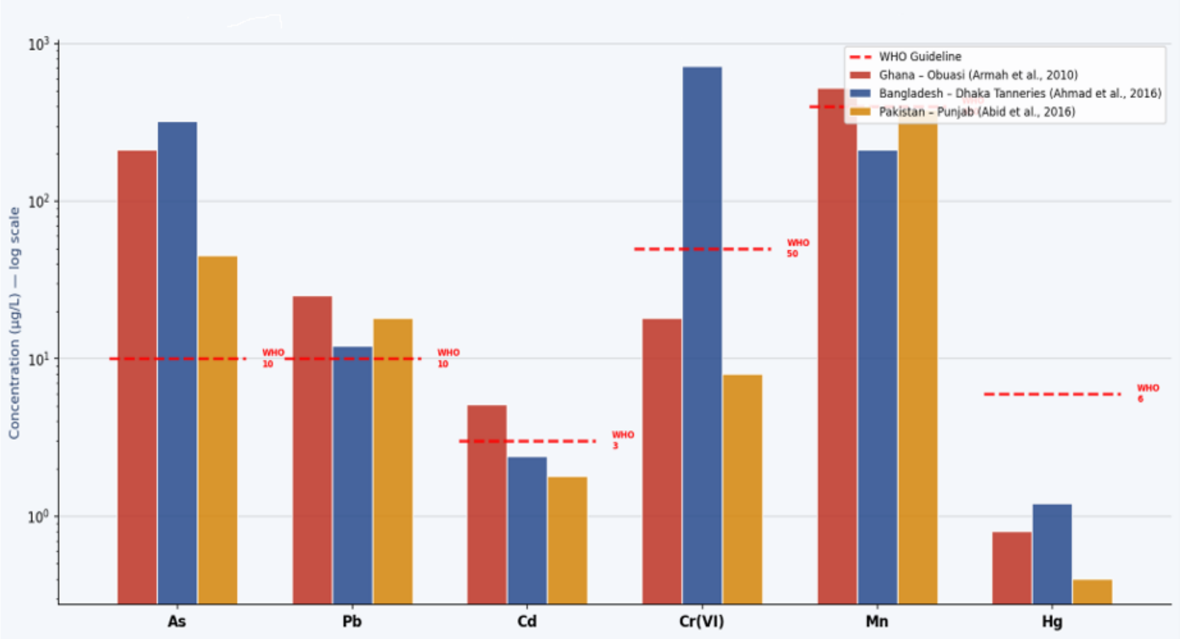


**Figure 4:** Amount of heavy metals in groundwater near industrial areas of Ghana, Bangladesh, and Pakistan, compared to the World Health Organization's (WHO) logarithmic guidelines for drinking water. Sources: Arma et al. (2010); Ahmed et al. (2016); Abid et al. (2016).

### 5.4 Exposure of lead in Pakistan's agricultural belt

Abid et al. (2016) sampled 120 groundwater wells in Punjab, the most cultivated province in Pakistan. They found lead content in 38% of wells exceeding 10 µg/L, while the maximum was 42 µg/L. Sources included pesticide residues, electroplating emissions from domestic industries, and irrigation from lead-contaminated canal water. Children under the age of five faced an average risk of 2.8 percent of lead alone nearly three times the safe limit because they were less overweight and had a relatively higher water intake per kilogram. The age-group risk classification in this study is a model on which further field studies should be followed.

### 5.5 Arsenic in Vietnam's Red River Delta

Berg et al. (2001) documented arsenic levels of up to 100-3,050 µg/L in shallow groundwater wells in Vietnam's Red River Delta, affecting water supplies for millions of people in Hanoi and surrounding areas. At the time of the study, many wells had never been tested before, and the health effects were not fully known to the population. It was one of the first large studies to highlight that arsenic contamination in Asia was geographically more widespread than ever before—not limited to Bangladesh and West Bengal, but also found in several Holocene delta systems in Southeast Asia.

## 6- Drinking Water Treatment Techniques for Heavy Metal Removal

The problem is determined by the risk assessment. Therapeutic techniques are-or are part of-practical solutions. There is no single technology that works for all metals in every context. The selection depends on the type of contamination and hybridization, initial quantity, chemistry of water matrix, available infrastructure, community size and cost. The following sections examine the key options currently available, with particular focus on what actually works in a resource-scarce environment at the community and household level.

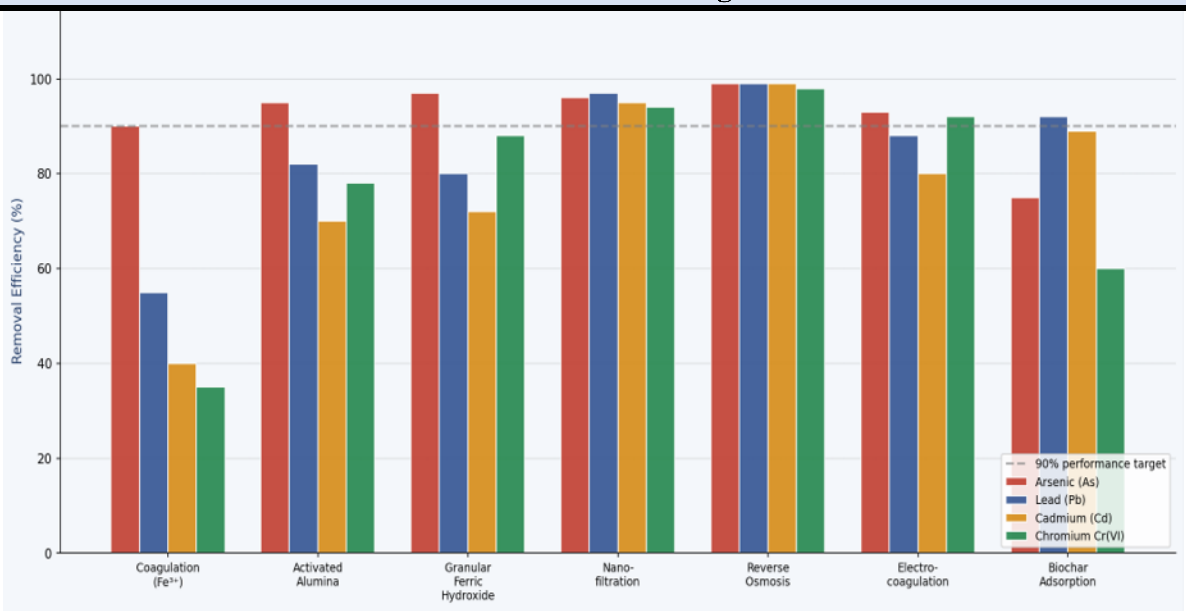


**Figure 5.** Comparison of removal efficiency (%) in seven cleaning techniques of arsenic, lead, cadmium, and chromium (VI). Shows a 90% performance target for reference. Sources: WHO (2022); Smedley & Kinneburg (2002); Mohan et al. (2014); Shi (2005). (Lamma & Krair, 2018; Zhmool et al., 2026)

### 6.1 Jammering and Yamuna

Conventional condensation by iron chloride ($FeCl_3$) or aluminum sulfate (alum) is the most widely used water treatment technology worldwide. It is effective in extracting As(V) from arsenic achieving 90-95% emission at pH 6-8 when it is absorbed into a cluster of iron hydroxide. However, the extraction of As(III) from arsenic through freezing alone is weak, usually between 40-60%, because As(III) is uncharged at pH in drinking water and is less absorbed by the freezing chemical mass. Initial oxidation by free chlorine or potassium permanganate converts As(III) to As(V) before freezing, which significantly improves overall performance (Smedley & Kinneberg, 2002). Extraction of lead and cadmium through condensation varies and is generally reduced by arsenic emissions, as these minerals are present in the form of dissolved divalant cations and not in the form of axionates.

### 6.2 Absorption-Based Therapy

Adsorption is the most researched heavy metal removal method and possibly the most versatile in point-of-use systems and local communities. Granular iron hydroxide (GFH) and activated alumina (AA) are the most proven arsenic removal mediums, with raw waste water content of less than 10 µg/L achieving effects of up to 500 µg/L in well-functioning fixed base columns. GFH has been widely implemented in South Asian community systems that are funded by NGOs and government programs.

Biochar which is produced from agricultural residues such as rice husks, sugarcane paga, and maize has emerged as a low-cost and promising absorbent source of lead, cadmium, and copper. Mohan et al. (2014) reviewed more than 100 studies and found that surface modified biochar over 300 m2/g eliminated 80-95% of $Pb^{2+}$ and $Cd^{2+}$ at pH 5-7. Their affordability and local availability make them attractive for low-income environments, although post-defunct recovery and safe disposal of consumer media are practical challenges.

### 6.3 Membrane filtration

Nanofiltration (NF) and reverse osmosis (RO) achieve the highest removal efficiency of all available metals: 95-99.9% for arsenic, lead, cadmium, and chromate. These membranes work by a combination of volume emission and charge repulsion across semi-permeable membranes. The physics is reliable. Economics is the challenge.

The energy consumption in RO requires a pressure between 7 to 40 bar as per the salinity of the feedwater. In an off-grid environment, this usually means diesel or solar power systems. Solar-powered ROs have been successfully deployed on a community scale in Bangladesh, India, and Pakistan, providing purified water at a cost of $0.05-$0.15 per liter for systems serving 50-500 households (Xie, 2005). Careful management is necessary to dispose of saline water which is a concentrated water that carries extracted minerals, so that secondary pollution does not arise.

## 6.4 Electrocoagulation

Electrocoagulation (EC) applies a direct electric current to the sacrificial iron or aluminum electrodes immersed in water, creating a mass of metal hydroxide without chemical additives. It can simultaneously remove arsenic, chromium(VI), fluoride, and lead from complex water matrix. Experimental studies in India and rural Mexico show that arsenic has been reduced from 200-800 µg/L to less than 10 µg/L, with energy consumption between 0.1-0.5 kWh/m³. EC systems are more compact than traditional coagulation plants and produce less sludge. Its main disadvantages include periodic replacement of electrodes and the sensitivity of electrical transmission of feedwater.

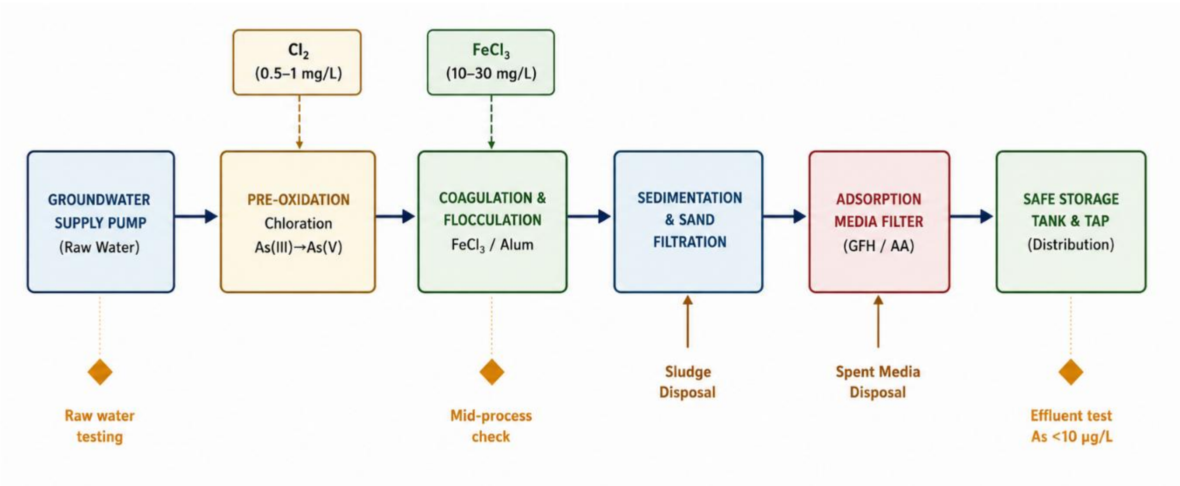


**Figure 5:** Process flow diagram of community scale arsenic and heavy metal removal treatment systems, showing pre-oxidation, coagulation slicing, sediment and filtration, and adsorption with chemical dosing points, effluent flows, and wastewater monitoring. Source: WHO (2022)

**Table 3 :** Comparison of Drinking Water Treatment Techniques for Heavy Metal Removal. Sources: WHO (2022), Smedley & Kinneburg (2002), Shi (2005), Mohan et al. (2014).

| Technology | Target Metals | Removal Performance | Estimated cost (USD/m³) | Key restrictions |
|---|---|---|---|---|
| Jim Jamney/Assembly | As(V)، Fe، Mn | (As(V)) ٪95-85 | $0.10-0.30 | Weak emission of As(III) without pre-oxidation |
| Anabolic Alumina | As، F، Pb | %99-90 | $0.15-0.40 | Chemical treatment is necessary for renewal |
| Granular Iron Hydroxide (GFH) | As، Cr، Pb | %99-95 | $0.20-0.50 | Media stuck in dirty water |
| Nano Filtration | AS، Pb، Cd، Cr | %99-95 | $0.50-$1.50 | Excessive use of energy; need for salt water management |
| Reverse osmosis | All Metals | %99.9-97 | $0.80-$2.00 | higher energy and capital costs; |
| Electrocoagulation | As، Cr(VI)، F، Pb | %98-90 | $0.12-0.45 | maintenance of electrodes; conductivity sensitivity |
| Absorption of biochar | Pb، Cd، Cu | %95-80 | $0.05-0.20 | Recycling Complex: Getting rid of used media |

## 7- Findings of Risk Characteristics through Field Studies

Figure 5 summarizes and compares the results of risk characteristics whether they are risk ratios or cancer risk values derived from the large field studies reviewed in this paper. These are real data for real communities, calculated by the USEPA framework.

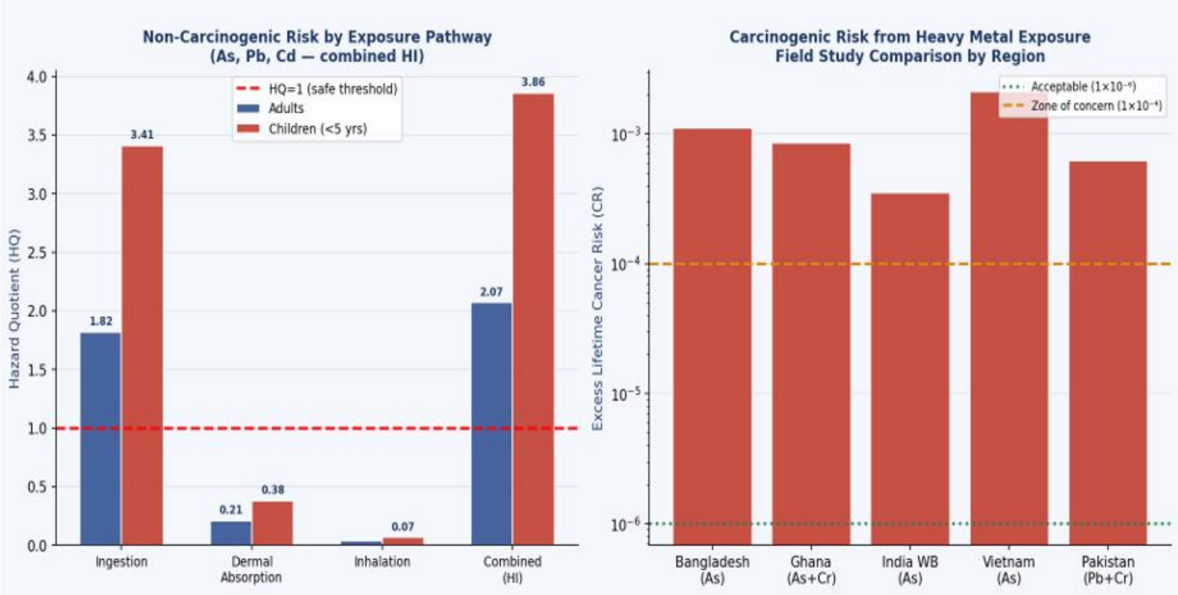


**Figure 6 Left:** Non-carcinogenic risk ratio during exposure for adults and children, including contributions of arsenic, lead, and cadmium. Right: Lifetime cancer risk by region from published field studies, showing USEPA values related to acceptable ($1\times10^{-6}$) and unacceptable ($1\times10^{4}$). Sources: Mukherjee et al. (2006), Arma et al. (2010), Chakraborty et al. (2016), Berg et al. (2001), Abid et al. (2016) (Mohammad et al., 2015; Lamma, 2020; Lamma & Sallam, 2018).

Several patterns are clearly visible. First, swallowing is the most dominant route of exposure, contributing 80-90% of the total non-cancerous risk across all study areas. Second, children consistently experience HQ and HI values 1.5 to 2.5 times higher than adults in the same household, as they are underweight and relatively high in water intake. It's not a trivial difference. The adult risk index is 2.07, which becomes 3.86 for children under the age of five, which puts them in the category of obvious anxiety.

Third, cancer risk values in the most affected areas are not slightly higher than the acceptable threshold, they are one in 1 in 1 above the upper acceptable threshold of $1\times10^{-4}$. CR $1\times10^{-3}$ means one case of appendix cancer for every 1,000 people. In a village with a population of 5,000, that means there are five more cancers due to drinking water alone. These are not statistical abstractions. They are human beings.

## 8. Political Landscape, Governance, and Regulatory Frameworks

### 8.1 International Framework

The human right to safe drinking water was recognized by the United Nations General Assembly in its resolution 64/292 in 2010. Sustainable Development Goal 6 aims to achieve global access to safe and affordable drinking water by 2030. The World Health Organization (WHO) Drinking Water Quality Guidelines (with Annexes to the 4th Edition, 2022) set international standards. These frameworks represent important qualitative promises. But it does not test a well itself nor process a litre of water. Implementation depends on the measures taken by the National Government.

### 8.2 National standards and the problem of non-conformity

The difference between international guidelines and national standards is very clear. For arsenic: The World Health Organization recommends 10 micrograms per liter. Bangladesh and India (for areas where better alternatives are not available) allow 50 µg/L a maximum of five times. The U.S. lowered the mechanical water level from 50 to 10 µg/L in 2001, affecting nearly 3,000 water systems and was one of the most important drinking water regulations in U.S. history (USEPA, 2023). The European Union has increased lead standards from 10 µg/L to 5 µg/L from 2028. These differences are not trivial, they determine how many people are considered acceptable risk. 30 µg/L Arsenic in the community is at acceptable risk as per Bangladesh standards and is in an area of concern as per WHO guidelines.

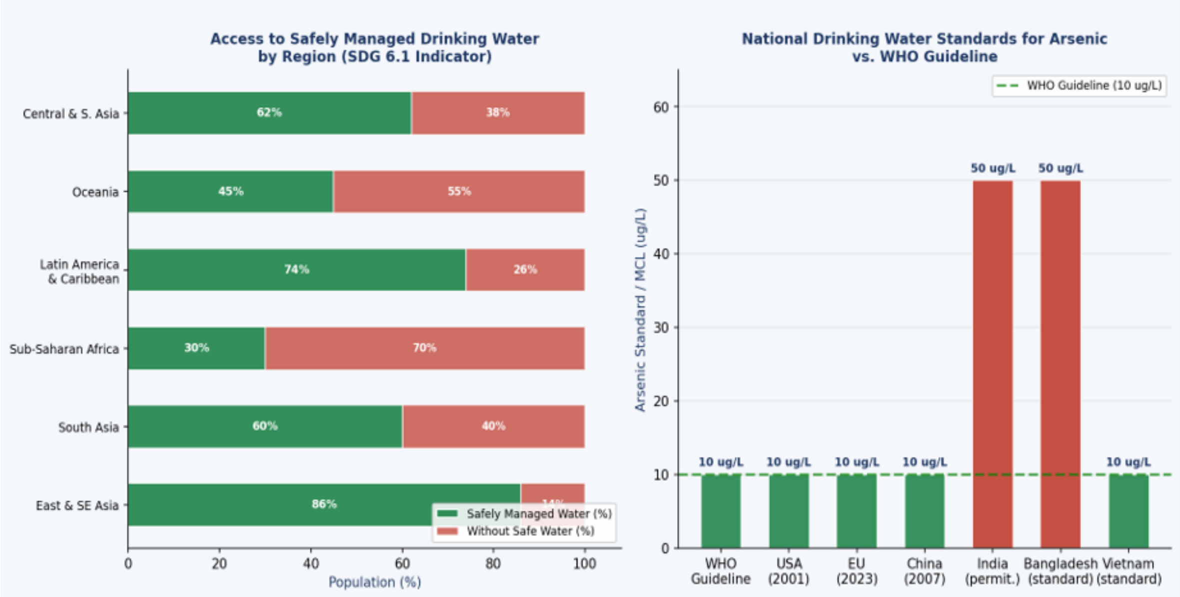


**Figure 7 Left:** Safely managed drinking water access by global region as SDG indicator 6.1 (WHO/UNICEF JMP 2023). Right: Comparison of national drinking water standards of arsenic in selected countries with WHO guidelines of 10 µg/L. Sources: WHO/UNICEF JMP (2023), USEPA (2023), WHO (2022).

### 8.3 The Problem of Surveillance Gaps and Data

Even where standards exist, oversight is often inadequate. The WHO-UNICEF Joint Monitoring Programme (2023) found that less than 55% of households in least developed countries have access to safely managed drinking water, a category that includes water quality testing as a specific component. Without oversight, these standards cannot be enforced. You can't protect people from pollution that you haven't measured. Reliable and inexpensive field test kits for arsenic (which is certified at the level of 10 µg/L), lead, and chromium, along with simple digital reporting systems, can significantly increase surveillance coverage in a resource-scarce environment. This is a solvable technical problem and largely depends on investment and political will.

### 8.4 Environmental Justice and Post-Justice Consequences

Heavy metal contamination in groundwater does not spread randomly. They congregate in poor, rural, locally or politically disadvantaged communities groups that lack the ability to defend themselves, move or buy alternative water sources. In the U.S., lead service line infrastructure is disproportionately concentrated in low-income neighborhoods and communities of color. In Bangladesh, rural households that do not lay land and have no alternative but to shallow pipe wells that bear the highest arsenic burden. This is environmental injustice in the strictest sense, the distribution of environmental damage does not match the distribution of economic benefit.

Any political framework that fails to clearly address this aspect of this justice will not be structurally able to reach those who need it most. Goodwill is not enough. All of these require clear targeting, community participation in design and monitoring, and legally enforceable accountability mechanisms.

## 9. Policy Recommendations

The following six recommendations emerge from the evidence examined in this paper. These were not impassioned statements. Each is based on documentary evidence of what works.

### 1) Adoption of Hazard-Based Water Quality Standards

National standards for heavy metals should be set based on actual carcinogenic and non-carcinogenic risk thresholds, and not just on outdated values or compliance cost arguments. According to the WHO, there should be a minimum of 10 µg/L for arsenic, and about 5 µg/L should be a clear route when access to treatment improves. For lead, any criteria above 5 µg/L are inconsistent with evidence of childhood neurotoxicity.

**2) Construction of Mandatory and Transparent Ground Water Monitoring Systems**

Every country that uses groundwater for public supply should require regular testing, the results of which should be announced in publicly accessible formats. The regulatory framework should specify test frequency, proven methods, and non-compliance outcomes.

**3) Invest in the right technology at the community and household level**

Centralized therapy works in well-funded urban systems. In rural and suburban areas, community-scale absorption units, or solar-powered electrocoagulation systems designed for local conditions and manageable by local technicians are a viable and proven option. The choice of technology should be context-based, not that which is familiar to trained engineers in a high-income environment.

**4) Application of Industrial and Agricultural Drainage Standards**

Tanneries, mines, fertilizer factories, and electroplating facilities face significant financial penalties for violations of stringent water discharge limits, third-party monitoring, and violations for heavy metals. Self-reporting systems are inadequate in an environment with weak governance capacity.

**5) Incorporating Groundwater Conservation into Spatial Planning**

Groundwater vulnerability maps should be included in the locations of industrial facilities, approval of mining licenses, and agricultural zoning decisions. Preventing contamination is a small fraction of the cost of treatment if repairs are technically feasible.

**6) Explicit Direct Investment for High-Risk and Marginalized Communities**

Risk assessment data should be used to prioritize investments, not just for risk documentation. The $1\times10^{-3}$ cancer risk in a rural community requires the same severity in the city as in the same number. Equity provisions such as support for slide indicators, community consultation requirements, and available legal remedies should be structural components of a water safety policy, not optional additions.

## 10- Debater

The picture that this paper has collected is evident in its extensive charts, even if there are uncertainties in specific figures. Heavy metal contamination in groundwater causes documented and serious harm to millions of people. The USEPA Risk Assessment Framework provides the tools to measure and describe this harm so accurately that regulatory decisions can be made. There are therapeutic methods that have the potential to reduce exposure to safe levels and have been successfully and widely used. Policy frameworks that can manage effective responses already exist in part at the national and international levels.

What is lacking is not knowledge. It is a consistent, fair and inspiring process. The disparity between the talk of science and the work of governments is the central issue in this area. To understand why this gap persists, it is important to look beyond technical factors.

There are some legitimate scientific skepticism that complicate the task. The default exposure criteria in the USEPA model may not accurately reflect actual behavior in specific communities. Children's vulnerability is not always modeled separately in a regulatory context. Mineral changes in the field keep changing according to conditions which are difficult to measure on a large scale. This uncertainty goes in the same direction: towards underestimating the real risks. This requires careful quality and careful decision-making, not deferral.

Dimensional justice is also an analytical challenge. Standard risk assessment models produce estimates of the average population. But the actual distribution of risk and risk across the population is not uniform, it is closely related to poverty, race, and political margins. Regulatory frameworks that put all residents of a geographic area at the same risk will systematically undermine those who are most vulnerable. A discrete risk assessment, with a clear focus on the most vulnerable subgroups, is a technical and ethical imperative.

One area that this paper did not discuss in detail was groundwater treatment that is, the actual cleaning of contaminated groundwater sources. It is technically difficult and economically difficult. In situ chemical depletion of chromium, lead-arsenic permeable reactive barriers, and natural vulnerability monitoring, these are active areas of research whose results are promising but do not contain comprehensive solutions. Work has been going on for decades on the treatment of polluted water bodies. The practical priority for most of the affected communities is to now have access to safe treated water, while long-term treatment continues simultaneously.

## 11- Conclusion

Heavy metal contamination in drinking groundwater is one of the biggest environmental health challenges that has not been adequately addressed in the 21st century. It is hidden from the senses, slow in its health effects, and disproportionately concentrated in communities that are unable to handle it on their own. This paper describes the complete journey from the source of pollution to health outcomes, through the U.S. Environmental Protection Agency's Risk Assessment Framework, Treatment Techniques Assessment, and Policy Analysis.

The significant results are alarming and consistent. Arsenic, lead, cadmium, chromium(VI), mercury, and manganese contaminate groundwater in large areas of South Asia, sub-Saharan Africa, and Southeast Asia in amounts that produce cancer risk values 10 to 1,000 times higher than the acceptable USEPA limit, and risk index values are two to four times higher than the safe limit. Children carry the highest burden per body weight. The most affected communities are those with the fewest alternatives and the least political voice.

Therapeutic techniques such as absorption media, coagulation, electrocoagulation, and membrane systems can reduce exposure to safe levels. It works. The question is whether investments will be made to implement them at the required scale. Ultimately, this question is more political than technical. Policy frameworks should establish standards that reflect real risks, enforce emission controls on pollutant sources, fund community-tailored treatment systems, and explicitly target the most vulnerable.

The science examined in this paper is not unclear. The necessary tools are in place to measure, solve and manage this problem. Clean water is not just a luxury for those with resources or political connections. It is the foundation of human health and dignity. We make these decisions collectively according to the standards, investments, and priorities we prioritize.

## References

1. Obaid, N., Khan, A. M., Shujaat, S., & Abbas, A. (2016). Health Risk Assessment of Heavy Metals in Groundwater in Punjab, Pakistan: A Case Study of Agricultural Areas. Environmental Pollution, 218, 1-10. https://doi.org/10.1016/j.envpol.2016.06.046
2. Ahmed, M.T., Batta, Z.A., & Islam, M.R. (2016). Assessment of Chromium Formation and Groundwater Health Risk Near Tenning Areas, Hazaribagh, Dhaka. Environmental Science and Technology, 50(14), 7419-7427. https://doi.org/10.1021/acs.est.6b00967
3. Arma, F. A., O'Brien, S. , Yaosin, D. O., Babu, A. N. M., and Bismarck, A. (2010). Mining and Heavy Metal Pollution: An Overview of the Aquatic Environment in Tarkwa (Ghana) through Multivariate Statistical Analysis. Journal of Environmental Statistics, 1(4), 1-13.
4. Berg, M. , Tran, H. S., Nguyen, T. S., Pham, H. F., Shortenloop, R. , and Geiger, V. (2001). Arsenic contamination of groundwater and drinking water in Vietnam: a human health risk. Environmental Science and Technology, 35(13), 2621-2626. https://doi.org/10.1021/es010027y

5. Bhattacharya, B., Mukherjee, A. B., Jakes, J. , and Nord Coast, S. (2007). Metal Contamination at Wood Conservation Site: Characteristics and Experimental Studies on Treatment. Macroecology, 290(1-3), 165-180. https://doi.org/10.1016/S0048-9697(01)01070-9
6. Chakraborty, D., Singh, S. K., Rahman, M. M.D., R. K., Mukherjee, S. S., Patty, S., & Carr, P. B. (2016). Arsenic Contamination in Groundwater in Ganga River Basin: Future Health Hazard. International Journal of Environmental Research and Public Health, 13(5), 478. https://doi.org/10.3390/ijerph13050478
7. Guo, H., Yang, S., Tang, X., Li, Y., & Xin, Z. (2014). Implications for the movement of arsenic in shallow reservoirs in the Hitao Basin of Inner Mongolia. Macroecology, 393(1), 131-144. https://doi.org/10.1016/j.scitotenv.2007.12.02
8. International Agency for Research on Cancer (IARC). (2012). Arsenic, Metals, Fibers, and Dust: An Overview of Human Carcinogens. IARC Studies on Carcinogenic Risk Assessment in Humans, 100C. https://monographs.iarc.who.int/wp-content/uploads/2018/06/mono100C.pdf
9. Lamma, O. A. (2024). Innovative Remediation Strategies for Tackling Groundwater Pollution: A Comparative Analysis. African Journal of Advanced Pure and Applied Sciences, 90-98.
10. LAMMA, O. A. (2023). Beneath the Surface: Unveiling the Silent Threat of Groundwater Contamination. Bani Waleed University Journal of Humanities and Applied Sciences, 8(5), 380-393.
11. Lamma, D. O. A. (2020). Study on groundwater analysis for drinking purpose in Mangalagiri Mandal regions, Andhra Pradesh, India. International Journal of Appl ied Research, 6(1), 148-153.
12. Mohammad, M. J., Krishna, P. V., Lamma, O. A., & Khan, S. (2015). Analysis of water quality seasonal variations of paler reservoir, Khammam district, Telangana, India. International Journal of Current Research in Chemistry and Pharmaceutical Sciences, 2(2), 31-43.
13. Lenoir, P. B., Horning, R. Khoury, J. , Yolton, K. , Baghrust, b. Bellinger, D. S., Canfield, R. L., Detrick, K. N., Bernshine, R. , Green, T. , and Roberts, R. (2005)- Children's low-level environmental lead exposure and mental functioning: A joint international analysis. Environmental Health Perspectives, 113(7), 894-899. https://doi.org/10.1289/ehp.7688
14. Mohan, D. Saraswat, A. , Oak, Y. S., and Pittman, C. (2008). Yu, Jr. (2014). Removal of organic and inorganic contaminants from water through biochar, a low-cost and sustainable renewable material—a critical review. Biosource Technology, 160, 191-202. https://doi.org/10.1016/j.biortech.2014.01.120
15. LAMMA, O. A., & KRAIR, S. S. A. (2018). To Study The Relation Between The Environmental law and climate change. Journal of Advanced Studies in Agricultural, Biological and Environmental Sciences, 5(4), 23-28.
16. Lamma, O. A., & Sallam, R. M. A. (2018). Analysis of water quality of Lingala Munner Krishna district, AP, India. J. Adv. Stud. Agricult. Biol. Environ. Sci, 5(3), 22-27.
17. Lamma, O. A. (2021). Waste disposal and landfill: Potential hazards and their impact on groundwater. International Journal of Geography, Geology and Environment, 3(2), 133-141.
18. Lamma, O., & Swamy, A. V. V. S. (2015). E-waste, and its future challenges in India. Int J Multidiscip Adv Res Trends, 2(I), 12-24.
19. Lamma, O., Abubaker, M., & Lamma, S. (2015). Impact of reverse osmosis on purification of water. Journal of Pharmaceutical Biology, 5(2), 108-112. 19. Lamma, O. A., AVVS, S., & Alhadad, A. A. M. (2019). A study on Isolation and purification

of Laccases from different fungal micro organisms and study the partial characterization.
20. Mukherjee, A., Bhattacharya, B., Shi, F., Freire, A. A., Mukherjee, A. B., She, Z. M., Jacques, J., & Bandishu, J. (2006). Chemical development in groundwater with high arsenic in the Hohit Basin (Inner Mongolia, China) and its difference from the West Bengal Basin (India). Applied Geochemistry, 24(10), 1835-1851. https://doi.org/10.1016/j.apgeochem.2009.06.002
21. Mohammad, M. J., Krishna, P. V., Lamma, O. A., & Khan, S. (2015). Analysis of water quality using Limnological studies of Wyra reservoir, Khammam district, Telangana, India. Int. J. Curr. Microbiol. App. Sci, 4(2), 880-895.
22. Lamma, O. A. (2021). Groundwater problems caused by irrigation with sewage effluent. International Journal for Research in Applied Sciences and Biotechnology, 8(3), 64-70.
23. Lamma, O. A., & Swamy, A. V. V. S. (2018). Assessment of ground water quality at selected industrial areas of Guntur, AP, India. Int. J. Pure App. Biosci, 6(1), 452-460.
24. Lamma, O. A., Swamy, A. V. V. S., & Subhashini, V. (2018). Ground Water Quality In The Vicinity of Industrial Locations In Guntur, AP, India. International Journal of Engineering Science Invention, 7(1), 72-80.
25. Six, MS. (2005). Evaluation of Arsenic Depletion by Pressure Driven Membrane Processes. CD desalination, 172(1), 85-97. https://doi.org/10.1016/j.desal.2004.07.031
26. Smedley, B. L., & Kenneborough, D. J. (2002). Examine the source, behavior, and distribution of arsenic in natural waters. Applied Geochemistry, 17(5), 517-568. https://doi.org/10.1016/S0883-2927(02)00018-5
27. Smith, A. H., Langas, E. (2010). (2009). O. , & Rahman, M. (2000). Arsenic contamination in drinking water in Bangladesh: a public health emergency. Bulletin of the World Health Organization, 78(9), 1093-1103.
28. U.S. Environmental Protection Agency (USEPA). (2023). National Regulations for Primary Drinking Water: Improvement in Lead and Copper Bases. Federal Register, 88(97), 84878-84949. https://www.epa.gov/dwreginfo/lead-and-copper-rule-revisions
29. World Health Organization (WHO). (2022). Drinking Water Quality Guidelines: Fourth Edition Containing First and Second Additional Materials (Fourth Edition, First and Second Supplements). World Health Organization Publishing House. https://www.who.int/publications/i/item/9789240045064
30. Joint WHO/UNICEF Surveillance Programme (JMP). (2023)- Progress in Household Drinking Water, Sanitation, and Hygiene 2000-2022: Special Focus on Gender. The United Nations Human Rights Fund and the World Health Organization. https://washdata.org/reports/jmp-2023-update-sdg6
31. Zhmool, H. S., Adel, A. S., Abdaslam, N. M., Abboub, A. D., Sallam, R. M., & Alhadad, A. A. (2026). Chemical Characteristics of Hospital Wastewater and Their Association with Antibiotic Resistance Patterns in Sabratha, Libya. Libyan Open University Journal of Applied Sciences (LOUJAS), 346-354.
32. Zhmool, H. S., Banana, A. A., Abboub, A. D., Mohamed, G. S., Sallam, R. M., & Alhadad, A. A. (2026). Microbiological and Physicochemical Assessment of Antibiotic-Resistant Bacteria in Hospital Wastewater: A Case Study from Sabratha Teaching Hospital, Libya. Libyan Open University Journal of Medical Sciences and Sustainability, 38-48.