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# AN ASSESSMENT OF WORLDWIDE SCENARIOS WITH SPECIAL REFERENCE TO INDIA ON FLUORIDE CONTAMINATION IN GROUNDWATER

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**Abstract**

A basic human right is the availability of clean drinking water, but groundwater contamination—especially from fluoride—poses a serious threat to the environment and public health worldwide. Around 200 million people worldwide are impacted by fluoride pollution that exceeds the WHO's acceptable limit of 1.5 mg/L, which has been found in over 100 nations within the last ten years. The Americas and Australia have fewer instances, whereas Africa, Asia, and Europe have the largest concentrations. Both natural processes, including the weathering of fluoride-rich rocks, and human actions, like the use of pesticides, phosphate fertilisers, and sewage sludge, can introduce fluoride into water systems. From dental and skeletal fluorosis to non-skeletal ailments including muscular weakness, anaemia, and urinary abnormalities, excessive fluoride exposure can result in major health issues. SDG 3 (Good Health and Well-Being) and SDG 6 (Clean Water and Sanitation) of the UN's Sustainable Development Goals are directly related to this problem, emphasising how urgently fluoride pollution must be addressed in order to provide everyone with access to clean drinking water by 2030.

**Keywords:** Groundwater, WHO, Dental Fluorosis, Skeleton Fluorosis, SDG Goals.

## 1. INTRODUCTION

All life on Earth depends on clean water, which has a direct influence on our quality of life. Only 10.63 million cubic kilometres of the 1386 million cubic kilometres of water on our globe are freshwater and only 30.1% of it is groundwater. Since it irrigates 70% of agricultural fields and supplies drinking water to half of the world's population, this "hidden sea" of groundwater has grown in importance.

However, these groundwater supplies are under unprecedented stress due to decreasing surface water dependence and increasing population demands. The natural cycles of several elements in groundwater have been disturbed by human activity, with fluoride and arsenic being the most common and troublesome pollutants. Because of its toxicity—even trace levels of fluoride can have negative health effects—fluoride poisoning is especially alarming. Although fluoride is necessary for human health, too much of it can be harmful [1, 2].

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A number of variables, including as ionic concentrations, rock-water interactions, atmospheric deposition, pH-based dissolution, and the presence of carbonate and bicarbonate ions, influence groundwater fluoride levels. Fluorosis, which is mostly brought on by drinking water tainted with fluoride, affects more than 200 million people in 25 nations. The primary source of exposure to fluoride is drinking water, even though it can be found in food and the air.

Figure 2 shows Fluoride contamination sources in groundwater. Beyond its physical implications, which include issues with bones and teeth, damage to muscles and nerves, and sensations like nausea and stomach pain, it also causes serious economical problems. Due to fluoride pollution, many communities have been forced to stop using certain water sources, demonstrating how this problem has expanded over the world and now affects at least 25 nations.

Even though the world's groundwater resources are diminishing, mainly in Asia, Africa, and North America, population expansion has resulted in a greater reliance on groundwater, especially in developing countries [4,5]. Figure 1 shows average percentage of Fluoride Concentration in various countries.

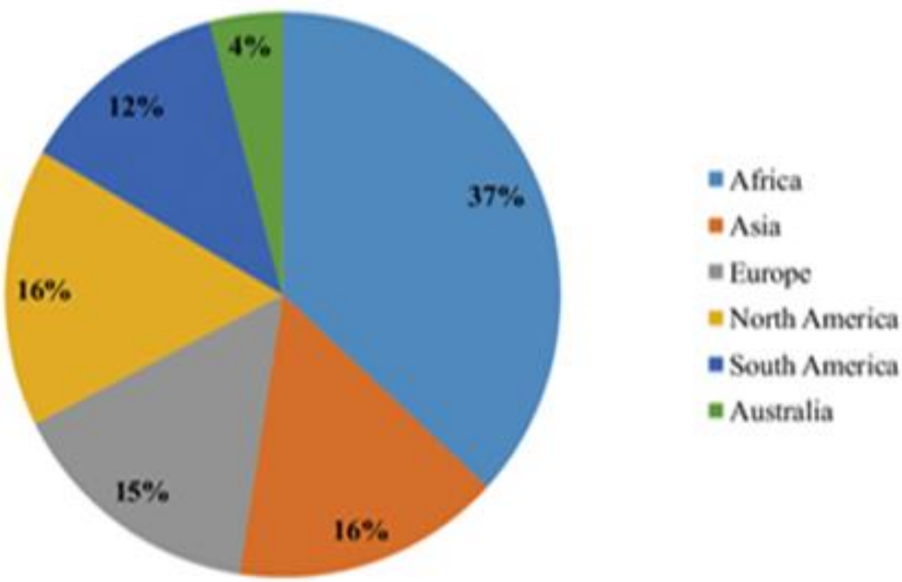


**Fig 1: Average percentage of Fluoride Concentration in various countries [31]**

Approximately 500 million people in 106 countries are impacted by fluoride pollution, and over 2.5 billion people globally rely on groundwater for drinking. Although the WHO has set a safe fluoride limit of 1.5 mg/L in drinking water, several nations—including those in Asia, Africa, and the Americas—report high fluoride levels. India, which has 14% of the world's naturally occurring fluoride, presents a very difficult problem [3, 6].

The guideline sand standards for fluoride in drinking water are presented in Table 1. Extensive groundwater extraction exacerbates the issue there by raising fluoride

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concentrations through mineral leaching and rock weathering, particularly in regions with high bicarbonate and low calcium levels. According to WHO guidelines, many water sources are unfit for drinking due to the extensive pollution, which poses serious health hazards to the local people.

## 2. FLUORIDE IN GROUNDWATER

Henri Moissan discovered fluorine in 1886. It is the ninth element on the periodic table and the thirteenth most prevalent element in the crust of the Earth, accounting for 0.32% of its mass. Its ion (F-), one of the most electronegative and reactive elements known, may readily replace hydroxide (OH-) in minerals because of its comparable charge and size.

There are three primary types of fluorine: fluorosilicic acid (H2SiF6), sometimes referred to as hexosilicic acid; moderately soluble sodium fluoride (NaF); and extremely water-soluble hydrogen fluoride (HF), which produces hydrofluoric acid.

Fluoride, a lithophile element with atmophile characteristics, is frequently found in minerals that create rocks, especially metamorphic basement rocks, alkaline volcanic rocks, and minerals such as micas, amphiboles, biotite, and clay minerals [4,6,7].

The breakdown of fluoride-rich rocks, hydrothermal spring discharge along fault lines, and late-stage hydrothermal fluids are some of the ways fluoride gets into groundwater. Table 2 exhibits the range of fluoride in different types of rocks.

**Table 1: Guidelines and standards for fluoride in drinking water [2]**

| Countries/Bodies | Value(mg/l) |
|---|---|
| World Health Organization (WHO) | 1.5 (Guideline value) |
| Australia | 1.5 (Permissible limit) |
| Bureau of Indian Standards (BIS) | 1 (Acceptable limit) |
| | 1.5 (Permissible limit) |
| Canada | 1.5 (Permissible limit) |
| European Union | 1.5 (Permissible limit |
| Ireland | 1.5 (Permissible limit) |
| Japan | 0.8 (Standard value) |
| New Zealand | 1.5 (Permissible limit) |
| Malaysia | 1.5 (Permissible limit |
| Singapore | 0.7 (Max. prescribed quantity) |
| South Korea | 1.5 (Permissible limit) |
| United States Environment Protection Agency (USEPA) | 4 (Max. contaminant level) |
| | 2 (Secondary max. contaminant level) |

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Approximately 330 mg/kg is found in soil, 0.9-1.4 mg/L in saltwater, 0.1-1.2 mg/L in groundwater, and 0.01-0.3 mg/L in surface water, depending on the environment.

Since the solubility of the primary fluoride-bearing mineral, fluorite ($CaF_2$), controls the fluoride concentration in most liquids, high fluoride concentrations are often found in waters that are rich in sodium ($Na^+$), potassium ($K^+$), chloride ($Cl^-$), and calcium ($Ca^{2+}$).

Because of increased contact and residence durations with fluoride-bearing minerals during rock-water interactions, groundwater often contains more fluoride than surface water [10,11].

**Table 2: Types of rocks and range of fluoride in the rocks [2]**

| Type of rocks | Range of fluoride(ppm) |
|---|---|
| Basalt | 20–1,060 |
| Granites and gneisses | 20–2,700 |
| Shales and clays | 10–7,600 |
| Limestones | 0–1,200 |
| Sandstones | 10–880 |
| Coal (ash) | 40–480 |

Aside from natural sources, manufacturing operations, fertiliser use, and the coal and aluminium industries are some of the anthropogenic ways that fluoride enters waterways. Under certain circumstances, fluoride mostly appears in natural waters as free fluoride ions via the complexes of Be, B, Al, and Si.

The primary determinants of the elevated fluoride content in groundwater include hydrogeochemistry, geology, geomorphology, evaporation, precipitation, and climate. Depending on the weathering and availability of leachable fluoride in rocks with comparable lithologies or climates, fluoride concentrations can occasionally vary greatly [12, 13]. The weathering and subsequent leaching of fluoride-containing minerals found in rocks and soil, such as fluorite ($CaF_2$), cryolite ($Na_3AlF_6$), fluocerite ($CeF_3$), yttrofluorite (Ca, Y) $(F, O)_2$, villianmite (NaF), sellaite ($MgF_2$), fluorapatite ($Ca_5(PO_4)_3F$), etc., as well as volcanoes, are the source of fluoride in groundwater.

Several fundamental elements impact fluoride leakage into groundwater. pH levels are important because fluoride leaching from rocks is encouraged by alkaline conditions, which are indicated by high bicarbonate levels. Fluoride concentration and total dissolved solids are positively correlated, indicating that fluoride solubility is increased by greater ionic interactions [16, 17].

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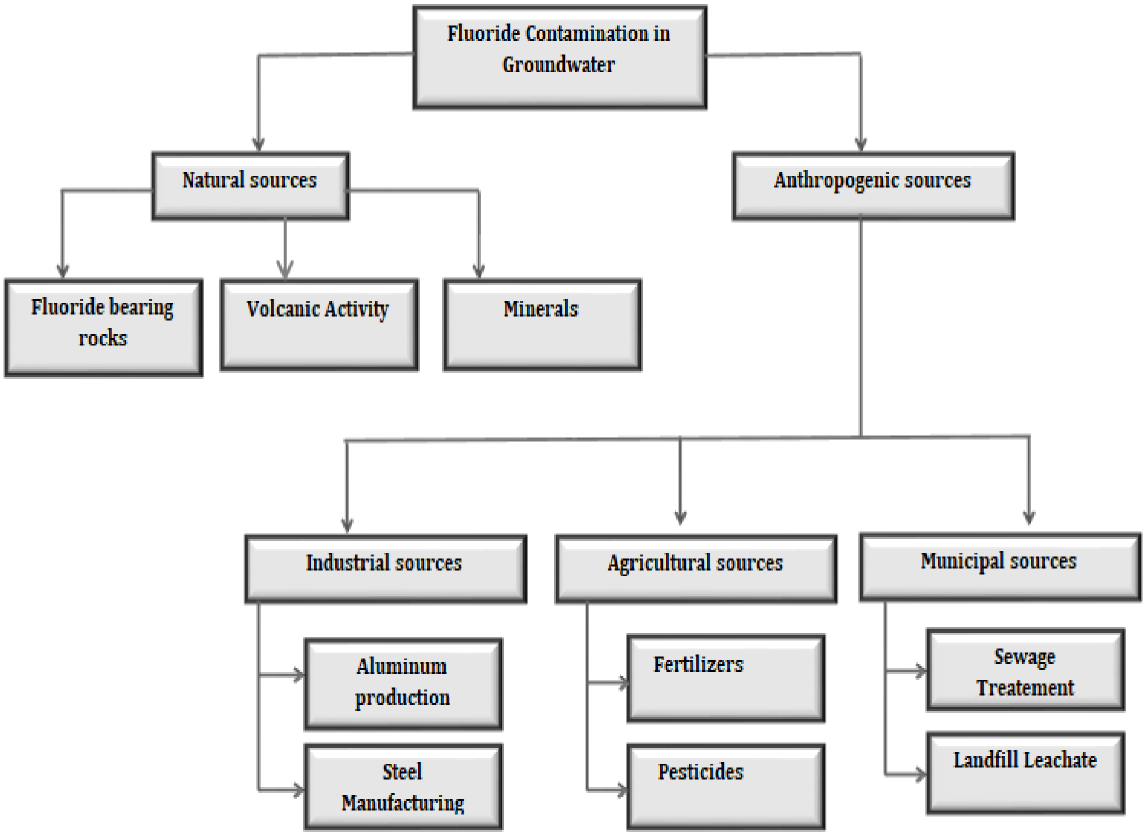


**Fig 2: Fluoride contamination source in groundwater**

Interestingly, fluoride levels are negatively correlated with calcium and positively correlated with bicarbonate. Groundwater ions are concentrated by evaporation processes, and fluoride enrichment is made possible when calcium precipitates out.

Another important factor is carbon dioxide, which produces acidic conditions that weather silicate rocks and release fluoride when CO2-enriched air combines with rainfall. Higher fluoride concentrations are usually triggered by an increase in the sodium-to-calcium ratio.

Other important factors include: (i) Clay content, which slows water movement and increases rock-water contact time (ii) Aquifer depth, though correlations exist at both deep and shallow levels (iii) Precipitation and dissolution processes (iv) Temperature and pressure conditions (v)Rock-water interactions, particularly in deep aquifers where prolonged contact occurs. Research has also identified correlations between fluoride and other elements, such as boron (as seen in Canada's Manitoba region) and chloride in various groundwater systems [3, 11,17].

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## 3. HEALTH RISK

Understanding different pollutants and the health concerns they offer has become a major public health problem, as has the quality of groundwater for drinking. A complicated story spanning more than 200 years of scientific advancements and advancements in public health is shown by the connection between fluoride and human health [18]. The finding of fluoride in an elephant's fossil tooth by Morichini in 1803, which was the first proof of fluoride's link to dental resilience, marked the beginning of fluoride's historical relevance in oral health. When dentist F. S. McKay noticed anomalous tooth colouration, referred to as "colourful teeth," among communities in the southwestern United States in the 1930s, this idea was further developed.

**Table 3: Health Effects of Fluoride Exposure**

| Fluoride Concentration (mg/L) | Exposure Category | Health Effects | Risk Level | Population Groups at Risk |
|---|---|---|---|---|
| <.5 | Deficient | Increased dental caries risk, Potential reduced bone density | Low | Children- Elderly |
| .5-1.5(WHO guideline) | optimal | - Dental caries prevention, Normal bone development | Beneficial | General population |
| 1.5-3.0 | Mild excess | Mild dental fluorosis, White spots on teeth, Slight gastrointestinal discomfort | Moderate | Children under 8 years- Pregnant women |
| 3.0-6.0 | Moderate excess | Moderate to severe dental fluorosis, Early signs of skeletal fluorosis, Joint stiffness, Gastric problems | High | Children- Elderly- People with kidney disorders- Manual labourers |
| 6.0-10.0 | Severe excess | Severe dental fluorosis, Skeletal fluorosis, Reduced mobility, Muscle fiber degeneration, Neurological effects | Very High | All age groups- Particularly vulnerable: • Malnourished individuals • Those with calcium deficiency |
| >10.0 | Critical excess | Crippling fluorosis, Severe bone deformities, Neurological damage, Kidney failure, Endocrine disruption, Possible carcinogenic effects | Critical | Entire exposed population- Severe risk for: • Children • Elderly • Immunocompromised |

This finding sparked a flurry of study to find the ideal levels of fluoride in drinking water to prevent tooth cavities. Consequently, by the early 1950s, industrialised countries had started water fluoridation programs, with a special emphasis on providing fluoride-controlled drinking water to children in order to improve their oral health. The effects of fluoride on human health exhibit a fine equilibrium [19]. Fluoride has several health

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advantages when taken in moderation, such as a lower risk of dental cavities and improved bone growth.

Fluoride has been found to enhance tooth structural stability and reduce mineral solubility, both of which promote improved dental health. However, this helpful mineral has become a major environmental worry due to the fast rate of industrialisation and population expansion, especially with relation to the quality of drinking water. The problem has gotten more difficult in modern-day India, where excessive fluoride exposure is causing serious public health issues in a number of areas. Because of high fluoride levels in their drinking water and groundwater supplies, Andhra Pradesh, Tamil Nadu, Kerala, Karnataka, Bihar, Gujarat, Rajasthan, and Punjab are facing severe fluorosis risks [1, 2, 19]**.** This pervasive pollution emphasises how important it is to implement balanced water management techniques that can preserve healthy fluoride levels while avoiding overexposure that can cause health issues. The transformation of fluoride from a dental health advantage to an environmental hazard highlights the intricate difficulties public health officials have when regulating the quality of water for sizable populations. The negative health effects of excessive fluoride exposure are a major worldwide public health issue, showing up as a number of severe medical disorders. Dental fluorosis, skeletal fluorosis, crippling fluorosis, and osteosclerosis are the main health problems linked to high fluoride consumption. In addition to these well-established ailments, fluoride exposure has been connected to effects on pineal gland health, reproductive system function, and IQ. Gastroenteritis, excessive salivation, appetite loss, muscular weakness, stiffness, restlessness, sweating, breathing problems, ventricular irregularities, and elevated heart rate are additional health issues. The health consequences of fluoride contamination in groundwater are presented in Table 3.

These health problems have been reported in Ghana, India, China, and Canada, among other nations. When fluoride concentrations in drinking water above 1.5–2 mg/L, dental fluorosis becomes a common health problem. Initial white, opaque spots on teeth give way to increasingly severe brown or black surface discolouration as the illness worsens [20,21]. Due to obvious tooth decay, dental fluorosis can cause substantial psychological discomfort for those who are affected, in addition to its medical effects. In 14 states and over 150,000 villages, dental fluorosis has become endemic in India alone. Bihar, Gujarat, Madhya Pradesh, Rajasthan, and Uttar Pradesh have the highest prevalences. When fluoride levels in drinking water exceed 4–8 mg/L, skeletal fluorosis develops, which is characterised by increased bone density, stiffness and soreness in the joints, abnormalities of the spinal column, and excessive bone growth.

There are three severity degrees for the condition: mild, moderate, and severe. While fluoride concentrations above 10 mg/L can cause debilitating fluorosis, a serious disorder that is very common in industrial settings and can damage the neurological, hepatic, and renal systems, fluoride levels above 8 mg/L can cause osteosclerosis. There have been reports of this severe type of fluorosis in several parts of Asia and Africa. The effects of fluoride on brain function and cognitive development, especially in children, have drawn a lot of attention from scientists and generated debate. Excessive fluoride exposure has

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been shown to lower children's IQ and growth hormone production while also altering the central nervous system's demand for energy[22,23]. The substance can affect G protein activity, change immune system control, and reduce the synthesis of triiodothyronine (T3) and thyroxine (T4) hormones, among other impacts on hormonal systems, including thyroid function. Reduced testosterone production, decreased fertility in females, and poor sperm motility in men are reproductive health issues linked to excessive fluoride exposure. Because fluoride tends to build up in bone tissue, the U.S. National Toxicology Programme has also revealed possible cancer risks linked to fluoridated drinking water, specifically with regard to malignancies connected to the bones. Cases like Yellowstone National Park, where naturally high fluoride levels influence local animals, especially deer populations, serve as examples of the extensive effects of fluoride poisoning. Given these wide-ranging health impacts, fluoride poisoning has become a major global health concern.

Children are especially susceptible to its negative effects, thus public health authorities across the world must act quickly to address this issue. The connection between groundwater fluoride intake and human health is complicated and has two sides, acting as a double-edged sword. Because they prevent dental cavities, promote bone growth, facilitate mineralisation, and contribute in the creation of tooth enamel, low fluoride concentrations—between 0.5 and 1.0 ppm—are crucial for human health. The substance functions by creating a protective crystalline framework surrounding dental enamel, where fluoride displaces the hydroxide ion to generate fluorapatite, which is made up of hydroxyapatite (crystalline calcium phosphate), which makes up 87% of tooth enamel. On the other hand, consuming too much fluoride might cause serious health issues. Long-term exposure to high fluoride levels (>4 ppm) can induce bone calcification, which can lead to osteoporosis and osteosclerosis, while chronic exposure renders teeth hard and brittle, culminating in dental fluorosis[27,28,29].

At the cellular level, fluoride has been identified as a disruptor of intracellular redox homeostasis, causing oxidative stress, apoptosis, increased protein carbonyl content, lipid peroxidation, and altered gene expressions related to stress response, cell-cell communications, metabolic enzymes, cell cycle, and signal transduction. Fluoride pollution comes from both man-made and natural sources. The fluoride concentration in soil is influenced by the natural weathering of minerals such mica, apatite, topaz, and fluorite/fluorspar. The pollution is further exacerbated by industrial operations, especially in the steel, aluminium, zinc, glass, ceramic, fertiliser, and fertiliser industries. As a result, there are more exposure pathways outside drinking water due to bioaccumulation in the food chain, which puts babies and kids at very high risk. Studies conducted all across the world have shown how ubiquitous fluoride pollution is. Widespread fluorosis has been reported in the Jilin area of China, especially in infants and pregnant women who have been exposed to water that contains more than 1.0 mg/L fluoride [16,17,28].

Ironically, dental fluorosis has been connected to insufficient fluoride dose in Iran. Similar issues have been reported in the Guadiana Valley of Mexico, the Walawe River basin in Sri Lanka, and several Indian states, including Orissa, Tripura, Punjab, Telangana, and

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Uttar Pradesh. To evaluate the health concerns associated with fluoride, researchers have used a variety of health index models. These include the DMFT (Decayed, Missing, Filled Teeth) Index, Dean's Index (DI), and the Community Fluorosis Index (CFI). Children are more at risk from fluoride exposure than adults, according to recent research that have used the USEPA technique and other risk assessment instruments[30,31]. For example, a study conducted in northwest China found that adults maintained an acceptable average of 0.42, whereas children's health risk value averaged 1.51.Research on fluoride's co-occurrence with other pollutants, such uranium and arsenic, has shed further light on the combined health concerns. According to studies conducted in Pakistan and the Brahmaputra floodplain, Some combinations of contaminants nevertheless create serious health concerns, especially for youngsters, even if they may not be very likely to cause cancer. These results highlight the need of thorough water quality monitoring and the necessity of focused efforts to shield susceptible groups—children in particular—from excessive fluoride exposure through a variety of environmental routes.

## 4. WORLD SCENARIO

According to a thorough international investigation, fluoride pollution of groundwater is a widespread problem that affects more than 100 countries globally, with levels above the WHO's maximum allowable limit of 1.5 mg/L. The African continent carries the largest load with 38 afflicted nations, followed by Asia with 28 countries, Europe with 23 countries, South America with 5 countries, North America with 3 countries, and Australia with 2 impacted areas [29,33]. Figure 3 shows fluoride-affected areas superimposed on the world climate map. Among these continents, certain countries are more affected than others: Germany in Europe, Argentina in the Americas, India in Asia, and Kenya in Africa.

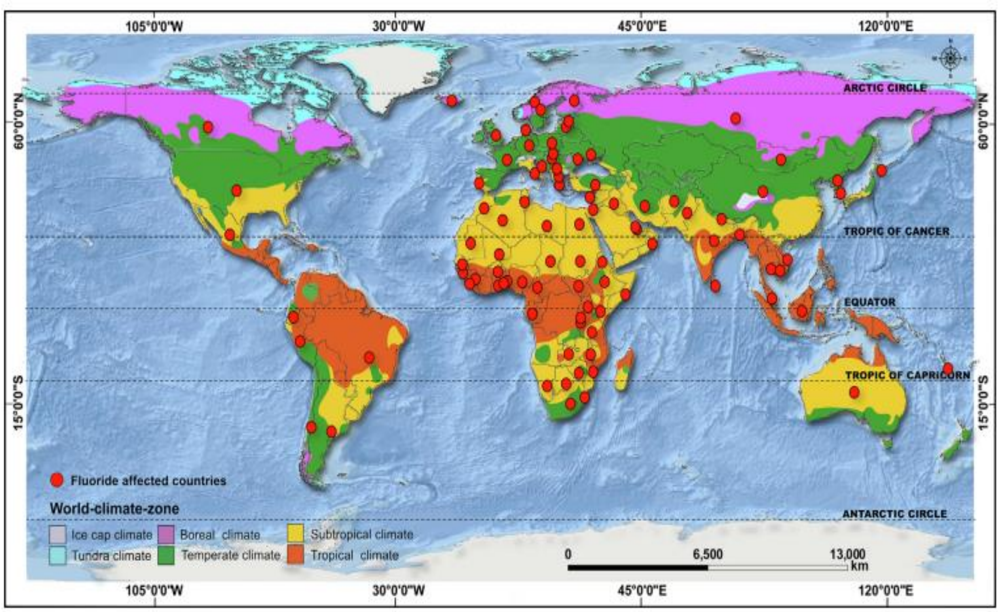


**Fig 3: Fluoride-affected areas superimposed on the world climate map [1]**

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The extent of this pollution is astounding; studies show that over 200 million individuals worldwide drink water that contains hazardous amounts of fluoride. China, Sri Lanka, India, portions of Iran, Pakistan, and Jordan have all shown extremely high levels of contamination, making Asian nations especially heavily afflicted. Table 4 shows the list of countries affected by fluoride contamination in groundwater. For example, fluoride levels as high as 21.5 mg/L were observed in China in 2000; however, more recent tests indicate considerable improvement, with values ranging from 0.01 to 6.30 mg/Significant fluoride pollution has been reported in a number of places outside of Asia, including Nigeria, the African Rift Valley, Northern Mexico, Kenya, Iran, and Japan. A growing number of countries, including Nepal, the Koreas, Libya, Ghana, Sudan, Burundi, Tanzania, Ethiopia, Algeria, Australia, and Chile, are on the list of seriously impacted countries [34,36]. Given that the majority of fluoride-rich zones are located in regions with alkaline intrusions or high-grade metamorphic terranes, the geological context of this pollution is noteworthy. Particularly in dry or semi-arid climates, geothermal hot springs and volcanic regions are linked to several polluted sites. This worldwide environmental health issue is exacerbated by the discovery of additional sources of pollution in sedimentary rocks, particularly limestone and shales[34,38].

## Africa

For more than 435 million people in Africa, groundwater is an essential source of drinking water. However, the problem of fluoride pollution in groundwater affects a sizable section of the continent. Exposure to fluoride levels above 1.5 mg/L affects about 81 million individuals and can cause serious health issues. Because of the region's fluoride-rich rocks and volcanic activity, countries in the East African Rift Valley, such as Kenya, Tanzania, and Ethiopia, are most impacted. High fluoride levels in groundwater are a problem in other nations as well, including as South Africa, Malawi, and Nigeria. Fluoride concentrations vary by area due in part to the geological makeup of the African continent, which includes a variety of rock formations. While fluoride levels are naturally low in certain places, they are high in others, particularly in locations containing granitic and volcanic rocks. Long-term exposure to excessive fluoride levels can have serious health effects, such as skeletal and dental fluorosis. A multifaceted strategy is needed to address this problem, one that includes public awareness efforts, treatment technology, and water quality monitoring.

## South Africa

High fluoride levels in groundwater are a problem for South Africa and many other sub-Saharan African nations. When taken in excess, this naturally occurring mineral can cause serious health issues even though it is necessary in tiny amounts. In areas with high fluoride levels, dental fluorosis—which is characterised by tooth discolouration and pitting—is a prevalent problem. The issue is especially serious in Malawi, where hot springs contaminate water supplies and lead to localised epidemics of severe dental fluorosis. Groundwater fluoride levels are mostly determined by the region's geological makeup, which includes a variety of rock formations. Higher concentrations are found in some places, particularly those with granitic and volcanic rocks, whereas naturally low

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amounts are found in others. A comprehensive strategy is needed to address this problem, one that includes public awareness programs, treatment technology, and water quality monitoring to reduce the health concerns associated with high fluoride ingestion.

### Europe

High fluoride levels in groundwater, especially in Central Europe, are another problem facing Europe. Across the continent, millions of individuals are exposed to levels higher than the 1.5 mg/L recommended limit. There have been reports of high fluoride levels in certain areas of Finland, Estonia, Serbia, Italy, Germany, France, Greece, Spain, Hungary, Moldova, Ukraine, Sweden, Portugal, Poland, Norway, North Macedonia, Ireland, Denmark, Russia, and the Czech Republic. Geological elements like volcanic activity and mineral-rich rocks, as well as human activities like industrial emissions and agricultural practices, are some of the different origins of this pollution. Dental fluorosis and perhaps skeletal fluorosis are the results of extended exposure to excessive fluoride levels. In order to address this issue and safeguard public health, extensive water quality monitoring, efficient treatment technology, and public awareness programs are needed.

**Table 4: List of countries affected by fluoride contamination in groundwater [1]**

| Continent | Countries |
|---|---|
| **Africa (38)** | Algeria, Benin, Botswana, Burkina Faso, Burundi, Cameroon, Chad, Cote D'Ivoire, Egypt, Eritrea, Ethiopia, Gabon, Ghana, Gunia, Kenya, Libya, Malawi, Mali, Mauritania, Morocco, Mozambique, Namibia, Niger, Nigeria, Rwanda, Senegal, Sierra Leone, Somalia, South Africa, South Sudan, Sudan, Swaziland, Tanzania, Togo, Tunisia, Uganda, Zambia and Zimbabwe |
| **Asia (28)** | Afghanistan, Bahrain, Bangladesh, Cambodia, China, India, Indonesia, Iran, Iraq, Israel, Japan, Jordan, Malaysia, Mongolia, Myanmar, Nepal, North Korea, Oman, Palestine, Pakistan, Qatar, Saudi Arabia, South Korea, Sri Lanka, Thailand, Yemen, Turkey and Vietnam |
| **Europe (24)** | Croatia, Cyprus, Denmark, Estonia, Finland, France, Germany, Greece, Greek, Hungary, Iceland, Italy, Latvia, Moldova, North Macedonia, Norway, Poland, Portugal, Serbia, Slovakia, Spain, Sweden, UK, and Ukraine |
| **North America (3)** | Canada, Mexico and the United States |
| **South America (5)** | Argentina, Brazil Chile, Ecuador, and Peru |
| **Australia (2)** | Australia and Vanuatu |

### South America

High fluoride levels in groundwater are a problem in South American nations including Brazil, Argentina, Ecuador, Chile, and Peru. With more than 1.2 million people drinking water containing high amounts of fluoride, Argentina is especially affected. Geological elements such as mineral-rich rocks and volcanic activity are the main natural sources of this pollution. Because to the presence of less sediments and volcanic glass shards, areas in Argentina such as the Chaco-Pampean Plain are severely impacted. High fluoride concentrations in Chile are a result of geothermal regions like El Tatio. Significant

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health hazards, such as dental fluorosis and perhaps skeletal fluorosis, are associated with these excessive levels. In order to address this issue and safeguard public health, extensive water quality monitoring, efficient treatment technology, and public awareness programs are needed.

### North America

Elevated fluoride levels in groundwater are a problem in North America, especially in nations like the US, Canada, and Mexico. Millions of individuals are exposed to drinking water that has more over the 1.5 mg/L recommended limit. Geological elements like as volcanic activity, mineral-rich rocks, and human activities like farming are some of the main causes of this pollution. In Mexico, volcanic activity, mineral deposits, and agricultural activities are frequently linked to areas with elevated fluoride levels. Because of certain geological formations, fluoride concentrations are higher in places like Labrador and Alberta in Canada. States like Arizona, Colorado, Ohio, Texas, and Oklahoma are most impacted in the US, and geological and human-caused reasons are connected to elevated levels. Significant health hazards, such as dental fluorosis and perhaps skeletal fluorosis, are associated with these excessive levels. In order to address this issue and safeguard public health, extensive water quality monitoring, efficient treatment technology, and public awareness programs are needed.

### Asia

High groundwater fluoride levels have a major effect on millions of people in Asia, including Pakistan, Sri Lanka, China, Indonesia, Japan, and Korea. Millions of people in Pakistan are exposed to tainted water as a result of anthropogenic activity and geological reasons, making the problem there especially serious. Similar issues exist in Sri Lanka, where high fluoride levels are caused by crystalline rock weathering. Another severely impacted nation is China, where pollution is pervasive in many areas. The high fluoride levels are caused by a variety of factors, including human activity, mineral-rich rocks, and volcanic activity. Areas with high fluoride concentrations may also be found in Korea, Japan, and Indonesia; these regions are frequently linked to geological processes such mineral weathering and volcanic activity. Significant health hazards, such as dental fluorosis and perhaps skeletal fluorosis, are associated with these excessive levels. In order to address this issue and safeguard public health, extensive water quality monitoring, efficient treatment technology, and public awareness programs are needed.

## 5. INDIAN SCENARIO

One of the most significant environmental and public health issues in India is groundwater fluoride poisoning, which affects an estimated 66 million people in 19 states. India, the largest groundwater consumer in the world, uses over 251 billion cubic meters of groundwater a year for a variety of uses (Fig 5). As a result of growing population pressures and a growing reliance on groundwater supplies, India is now at serious risk of fluoride poisoning. An important factor in this dilemma is the geological makeup of India's landscape. The nation has around 14% of the world's naturally occurring fluoride

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resources, mostly in the form of metamorphic complexes, crystalline basement rocks, and granitic terrains. Fluoride concentrations in states like Rajasthan, Andhra Pradesh, Gujarat, Tamil Nadu, and Uttar Pradesh are reported to be far higher than the 1.5 mg/L WHO-recommended limit, with some areas reporting levels as high as 48 mg/L. Anthropogenic elements, such as intense agricultural practices, industrial operations, and unsustainable groundwater extraction patterns, worsen this geogenic pollution[32,35,37]. India has a serious fluoride problem, which is made worse by its particular hydrogeological circumstances. Fluoride movement and concentration in groundwater are influenced by the nation's varied climatic patterns, which range from dry to tropical. Fluoride concentrations are often higher in dry and semi-arid areas with high evaporation rates and little rainfall. The weathering of fluoride-containing minerals like fluorite, apatite, and biotite exacerbates the issue, particularly in areas with alkaline soils and calcium-deficient aquifers. This pervasive pollution has serious health consequences. Millions of Indians suffer from endemic fluorosis, which can take the form of dental, skeletal, or non-skeletal conditions. This condition is most prevalent in rural regions where there are few other water sources. With impacted people experiencing less job capability, higher healthcare expenditures, and a lower quality of life, the socioeconomic effect is as considerable. According to studies, up to 40% of school-age children in badly impacted areas have dental fluorosis, and 3-7% of adults in high-fluoride zones have skeletal fluorosis [39].

The severity of contamination varies significantly across different regions of India. Several states in southern India have reported extremely alarming levels. With fluoride levels as high as 7.4 mg/L, 57% of groundwater tests in Telangana's Medak district are deemed unsafe for human consumption. Due to the presence of granitic rocks, alkaline conditions, and river sediment deposits, investigations have shown that fluoride concentrations in Andhra Pradesh range from negligible quantities to 9.75 mg/L in a number of districts, including Hyderabad and Guntur. Twenty-three percent of groundwater tests in the Shanmuganadhi river basin exceeded safe levels, according to the report. 58% of samples in the Krishnagiri district of Tamil Nadu have high fluoride levels, whilst values as high as 3.3 mg/L are recorded in the ThoothuKudi district. 70% of examined samples in the Tumkur and Kolar districts of Karnataka are found to be over allowable levels. The situations in Central and Northern India are similarly worrisome[40]. While western Haryana exhibits higher fluoride levels together with heavy nitrate pollution, indicating human origins, Punjab's Bathinda and Faridkot districts have reported fluoride levels as high as 10.6 mg/L. According to research, 32% of sample sites in central Rajasthan expose inhabitants to 4 ppm of fluoride per day, with 30% of habitations in the Nagaur district surpassing safe levels. Fluorosis affects 80% of villagers in Uttar Pradesh, where the Unnao district records highest levels of 13.9 ppm (mean 4.02 ppm). This is a very severe instance. While 48% of 658 examined samples in Agra's Kheragarh Tehsil surpassed allowable limits, the Banda district displays values of 0.32 to 3.5 ppm. Similar pollution patterns may be seen in eastern India. Studies have shown that fluoride has bio accumulated in soil and food crops in the lateritic districts of Purulia and Bankura in West Bengal. In certain areas, just 17% of samples meet WHO standards, and intensive

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agriculture has been found to be a significant source of pollution. Nearly half of the examined samples (402 out of 840) in the Garwa area of Jharkhand exceeded safe levels [41,42]. While the industrial area of Angul District exhibits declining groundwater quality as a result of hydrogeochemical circumstances, Orissa's Nayagarh district finds significant pollution levels linked to fluoride-enriched hot springs. Currently, in India 22 states and 223 districts have been affected by elevated levels of fluoride in groundwater (Fig. 4). The sources of pollution differ greatly by area and include hydrogeochemical conditions, intense agriculture, industrial operations, and natural geological elements (such granitic rocks and hot springs).

**Table 5: State/Union territory-wise details of fluoride concentration in groundwater in India**

| States | No of districts affected | Districts(in parts) |
|---|---|---|
| Andhra Pradesh | 19 | Adilabad, Anantpur, Chitoor, Guntur, Hyderabad, Karimnagar, Khammam, Krishna, Kurnool, Mehboobnagar, Medak, Nalgonda, Nellore, Prakasham, Rangareddy, Vishakhapatnam, Viziangaram, Warangal, West Godawari |
| Assam | 4 | Goalpara, Kamrup, Karbi Anglong, Naugaon |
| Bihar | 9 | Aurangabad, Banka, Buxar, Jamui, Kaimur, Munger, Nawada, Rohtas, Supaul |
| Chhattisgarh | 12 | Bastar, Bilaspur, Dantewara, Janjgir-Champa, Jashpur, Kanker, Korba, Koriya, Mahasamund, Raipur, Rajnandgaon, Suguja |
| Delhi | 6 | East Delhi, New Delhi, Northwest Delhi, South Delhi, Southwest Delhi, West Delhi |
| Gujarat | 18 | Ahmedabad, Amreli, Anand, Banaskantha, Bharuch, Bhavnagar, Dahod, Junagarh, Kachchh, Mahesana, Narmada, Panchmahals, Patan, Rajkot, Sabarkantha, Surat, Surendranagar, Vadodara |
| Haryana | 14 | Bhiwani, Faridabad, Gurgaon, Hissar, Jhajjar, Jind, Kaithal, Kurkshetra, Mahendragarh, Panipat, Rewari, Rohtak, Sirsa, Sonepat |
| Jammu & Kashmir | 2 | Rajauri, Udhampur |
| Jharkhand | 6 | Bokaro, Giridih, Godda, Gumla, Palamau, Ranchi |
| Karnataka | 20 | Bagalkot, Bangalore, Bellary, Belgaum, Bidar, Bijapur, Chamarajnagar, Chikmagalur, Chitradurga, Devangere, Dharwar, Gadag, Gulbarga, Haveri, Kolar, Koppala, Mandya, Mysore, Raichur, Tumkur. |
| Kerala | 1 | Palakkad |
| Madhya Pradesh | 19 | Bhind, Chhatarpur, Chhindwara, Datia, Dewas, Dhar, Guna, Gwalior, Harda, Jabalpur, Jhabua, Khargone, Mandsaur, Rajgarh, Satna, Seoni, Shajapur, Sheopur, Sidhi. |
| Maharashtra | 8 | Amrawati, Chandrapur, Dhule, Gadchiroli, Gondia, Jalna, Nagpur, Nanded, |
| Odisha | 11 | Angul, Balasore, Bargarh, Bhadrak, Boudh, Cuttack, Deogarh, Dhenkanal, Jajpur, Keonjhar, Suvarnapur |
| Punjab | 11 | Amritsar, Bhatinda, Faridkot, Fatehgarh-Saheb, Firozpur, Gurdaspur, Mansa, Moga, Muktsar, Patiala, Sangrur, |
| Rajasthan | 30 | Ajmer, Alwar, Banswara, Barmer, Bharatpur, Bhilwara, Bikaner, Bundi, Chhittorgarh, Churu, Dausa, Dholpur, Dungarpur, Ganganagar, Hanumangarh, Jaipur, Jaisalmer, Jalore, Jhunjhunu, Jodhpur, Karauli, Kota, Nagaur, Pali, Rajasamand, SawaiMadhopur, Sikar, Sirohi, Tonk, Udaipur |
| Tamil Nadu | 16 | Coimbatore, Dharmapuri, Dindigul, Erode, Karur, Krishnagiri, Namakkal, Perambalur, Puddukotai, Ramnathpuram, Salem, Shivaganga, Theni, Thiruvannamalai, Vellore, Virudunagar |
| Uttar Pradesh | 10 | Agra, Aligarh, Etah, Firozabad, Jaunpur, Kannauj, Mahamayanagar, Mainpuri, Mathura, Maunathbhanjan, |

Source: hhttps://cgwb.gov.in/en/overview-ground-water-quaility

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Studies in the Ganga alluvial plain have shown that fluoride concentrations in dug wells are greater than those in deeper bore wells, indicating that the issue is more severe in regions with shallow aquifers. Since fluorosis cases are on the rise nationwide as a result of this pervasive pollution, it is an important public health issue that needs to be addressed right once. Table 5 summarizes State/Union territory-wise details of fluoride concentration in groundwater in India [45]. We separated India geographically into many zones, including Southern India, Eastern India, Western India, North-Western India, North Eastern India, North India, and Central India, in order to conduct a systematic assessment of the fluoride pollution in Indian groundwater:

**Southern India** Across fifty-eight districts in southern India, the problem of groundwater fluoride pollution has become a major concern, with differing degrees of severity among states. Twenty districts are impacted in Karnataka, the most, followed by seventeen in Tamil Nadu, thirteen in Andhra Pradesh, six in Telangana, and two in Kerala. Twenty of Karnataka's thirty districts have fluoride concentrations in groundwater supplies that are more than 1.5 mg/L, making it the most afflicted state in southern India and the second most affected state in the country. With Archaean crystalline rocks making up over 79% of the state's land area, Karnataka's geological makeup is a major factor in this pollution. The areas with gneissic and granitic formations have the greatest fluoride concentrations because of the geogenic circumstances and semi-arid environment that facilitate the release of fluoride-rich minerals into groundwater. The situation is particularly bad at Hathiguddur village in the Gulbarga region, where fluoride levels are higher than 7.4 mg/L. This causes a number of health problems for the people, such as gout, arthritic symptoms, and bone illnesses. Although it is less common, three districts in Kerala—Palakkad, Allepey, and Kasaragod—are impacted by fluoride pollution. Hornblende biotite gneiss rocks are the main source of pollution in Palakkad, but fluoride levels in Allepey surpass 2.88 mg/L and in Kasaragod they are 2.0 mg/L. This pollution is caused by a number of variables, such as low rainfall, alkaline ambient conditions, prolonged water residence time in aquifers, intense irrigation methods, and low dilution rates. The release of fluoride from fluorine-bearing rocks is especially facilitated by the presence of alkaline water that has lost calcium. With seventeen impacted districts, Tamil Nadu is a complicated instance where high fluoride levels are caused by both geogenic (natural) and anthropogenic (man-made) reasons. This intricacy is best illustrated by the Dharmapuri area, where fluoride concentrations range from 0.15 mg/L to 6.48 mg/L. The weathering of epidote hornblende gneissic rocks in hard rock aquifers is the main cause of the intriguing pattern whereby deeper groundwater wells exhibit greater fluoride concentrations than shallow wells. The neighbouring Puducherry area likewise exhibits significant pollution, with fluoride levels as high as 1.78 mg/L. This highlights the widespread nature of this environmental health concern in southern India.

**Western and Central India** Groundwater fluoride pollution is a major problem in Western and Central India, which includes eighty-three districts in many states. This environmental problem affects fifty-three districts in Western India, with Rajasthan suffering the brunt of it since all thirty-three of its districts exhibit pollution

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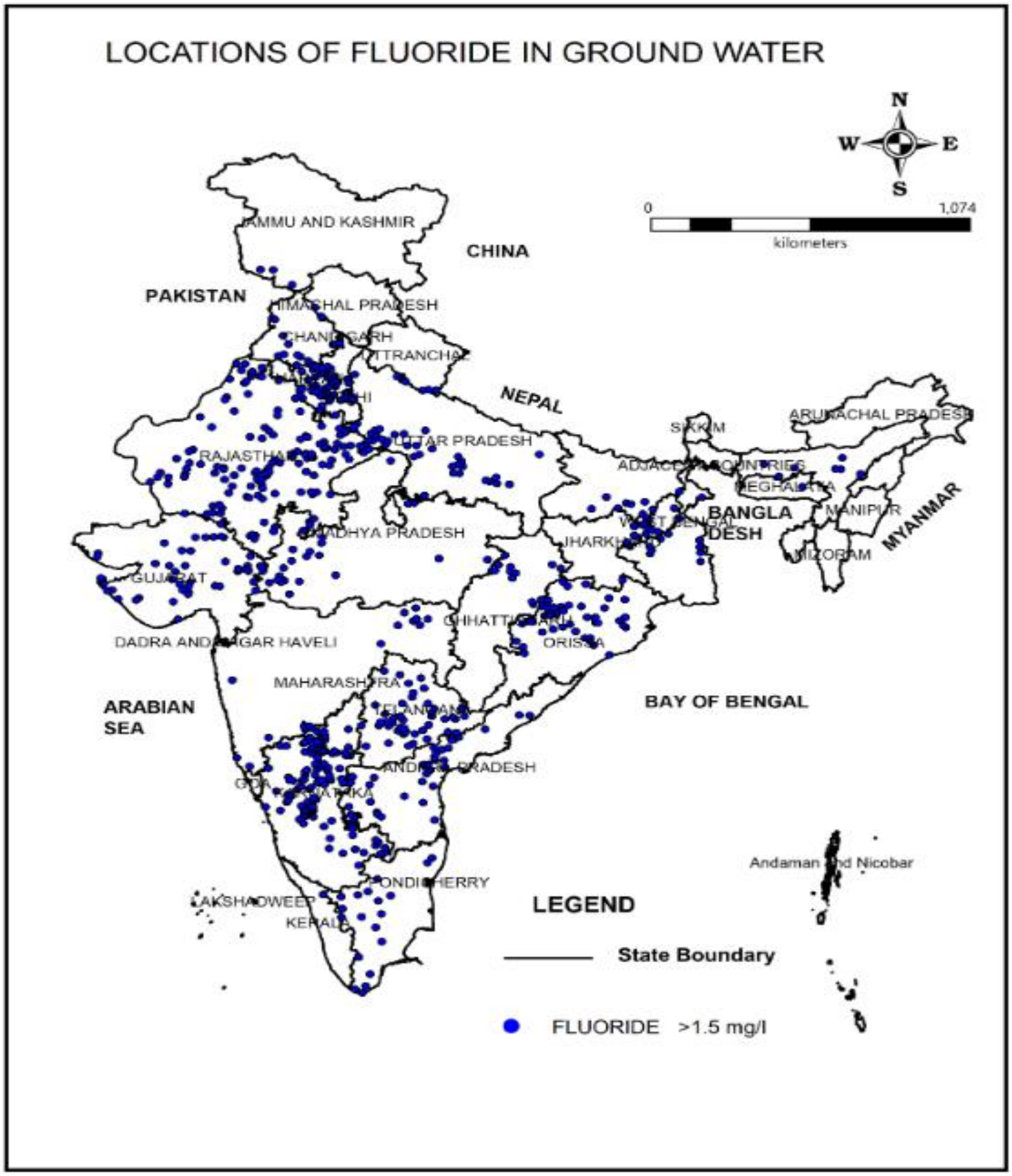


**Fig 4: Fluoride-affected states in India, where 223 districts in 22 states are affected**

(Source: modified figure of CGWB, http://cgwb.gov.in/sites/default/files/inline-files/ fluoride.jpg)

Maharashtra reported pollution in eight areas, whereas Gujarat has twelve afflicted districts. With thirty impacted districts divided between Madhya Pradesh (nineteen districts) and Chhattisgarh (eleven districts), Central India is also plagued by this problem.

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Many studies have been done in Rajasthan's northern and western areas, and the situation there is very dire. The state's northeast region has concerning fluoride levels of more above 8.2 mg/L. The breakdown, separation, and dissolution of fluoride-rich minerals like biotite and muscovite are the main natural geological processes that cause the pollution. Numerous rock types, such as granites, gneisses, mica, schists, limestone, sandstone, phosphorite, shales, clays, acid igneous rocks, basalts, and alluvium, include these minerals. Researchers link the seasonal variations of this pollution to irrigation pumping methods and rainfall recharge patterns, which is an intriguing feature. Geogenic fluoride ion concentrations in Rajasthan's Bharatpur area can reach 8.70 mg/L, which is a worrying situation. The situation in Central India is equally concerning, especially in the district of Rajnandgaon, where fluoride concentrations have been found to be among the highest in the area at over 18.5 mg/L. These high levels of pollution have serious health effects, with fluorosis becoming common among the local people mainly as a result of drinking tainted water. Various researchers have found considerable fluoride contamination in Gujarat's groundwater throughout the years. In order to address the rising problem of fluoride pollution in groundwater resources, comprehensive water quality management techniques and public health initiatives are urgently needed, as evidenced by the extensive contamination throughout Western and Central India.

**Northern India** Fifty-one districts in six states are affected by the widespread problem of fluoride pollution in groundwater in Northern India. Two districts in Jammu and Kashmir, eleven in Punjab, fourteen in Haryana, five in Delhi, ten in Uttar Pradesh, and nine in Bihar are among the impacted areas. Among these states, Uttar Pradesh emerges as one of the most seriously damaged regions in the whole country, with the pollution having a catastrophic toll on public health. With around half of the state's population exhibiting obvious symptoms of fluorosis, the situation in Uttar Pradesh is especially dire. Bone abnormalities and teeth mottling are the two main ways that these health effects appear. Around 90% of the local population is impacted by high fluoride concentrations in their water supply, making the districts of Unnao and Pratapgarh the focal point of this dire problem. The Quaternary-Upper Tertiary deposits that are present in many areas of the state have been identified by experts as the main source of fluoride, making the geological background of this pollution crucial. In the Sonbhadra district's Chopan block, where groundwater fluoride levels above 6.7 mg/L, there is a particularly alarming instance. Granitic and phyllite rocks make up the region's unique geological makeup, which is responsible for this high concentration.

This geological link shows how much of the fluoride pollution in the area comes from natural sources and emphasises how difficult it is to provide clean drinking water in places where the bedrock itself has large concentrations of minerals that contain fluoride. The extensive and serious extent of this pollution throughout Northern India, especially in Uttar Pradesh, highlights the pressing need for public health initiatives and all-encompassing water treatment measures to safeguard impacted communities.

**Eastern and North eastern India** although the effects of fluoride poisoning in groundwater vary by state, they are felt throughout Eastern and North-eastern India. This

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environmental problem affects 25 districts in three states in Eastern India, with Odisha having the most impacted (11 districts), followed by West Bengal (eight districts) and Jharkhand (6 districts). The least contaminated area in India is the northeast, which exhibits relatively lower levels of pollution.

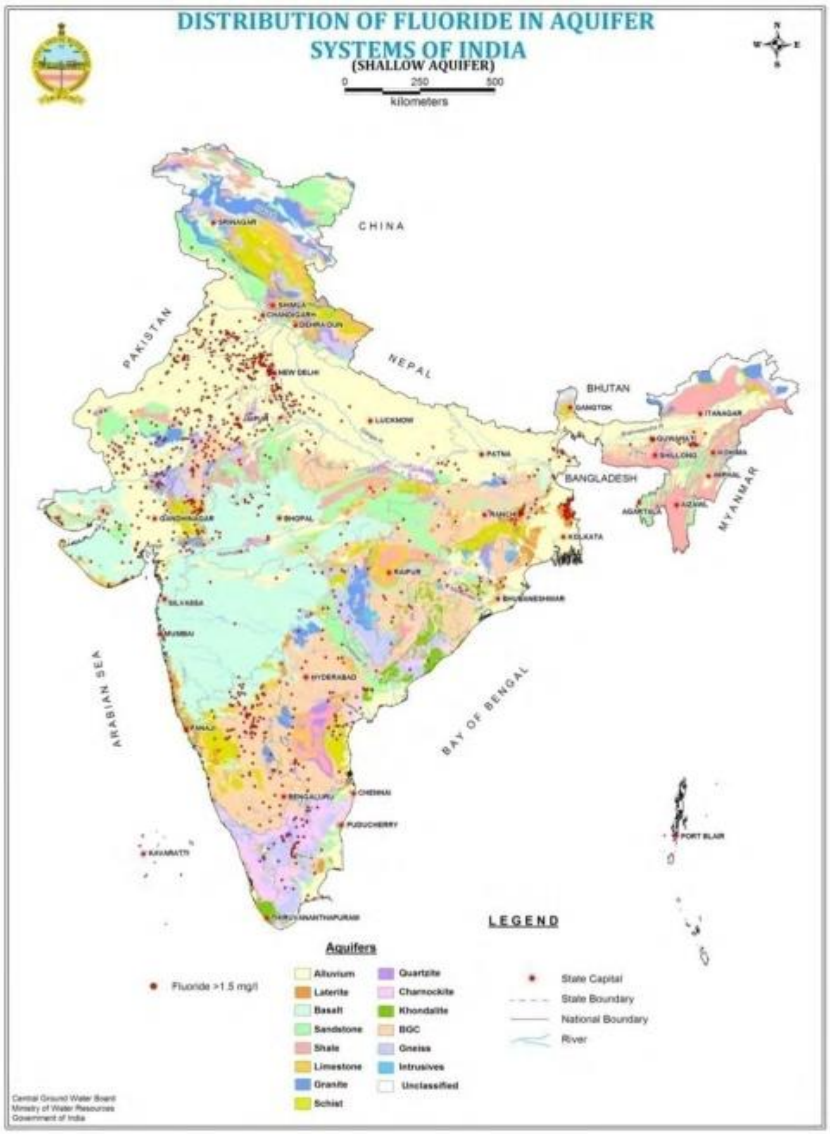


**Fig 5: Distribution of fluoride in aquifer systems of India (CGWB, https://cgwb.gov.in/cgwbpnm/public/uploads/documents/ 1686055710748531399file.pdf)**

There are five impacted districts in Assam and one in each of Manipur and Tripura in this region. Because of its distinct geological makeup, Odisha, which is located on India's east coast, makes for an especially fascinating case study. About 73% of the state's land area is made up of Precambrian rock formations, which provide ideal conditions for fluoride

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poisoning. Both anthropogenic (caused by human activity) and geogenic (caused by natural geological processes) sources of fluoride pollution in the state's groundwater. Fluoride concentrations in the state's phreatic aquifers (shallow groundwater systems) surpass 4 mg/L, demonstrating the gravity of the problem. The industrialised parts of the Angul district, whose fluoride concentrations may reach 4.4 mg/L due mainly to current mining activities, provide a noteworthy illustration of how human activity affects fluoride levels. An intriguing distinction that could provide information about elements that assist avoid or minimise fluoride pollution is the North Eastern states' comparatively lesser impact of fluoride contamination when compared to other parts of India. The thorough analysis of fluoride contamination in Eastern and North-eastern India emphasises the intricate relationship between groundwater quality, human activity, and natural geological formations, underscoring the necessity of region-specific strategies for managing water quality and safeguarding public health.

## 6. CONCLUSION

One of the biggest problems facing the world's environment is fluoride pollution of groundwater, which is especially severe in Asia and Africa. This pervasive problem, which is essentially related to intricate geological and hydrogeological processes, has started to show up outside of its usual borders and is currently found in North and South American, European, and other regions, indicating a growing geographic influence. From a geological standpoint, some geological conditions and formations are strongly correlated with the contamination patterns. High-grade metamorphic terranes with granitoid intrusions and alkaline plutons, sometimes in combination with extrusive volcanic formations, are usually found in the most seriously impacted locations. These geological features are often associated with geothermal activity and volcanic zones, particularly in areas with dry or semi-arid climates. There is an intriguing contrast between planned fluoridation and natural contamination when it comes to fluoride control in water systems. As a public health intervention, water fluoridation is actively used in many countries across several continents. This list illustrates the intricate link between helpful and detrimental fluoride levels in water supplies and includes a variety of countries, including Brazil, India, the United States, Malaysia, and several European countries. Because of this issue's complexity, a comprehensive policy strategy that incorporates a number of elements is required. The hydrogeological features, socioeconomic realities, and particular climatic circumstances of the impacted areas must all be taken into consideration for effective solutions. The establishment of strategic assessment frameworks and the deployment of reliable water monitoring systems are essential to success. Furthermore, it has become clear that including stakeholders and local communities in the decision-making process is essential to creating long-lasting solutions. As a result, treating fluoride pollution in groundwater necessitates an intricate, multidimensional strategy that blends scientific knowledge with useful implementation techniques. The key to success is combining community involvement, policy formulation, and geological and hydrogeological competence while taking into account the particulars of each impacted area. This all-encompassing strategy is crucial for safeguarding public

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health and water quality globally. The intricacy of this problem is shown by the scientific study, which highlights the necessity for customised solutions that take local circumstances into account while keeping a worldwide viewpoint on the management of water resources and the preservation of public health.

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