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Temporal Dynamics of Groundwater Quality in the Industrial Belt of Chandrapur, Maharashtra

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Abstract

The Study focuses on analysing the seasonal change of groundwater quality of the industrial belt of Chandrapur district, Maharashtra, with particular respect to fluoride contamination. Samples of groundwater at seven different borewells in the Korpana subdistrict were examined in terms of the following main parameters of physicochemical parameters, namely pH, total dissolved solids (TDS), electrical conductivity (EC), total hardness, alkalinity, dissolved oxygen (DO), and fluoride. The levels of fluoride were 0.80 to 2.50 mg/L, with some of the samples in summer being above the World Health Organization (WHO) limit of 1.5 mg/L. High levels of fluoride are an indicator of the possible dangers of dental fluorosis in the local residents. The contaminant concentrations decreased significantly as a result of monsoonal recharge, and this is an indication of seasonal dilution. The paper recommends that groundwater should be monitored regularly, defluoridation efforts should be maintained, and that community-based awareness should be created to reduce risks caused by fluorides and to provide sustainable access to safe drinking water in the area.

Keywords: Groundwater quality, Fluoride contamination, Seasonal variation, public health

1. Introduction

Groundwater, characterized as the aqueous resource retained within the interstitial spaces of soil and the fissures of geological structures beneath the Earth's crust, constitutes one of the most essential natural assets for the sustenance of life and the advancement of civilization. It operates as

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a fundamental element of the global hydrological cycle, acting as both a storage reservoir and a continuous contributor to surface water systems, including rivers, lakes, streams, and wetlands. The natural replenishment of groundwater transpires through the mechanism of recharge, predominantly facilitated by precipitation and the ensuing infiltration of rainwater or snowmelt into the subterranean strata. Its function is particularly critical in semi-arid and arid regions, where surface water availability is frequently limited and sporadic, rendering groundwater the principal source of freshwater essential for human existence and socio-economic progress.

Across the world, groundwater plays a vital role in meeting domestic needs, sustaining agriculture, supporting industrial processes, and maintaining ecological balance. In India, now the largest user of groundwater globally, this reliance is even more pronounced, largely because agriculture remains the primary source of income for a major share of the population. While groundwater naturally contains beneficial minerals and trace elements essential for human health, the presence of contaminants above acceptable limits can lead to serious health problems. This interplay between useful and harmful constituents underscores the necessity for ongoing assessment and effective management of groundwater systems to secure safe and sustainable supplies for future generations [1]. Groundwater quality remains a major concern because it is governed by a combination of physical, chemical, and biological factors. Although it is naturally clear, odourless, and largely free from taste, its safety is often questioned due to the presence of chemical contaminants and microbial threats. In recent years, this concern has grown significantly as rapid urban growth, expanded industrial activities, and rising population pressures have increased the demand for reliable and safe water for drinking, household use, and agriculture [2].

Groundwater has become the backbone of water security across the globe, yet its sustainability is increasingly threatened by overexploitation and contamination. With rapid population growth, intensification of agriculture, and expanding industrialization, mounting pressure has been placed on groundwater resources, leading to alarming depletion in both quantity and quality [3]. The deterioration of groundwater quality is now recognized as a global concern, not only because it undermines human health, but also due to its long-term impacts on environmental integrity and sustainable economic development [4]. The concept of groundwater sustainability emphasizes the responsible use and management of groundwater resources to fulfil present-day needs without compromising their availability and quality for future generations, while avoiding undesirable environmental and socioeconomic consequences [5].

In India, groundwater is the main source of drinking water, particularly in rural areas where it meets almost 90% of the total water demand. Despite being widely regarded as naturally clean, its quality has been increasingly compromised by human activities. Unregulated industrial discharges, agricultural chemicals, and household waste have all contributed to changes in its original chemical composition. Contamination pathways are strongly influenced by the characteristics of the soil, which acts as a natural filter. Soil properties, including texture, organic matter content, microbial activity, and mineral composition, govern its capacity to adsorb, retain, or degrade pollutants. Clay-rich soils, for instance, are effective at binding cations like heavy metals due to their high surface area and charge properties, while organic-rich soils enhance the adsorption of organic contaminants. Furthermore, microbial degradation within soils facilitates the transformation of complex toxic compounds into less harmful byproducts. However, in highly permeable sandy soils, pollutants can migrate more quickly, reducing the residence time necessary for effective filtration. Thus, the complex interplay between soil properties, hydrogeological conditions, and anthropogenic pressures largely dictates the vulnerability of groundwater to contamination [6].

Fluoride is a colourless, odourless, and tasteless ion, making its presence in drinking water difficult to detect without laboratory testing. Although small amounts are essential for the proper formation of teeth and bones, higher concentrations can lead to significant health problems [7]. Because fluoride does not readily break down in the environment, it can accumulate in groundwater, particularly in regions with fluoride-rich geological formations. Research shows that granitic aquifers often exhibit elevated fluoride levels due to long-term interactions between water and surrounding rock minerals [8].

The distribution of fluoride in groundwater is influenced by a complex interplay of geological, geomorphological, hydrogeological, and climatic factors. Its spatial and seasonal variations are challenging to predict, as both natural processes and human activities contribute to its concentration [9]. Several investigations across India have reported high fluoride levels in groundwater, especially in states heavily dependent on aquifers for drinking water [10]. This ongoing concern highlights the necessity for continuous surveillance, location-specific hydrogeochemical assessments, and the adoption of sustainable fluoride mitigation approaches to protect water quality and public health.

1.1. Factors Governing Fluoride Concentration in Groundwater Resources

Fluoride in groundwater remains an important subject within hydrogeochemistry due to its direct relevance to environmental quality and public health. Although concentrations up to roughly 1 mg/L contribute positively to dental health and bone integrity, levels above this threshold can be harmful.

Its natural abundance in groundwater is shaped by several interacting geological and environmental variables. These include water temperature and pH, the solubility of fluoride-rich minerals such as fluorite (CaF_2), cryolite (Na_3AlF_6), mica, and sellaite (MgF_2), as well as the duration of contact between groundwater and these mineral sources [10]. The capacity of aquifer materials to exchange hydroxide ions with fluoride further influences how much fluoride enters solution [11].

Human activities have increasingly added to the fluoride burden in groundwater systems. Industrial operations, particularly coal burning, and the widespread use of phosphate fertilizers introduce substantial fluoride into soils and water bodies [12]. In agricultural areas, fertilizers are a major contributor, as fluoride leaches from the soil profile into groundwater and can return through irrigation, intensifying long-term accumulation [13].

The health impacts of excessive fluoride exposure are now recognized as a serious concern, especially in areas undergoing rapid development. Dental fluorosis, marked by changes in tooth enamel, occurs when children are exposed to high fluoride levels during tooth formation, while long-term intake in adults can lead to skeletal fluorosis, characterized by chronic joint pain, bone hardening, and, in severe cases, physical deformities [14]. Drinking water remains one of the most significant exposure routes, particularly in regions where aquifers naturally contain high fluoride or where water supplies are artificially fluoridated [15,16].

1.2. Interaction of Physicochemical Factors with Fluoride Dynamics in Drinking Water Sources

Recent research has consistently highlighted the strong influence of physicochemical parameters on the occurrence, mobility, and risks associated with fluoride contamination in groundwater. A global review by Shaji et al. [17] emphasized that pH, alkalinity, electrical conductivity (EC), total dissolved solids (TDS), and ion concentrations, particularly calcium, magnesium, sodium, and chloride, play decisive roles in controlling fluoride distribution. Elevated fluoride levels are frequently associated with alkaline pH and low calcium or magnesium, conditions that enhance fluoride solubility and mobility, especially in arid and semi-arid regions. Complementing this, Podgorski et al. [18] demonstrated through machine learning and predictive mapping that high pH and alkalinity are robust predictors of fluoride enrichment, while inverse relationships with calcium and magnesium and positive correlations with sodium, TDS, and temperature reaffirm the geochemical drivers of fluoride mobilization. The implications of such hydrochemical interactions extend to remediation practices, as highlighted by Ahmad et al. [19], who showed that adsorption-based defluoridation is strongly pH-dependent and often compromised under conditions of high TDS and low divalent cations, necessitating site-specific treatment strategies. Case-specific analyses, such as the work of Wang et al. [20] in China, further support these findings, confirming through multivariate statistics that pH, alkalinity, and nitrate are key predictors of fluoride levels, with anthropogenic inputs compounding natural geogenic contributions. Most recently, Zhao et al. [21] extended the scope of fluoride risk assessment by integrating groundwater, soil, and crop data, identifying pH, TDS, and local geological context as critical determinants of fluoride transfer into water supplies and the food chain, thereby posing multi-exposure health risks. Collectively, these studies underscore the intricate relationship between groundwater chemistry and fluoride dynamics, while highlighting the necessity of tailored monitoring and management strategies in fluoride-prone regions.

1.3. Health Implications of Excess Fluoride Exposure

High levels of fluoride in drinking water are strongly linked to a range of adverse health outcomes. Prolonged exposure may lead to dental and skeletal fluorosis, neurological impairment, thyroid dysfunction, renal damage, and increased bone fragility [22]. Moderate excess intake has also been associated with reduced cognitive performance in children and enamel mottling [23]. While some studies indicate that fluoride at slightly elevated concentrations may reduce dental caries without increasing the risk of cancer or cardiovascular disease [24], chronic exposure beyond the permissible limit remains a major public health concern. Regional investigations further highlight that both fluoride excess and deficiency can be detrimental, particularly in vulnerable groups such as infants and children [25].

1.4. Objectives of the Study

This study aims to examine the seasonal variation in key physicochemical parameters and fluoride concentrations in groundwater from villages situated near industrial zones in the Chandrapur District of Maharashtra during the summer and monsoon seasons of 2023. The research seeks to identify the major chemical factors responsible for the dissolution and movement of fluoride within these aquifers and to understand how seasonal changes influence its distribution. By evaluating these temporal fluctuations, the study intends to clarify the geochemical and environmental processes that contribute to fluoride enrichment in this industrially affected region.

A distinguishing feature of this work is its focus on an active industrial corridor, offering insight beyond earlier investigations in Maharashtra that primarily addressed rural or naturally occurring sources of fluoride. Furthermore, no detailed comparative assessment of pre-monsoon and monsoon groundwater conditions has been undertaken in this area since 2013. This study, therefore, provides an updated and novel perspective essential for guiding effective mitigation measures, improving drinking-water safety, and supporting sustainable groundwater management in the industrial belt of Chandrapur.

2. Study Area

The present investigation was carried out in Chandrapur district, Maharashtra, a region widely recognized for its substantial mineral reserves, particularly coal, which has earned it the designation of the "Black Gold City." Geographically **(Figure 1),** Chandrapur lies in the eastern part of Maharashtra within the Vidarbha region and forms a part of the Wainganga and Wardha river basins [21]. The district is positioned at 19°44′27″ N latitude and 78°59′21″ E longitude, encompassing varied physiographic features influenced by both natural and anthropogenic activities. The climate is predominantly tropical, characterized by extreme seasonal variations in temperature, ranging from a minimum of 2.8 °C during winter to a peak of 49 °C in summer. The average annual rainfall is approximately 1420 mm, predominantly received during the southwest monsoon, which significantly influences groundwater recharge dynamics. Agriculture remains a major livelihood source, with paddy serving as the principal crop cultivated across the district.

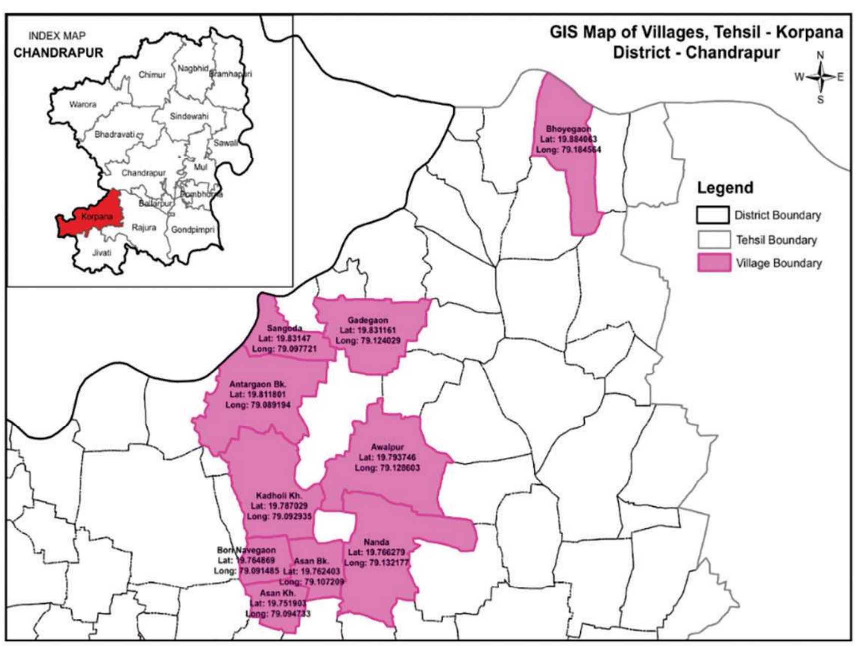

Figure 1: Location map of the study area showing Chandrapur district (inset) and the selected sampling villages within Korpana Subdistrict, Maharashtra, where groundwater samples were collected for seasonal quality assessment

2.1. Sampling Sites

To ensure representative coverage of the study region, Groundwater samples were collected from seven strategically selected locations within the Korpana Subdistrict of Chandrapur district. The sites were chosen based on a reconnaissance survey to capture spatial variability in groundwater quality across the industrially influenced belt of the region. Each sampling location was georeferenced using a handheld GPS device and geographic coordinates to ensure spatial accuracy and reproducibility in future assessments. A water quality assessment study was conducted at seven distinct locations (borewells) within the Korpana administrative block to characterize the groundwater quality, Chandrapur District, Maharashtra. The selected villages, viz Bori Navegaon, Gadegaon, Sangoda, Antargaon, Kadholi, Asan, and Nanda, were strategically chosen to represent the geographic and hydrogeochemical diversity across the region **(Table 1).** Sampling coordinates for each site were determined with reference to regional maps and are in alignment with the latitude and longitude boundaries of Korpana Subdistrict, falling within approximately 19.70° to 19.79° North and 78.96° to 79.04° East. Each site serves as a critical node in the comprehensive evaluation of local water resources, forming the basis for systematic analysis of physicochemical properties, with particular focus on fluoride occurrence and distribution.

Table 1: Sampling sites in Korpana Tehsil, Chandrapur District, with geographic coordinates

Site Code	Village Name	Latitude (°N)	Longitude (°E)
S1	Bori Navegaon	19.764869	79.091485
S2	Gadegaon	19.831161	79.124029
S3	Sangoda	19.83147	79.097721
S4	Antargaon	19.811801	79.089194
S5	Kadholi	19.787029	79.092935
S6	Asan	19.762403	79.107209
S7	Nanda	19.766279	79.132177

3. Materials and Methods

3.1. Sample Collection:

Water samples were collected from borewells across seven villages within the Korpana of the Chandrapur district, Maharashtra **(Figure 2)**. All samples were collected in pre-cleaned, sterile polypropylene bottles. Before collection, each bottle was rinsed three times with the respective groundwater sample. To ensure a representative sample, the borewells were pumped for 5-10 minutes until the electrical conductivity (EC) readings stabilized. All samples were collected with strict adherence to standard protocols to minimize contamination.

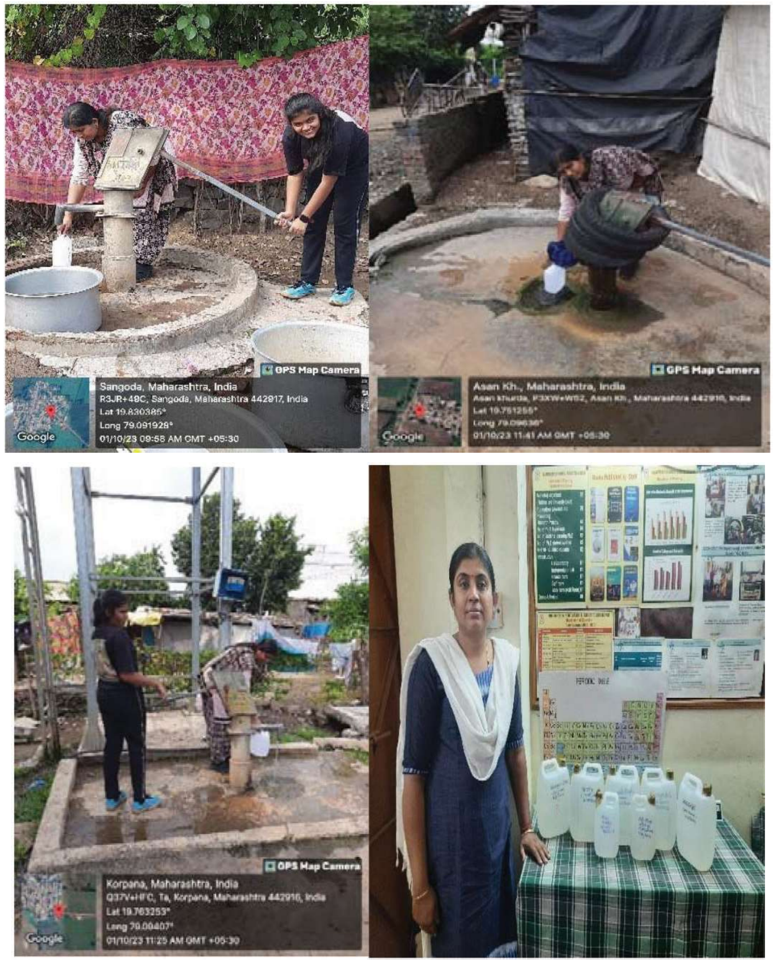

Figure 2: Photographs showing the process of groundwater sample collection from various borewell sites in the Korpana block, Chandrapur district, Maharashtra, during the 2023 seasonal study.

Figure 3: Laboratory Examination of Collected Water Samples for Quality Evaluation

3.2. Physicochemical Analysis

A suite of ten key physicochemical parameters was analyzed for each groundwater sample. Field parameters, including temperature, electrical conductivity (EC), total dissolved solids (TDS), and hydrogen ion concentration (pH), were measured on-site using a portable water quality field kit. The remaining parameters, including total hardness, alkalinity, dissolved oxygen (DO), and fluoride, were analyzed in the laboratory following the Standard Methods for the Examination of Water and Wastewater (APHA, 2017). All reagents and standards were prepared using double-distilled water and analytical-grade chemicals to ensure data accuracy and reproducibility [26]. All glassware used for these determinations was rinsed with distilled water and acid-cleaned prior to use to prevent contamination. The analyses were performed in triplicate to ensure accuracy and reproducibility.

3.3. Analytical Methods:

1. **Total Alkalinity:** Total alkalinity was determined by the acid-base titration method using a standard 0.02N sulfuric acid solution. The titration employed phenolphthalein and methyl orange as indicators to quantify the contribution of hydroxides, carbonates, and bicarbonates to the water's alkalinity [27].
2. **Total Hardness:** Total hardness, attributed to the presence of calcium and magnesium salts, was measured using the Ethylenediaminetetraacetic acid (EDTA) titrimetric method. The procedure involved titrating the samples with a 0.01M EDTA solution in the presence of a basic buffer and indicators such as Eriochrome Black T and Murexide [28].
3. **Fluoride Concentration:** Fluoride concentration was determined using the colorimetric SPADNS (sodium 2-(para-sulfophenylazo)-1,8-dihydroxy-3,6-naphthalene disulfonate) method [27,29]. This technique is based on the reaction of fluoride ions with a reagent containing SPADNS under slightly alkaline conditions, forming a coloured complex. The colour intensity, which is inversely proportional to the fluoride concentration, was measured using a spectrophotometer at a wavelength of 570 nm.
4. **Dissolved Oxygen (DO)** was determined by the Winkler iodometric titration method [30]. The method involves fixation of oxygen using manganous sulfate and alkaline iodide-azide reagents, followed by titration with standardized sodium thiosulfate solution.
5. **Chemical Oxygen Demand (COD)** was measured by the closed reflux dichromate method (IS). In this procedure, organic matter in the water sample is oxidized by potassium dichromate in the presence of concentrated sulfuric acid and silver sulfate catalyst under reflux conditions. The excess dichromate is titrated against ferrous ammonium sulfate to determine the oxygen equivalent of the consumed dichromate [31].
6. **Biochemical Oxygen Demand (BOD)** was determined by the five-day BOD test (IS). Samples were incubated at 20 ± 1°C for five days in the

dark, and the difference between initial and final dissolved oxygen concentrations was used to calculate BOD, expressed in mg/L [32].

7. **Electrical conductivity and total dissolved solids were measured** using a portable digital EC/TDS meter. The instrument was first calibrated with a 0.01 M potassium chloride (KCl) standard solution, which has a known conductivity of 1413 µS/cm at 25 °C, to ensure accuracy. After calibration, the probe was rinsed and immersed in each groundwater sample, and conductivity readings were recorded at a controlled temperature of 25 ± 1 °C. TDS values were obtained directly from the instrument, which converts conductivity to dissolved solids using an in-built conversion factor [33,34].

4. Result and Discussion

4.1. Physicochemical Parameters

Table 2 summarizes the physical and demand-related characteristics of groundwater samples collected during the summer season of 2023 from seven borewell sites in the Korpana block, Chandrapur district. The **pH values** ranged from **6.68 (Antargaon)** to **7.31 (Bori Navegaon),** remaining within the acceptable range of 6.5–8.5 as prescribed by the World Health Organization (WHO, 2017). The **electrical conductivity (EC)** values, however, were considerably high, varying between **780 and 1334 µS/cm,** well above the permissible limit of 400 µS/cm. This indicates an increased ionic concentration and mineralization of the groundwater, likely due to industrial effluent discharge and natural leaching from mineral-bearing rocks. The **total dissolved solids (TDS)** concentrations also exceeded the WHO guideline value of 500 mg/L, ranging from **468 mg/L to 753 mg/L,** with the highest values found in Bori Navegaon and Kadholi. Elevated TDS and EC levels suggest reduced water suitability for drinking and possible long-term salinity buildup in agricultural soils **(Table 2).** While pH values in the Arjunanadi basin largely remained within acceptable limits, the spatial variability of TDS, EC, and fluoride underscored increasing stress on groundwater systems despite alignment with Sustainable Development Goal (SDG) 6, which emphasizes universal access to safe water and sanitation [35].

Table 4 presents the same parameters for the **monsoon season of 2023,** highlighting the influence of seasonal recharge. The **pH values** ranged between **7.58 (Sangoda)** and **8.10 (Bori Navegaon),** indicating slightly more alkaline conditions due to the dilution of acidic ions by rainfall infiltration. The **temperature** dropped to between **28°C and 31°C,** reflecting cooler ambient conditions and increased groundwater circulation. Both **EC (712–1295 µS/cm)** and **TDS (450–724 mg/L)** values declined compared to the summer season, demonstrating partial dilution of dissolved salts. However, most samples still remained above the WHO thresholds, showing that although monsoonal recharge temporarily improves water quality, ionic enrichment persists because of continuous mineral dissolution and anthropogenic inputs **(Table 4).**

These observations confirm that **seasonal rainfall enhances groundwater quality only marginally,** as recharge dilutes contaminants but cannot fully reverse industrial and geogenic impacts. Similar seasonal dilution effects have been reported in **Rajasthan and Telangana,** where monsoon rains lowered fluoride and TDS concentrations without restoring the baseline quality of groundwater [36,37].

4.2. Dissolved Oxygen and Organic Load

As shown in **Table 2**, during the **summer season**, the **dissolved oxygen (DO)** content ranged from **6.0 to 6.7 mg/L**, slightly above the minimum desirable limit of 5 mg/L. This indicates moderate aeration within the aquifer. In contrast, the **biochemical oxygen demand (BOD)** and **chemical oxygen demand (COD)** values were considerably high, reflecting organic and chemical contamination. Bori Navegaon recorded a BOD of **27 mg/L** and COD of **63 mg/L,** both exceeding WHO limits (<5 mg/L and <10 mg/L, respectively). These elevated values point to the infiltration of untreated wastewater and industrial effluents into the subsurface, contributing to the overall organic load during the dry period.

In the **monsoon season**, the results presented in **Table 4** show a general decline in organic load due to dilution by rainwater. For instance, COD dropped from **63 mg/L to 20.3 mg/L** at Bori Navegaon and from **74 mg/L to 12.1 mg/L** at Gadegaon. Nevertheless, certain locations, including **Asan (BOD = 35 mg/L)** and **Nanda (COD = 70 mg/L),** still displayed high organic content, suggesting persistent contamination from surface runoff carrying organic matter and industrial waste.

These results are consistent with observations from industrial regions in **Chhattisgarh and Gujarat,** where rainfall helps reduce but not eliminate organic pollutants in groundwater [38,39]. This highlights the need for stricter control over wastewater disposal and continuous monitoring of groundwater quality to prevent long-term degradation **(Tables 2 and 4).**

4.3. Hardness and Alkalinity

Table 3 presents the **inorganic parameters** measured during **summer 2023**, showing that **total hardness** ranged from **221 mg/L (Bori Navegaon)** to **381 mg/L (Gadegaon),** exceeding the WHO limit of 200 mg/L across all sampling sites. The hardness is mainly attributed to the presence of calcium and magnesium ions released through the dissolution of carbonate and bicarbonate minerals. Similarly, **total alkalinity** values ranged from **285 mg/L (Sangoda)** to **480 mg/L (Gadegaon),** again above the acceptable limit of 200 mg/L. High alkalinity suggests an excess of bicarbonates and carbonates, which, while stabilizing pH, may lead to scaling in pipes and irrigation channels **(Table 3).**

The **monsoon results** in **Table 5** reveal a slight reduction in both parameters due to seasonal recharge but still remain above permissible limits. Total hardness varied between **224 mg/L (Kadholi)** and **357 mg/L (Gadegaon),** and alkalinity ranged from **252 mg/L (Antargaon)** to **509 mg/L (Bori Navegaon) (Table 5).** These consistently high values confirm that the aquifer possesses strong buffering capacity and that **carbonate dissolution and industrial effluents** continue to influence water chemistry even during wet periods.

Persistent hardness and alkalinity not only affect the aesthetic quality of drinking water but also pose potential health concerns such as **gastrointestinal irritation and kidney stone formation,** as reported in earlier studies [40]. Therefore, **periodic testing, softening treatments, and groundwater recharge management** are essential to improve the quality and usability of groundwater in this region.

Table 2: Assessment of Physical and Demand-Related Water Quality Characteristics of Summer 2023

SR. NO	Sampling Sites	pH	Temp (°C)	DO	BOD	COD	TDS (mg/l)	EC (µS/cm)
1.	Bori Navegaon	7.31	35	6.2	27	63	753	1162
2.	Gadegaon	7.22	40	6.1	12	74	717	1095
3.	Sangoda	7.23	42	6.3	22	36	612	958
4.	Antargaon	6.68	39	6.7	2	48	468	780
5.	Kadholi	7.25	39	6	4	8	709	1334
6.	Asan	7.02	41.5	6.2	14.5	12	742	1141
7.	Nanda	6.95	43	6.4	20	36	696	1105
Standard Limit (WHO, 2017)		**6.5 to 8.5**	**-**	**5 mg/l**	**Less than 5mg/l**	**Less than 10mg/l**	**500mg/l**	**400 (µS/cm**

Table 3: Assessment of Inorganic Water Parameters of Summer 2023

SR. NO.	Sampling Sites	Total Alkalinity	Total Hardness	Fluoride (mg/l)
1.	Bori Navegaon	475	221	0.84
2.	Gadegaon	480	381	1.12
3.	Sangoda	285	284	1.3
4.	Antargaon	300	343	1.36
5.	Kadholi	445	246	1.40
6.	Asan	330	331	1.94
7.	Nanda	355	275	2.06
Standard Limit (WHO, 2017)		**200**	**200**	**1.5 mg/L (Maximum)**

Table 4: Assessment of Physical and Demand-Related Water Quality Characteristics of Monsoon 2023

SR. NO.	Sampling Sites	pH	Temp (°C)	DO	BOD	COD	TDS (mg/l)	EC (µS/cm)
1.	**Bori Navegaon**	8.1	28	6	BQL	20.3	724	1116
2.	**Gadegaon**	7.91	30	6.9	15	12.1	690	1058
3.	**Sangoda**	7.58	30	6.8	20	12.1	600	921
4.	**Antargaon**	7.83	29	6.5	BQL	57	450	712
5.	**Kadholi**	8.07	30	6.8	10	33	682	1295
6.	**Asan**	7.75	30	7	35	30	714	1095
7.	**Nanda**	7.79	31	6.8	22	70	670	1062
Standard Limit (WHO, 2017)		**6.5 to 8.5**	**-**	**5 mg/l**	**Less than 5mg/l**	**Less than 10mg/l**	**500mg/l**	**400 µS/cm**

Table 5: Assessment of Inorganic Water Parameters of Monsoon 2023

SR. NO.	Sampling Sites	Total Alkalinity	Total Hardness	Fluoride (mg/l)
1.	**Bori Navegaon**	509	251	0.90
2.	**Gadegaon**	483	357	1.08
3.	**Sangoda**	331	230	0.67
4.	**Antargaon**	252	313	1.39
5.	**Kadholi**	499	224	1.32
6.	**Asan**	430	304	0.87
7	**Nanda**	378	229	1.20
Standard Limit (WHO, 2017)		**200**	**200**	**1.5 mg/L (Maximum)**

4.4. Fluoride Concentration and Health Implications

Fluoride levels during summer (0.84–2.06 mg/L) were particularly concerning. Nanda (2.06 mg/L) and Asan (1.94 mg/L) exceeded the WHO limit of 1.5 mg/L, posing risks of dental fluorosis **(Figure 3)**. Similar exceedances have been reported in fluoride belts of Andhra Pradesh and Maharashtra, where groundwater fluoride concentrations surpass safe levels due to weathering of fluoride-bearing minerals like fluorite and apatite [41].

Figure 4: Clinical Manifestations of Dental Fluorosis in Affected Children

Monsoon sampling indicated significant dilution, with fluoride levels ranging from 0.67 mg/L (Sangoda) to 1.39 mg/L (Antargaon). Notably, only Antargaon approached the critical threshold of 1.5 mg/L, while most sites recorded values below it**.** This highlights the seasonal buffering capacity of monsoon recharge. However, since fluoride re-concentration occurs post-monsoon due to evaporation and reduced recharge, chronic exposure risk remains high throughout the year [42].

Fluoride plays a vital role in the prevention of dental caries when present within recommended limits; however, excessive exposure can result in dental fluorosis and other health complications. The primary risk, dental fluorosis, is particularly evident in children due to higher fluoride intake relative to body weight. In the present study, visible dental discoloration and enamel degradation were observed among rural children from sampling locations with elevated fluoride levels, indicating the adverse effects of prolonged fluoride exposure. At optimal concentrations, fluoride remains safe and beneficial for oral health, but elevated groundwater concentrations significantly increase the risk of fluorosis, particularly in young populations. Similar findings have been reported in Karnataka, India, where fluoride exposure posed a moderate risk to children under eight years of age [43], and in southeastern Turkiye, where high fluoride concentrations were strongly associated with widespread dental fluorosis [44]. Conversely, suboptimal fluoride levels can also impair oral health, underscoring the need for balanced fluoride management [45]. Recent reviews further indicate that community water fluoridation still contributes to caries prevention, though with smaller effect sizes compared to earlier studies [46].

Similarly, High fluoride concentrations have been reported in several parts of South Asia, making groundwater unsuitable for both drinking and irrigation. In the semi-arid region of Dausa district, Rajasthan, fluoride contamination has been linked to the weathering of fluoride-bearing rocks, intense evaporation, and human activities, rendering groundwater unfit for consumption and agriculture [47]. Similarly, groundwater in South Punjab, Pakistan, shows elevated fluoride and nitrate concentrations that pose significant non-carcinogenic health risks to local communities, emphasizing the urgent need for effective mitigation and water management strategies [48].

4.5. Comparative Seasonal Dynamics

The observed seasonal pattern reveals a pronounced contrast between summer and monsoon conditions in groundwater quality. During summer, factors such as evapoconcentration and reduced recharge drive the accumulation of dissolved constituents, resulting in elevated concentrations of fluoride, hardness, electrical conductivity (EC), total dissolved solids (TDS), biochemical oxygen demand (BOD), and chemical oxygen demand (COD). This pattern aligns with findings from studies in other fluoride-impacted regions, where the dry season generally promotes increased fluoride mobilization due to greater ion concentration and limited dilution [49]. In contrast, during the monsoon season, enhanced rainfall and groundwater recharge dilute contaminant loads, lowering fluoride concentrations and partially alleviating the concentration of soluble species. However, the persistence of elevated EC, hardness, and alkalinity beyond WHO and national guideline values illustrates that dilution alone is insufficient to restore water quality. Instead, the enduring levels suggest a combined influence of anthropogenic and geogenic drivers such as industrial effluents, evaporation, and rock-water interactions that continuously replenish ion loads. Similar mixed influences have been documented in other regional studies [50], which reported higher EC/TDS in the dry season but persistent hardness above thresholds even after dilution.

Ultimately, these results underscore that while seasonal dilution can temporarily moderate fluoride levels, the baseline hydrochemical footprint shaped by industrial activity and geological substrate ensures that groundwaters remain at risk. These findings emphasize that while seasonal dilution temporarily alleviates fluoride contamination, the persistence of excess hardness and EC underscores the combined impact of industrial activity and geogenic factors on groundwater chemistry.

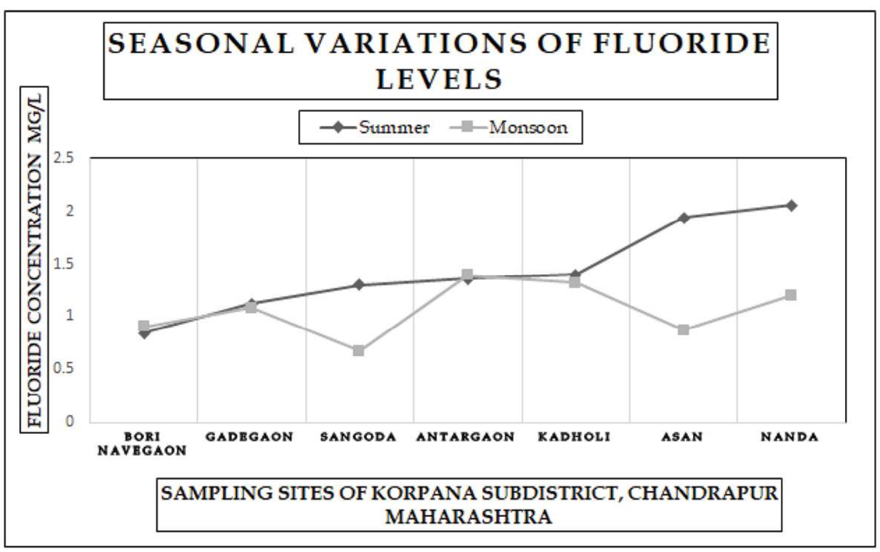

Figure 5: Seasonal variation of fluoride concentration in groundwater across sampling sites of Korpana block (Summer 2023 vs. Monsoon, 2023).

4.6. Implications for Public Health and Management

Chronic consumption of drinking water with fluoride concentrations above 1.5 mg/L is linked to enamel discolouration (dental mottling), progressive bone deformities, and persistent joint pain, as reported in Indian fluorosis-endemic areas [51,52]. Local hydrogeochemical surveys in Korpana have recorded fluoride levels that place residents' children especially at an elevated health risk. Additionally, high water hardness and alkalinity in affected wells have been associated with gastrointestinal upset and a greater likelihood of kidney stone formation [53].

The study highlights the need for integrated mitigation strategies, such as:

- Deployment of low-cost defluoridation technologies (activated alumina, Nalgonda technique).
- Rainwater harvesting and managed aquifer recharge to enhance dilution.
- Community awareness programs for safe water use and preventive health monitoring.
- Strict regulation of industrial effluent discharge to reduce COD/BOD loads.

Such interventions are critical to ensuring safe drinking water security in Chandrapur's industrial belt.

5. Conclusion

The present study provides an in-depth assessment of the temporal dynamics of groundwater quality in the industrial belt of Chandrapur, Maharashtra, with particular emphasis on fluoride contamination. Seasonal analysis revealed that while most physicochemical parameters fell within the general permissible limits for drinking water, several critical indicators, including **total dissolved solids (TDS), electrical conductivity (EC), hardness, and alkalinity,** consistently exceeded the World Health Organization (WHO) recommended standards. These deviations reflect the dual influence of **geogenic mineral dissolution** and **anthropogenic inputs from industrial activities i**n the region.

Fluoride emerged as the most significant contaminant of health concern. Concentrations ranged from **0.84 to 2.06 mg/L in summer**, with two sites (Asan and Nanda) surpassing the WHO guideline limit of 1.5 mg/L, thereby posing a considerable risk of fluorosis. Monsoonal recharge substantially reduced fluoride levels, with concentrations ranging from **0.67 to 1.39 mg/L**, keeping most sites within the safe threshold. This seasonal variation highlights the critical role of rainfall and aquifer recharge in modulating groundwater chemistry, although the persistence of elevated values during dry months suggests chronic exposure risks for local populations.

In addition, high BOD and COD values during summer indicate significant **organic and industrial pollution,** with monsoon dilution offering only temporary relief. Such trends demonstrate the cumulative pressure on groundwater resources from both natural processes and unregulated effluent discharges.

Overall, the findings underscore that **groundwater in the Korpana block is vulnerable to seasonal stress and contamination,** with fluoride contamination being the most pressing issue from a public health perspective. The observed patterns strongly advocate for the implementation of **continuous monitoring systems, sustainable groundwater management strategies, strict industrial effluent regulations, and community-level defluoridation interventions.** Addressing these challenges through an integrated framework will not only mitigate fluoride-associated health risks but also contribute to ensuring **safe and sustainable drinking water security** for the rural population of Chandrapur district.

6. Recommendations

1. Implementation of Continuous Groundwater Monitoring Systems

A decentralized groundwater monitoring network should be established in the industrial belt of Chandrapur. Regular seasonal sampling (pre-monsoon, monsoon, and post-monsoon) with real-time data reporting can provide early warnings of fluoride surges and ionic load fluctuations. Such surveillance systems would help policymakers and local authorities to track contamination trends and intervene promptly.

2. Adoption of Cost-Effective Defluoridation Technologies

Fluoride levels exceeding 1.5 mg/L in sites such as Asan and Nanda highlight the urgent need for treatment solutions. Community-scale defluoridation units based on activated alumina, bone char, and the Nalgonda technique are proven low-cost methods in rural India. Pilot-scale deployment and performance evaluation in Chandrapur villages can guide large-scale adoption.

3. Promotion of Rainwater Harvesting and Managed Aquifer Recharge (MAR)

Monsoon recharge significantly diluted fluoride concentrations in this study. This suggests that rainwater harvesting and aquifer recharge structures can be leveraged to sustain dilution year-round. Artificial recharge using percolation tanks, recharge wells, and farm ponds can reduce contaminant concentrations while enhancing groundwater sustainability.

4. Industrial Effluent Regulation and Treatment

Elevated BOD and COD levels in summer samples indicate anthropogenic organic loading, likely from untreated or partially treated industrial discharges. Strengthening of effluent treatment plant (ETP) compliance, regular audits, and strict enforcement of discharge standards under the Water (Prevention and Control of Pollution) Act, 1974, are essential to protect groundwater from further degradation.

5. Development of Alternative Drinking Water Sources

For villages with persistent fluoride contamination, safe surface water sources, piped water supply schemes, and community-based desalination units should be prioritized. Blending high-fluoride groundwater with low-fluoride sources may also be adopted as a short-term mitigation strategy.

6. Public Health Interventions and Community Awareness

Health surveys in the study area should assess early signs of dental and skeletal fluorosis, especially in children. Awareness campaigns on the safe use of groundwater, boiling practices, and the use of low-fluoride sources during summer months should be prioritized. Training programs for local women's self-help groups and youth organizations can enhance community participation in water safety initiatives.

7. Implement Long-Term Monitoring Programs

Authorities and research institutions should establish systematic, multi-year monitoring of groundwater quality across seasons to identify long-term trends of fluoride and associated contaminants, ensuring early detection of risks.

8. Adopt Isotopic and Geochemical Tracing Approaches

The use of stable isotope techniques ($\delta^{18}O$, $\delta^{2}H$) and hydrogeochemical modeling is recommended to distinguish between geogenic and anthropogenic contributions, thereby guiding more accurate source-based management strategies.

9. Conduct Regular Health Assessments

Public health departments should undertake periodic epidemiological surveys, especially targeting children and vulnerable populations, to assess the prevalence of dental and skeletal fluorosis and quantify community-level health impacts.

10. Promote Low-Cost Mitigation Technologies

Local governments and NGOs should encourage field-level adoption of defluoridation techniques such as activated alumina, bone char, and the

Nalgonda method, along with rainwater harvesting systems, to provide affordable and safe alternatives in rural areas.

11. Develop Geospatial Risk Maps

Integration of GIS-based groundwater vulnerability assessments with population and health data is recommended to identify high-risk areas, priorit-ize interventions, and support evidence-based policymaking for sustainable water management.

12. Integration of Geospatial and Hydrogeochemical Modeling

To better predict fluoride distribution, GIS-based vulnerability mapping and hydrogeochemical modeling should be undertaken. Such approaches can identify fluoride hotspots, seasonal shifts, and recharge pathways, aiding in targeted interventions and sustainable water resource management.

13. Policy-Level Interventions for Water Security

The findings highlight the need for district-level water safety plans under the National Rural Drinking Water Programme (NRDWP) with explicit provisions for fluoride control. Allocation of state and central funds for infrastructure, combined with academic–government partnerships, can ensure long-term mitigation and community resilience

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8. Author Contributions

Dipti G. Iyer: Conceptualization, methodology design, data collection, data analysis, and preparation of the original draft.

Dr (Mrs.) Vaishali P. Meshram: Conceptualization, methodological guidance, supervision, critical review, and editing of the manuscript.

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10. Conflict of Interest

The authors declare that they have no known financial or non-financial conflicts of interest that could have appeared to influence the work reported in this paper.

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