Groundwater Quality and Ecological Implications in the Industrial Twin Cities of Surendranagar and Wadhavan, Gujarat

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Abstract

Groundwater serves as an essential natural resource, underpinning domestic consumption, enhancing agricultural output, and maintaining ecosystem balance. The rapid pace of industrialization and urban expansion has significantly impacted groundwater quality in various regions of India, leading to heightened concerns about environmental sustainability and ecological well-being. This study examines the quality of groundwater, the impact of industrial pollution, and the correlation with plant diversity in the industrial twin cities of Surendranagar and Wadhavan, Gujarat, India. The area exhibits a diverse array of industrial operations, encompassing textiles, chemicals, pharmaceuticals, ceramics, engineering sectors, and traditional dyeing methods like Bandhani. These activities place considerable strain on groundwater resources due to effluent discharge, poor waste management, and extensive groundwater extraction.

This research delineates the characteristics of the study area, provides a summary of essential groundwater quality parameters, and details the standard analytical methods and Water Quality Index (WQI) methodologies typically employed for groundwater assessment. The discussion extends to the potential ecological consequences of groundwater quality degradation, specifically its impact on soil characteristics, the health of vegetation, and the diversity of plant life. This document emphasizes the necessity of systematic groundwater monitoring, sustainable industrial practices, and integrated water resource management by synthesizing existing knowledge and pinpointing key environmental issues, thereby enhancing environmental resilience in regions undergoing industrial development.

Keywords: Groundwater quality, Environmental resilience, Industrial pollution, Water Quality Index (WQI), Plant diversity, Surendranagar, Wadhavan

1. Introduction

Groundwater represents a significant segment of the global freshwater supply and acts as the main source for drinking water, irrigation, and industrial applications in numerous areas. Water is found below the Earth's surface in soil and rock formations referred to as aquifers, where it gradually flows through pores, fractures, and interstitial spaces. Groundwater is essential for maintaining hydrological balance, as it contributes to the recharge of rivers, lakes, wetlands, and springs, particularly in semi-arid and arid areas. In India, a substantial portion of freshwater usage is derived from groundwater resources. Nonetheless, the combination of over-extraction and pollution from industrial, agricultural, and residential activities has resulted in significant deterioration of groundwater quality. Contaminants originating from industrial discharges, waste disposal sites, sewage systems, and agricultural runoff can infiltrate soil strata, leading to the development of contaminant plumes in aquifers. The dispersion of these plumes can cover extensive regions and ultimately come into contact with drinking water wells, presenting significant threats to both human health and ecological systems.

The relationship between the chemistry of groundwater and the surrounding geological formations plays a crucial role in defining the natural composition of groundwater. The typical dissolved constituents consist of ions such as calcium, magnesium, sodium, bicarbonate, sulphate, and chloride. Human activities contribute to increased levels of nitrates, phosphates, heavy metals, oil and grease, along with various other harmful substances. The stratigraphic characteristics of a region, encompassing sandy soils, fractured bedrock, clay layers, and karst limestone formations, significantly affect the movement and longevity of pollutants.
Surendranagar and Wadhavan are industrial twin cities located in the central region of Gujarat, India, along the banks of the Bhogavo River. The region experiences extreme climatic conditions, with temperatures ranging from 7.8°C to 45.6°C and an average annual rainfall of about 760 mm. The area falls under Seismic Zone III and is rich in mineral resources such as silica sand, fire clay, white clay, and moulding sand. Over the past few decades, the growth of small-scale and large-scale industries has intensified pressure on groundwater resources, raising concerns about water quality and its impact on surrounding vegetation and plant diversity. Environmental resilience refers to the capacity of ecosystems to withstand, adapt to, and recover from environmental stressors such as pollution. Groundwater quality directly affects soil chemistry, plant nutrient availability, and overall vegetation health. Therefore, assessing groundwater quality and understanding its ecological implications are essential for sustainable development in industrial regions.

2. Environmental Context of the Industrial Study Area

Surendranagar district is home to over 8,600 registered small-scale industrial units that function across various sectors, including textiles, chemicals, ceramics, food processing, pharmaceuticals, engineering goods, rubber, and dyes. Notable entities in the industrial sector comprise PepsiCo India Holding Ltd., Mepro Pharmaceuticals, Luxite Industries, Rimtex Group, Biodeal Laboratories, and Panama Group. Wadhavan is notably recognized for its traditional Bandhani textile sector.
Industrial clusters frequently exist near residential and agricultural zones, heightening the risk of groundwater contamination. The reliance of local communities on groundwater for drinking, irrigation, and domestic purposes underscores the importance of evaluating groundwater quality in the area.

3. Literature Review

The evaluation of groundwater quality has emerged as a pivotal focus within environmental science, driven by escalating human-induced pressures including industrialization, urbanization, and intensive agricultural practices. A multitude of national and international research efforts have highlighted that groundwater contamination tends to be subtle, enduring, and challenging to address, underscoring the necessity for early evaluation and ongoing surveillance.

3.1 Assessment of Groundwater Quality Based on Physico-Chemical Characteristics

Initial investigations conducted by Trivedi and Goel (1986) alongside Rao and Datta (1979) laid down standardized chemical and biological techniques for assessing water quality, thereby establishing a crucial groundwork for subsequent groundwater research in India. The studies emphasized that factors including pH, electrical conductivity (EC), total dissolved solids (TDS), hardness, alkalinity, chloride, sulphate, nitrate, and fluoride serve as essential indicators for assessing the suitability of groundwater for drinking, irrigation, and ecological sustainability.

Gupta et al. conducted an examination of drinking water quality in Delhi, revealing that swift urban growth and industrial effluents have notably impacted groundwater chemistry, leading to elevated levels of TDS, hardness, and nitrates that exceed acceptable thresholds. Comparable findings were documented by Kavitha and Elangovan (2010) in the Erode district of Tamil Nadu, indicating a strong correlation between the decline in groundwater quality and the activities of textile and dyeing industries.

Manjesh Kumar and Ramesh Kumar (2013) conducted an assessment of groundwater quality in granite mining regions of Jhansi, noting increased levels of calcium, magnesium, nitrate, and fluoride. Their investigation highlighted that mining and related industrial operations play a substantial role in groundwater contamination due to leaching and inadequate waste management practices.

3.2 Application of Water Quality Index in Groundwater Quality Assessment

The Water Quality Index (WQI) serves as a valuable instrument for synthesizing various water quality parameters into a singular numerical representation, thereby enhancing the accessibility of water quality data for both policymakers and the broader public. Tiwari and Ali Manzoor (1988) were pioneers in the application of WQI concepts to Indian rivers, demonstrating its significance in ecological and pollution research.

Shivasharanappa et al. (2011) conducted an assessment of groundwater quality in Bidar city, Karnataka, utilizing seventeen physicochemical parameters to analyze both residential and industrial areas. The results indicated that the quality of groundwater in industrial regions was significantly inferior compared to that in residential areas, highlighting the impact of industrial discharges.

Sirajudeen et al. (2013) conducted an assessment of groundwater quality through the application of WQI in the Tiruchirappalli district, revealing alarmingly high WQI values ranging from 244 to 383.8. This finding underscores the critical level of pollution present and highlights the urgent need for treatment before any consumption. Rajankar et al. (2013) performed analogous investigations in the Wardha district of Maharashtra, validating that the Water Quality Index accurately represents the combined effects of pollution from industrial, agricultural, and domestic sources.

Rosu et al. (2011) illustrated the use of WQI for monitoring rural groundwater in Romania, highlighting that even areas without industrial activity can face groundwater deterioration as a result of poor sanitation and agricultural runoff.

3.3 Industrial Effluent-Induced Groundwater Contamination

A number of studies have highlighted the significant connection between industrial operations and the pollution of groundwater resources. Ramakrishna et al. (2009) conducted an investigation into the groundwater quality in Visakhapatnam, a coastal city undergoing rapid industrialization. Their findings revealed a significant presence of heavy metals, elevated salinity levels, and organic pollutants, particularly in areas characterized by industrial activity and slum conditions. The researchers identified these conditions as a result of unregulated industrial discharge and excessive groundwater extraction.

Amaliya and Sugirtha Kumar (2013) conducted an evaluation of groundwater quality in the Kanyakumari district through the application of Water Quality Index (WQI). Their findings highlighted the spatial variability in water quality, indicating that specific bore wells exhibited elevated levels of contamination. The findings of their research underscored the significant impact of localized industrial and human activities on the chemistry of groundwater.

3.4 Ecological Implications of Groundwater Quality on Plant Diversity

In addition to its relevance for human use, the quality of groundwater carries substantial ecological consequences. Stewart (1974) and Bernhart (1973) highlighted that groundwater contamination can modify soil chemistry, decrease nutrient availability, and hinder plant physiological processes. High levels of fluoride, sodium, and heavy metals have been recognized as harmful to plant health, resulting in diminished growth, chlorosis, and a decline in biodiversity.

Recent investigations conducted before 2016 have shown a growing correlation between groundwater deterioration and diminished environmental resilience, especially in semi-arid and industrial areas. Alterations in groundwater quality impact soil salinity, microbial activity, and nutrient cycling, which in turn affect plant diversity and the stability of ecosystems.

3.5 Synthesis of Literature and Identified Knowledge Gaps

A review of existing literature reveals that significant research has been conducted on the evaluation of groundwater quality through the use of physico-chemical parameters and Water Quality Index (WQI) methodologies in various regions both within India and internationally. A multitude of studies has effectively illustrated the impact of industrialization, urbanization, and agricultural methods on groundwater chemistry, especially within major metropolitan areas and densely industrialized regions. The research centers on assessing the appropriateness of groundwater for consumption and household use through a comparative analysis of observed parameters against established national and international benchmarks.

Nonetheless, there are still significant deficiencies that need to be addressed. Initially, there has been a lack of focus on medium-scale industrial cities like Surendranagar and Wadhavan, even though they are experiencing significant industrial growth and a rising reliance on groundwater resources. Secondly, a significant number of groundwater investigations focus on the classification of water quality, often neglecting to incorporate ecological aspects, especially the connection between groundwater quality and plant diversity. The ecological implications of groundwater pollution, particularly regarding soil chemistry, plant vitality, and ecosystem robustness, are still insufficiently investigated.

Moreover, limited research endeavors have sought to integrate a comprehensive evaluation that encompasses industrial activity patterns, hydrogeological features, and environmental resilience into a unified framework. The influence of particular contaminants, including fluoride, salinity, nutrients, oil and grease, and heavy metals, on plant physiological responses and species composition remains inadequately recorded in the industrial areas of semi-arid Gujarat.
Consequently, it is essential to provide a comprehensive overview that connects the evaluation of groundwater quality with the effects of industrial activities and their ecological consequences, with a particular emphasis on environmental resilience and the diversity of plant life. Filling this research gap will enhance our comprehension of ecosystems reliant on groundwater and aid in the sustainable management of groundwater resources and environmental planning in regions undergoing industrial development.

4. Materials and Methods : Groundwater Quality Parameters and Analytical Methods

4.1 Sampling and Standards

The evaluation of groundwater quality was conducted in accordance with the established protocols set forth by the American Public Health Association (APHA), the Bureau of Indian Standards (BIS), and the World Health Organization (WHO). Groundwater samples were obtained from designated sites within the industrial areas utilizing clean, pre-washed polyethylene containers. Samples were carefully preserved and transported to the laboratory under controlled conditions to avoid any physicochemical changes before analysis.

4.2 Physico-Chemical Parameters

The measurement of Electrical Conductivity (EC) was conducted to evaluate the ionic concentration and salinity levels in groundwater, reflecting the presence of dissolved salts originating from both natural and human-induced sources. The assessment of Total Dissolved Solids (TDS) was conducted to measure the overall mineral composition found in the water samples.
The measurement of hydrogen ion concentration (pH) was conducted to assess the acidity or alkalinity of groundwater, given that pH plays a critical role in chemical equilibria, metal solubility, and the biological availability of nutrients. The analysis focused on Dissolved Oxygen (DO), Biological Oxygen Demand (BOD), and Chemical Oxygen Demand (COD) to assess the oxygen levels and the organic pollution load present in groundwater. Dissolved oxygen was quantified through iodometric techniques, whereas biochemical oxygen demand and chemical oxygen demand were assessed to evaluate the presence of biodegradable and chemically oxidizable organic substances, respectively.
The analysis of alkalinity and total hardness was conducted to assess the buffering capacity and mineral composition of groundwater. The concentrations of calcium and magnesium were assessed to determine hardness characteristics and their impact on soil properties and nutrient absorption by plants.

4.3 Nutrients and Principal Ions

The analysis focused on nutrient parameters including nitrate (NO_3^-), phosphate (PO_4^{3-}), and sulphate (SO_4^{2-}) to evaluate nutrient enrichment and the associated risks of eutrophication. Increased levels of these parameters suggest the influence of industrial discharge, agricultural runoff, and sewage infiltration.
Chloride (Cl^-) and fluoride (F^-) were quantified as markers of both industrial and geogenic contamination. The concentration of chloride serves as an indicator of wastewater intrusion and the processes of evaporation, whereas fluoride levels were evaluated for their ecological impact and potential phytotoxicity.

The concentrations of sodium (Na^+) and potassium (K^+) were assessed to analyze the suitability of groundwater for irrigation purposes and to understand their potential impacts on soil structure and plant growth.

4.4 Organic Pollutants and Heavy Metals

The analysis of oil and grease content was conducted to determine the presence of hydrocarbon contamination linked to industrial activities. Heavy metals including arsenic (As), cadmium (Cd), chromium (Cr), and various trace metals were measured owing to their harmful effects, durability, and ability to accumulate in soil–plant systems.

4.5 Analytical Techniques

Standard laboratory techniques were employed to analyze the physico-chemical parameters. Titrimetric techniques were utilized to ascertain the levels of alkalinity, hardness, and chloride. The analysis of nutrients such as nitrate, phosphate, and sulphate was conducted using UV–Visible spectrophotometry. The application of flame photometry facilitated the estimation of sodium and potassium concentrations. Heavy metal analysis was conducted using atomic absorption spectrometry (AAS), whereas gravimetric methods were utilized for determining total dissolved solids and oil and grease content.

5. Environmental Resilience and Plant Diversity

The quality of groundwater plays a crucial role in determining soil chemistry and the availability of essential nutrients, which in turn impacts plant diversity and productivity. Increased salinity, the presence of heavy metals, and toxic ions can negatively affect plant physiological processes, diminish species richness, and modify community composition. Fluoride and heavy metals are well-documented for their detrimental effects on plant health. Robust groundwater systems contribute to the resilience of ecosystems by sustaining a variety of plant communities that can adjust to environmental stresses.

6. Conclusion

The overview highlights that the quality of groundwater in industrial areas such as Surendranagar and Wadhavan is facing heightened pressure as a result of swift industrial development and urban expansion. A thorough evaluation utilizing physicochemical parameters and the Water Quality Index offers significant understanding of water appropriateness and its ecological effects. Ensuring the quality of groundwater is crucial for safeguarding human health as well as for preserving plant diversity and enhancing environmental resilience. The implementation of sustainable industrial practices, along with efficient waste management and ongoing monitoring, is essential for the protection of groundwater resources in the area.

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