RESEARCH PAPER

Evaluation of Heavy Metal Pollution Index and Metal Index of Peri-Urban Area's Aquifers of Vadodara Region Gujarat

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ABSTRACT
Groundwater is vital for residential, agricultural, and industrial use. Nonetheless, increasing urbanization, industrialization, and agricultural advancement have intensified groundwater heavy metal contamination, particularly in peri-urban regions. This study analyzed the concentration and distribution of specific heavy metals in groundwater aquifers in peri-urban Vadodara, Gujarat, and evaluated the acceptability of groundwater for drinking using the HPI and MI. The research incorporated secondary data from academic literature, governmental documents, and environmental databases. Iron, zinc, copper, cadmium, chromium, nickel, and lead were evaluated against drinking water standards. Zinc, copper, and chromium were the predominant heavy metal contaminants, exhibiting notable regional and seasonal variations. HPI readings consistently fell below the critical threshold, whereas MI values indicated that the majority of groundwater samples were either highly pure or minimally affected. The groundwater quality in the study area was generally suitable for consumption; nevertheless, specific contamination hotspots indicated the necessity for ongoing monitoring, pollution mitigation, and sustainable groundwater management practices.

Keywords: Groundwater Quality; Heavy Metal Pollution Index (HPI); Metal Index (MI); Heavy Metal Contamination; Peri-Urban Aquifers; Vadodara Region, Gujarat

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1. INTRODUCTION

Groundwater is a crucial freshwater resource that significantly contributes to fulfilling household, agricultural, and industrial water requirements [1]. It functions as a dependable source of potable water for billions globally, especially in areas where surface water is limited or susceptible to pollution [2]. Groundwater typically exhibits superior quality and reduced vulnerability to waterborne infections as a result of natural filtration through soil and rock strata. Groundwater is extensively utilized for irrigation in agriculture, bolstering agricultural output, food security, and rural livelihoods, particularly in arid and semi-arid countries [3]. It ensures a reliable water supply during times of insufficient precipitation and drought. Groundwater is essential for industrial activities such as manufacturing, processing, and cooling operations, therefore fostering economic growth and job creation [4]. Its constant availability and accessibility via wells and boreholes render it a desirable resource across various geographical contexts. Consequently, the sustainable management of groundwater resources is essential to guarantee long-term water security and environmental sustainability for current and future generations [5].

Groundwater contamination by heavy metals frequently arises from anthropogenic activity, notably mining, smelting, and mineral processing operations. Correlation analysis and principal component analysis (PCA) indicate that metals like zinc (Zn), cadmium (Cd), and copper (Cu) often co-occur, suggesting a shared source of contamination [6]. Wastewater produced by smelting and mineral-processing businesses can significantly contaminate adjacent soils and groundwater with these metals [7]. Moreover, effluent from mine tailings and waste disposal sites facilitates the migration of heavy metals through soil and leachate into aquifers [8]. Increased levels of Cu, Zn, and Cd in groundwater are frequently linked to industrial discharges and polluted soils adjacent to mining sites. These findings underscore the substantial impact of industrial and mining operations on the degradation of groundwater quality and the buildup of hazardous metals in aquifers [9].

Heavy metal contamination poses a significant environmental and public health issue owing to its persistence, toxicity, and propensity to bioaccumulate in ecosystems. Metals like cadmium, lead, mercury, arsenic, chromium, copper, and zinc are emitted into the environment by industrial processes, mining operations, wastewater discharge, and inadequate waste disposal [10].

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In contrast to numerous contaminants, heavy metals are non-biodegradable and can endure in soil and water for extended durations [11]. Their accumulation negatively impacts soil fertility, water quality, and ecosystem health, endangering plants, animals, and microbes. Human exposure transpires via contaminated food, drink, and air, resulting in bioaccumulation within the organism [12]. Extended exposure to heavy metals can result in significant health consequences, including neurological diseases, developmental anomalies, organ impairment, metabolic malfunction, and cancer. Consequently, regulating heavy metal pollution is crucial for environmental sustainability and the safeguarding of public health [13].

Evaluating groundwater pollution is essential for guaranteeing potable water and safeguarding public health. Groundwater may be polluted by industrial discharges, agricultural runoff, urban garbage, and natural geological phenomena. Consistent monitoring facilitates the identification of contaminants, evaluates their distribution and migration, pinpoints pollution sources, and assesses related environmental and health concerns. Consequently, ongoing assessment of groundwater pollution is crucial for protecting both human communities and ecosystems [14].

The Heavy Metal Pollution Index (HPI) is a widely utilized instrument for assessing water quality, specifically measuring the extent of heavy metal contamination in aquatic environments. It consolidates the concentrations of multiple heavy metals into a singular numerical value by allocating weights according to their relative importance and allowable thresholds. The HPI offers a straightforward and efficient method for evaluating the cumulative effects of heavy metals on water quality [15]. The index facilitates the identification of pollution levels, the comparison of water samples, and the assessment of their fitness for consumption. An HPI score over the critical threshold of 100 signifies substantial heavy metal contamination and associated health hazards to humans [16].

The Metal Index (MI) serves as a crucial metric for assessing the impact of heavy metals on water quality and public health. The calculation involves comparing the measured concentrations of metals to their maximum permissible levels in drinking water standards [17]. MI offers a clear evaluation of pollution levels and assists in assessing the appropriateness of water for residential and potable use. Elevated MI values signify heightened metal contamination and augmented health concerns linked to water intake [18]. An MI value exceeding one often serves as a cautionary indicator, implying a decline in water quality and the necessity for corrective actions.

Indices like the Water Quality Index (WQI), Heavy Metal Pollution Index (HPI), and Metal Index (MI) are extensively utilized in groundwater quality research to assess the effects of natural and anthropogenic activities on water resources [19]. These indices amalgamate various water quality metrics into a singular value, hence facilitating the comprehension of intricate information. They evaluate the appropriateness of groundwater for potable and residential use, ascertain pollution levels, and contrast water quality among various places. Moreover, index-based evaluations facilitate efficient groundwater management, pollution surveillance, and informed decision-making by offering a comprehensive understanding of groundwater quality and related environmental and health hazards [20].

Peri-urban regions are transitional areas situated between urban and rural zones, distinguished by swift population increase, urban sprawl, and evolving land-use patterns. These regions frequently display a blend of residential, industrial, commercial, and agricultural operations, resulting in a distinctive socio-economic landscape. Peri-urbanization is propelled by migration, economic advancement, and the encroachment of urban areas into adjacent rural territories. Consequently, agricultural land is often transformed into developed regions, intensifying the strain on infrastructure, water supplies, and environmental quality. The dynamic characteristics of peri-urban zones render them significant for the examination of urban growth, resource management, and environmental sustainability [21].

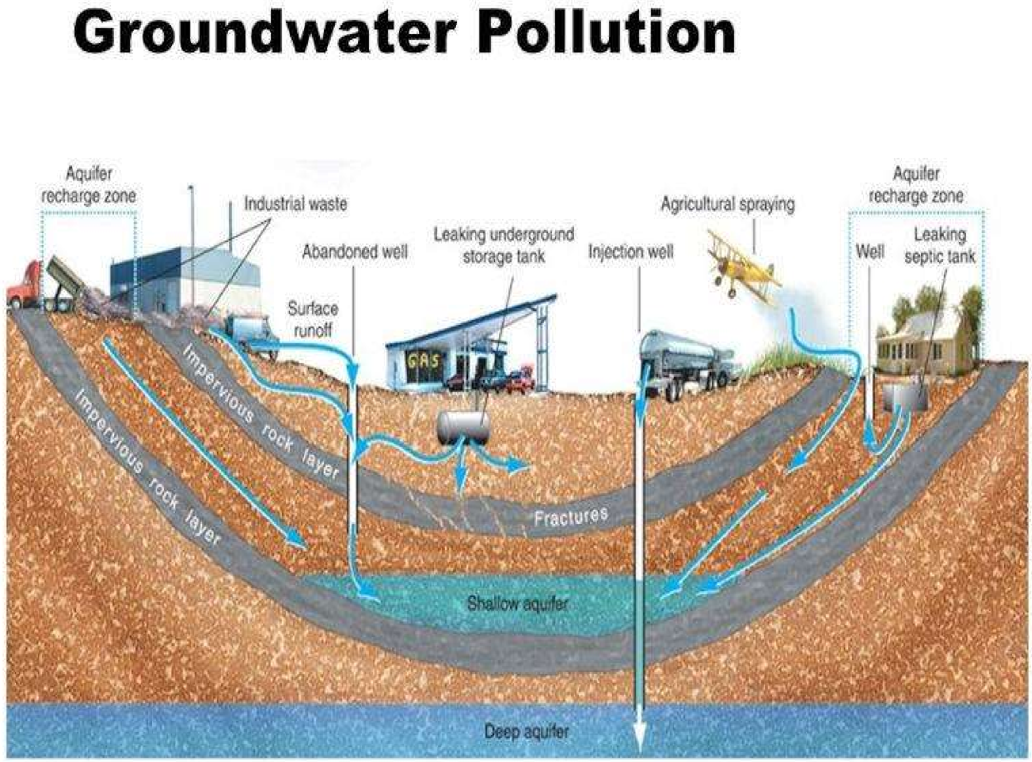

Figure 1. Conceptual illustration of major groundwater pollution sources and contaminant transport pathways.

Urbanization, industrial operations, and agricultural methods significantly influence aquifer quality. Accelerated development enhances impermeable surfaces, diminishing groundwater recharge and facilitating pollutant infiltration. Industrial operations emit heavy metals, chemicals, and untreated effluents that may pollute groundwater resources [22]. Agricultural practices, especially the overapplication of fertilizers and pesticides, introduce nitrates and other pollutants that into aquifers. Moreover, sewage discharge and domestic wastewater exacerbate the degradation of groundwater quality. Human activities modify the natural composition of groundwater, rendering it less appropriate for consumption and other uses. Consequently, sustainable land-use planning and pollution management are crucial for aquifer preservation [23].

Assessing groundwater quality in peri-urban regions is crucial for sustainable water resource management, given the escalating pressures from urbanization, industrialization, and agricultural practices. Peri-urban areas frequently undergo swift alterations in land use, resulting in the pollution of aquifers by heavy metals, fertilizers, and various contaminants. Routine groundwater quality evaluation aids in identifying pollution sources, tracking alterations in water quality, and assessing the appropriateness of groundwater for potable, agricultural, and home applications. Such assessments facilitate informed decision-making, pollution mitigation strategies, and efficient resource allocation. Thus, monitoring groundwater quality is essential for safeguarding public health, conserving ecosystems, and guaranteeing long-term water security.

2. REVIEW OF LITERATURE

Patel et al.,(2026) discussed The present study examined the seasonal variability, pollution status, ecological and human-health concerns of heavy metals in soils from the Jambuva municipal dump in Vadodara, Gujarat, India. In all seasons, the average concentrations of Fe (1404 mg/kg), Mn (46.4 mg/kg), Zn (28.6 mg/kg), Cr (8.35 mg/kg), Cu (8.18 mg/kg), Ni (2.59 mg/kg), Co (2.05 mg/kg), Pb (1.52 mg/kg), and Cd (0.65 mg/kg) showed clear anthropogenic enrichment, with some metals exceeding background Dilution, runoff, and leaching decreased metal concentrations during the monsoon, but pollutants re-accumulated in surface soils afterward. The pollution indicators (Igeo, Cf, Ef) showed considerable anthropogenic influence for Cd, Cr, Ni, and Pb. Cd had the highest enrichment and contamination, and ecological-risk evaluation revealed Cd and Cr as the main ecological hazards. Cr was the highest non-carcinogenic risk, mostly from dermal contact, and Cr and Ni exceeded USEPA recommended levels for adults and children. PCA indicated common anthropogenic origins, while two-way ANOVA showed substantial seasonal impacts ($p < .05$) on all metals and organic matter. These findings emphasize the need for better waste management and environmental monitoring [24].

Rana et al.,(2024) noted Road dust heavy metals can harm health through eating, inhalation, and skin contact. This study examined heavy metal contamination, distribution, and health effects in Bangladeshi industrial, capital city, and peri-urban street dust. ICP-MS investigated eight toxic heavy metals: Zn, Cu, Pb, Ni, Mn, Cr, Cd, and Co. Industrial areas had the greatest metal concentrations (Mn > Zn > Cr > Pb > Ni > Co > Cd) with average levels of 444.35, 299.25, 238.31, 54.22, 52.78, 45.66, and 2.73 mg/kg for small particles (≤20 μm). Conversely, multivariate statistical methods assessed pollution levels and sources. Traffic emissions, building, and industrial operations caused most pollution. Industrial areas had a pollutant load index of 2.45, while the capital city and peri-urban areas had 1.54 and 1.59. Hazard index values were below safety level 1, but health risk evaluations showed increased non-carcinogenic risks for children, particularly from Cr, Ni, Cd, and Pb. Cr poses the highest cancer risk via inhalation, with values of 1.13×10^{-4}–5.96×10^{-4}, falling within the threshold (10^{-4} to 10^{-6}) These findings emphasize the necessity for environmental monitoring and pollution control to reduce health risks [25].

Chaudharı et al.,(2024) discussed Groundwater is crucial to a large population in Gujarat, India. However, heavy metal contamination, especially drinking water, poses a major health risk. Recent significant industrial and agricultural growth has increased heavy metal contamination in the state. This study employs the Heavy Metal Pollution Index to measure Gujarati groundwater heavy metal contamination. The investigation covers the entire state's diverse physical, climatic, topographical, and geographical circumstances. HPI values from individual studies show heavy metal contamination. The findings highlight Gujarat's groundwater heavy metal contamination and health hazards. The Heavy Metal Evaluation Index, Degree of Contamination, Metal Index, and Water Pollution Index are other contamination indicators. These indices measure pollution by comparing heavy metal concentrations to limitations. The purpose is to help investors and regulators manage and minimize heavy metal contamination across the state. Additionally, the article examines ecologically acceptable, economically viable heavy metal removal methods for aquatic systems to protect the ecosystem. This study uses pollution indicators and remedial strategies to reduce heavy metal contamination in Gujarat groundwater [26].

Sanad et al.,(2024) conducted Groundwater, essential for irrigation and drinking, affects human health and society. This study analyzes thirty samples from diverse locations using thirty-three physicochemical criteria to assess groundwater quality in Mnasra, Gharb Plain. The Pollution Index of Groundwater (PIG), Nitrate Pollution Index (NPI), Water Quality Index (WQI), Irrigation Water Quality Index (IWQI), Multivariate Statistical Approaches (MSA), and Geographic Information System (GIS) are used to identify groundwater pollution sources. The study found Ca^{2+} as the dominant cation and Cl^- as the main anion. The Piper and Gibbs diagrams showed the importance of water-rock interactions and the common Ca^{2+}-Cl^- water type. 86.66% of samples had "Insignificant pollution" PIG scores. NPI had 1.48 to 7.06 nitrate contamination, with 83.33% of samples classified "Good" for drinking by the WQI. According to the IWQI, 80% of samples were "Excellent" and 16.66% were "Good". Agriculture heavily contaminated the eastern and southern regions, according to spatial study. These findings help Gharb decision-makers manage groundwater resources and promote sustainable water management [27].

Sarhat et al.,(2023) assessed The study uses two recent heavy metal pollution indicators, HIP and MI, to assess Sirwan River water quality. Twenty-four stations and the Sirwan River from downstream of Darbandikhan Dam to Jalawlaa Sub-district were sampled this term. Use of an Inductively Coupled Plasma Spectrometer (ICP) was used to examine seven heavy metals: Al, Fe, Zn, Cd, Pb, Ni, and Cr. The average HPI score for drinking and irrigation usage was (47.2) and (12.8), respectively, indicating that Sirwan River water is highly polluted for drinking but pure for irrigation. For residential and irrigation purposes, (MI) was (5.7) (seriously impacted) and (0.65) (pure). Thus, the study showed how man-made sources pollute Sirwan River water [28].

Patel et al.,(2023) stated Unlike surface water, groundwater is used for drinking, agriculture, and industry. Regular quality assessments and water resource maintenance are needed. Water Quality Index is the most used analytical approach for defining and measuring water quality. This study uses the WQI to evaluate South Gujarat groundwater quality. This study examines pH, turbidity, total dissolved solids, total hardness, calcium, magnesium, chloride, sulphate, nitrate, fluorides, and total alkalinity. Data from 2018–2022 is used. These data are assessed using the Weighted Arithmetic Water Quality Index Technique. The Indian Standard Drinking Water Specification code (IS: 10050-2012) checks parameter potability within permitted limits. The study above found that certain wells' groundwater quality exceeds the WQI. In 2018, four wells were unfit for drinking. Groundwater with a WQI above 51 is detrimental to human health and requires processing before use. For policymakers to define and provide groundwater quality values, this study will be helpful. WQI [29].

Masindi et al.,(2018) stated The environment and its components have been significantly contaminated by heavy metals. This has undermined the environment's capacity to support life and diminish its inherent worth. Heavy metals are naturally occurring substances; nevertheless, human activities significantly increase their presence in various environmental compartments. This diminishes the environment's capacity to support life as the health of humans, animals, and plants is jeopardized. This transpires due to bioaccumulation within food chains, stemming from the nondegradable nature of heavy metals. The remediation of heavy metals necessitates careful consideration to safeguard soil quality, air quality, water quality, human health, animal health, and other interconnected domains. The established physical and chemical cleanup solutions for heavy metals are costly, impractical, time-intensive, and generate additional environmental waste. This chapter encapsulates the issues associated with heavy metal contamination and the diverse remediation technologies available. A case study was conducted in South African mines [30].

Singaraja et al.,(2015) conducted In Thoothukudi District, Tamilnadu, India, the study examines coastal aquifer groundwater heavy metal pollution risk. Districtwide, 80 groundwater samples were taken. A combined technique uses pollution evaluation indices, PCA, and CM to assess groundwater contamination intensity and source. The typical groundwater heavy metal abundance order is Cr [Cu[Pb[Fe [Zn[Ni [Mn [Cd]. The HPI, HEI, and degree of contamination were calculated. HPI, HEI, and Cd spatial distribution maps show higher indices in the north eastern Industrial region (SIPCOT). Factor score maps indicate that landfill leachate and industry are ubiquitous. The correlation matrix of heavy metal elements shows that the groundwater has assimilated contaminants from chemical industry, landfill leachate, and municipal sewage systems in the research area. This study found that tannery and auxiliary effluents and landfill leachate are the main sources of groundwater heavy metal pollution. Heavy metal distribution in groundwater is environmental and health-threatening and needs care [31].

3. OBJECTIVES

a) To evaluate the concentration and distribution of selected heavy metals in groundwater aquifers of the peri-urban areas of the Vadodara region, Gujarat.

b) To assess the extent of groundwater contamination and its suitability for drinking purposes using the Heavy Metal Pollution Index (HPI) and Metal Index (MI).

4. RESEARCH METHODOLOGY

4.1 Research Design

In this study, the authors used descriptive and analytical research methods in secondary research. The aim of this study was to analyze the extent of the contamination of the groundwater aquifers in peri-urban Vadodara, Gujarat by heavy metals and to assess the acceptability of the groundwater for potable use of the city by using the Heavy Metal Pollution Index (HPI) and Metal Index (MI). The data and information used in the research have been obtained from previously published reports and datasets regarding groundwater quality from scientific publications, governmental agencies, environmental monitoring organizations and peer-reviewed publications. To systematically assess water quality and potential environmental hazards, a quantitative method was used to examine the concentration of heavy metals and calculate pollution indices.

4.2 Data Collection

Secondary data sources were used for the research. The groundwater quality data and concentration of heavy metals were collected from published articles of research studies, governmental reports, environmental databases and records of groundwater monitoring relevant to the study area (Vadodara and the surrounding peri-urban area). Heavy metal data (iron (Fe), zinc (Zn), copper (Cu), cadmium (Cd), chromium (Cr), nickel (Ni), and lead (Pb)) were collected from reliable sources. The drinking water standards and allowable levels were obtained from the World Health Organization (WHO) and other reputable agencies. The collected data were thoroughly analyzed, organized, and compiled to ensure consistency, reliability, and relevance to the study's goals.

4.3 Sampling

Due to the reliance on secondary data, purposeful sampling was utilized for the selection of datasets and published studies. Only studies and reports that included comprehensive data on groundwater quality, heavy metal concentrations, and sampling sites within the Vadodara region or similar peri-urban settings were considered. Datasets without complete information, ambiguous methodology, or inadequate heavy metal data were omitted from the analysis. This sampling method guaranteed that only reliable and scientifically substantiated information was employed for the evaluation of groundwater contamination.

4.4 Data Analysis Tools and Techniques

Data gathered was secondary data, analyzed using descriptive statistical techniques, and indicators of groundwater contamination. The presence of heavy metals concentration were assessed based on the acceptable limits recommended by WHO for drinking water. Heavy Metal Pollution Index (HPI) was calculated to determine the level of heavy metal pollution in the groundwater. Various heavy metals were used to calculate the total effect on water quality of the different pollutants using the Metal Index (MI). Data was summarized using statistical methods such as mean, minimum, maximum, etc. and standard deviation. The obtained index values were compared with the criteria for classification to determine the pollution status and health risks associated with ground water use.

4.5 Ethical Considerations

The research did not require direct contact with human or animal subjects and only used secondary data that is publicly available. Ethical research procedures, however, were strictly followed in the investigation. All data sources, research articles, reports and reference materials have been appropriately referenced and attributed for integrity and plagiarism. Steps were taken to ensure accuracy, clarity, and validity of the collected data. The results were interpreted objectively, free from manipulation or misinterpretation of data. The study sought to deliver dependable data that would aid in groundwater quality management and environmental sustainability in the Vadodara region by following to these ethical norms.

5. RESULT AND ANALYSIS

Objective1: To evaluate the concentration and distribution of selected heavy metals in groundwater aquifers of the peri-urban areas of the Vadodara region, Gujarat.

Investigations of groundwater in various parts of Gujarat have consistently indicated substantial spatial and seasonal fluctuations in heavy metal content. Among the examined metals, Zn is frequently recognized as the predominant element with the highest concentration, succeeded by Cu and Cr, signifying their enhanced mobility and accumulation in aquifer systems. Seasonal fluctuations indicate that post-monsoon groundwater typically displays increased concentrations of metals like Cd, Co, Ni, and Pb, while pre-monsoon samples often demonstrate heightened levels of As, Cr, and Mn [32]. The fluctuations indicate that groundwater recharge during monsoon seasons, dilution effects, evaporation rates, and evolving hydrogeological conditions substantially affect the transport and distribution of heavy metals in aquifers. Moreover, numerous studies have indicated the existence of trace heavy metals such as Fe, Zn, Mn, As, and Se, exhibiting an irregular spatial distribution across various groundwater zones [33]. This variability is primarily influenced by aquifer properties, mineral content, and groundwater flow dynamics. The fluctuation in metal content is additionally affected by natural geochemical processes such mineral dissolution, weathering, and rock-water interactions, as well as human activities such as agricultural runoff and industrial discharges. The literature demonstrates that heavy metal concentrations in groundwater aquifers exhibit significant variability both spatially and temporally, influenced by natural hydrogeological conditions and external pollution sources [34].

Table 1. Selected Heavy Metals and Drinking Water Standards

Heavy Metal	Symbol	WHO Permissible Limit (mg/L)	Major Sources of Contamination	Health Effects
Iron	Fe	0.3	Natural weathering, industrial discharge	Staining, taste issues
Zinc	Zn	3.0	Industrial effluents, galvanized materials	Gastrointestinal effects at high levels
Copper	Cu	2.0	Industrial waste, plumbing corrosion	Liver and kidney damage (high exposure)
Cadmium	Cd	0.003	Batteries, fertilizers, industrial waste	Kidney damage, carcinogenic effects
Chromium	Cr	0.05	Electroplating, tanning industries	Cancer risk, skin disorders
Nickel	Ni	0.07	Industrial discharge, metal processing	Allergic reactions, toxicity
Lead	Pb	0.01	Paints, batteries, industrial waste	Neurological disorders, developmental effects

Objective2: To assess the extent of groundwater contamination and its suitability for drinking purposes using the Heavy Metal Pollution Index (HPI) and Metal Index (MI).

Table 2. Groundwater Quality Assessment Based on HPI and MI

Assessment Parameter	Observation in Study	Interpretation
Dominant Heavy Metals	Zn > Cu > Cr	Higher mobility and occurrence in groundwater
Spatial Variation	Present	Uneven distribution across peri-urban aquifers
Seasonal Variation	Present	Influenced by recharge and hydrogeological conditions
Heavy Metal Pollution Index (HPI)	Mostly < 100	Groundwater generally not critically polluted
Metal Index (MI)	Mostly Very Pure to Slightly Affected	Suitable for drinking purposes
Localized Hotspots	Identified	Require monitoring and pollution control
Overall Groundwater Status	Generally Suitable	Continuous monitoring recommended

The evaluation of groundwater quality by the Heavy Metal Pollution Index (HPI) and Metal Index (MI) offers a definitive assessment of contamination levels and the suitability of drinking water in the research region. The HPI results demonstrate that most groundwater samples are classified within the low to medium pollution range, with values consistently below the critical threshold of 100. This indicates that, in general, the groundwater system is not significantly affected by heavy metal contamination. Nevertheless, regional heterogeneity in

HPI values reveals isolated regions with comparatively elevated contamination levels, signifying an unequal distribution of heavy metals across the aquifer system.

The MI results indicate significant variance in groundwater quality among test locations. The majority of samples are categorized as very pure to minimally impacted, indicating generally satisfactory water quality conditions. A lesser percentage of samples is classified as mildly to significantly affected, signifying localized heavy metal enrichment and probable contaminated areas. Increased MI values at specific sites indicate human impact and localized metal deposition.

The comprehensive examination of HPI and MI indicates that although a significant percentage of groundwater samples are potable, several places exhibit contamination that could provide health risks if ingested untreated. The regional variability noted in both indices indicates that groundwater quality is influenced by a blend of natural hydrogeological processes and anthropogenic activity. The findings underscore the necessity of ongoing monitoring and comprehensive evaluation of heavy metal contamination to guarantee safe and sustainable groundwater use in the research region.

6. DISCUSSION

The present study aimed at evaluating the concentration and distribution of certain heavy metals present in groundwater aquifers of peri-urban areas of the Vadodara region in Gujarat and the suitability of the groundwater for drinking purpose by using the Heavy Metal Pollution Index (HPI) and Metal Index (MI). The results show that the distribution of the groundwater contamination by heavy metals is very scattered, indicating the impact of both natural geology and human activities.

The dominance of the metals like zinc, copper and chromium with respect to other metals is consistent with their presence in ground water systems of industrialised areas or other parts of the state, Gujarat, as reported in earlier studies. Chaudhari et al. (2024) also found that heavy metal pollution is a major groundwater quality issue in Gujarat. This is because the distribution of the heavy metals in the aquifer is not uniform, which indicates that local hydrogeologic characteristics, groundwater flow patterns, and land use all have an impact on heavy metal concentrations.

The HPI analysis showed that the concentration of most of the groundwater samples was lower than the critical value (100), thereby suggesting that the groundwater is not highly polluted in the study area. This result is consistent with Sarhat et al. (2023) who observed that contamination in groundwater could not be an issue if the contamination is localized. The presence of areas with comparatively higher HPI values, however, indicates the need for monitoring and management interventions on a site-specific level. This may be due to industrial effluents, waste disposal practices and urbanisation in peri-urban areas causing contamination.

Likewise, the Metal Index (MI) assessment showed that most of the groundwater samples were in very pure to slightly affected category, thus showing good suitability for drinking purpose. However, a small percentage of the samples had moderate contamination and could pose a health risk if drinking this water regularly without treatment. The results corroborate previous research that has highlighted the potential for long term health effects from even moderate exposures to heavy metals stemming from bioaccumulation.

The study concludes that continuous monitoring of groundwater quality is important in the fast growing peri-urban areas. Ground water in the Vadodara area is generally found to be potable but there are localized contamination hotspots, which need immediate attention. In order to sustain groundwater use and safeguard public health, it is crucial to employ effective pollution control measures, practice good waste management, and routinely assess the status of the groundwater with the use of indices, like HPI and MI.

7. CONCLUSION

Groundwater, one of the most valuable sources of freshwater is considered for domestic, agricultural, and industrial use, especially in the peri-urban areas, which are rapidly developing. The present study aimed to evaluate the concentration and distribution of selected heavy metals in the groundwater aquifers of Vadodara, Gujarat and to assess the quality of the groundwater by the application of two indices, Heavy Metal Pollution Index (HPI) and Metal Index (MI). The results indicate that there are several natural hydrogeological phenomena and anthropogenic sources including industrial discharge, urbanization, agricultural runoff and poor waste disposal practices that affect the contamination of groundwater with heavy metals.

Spatial and seasonal variations in the concentrations of heavy metals were found in groundwater aquifers. Some of the most significant contaminants identified were metals, including zinc, copper, and chromium, suggesting increased mobility and persistence within the groundwater system. These variations observed indicate that the distribution and accumulation of heavy metals in aquifers of peri-urban areas are influenced by local geological conditions, recharge patterns from the groundwater, land use and anthropogenic activities.

HPI/MI gave a thorough evaluation of groundwater quality and drinking water suitability. Most HPI values were generally below the critical load, which suggests that in general high concentrations of heavy metals in the environment were not widespread in the study area. Likewise, the majority of groundwater samples in the MI were rated as very pure to slightly affected indicating that a significant portion of the groundwater resources may be used for drinking and domestic purposes. The presence of high index values at some sites, however, indicates areas of local contamination which can be a concern to health if not addressed.

The results highlighted that the quality of groundwater in the peri-urban area of Vadodara is quite satisfactory at present, but it may become more polluted in the future due to the growth of urbanization and industrialization. Hence, it is important and necessary to monitor groundwater continuously and determine the concentrations of these dangerous metals at regular intervals and use pollution indices like HPI and MI for early detection of contamination and effective groundwater management.

Overall, sustainable protection of groundwater sources depends on a multi-sectoral approach combining environmental monitoring, protecting groundwater, waste management and responsible land use planning. These measures will contribute to protecting groundwater resources, public health and to water security for the increasing population of the Vadodara region.

REFERENCE

[1] Li, P., Wu, J., & Shukla, S. (2022). Achieving the One Health Goal: Highlighting Groundwater Quality and Public Health. Water. ; https://doi.org/10.3390/w14213540

[2] Siebert, S., Burke, J., Faurès, J., Frenken, K., Hoogeveen, J., Döll, P., & Portmann, F. (2010). Groundwater use for irrigation - a global inventory. Hydrology and Earth System Sciences, 14, 1863-1880. https://doi.org/10.5194/HESS-14-1863-2010.

[3] Ruud, N., Harter, T., & Naugle, A. (2004). Estimation of groundwater pumping as closure to the water balance of a semi-arid, irrigated agricultural basin. Journal of Hydrology, 297, 51-73. https://doi.org/10.1016/J.JHYDROL.2004.04.014

[4] Gleeson, T., Alley, W., Allen, D., Sophocleous, M., Zhou, Y., Taniguchi, M., & Vandersteen, J. (2012). Towards Sustainable Groundwater Use: Setting Long- Term Goals, Backcasting, and Managing Adaptively. Groundwater, 50. https://doi.org/10.1111/j.1745- 6584.2011.00825.x.

[5] Schmoll, O. (Ed.). (2006). Protecting groundwater for health: managing the quality of drinking-water sources. World Health Organization.

[6] Panda, U. C., Rath, P., Bramha, S., & Sahu, K. C. (2010). Application of factor analysis in geochemical speciation of heavy metals in the sediments of a lake system—Chilika (India): a case study. Journal of Coastal Research, 26(5), 860-868. DOI: 10.2112/08-1077.1

[7] Al-Hobaib, A. S., Al-Jaseem, Q. K., Baioumy, H. M., & Ahmed, A. H. (2013). Heavy metals concentrations and usability of groundwater at Mahd Adh Dhahab gold mine, Saudi Arabia. Arabian Journal of Geosciences, 6(1), 259-270. https://doi.org/10.1007/s12517-011-0344-1

[8] Sun, W., Sang, L., & Jiang, B. (2012). Trace metals in sediments and aquatic plants from the Xiangjiang River, China. Journal of Soils and Sediments, 12(10), 1649-1657. DOI https://doi.org/10.1007/s11368-012-0596-8

[9] Gong, X., Chen, Z., & Luo, Z. (2014). Spatial distribution, temporal variation, and sources of heavy metal pollution in groundwater of a century-old nonferrous metal mining and smelting area in China. Environmental monitoring and assessment, 186(12), 9101-9116. DOI https://doi.org/10.1007/s10661-014-4069-y

[10] Dixit, R., Wasiullah, X., Malaviya, D., Pandiyan, K., Singh, U. B., Sahu, A., ... & Paul, D. (2015). Bioremediation of heavy metals from soil and aquatic environment: an overview of principles and criteria of fundamental processes. Sustainability, 7(2), 2189-2212. https://doi.org/10.3390/su7022189

[11] Gupta Mahendra, K., Kiran, K., Amita, S., & Shikha, G. (2014). Bioremediation of heavy metal polluted environment using resistant bacteria. J. Environ. Res. Develop, 8(4), 883-889.

[12] Chandra, R., Bharagava, R. N., Kapley, A., & Purohit, H. J. (2011). Bacterial diversity, organic pollutants and their metabolites in two aeration lagoons of common effluent treatment plant (CETP) during the degradation and detoxification of tannery wastewater. Bioresource Technology, 102, 2333–2341. 10.1016/j.biortech.2010.10.087

[13] Mishra, S., Bharagava, R. N., More, N., Yadav, A., Zainith, S., Mani, S., & Chowdhary, P. (2018). Heavy metal contamination: an alarming threat to environment and human health. In Environmental biotechnology: For sustainable future (pp. 103-125). Singapore: Springer Singapore. https://doi.org/10.1007/978-981-10-7284-0_5

[14] Wang, Y., Yuan, S., Shi, J., Ma, T., Xie, X., Deng, Y., ... & Jiang, G. (2023). Groundwater quality and health: making the invisible visible. Environmental Science & Technology, 57(13), 5125-5136. https://doi.org/10.1021/acs.est.2c08061

[15] Prasad B, Bose JM (2001) Evaluation of the heavy metal pollution index for surface and spring water near a limestone mining area of the lower Himalayas. Environ Geol 41(1–2):183–188. https://doi.org/10.1007/s002540100380

[16] Dheeraj, V. P., Singh, C. S., Sonkar, A. K., & Kishore, N. (2024). Heavy metal pollution indices estimation and principal component analysis to evaluate the groundwater quality for drinking purposes in coalfield region, India. *Sustainable Water Resources Management*, *10*(1), 31. https://doi.org/10.1007/s40899-023-01013-y

[17] Balakrishnan, A., & Ramu, A. (2016). Evaluation of heavy metal pollution index (HPI) of ground water in and around the coastal area of Gulf of Mannar biosphere and Palk Strait. Journal of Advanced Chemical Sciences, 331-333.

[18] Ameh, E. G., & Akpah, F. A. (2011). Heavy metal pollution indexing and multivariate statistical evaluation of hydrogeochemistry of River PovPov in Itakpe Iron-Ore mining area, Kogi State, Nigeria.

[19] WHO (2011) WHO Guidelines for Drinking-water Quality, fourth ed. World Health Organization

[20] Krishna Kumar, S., Logeshkumaran, A., Magesh, N. S., Godson, P. S., & Chandrasekar, N. (2015). Hydro-geochemistry and application of water quality index (WQI) for groundwater quality assessment, Anna Nagar, part of Chennai City, Tamil Nadu, India. Applied Water Science, 5(4), 335-343. https://doi.org/10.1007/s13201-014-0196-4

[21] Biegańska, J., Środa-Murawska, S., Kruzmetra, Z., & Swiaczny, F. (2018). Peri-urban development as a significant rural development trend.

[22] Paul, M. J., & Meyer, J. L. (2001). Streams in the urban landscape. Annual review of Ecology and Systematics, 32(1), 333-365. https://doi.org/10.1146/annurev.ecolsys.32.081501.114040

[23] Khatri, N., & Tyagi, S. (2015). Influences of natural and anthropogenic factors on surface and groundwater quality in rural and urban areas. Frontiers in life science, 8(1), 23-39. https://doi.org/10.1080/21553769.2014.933716

[24] Patel, J., Mujumdar, S., & Giri Gosai, H. (2026). Assessment of non-carcinogenic and carcinogenic health risks due to heavy metal contamination in MSW landfill soil, Vadodara, Gujarat, India. Soil and Sediment Contamination: An International Journal, 1-36. https://doi.org/10.1080/15320383.2026.2639034

[25] Rana, M. S., Wang, Q., Wang, W., Enyoh, C. E., Islam, M. R., Isobe, Y., & Kabir, M. H. (2024). Sources, distribution, and health implications of heavy metals in street dust across industrial, capital city, and peri-urban areas of Bangladesh. Atmosphere, 15(9), 1088. https://doi.org/10.3390/atmos15091088

[26] Chaudharı, M., Chotalıya, R., Ali, G., Pandya, A., & Shrivastav, P. (2024). Assessment of heavy metal contamination in the groundwater of Gujarat, India using the Heavy Metal Pollution Index. Environmental Research and Technology, 7(3), 471-488. DOI https://doi.org/10.35208/ert.1433696

[27] Sanad, H., Mouhir, L., Zouahri, A., Moussadek, R., El Azhari, H., Yachou, H., ... & Dakak, H. (2024). Assessment of groundwater quality using the pollution index of groundwater (PIG), nitrate pollution index (NPI), water quality index (WQI), multivariate statistical analysis (MSA), and GIS approaches: A case study of the Mnasra Region, Gharb Plain, Morocco. Water, 16(9), 1263. ; https://doi.org/10.3390/w16091263

[28] Sarhat, A. R., & Al-Obaidi, B. S. (2023). Assessment of heavy metal pollution in Sirwan river by heavy metal pollution index (HPI) and metal index (MI). Water Conservation Science and Engineering, 8(1), 12.

[29] Patel DD, Mehta DJ, Azamathulla HM, Shaikh MM, Jha S, Rathnayake U. Application of the weighted arithmetic water quality index in assessing groundwater quality: A case study of the South Gujarat region. Water. 2023 Oct 8;15(19):3512. https://doi.org/10.1007/s41101-023-00187-y

[30] Masindi, V., & Muedi, K. L. (2018). Environmental contamination by heavy metals. Heavy metals, 10(4), 115-133.

[31] Singaraja, C., Chidambaram, S., Srinivasamoorthy, K., Anandhan, P., & Selvam, S. (2015). A study on assessment of credible sources of heavy metal pollution vulnerability in groundwater of Thoothukudi districts, Tamilnadu, India. Water Quality, Exposure and Health, 7(4), 459-467. https://doi.org/10.1007/s12403-015-0162-x

[32] Upadhyaya, D., Survaiya, M. D., Basha, S., Mandal, S. K., Thorat, R. B., Haldar, S., ... & Mody, K. H. (2014). Occurrence and distribution of selected heavy metals and boron in groundwater of the Gulf of Khambhat region, Gujarat, India. Environmental Science and Pollution Research, 21(5), 3880-3890. https://doi.org/10.1007/s11356-013-2376-4

[33] Dubey, M. O. N. I. K. A., & Ujjania, N. (2021). Heavy metal contamination and pollution load index in estuarine environment of Tapi river, India. Asian Journal of Microbiology, Biotechnology and Environmental Sciences, 23, 456-459.

[34] Chaudharı, M., Chotalıya, R., Ali, G., Pandya, A., & Shrivastav, P. (2024). Assessment of heavy metal contamination in the groundwater of Gujarat, India using the Heavy Metal Pollution Index. Environmental Research and Technology, 7(3), 471-488. DOI https://doi.org/10.35208/ert.1433696