IJNRD.ORG ISSN : 2456-4184
INTERNATIONAL JOURNAL OF NOVEL RESEARCH AND DEVELOPMENT (IJNRD) | IJNRD.ORG
An International Open Access, Peer-reviewed, Refereed Journal

Evaluating The Effects Of Soil Contamination On The Quality Of Ground Water In Different Localities Of Bhopal

[1]Divya Bhargava
[1]Research Scholar
[1]Department Of Chemistry,
[1]IES University, Bhopal, India

Abstract : Groundwater is a vital resource that is susceptible to contamination from various anthropogenic sources. This research investigates the impact of soil contamination of groundwater quality across diverse localities in Bhopal, aiming to comprehend the potential risks posed to this vital water resource. Bhopal, a rapidly growing urban center, faces escalating concerns regarding soil pollution due to industrial activities, urbanization, and agricultural practices. This research investigates the intricate relationship between soil contamination and groundwater quality in various localities of Bhopal. Soil and groundwater samples were collected from distinct regions, and a battery of tests was conducted to assess parameters such as pH, electrical conductivity (EC), and concentrations of heavy metals including Mn, Hg, Cd, Pb, and Cr. The findings reveal substantial variations in soil and groundwater characteristics across the sampled sites. Alkaline soils, exemplified by a pH of 8.7, were identified, suggesting the potential for elevated groundwater pH in certain areas. Concurrently, the analysis of heavy metal concentrations in soil and groundwater samples demonstrated a spatial correlation, with elevated levels in specific localities indicating potential pathways of contamination. Notably, localities such as Govindapura Industrial area, Hamidia Road, and BHEL area exhibited increased heavy metal concentrations, aligning with higher levels in corresponding groundwater samples, emphasizing the link between soil and groundwater quality. The study also examined electrical conductivity as an indicator of ion content, revealing a correlation between soil and groundwater EC. The variation in other parameters, including Cl-, Mg, Na+, K+, and hardness, further underscored the diverse influences on water quality. By adopting an integrated approach, incorporating multi-parameter assessments and community engagement, this research provides a foundation for sustainable water management practices tailored to the unique challenges posed by different localities in Bhopal**.**

***IndexTerms* - Groundwater quality, soil contamination, Bhopal, pH, electrical conductivity (EC), heavy metals concentrations.**

1. INTRODUCTION

Groundwater is a critical component of the Earth's water cycle. It's the water found underground in the cracks and spaces in soil, sand, and rock. This water is stored in, and moves slowly through, layers of soil, sand, and rocks called aquifers. The process begins with precipitation, such as rain or snow that falls on the surface of the land. Some of this water is used by plants or evaporates back into the atmosphere, but a portion of it seeps into the ground in a process called infiltration. As the water moves down through the soil, it fills up the spaces between particles of soil and rock until it reaches a depth where these spaces are completely filled with water. This area is known as the saturated zone. The top of this zone is called the water table. Above the water table, in what is known as the unsaturated zone, the spaces between soil and rock particles contain both air and water. Below the water table, in the saturated zone, these spaces are filled with water. Groundwater continues to move, very slowly, through the saturated zone and the aquifers within it. It can eventually discharge to the surface naturally at springs, or it can be brought to the surface by wells. Groundwater is a vital source of fresh water for many communities. It can be used for drinking, irrigation, and to supply water to industries. However, it's also vulnerable to pollution from human activities, which can affect its quality and make it unsafe for use.

The quality of groundwater, a crucial resource for drinking, irrigation, and industrial use, is increasingly under threat due to various anthropogenic activities. One such activity is soil contamination, which can occur due to the improper disposal of industrial waste, excessive use of fertilizers and pesticides in agriculture, and leakage from landfill sites. The effects of soil contamination on groundwater quality can be severe. Contaminants in groundwater can pose a risk to human health and the environment. For example, exposure to heavy metals such as lead and mercury can cause neurological damage and other health problems. Exposure to nitrates can cause methemoglobinemia, a condition that reduces the ability of blood to carry oxygen. In addition, contaminated groundwater can affect the taste, odor, and appearance of drinking water, making it less appealing to consumer.

Several studies have been conducted by scientists all around the world to analyze the groundwater quality, their possible causes and its effects on human health. In the study conducted by Ramalingam, Panneerselvam, and Kaliappan (2022) [1], the specific objective was to assess the human health implications arising from continuous nitrate contamination in groundwater across diverse age groups. Forty groundwater samples collected during the post-monsoon season underwent laboratory analysis for major ions. The Chadha plot identified primary contamination sources as weathering of parent rocks, ion exchange processes, and salt leaching. Nitrate concentrations ranged from 24 to 78 mg/L with a mean of 46.45 mg/L. The Nitrogen Pollution Index (NPI) revealed 40% and 17.5% of locations to be moderately and significantly polluted, respectively. Akhtar et al. (2021) [2] aimed to review essential pollutants discharged from anthropogenic activities based on land-use sectors, emphasizing industrial, urban, and agricultural practices. The study also addressed pollutants from natural processes, including climate change, natural disasters, geological factors, soil/matrix interactions, and hyporheic exchange in aquatic environments.

Furthermore, Kumari and Rai's (2020) [3] study in southern Haryana sheds light on the critical issue of groundwater contamination, highlighting the presence of elevated concentrations of HCO_3, Na, Mg, and SO_4 beyond the permissible limits set by BIS standards. The assessment of water quality using the Water Quality Index (WQI) reveals that nearly half of the studied area exhibits poor and very poor water quality for drinking purposes, underscoring the urgency for remedial actions to safeguard public health. In the context of irrigation groundwater suitability, Kumari and Rai employ various methods, such as EC, SAR, RSC, SP, KR, MH, PI, Piper-trilinear diagram, and USSL diagram. While certain parameters like SAR, RSC, and PI suggest excellent and safe water quality for irrigation, others, such as SP, KR, and MH, raise concerns about unsuitability and potential risks associated with irrigation practices. Complementing these findings, Kapelewska et al.'s (2019) [4] research contributes valuable insights into the groundwater quality near Municipal Solid Waste Landfill (MSW) sites, employing indices like the Landfill Water Pollution Index (LWPI) and Nemerow Index (PI), along with chemometric expertise. Their analysis of eleven physicochemical parameters in landfill leachates and groundwater samples near MSW landfill sites in NE Poland reveals a substantial negative impact on groundwater quality. On the same grounds, Opoku-Kwanowaa et al.'s (2020) [5] focus on China emphasizes the significance of addressing pollution from agricultural practices, proposing practical interventions to ensure sustainable water quality.

Boateng, Opoku, and Akoto's (2019) [6] study focused on assessing the pollution levels, identifying sources of heavy metals, and evaluating associated human health risks in groundwater. Utilizing the Standard Methods for the Examination of Water and Wastewater for sampling and treatment, the study found that mean concentrations of Pb, Fe, Cd, and Cr exceeded World Health Organization limits for drinking water, indicating contamination. Hazard index values suggested adverse health effects at specific sites, emphasizing the potential risks associated with heavy metal exposure. In a related context, Khanoranga and Khalid (2019) [7] investigated the impacts of brick kilns pollution on groundwater quality in Balochistan. Analyzing twenty-two physicochemical parameters, they found that several exceeded WHO limits, categorizing the water as CaCl and NaCl type according to the Piper Hill diagram. The groundwater quality index indicated poor water quality for drinking purposes, prompting concerns for local residents. Sodium absorption ratio, residual sodium carbonate, sodium percentage, and permeability index assessments highlighted limited suitability for irrigation. Meanwhile, Elemile et al. (2019) [8] explored the impact of abattoir activities on groundwater quality in Omu-Aran, Nigeria. Assessing physicochemical characteristics in water samples collected at varying distances from abattoirs, the study found significant differences in parameters, except total coliform, between studied and control wells. Water quality improved with increasing distance from the abattoir, emphasizing the potential impact of abattoirs on groundwater quality.

Celestino et al.'s (2019) [9] investigation focused on assessing groundwater quality in a wastewater-irrigated region, utilizing the water quality index (WQI) for drinking purposes and employing multivariate geostatistical tools such as principal component analysis (PCA) and K-means clustering. The study revealed the significant impact of salinization, pollution from wastewater irrigation and fertilizers, and geogenic sources on groundwater quality. Clustering identified two distinct clusters with varying suitability for drinking purposes, emphasizing the need for nuanced water management strategies in the Mezquital Valley. Khanna and Gupta (2018) [10] highlighted the consequences of escalating agrochemical use, particularly pesticides and fertilizers, on groundwater quality, identifying agriculture as both a cause and victim of pollution. Deshmukh and Aher (2016) [11] focused on the impact of Municipal Solid Waste (MSW) on groundwater quality near a dumping yard, employing water quality index (WQI) and GIS integration to underscore the urgency of pollution control measures. McGrane's (2016) [12] review emphasized the complexities of urban hydrology, linking impervious surfaces, leaky infrastructure, and contaminants to water quality challenges in urban environments. Oni and Fasakin (2016) [13] utilized the water quality index (WQI) method to assess groundwater and surface water quality near a dumpsite in Nigeria, revealing poor water quality attributed to high lead content. Varol and Davraz's (2015) [14] study assessed seasonal variations in groundwater quality, emphasizing the influence of water-rock interaction and agricultural activities using water types and the Water Quality Index (WQI).

Han et al. (2014) [15] investigated groundwater inorganic contamination around a municipal landfill site in Zhoukou city, Henan province, China, utilizing stable isotopic compositions (δ18O and δ2H) and physico-chemical parameters. The study identified TDS, Cl^-, NH4+, Fe, and Mn concentrations as key indicators of groundwater pollution caused by landfill leachate percolation, with a two-dimensional advective–dispersive transport model revealing the constrained contamination plume after 13 years of landfill operation. Schoumans et al. (2014) [16] addressed water quality improvements mandated by the EU Water Framework Directive (WFD), emphasizing diffuse pollution from agriculture as a growing concern. The study evaluated 83 measures across 30 countries, focusing on nutrient loss reduction from rural areas to surface waters at catchment scale. Calijuri et al. (2012) [17]

conducted a comprehensive study on surface and groundwater quality in a karstic watershed influenced by urban growth, employing multivariate statistical techniques such as principal components analysis (PCA) and cluster analysis. The results highlighted the integrated effects of human activities and natural karstic characteristics on water quality. Zhang et al. (2012) [18] assessed water quality using fuzzy membership analysis and multivariate statistics, categorizing surface water and groundwater into irrigation classes and identifying principal components influencing water quality assessment. Pollock, Kookana, and Correll (2005) [19] investigated the spatial variability of groundwater impact due to atrazine in relation to soil type and depth, revealing the importance of soil sorption capacity for accurate impact assessments. Zalidis et al. (2002) [20] addressed the detrimental effects of agricultural practices on soil and water quality, emphasizing the need for a functional evaluation of soils to develop accurate monitoring systems. Collectively, these studies contribute diverse perspectives to the understanding of groundwater quality challenges, encompassing contamination sources, regulatory frameworks, and methodologies for sustainable management.

2. NEED OF STUDY

This research aims to evaluate the effects of soil contamination on the quality of groundwater in different localities of Bhopal, a city that has witnessed significant industrial growth over the past few decades. By analyzing the correlation between soil contamination and groundwater quality, this study hopes to contribute valuable insights to the field of environmental science and help inform policies for sustainable water management. To analyze the quality of groundwater, hydrologists take samples of water from different wells and have them chemically analyzed. Chemical methods involve analyzing the chemical composition of water, such as the concentration of dissolved solids, nutrients, and contaminants. Chemical methods are useful for identifying specific contaminants and determining their concentrations in water. The analysis involves determining the chemical characteristics of the water, such as pH and the presence of contaminants such as heavy metals. The results of the analysis are then compared to established benchmarks for the protection of human health.

3. TOPOLOGY OF BHOPAL

Bhopal is situated in the fertile plain of the Malwa Plateau, and lies just north of the Vindhya Range, along the slopes of a sandstone ridge. The district is an undulating high plain occupied for cultivation and settlements, flanked by small hilly tracts in the south, west, east, and northwest. The annual rainfall in Bhopal is about 1240 mm [21]. The Soil and Land Use Survey of India (SLUSI) provides detailed scientific data on soil and land characteristics in India. According to SLUSI, the study area for soil resource mapping in Bhopal is the district, and the survey period was from 2003-2021. The survey covered 277 districts and used a scale of 1:50,000. The report provides detailed information on the soil resources of the area, including soil types, soil depth, and soil fertility.

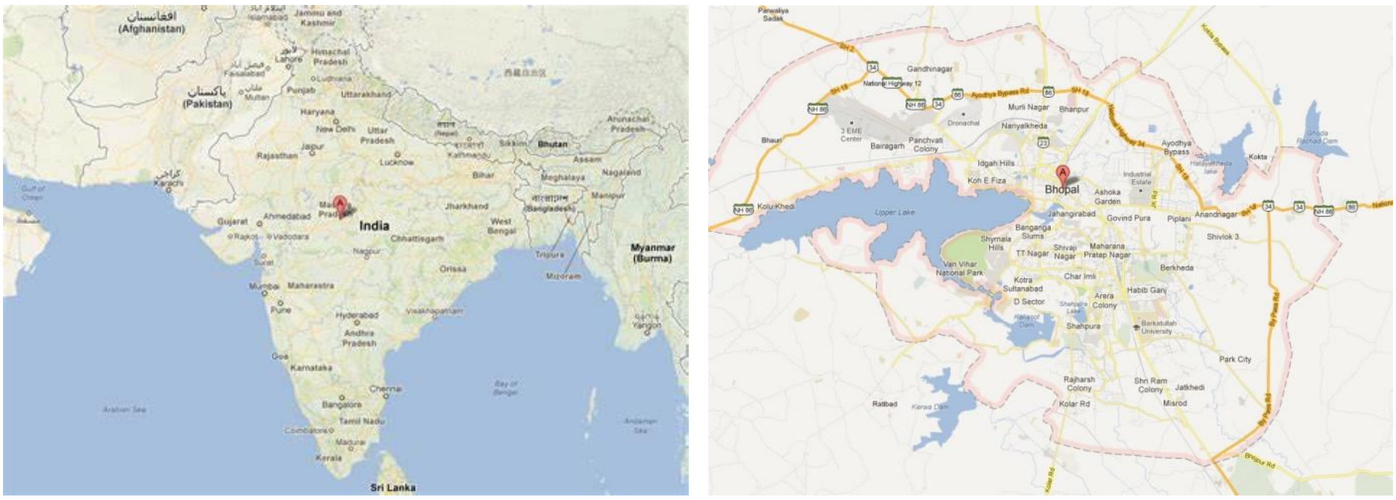

Figure 3.1 Location and topography of Bhopal

Sources of soil contamination in Bhopal include municipal wastes, industrial effluents, chemical fertilizers, and pesticides. Irrigation with contaminated groundwater and river water are also responsible for soil contamination [22]. The toxic waste generated during the operation of the Union Carbide pesticide plant from 1969 to 1984 was dumped in and around the plant, leading to severe soil and water contamination [23]. The U.K.-based Bhopal Medical Appeal and the Sambhavna Clinic say water contamination is worsening as chemicals leach through soil into the aquifer.

According to a study conducted by ICAR-Indian Institute of Soil Science, Bhopal, heavy metals have built up in soils due to industrial activities, and the nature of contamination varied with the type of industries operating. Groundwater contamination in Bhopal is caused by various sources such as partially or untreated discharge of domestic and industrial wastewater, excessive usage of chemicals in agriculture, and leakage from solar evaporation ponds located just outside of the factory site 21. The toxic waste generated during the operation of the Union Carbide pesticide plant from 1969 to 1984 was dumped in and around the plant, leading to severe soil and water contamination. Contaminated water from wells was pumped into 42 neighborhoods, affecting the health of thousands of people [23]. The contamination is being caused by water leaching through toxic waste that was buried on the factory site and by leakage from solar evaporation ponds located just outside of the factory site.

Figure 3.2 Some images of Bhopal showing soil and ground water contamination across different localities of Bhopal.

Groundwater in Bhopal is used for drinking and irrigation. Groundwater contributes to 60% of the district's irrigation needs. Although municipal water supply is mainly done through surface water sources (chiefly Upper Lake, Kolar Dam, and the Narmada River (Hoshangabad)). In some parts, the population still relies on groundwater from dug and tube wells for potable use without treatment. The increase in population in Bhopal has resulted in a greater demand for groundwater. Significant polluters are the partially or untreated discharge of domestic and industrial wastewater and excessive usage of chemicals in agriculture. Most rural localities and villages lack adequate sewage treatment infrastructure, polluting the groundwater with nutrients and pathogens. Chemical fertilizers and herbicides have increased groundwater nitrates, phosphates, and other organic components. Discharge of partially or untreated effluents has elevated heavy metals and other pollutants in groundwater

4. **RESEARCH METHODOLOGY**

4.1 Sample Collection

In this study, 6 sampling points were selected across diverse localities in Bhopal, considering variations in land use and anthropogenic activities. Clean, acid-washed containers were used for sample collection to prevent contamination, and groundwater samples were collected at each site using a peristaltic pump or a bailer, ensuring proper depth representation.

Table 4.1 Soil and Groundwater samples collected from different localities of Bhopal

Locality	Soil Sample	Water sample
Maharana Pratap Nagar	S1	W1
Govindpura Industrial Area	S2	W2
Hamidia Road	S3	W3
Van Vihar Area	S4	W4
Katara Hills	S5	W5
BHEL Area	S6	W6

Maharana Pratap Nagar is a peaceful and well-to-do area where many families reside. It is a very nice and beautiful locality with all basic amenities like hospitals, schools, colleges, and markets available nearby. The topography of this area is relatively flat, with no significant hills or valleys. The air quality in this area is satisfactory. Govindpura Industrial area is a hub of cottage and small-scale category industries, most of which are of engineering nature, including the work of fabrication, welding, and surface treatment. Hamidia Road is a busy commercial and residential locality in Bhopal. The topography of this area is relatively flat, with no significant hills or valleys. According to a report by the Madhya Pradesh Pollution Control Board, the Govindpura industrial area and Hamidia Road are two of the most polluted spots in Madhya Pradesh.

Van Vihar area is home to the Van Vihar National Park, a national park, zoo, and rescue center for wildlife located in the heart of Bhopal. The park is spread over an area of 4.45 km² and is home to a variety of flora and fauna. The topography of this area is relatively flat, with no significant hills or valleys. Katara Hills is spread over around 1,700 hectares and is a hub of biodiversity. The region embraces protected as well as revenue forests in equal measure. The topography of this area is hilly, with several hillocks, water bodies, grasslands, and geological formations. BHEL area is home to Bharat Heavy Electricals Limited (BHEL), a public sector undertaking, and its ancillary units. The topography of this area is relatively flat, with no significant hills or valleys. The air quality in these areas is satisfactory, but the groundwater availability and soil pollution levels are not known.

4.2 Soil Testing

Equipment Used:

a) ICP-MS apparatus for contaminant analysis.
b) Acid-washed containers and tools for sample collection.
c) Grinders and sieves for soil sample preparation.
d) Personal protective equipment, including gloves and lab coats.
e) Chemicals and reagents specific to the chosen analytical methods.

Testing Procedure:

Each soil sample container was labeled with the location, date, and time of collection. Soil samples were air-dried to remove moisture, followed by grinding and sieving to achieve a uniform particle size. Target contaminants were identified based on potential sources in each locality, including heavy metals. Inductively Coupled Plasma Mass Spectrometry (ICP-MS) was used for specific contaminant analysis.

4.3 Groundwater Testing

Equipment Used:

a) pH meter with calibrated electrodes
b) Acid-washed containers for sample collection
c) Peristaltic pump or bailer for sample retrieval
d) 0.45 µm pore size membrane filters
e) Nitric acid (HNO_3) for sample acidification
f) ICP-MS apparatus for heavy metal analysis
g) Standard buffer solutions for pH meter calibration
h) Pipettes, beakers, and other laboratory glassware
i) Gloves, safety glasses, and lab coats for personal protection

Testing Procedure:

The pH meter was calibrated using standard buffer solutions at pH 4, 7, and 10 before each measurement. Groundwater samples were gently stirred to ensure homogeneity, and the pH electrode was immersed into the sample, avoiding contact with the container walls. The pH value was recorded once the reading stabilized.

For heavy metal analysis, groundwater samples were filtered through a 0.45 µm pore size membrane to remove particulate matter. The filtered samples were acidified with nitric acid (HNO_3) to a pH below 2 to preserve the metals and prevent precipitation. Inductively Coupled Plasma Mass Spectrometry (ICP-MS) was utilized for heavy metal analysis, with standard solutions of known metal concentrations used for calibration.

Quality control measures included running duplicate analyses and comparing results to ensure data accuracy, as well as using certified reference materials for quality control and instrument calibration. Statistical analysis was performed on pH and heavy metal concentrations, and the results were spatially mapped to identify patterns and correlational trends between soil contamination and ground water quality across different localities.

5. RESULTS AND DISCUSSION

Below mentioned are the results of the experiments conducted. Different localities of Bhopal that have been select for soil and groundwater sample collection respectively as mentioned in Table 4.1. S1, S2, S3, S4, S5, S6 are the soil samples while W1, W2, W3, W4, W5, W6 are the respective groundwater samples of the mentioned localities. Table 5.1 gives the results of the various tests such as pH, electrical conductivity (EC) and concentrations of heavy metals such as Cu, Mg, Zn, S, P, Hg etc. present in the soil samples while Table 5.2 gives the same results for the respective ground water samples.

Table 5.1 Results for Soil Samples from different localities of Bhopal

Sample	pH	EC (ms/cm)	Mn	Hg	Cd	Pb	Cr	Cu	Zn	P	S	Fe
S1	7.4	1.52	5.89	0.11	6.9	6.7	2.93	16.48	102.4	22.45	14.2	789
S2	8.62	1.95	62.47	0.3	11.02	2.73	3.79	11.89	294.78	63.14	80.39	1529
S3	8.7	1.74	73.02	0.26	3.1	17.5	3.65	9.65	59.92	66.92	30.07	1232
S4	7.81	0.43	9.67	0.01	5.7	1.9	0.23	2.8	19.43	5.73	3.6	560
S5	7.91	0.32	29.4	0.03	2.4	4.6	2.46	3.6	3.59	10.68	4.4	432
S6	6.6	1.67	48.92	0.16	8.04	9.3	6.92	18.94	289.77	49.35	22.6	784

Table 5.2 Results for Water Samples from different localities of Bhopal

Sample	pH	EC (µc/cm)	Ca^{2+}	Hg	Cd	Pb	Cr	Cl^{-}	Zn	Mg	Na^{+}	K^{+}	Hardness
W1	7.7	1602	69.1	<0.1	2	2	<4	153	87	35.9	179	16.9	321
W2	8.47	893	28.5	1.7	4	2	5	104.2	5	18.2	148.5	1.2	142.1
W3	8.14	3255	178	<0.1	2.6	3	<4	328	29	95.4	206	105	838
W4	7.93	638	44	<0.1	1	2	32	53.9	22	27.4	62	6.9	224
W5	7.71	964	122	0.1	0.9	2	<4	55.9	11	45.2	36.2	6.5	492
W6	6.96	1231	275.6	<0.1	4.4	16	5	246.7	37	83.5	106.8	27.6	1032

5.1. Soil pH and Groundwater pH

The diverse soil pH values observed across different localities in Bhopal, ranging from 6.6 to 8.7, indicate a varied spectrum of soil acidity. While alkaline soils, exemplified by S3 with a pH of 8.7, may generally contribute to higher groundwater pH, the correlation is nuanced.

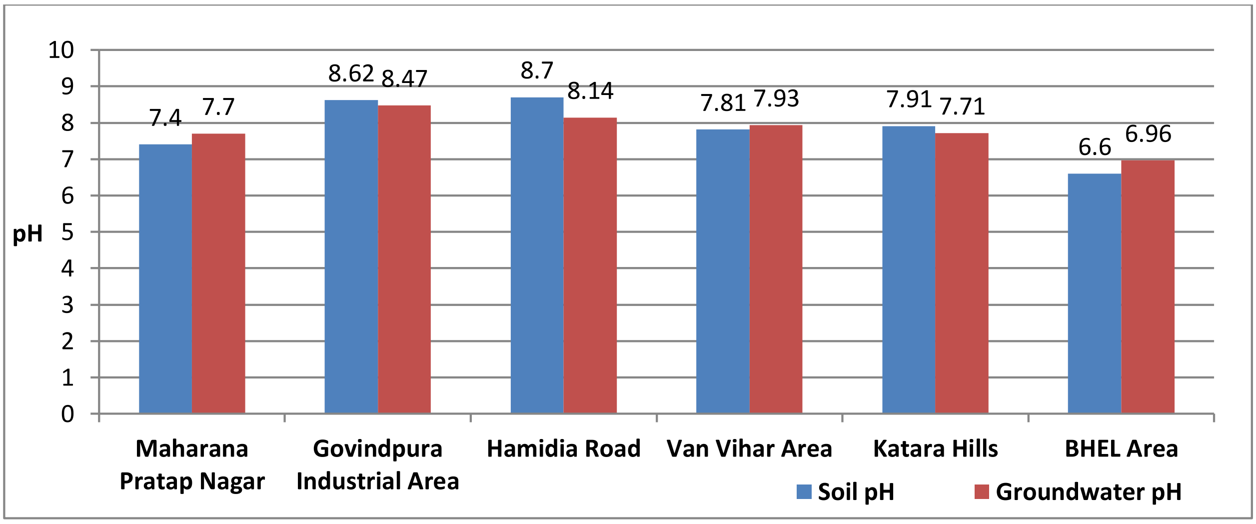

Figure 5.1 Correlation between pH levels of the respective soil and groundwater samples

Groundwater pH values ranging from 6.96 to 8.47 demonstrate that factors beyond soil pH alone play crucial roles in determining groundwater acidity or alkalinity. These factors may include the local geology, mineral composition, and specific hydrological conditions. Thus, while a general trend suggests that alkaline soils may contribute to elevated groundwater pH, the intricate nature of the hydrogeological system demands a more detailed investigation to unravel the complex interactions influencing groundwater quality.

5.2 Heavy Metal Concentrations

The analysis of heavy metal concentrations in both soil and groundwater samples reveals noteworthy trends. Soil samples, particularly S2, S3, and S6, exhibit elevated levels of heavy metals such as Mn, Hg, Cd, Pb, and Cr. Correspondingly, groundwater samples from localities with these contaminated soils, namely W2, W3, and W6, demonstrate higher concentrations of similar heavy metals. This spatial correlation suggests a potential pathway of heavy metal migration from soil to groundwater. However, the interplay of complex geochemical processes, including adsorption, precipitation, and ion exchange, necessitates further investigation to elucidate the specific mechanisms governing heavy metal mobility. Additionally, anthropogenic activities, such as industrial discharges or agricultural practices, may contribute to the observed heavy metal contamination, warranting comprehensive source identification and remediation strategies.

5.3 Electrical Conductivity (EC)

Electrical conductivity (EC) serves as a valuable indicator of ion content in both soil and groundwater. The observed variation in soil EC, ranging from 0.32 to 1.95 ms/cm, is reflected in the groundwater EC, which spans from 638 to 3255 µS/cm. Notably, W3, characterized by the highest groundwater EC, corresponds to S3, which also exhibits elevated soil EC. This correlation implies a relationship between soil ion content and groundwater EC, indicating that the movement of ions within the subsurface may influence overall groundwater quality. Understanding the mobility of ions, their interactions with soil particles, and potential leaching into groundwater is imperative for comprehending the complex dynamics of soil-water interactions in these diverse localities.

5.4 Other Parameters

In addition to heavy metals and EC, various other parameters, including Cl-, Mg, Na+, K+, and hardness, exhibit spatial variations across both soil and groundwater samples. The intricate interplay of geological, anthropogenic, and hydrological factors influencing these parameters underscores the complexity of water quality dynamics. Groundwater hardness, influenced by Ca2+ and Mg content, varies among localities, with W6 displaying the highest hardness. These variations emphasize the need for a holistic assessment of multiple parameters to comprehensively understand groundwater quality in different Bhopal localities.

Furthermore, the unique signatures of Cl-, Mg, Na+, and K+ may provide insights into potential contamination sources, land use practices, and hydrogeological characteristics that contribute to the observed variations.

5.5 Overall Correlation

The overarching correlation between soil contamination and groundwater quality becomes apparent in localities where elevated heavy metal concentrations in soil (S2, S3, S6) align with corresponding increases in heavy metals in groundwater (W2, W3, W6). This spatial correspondence implies a potential linkage between soil and groundwater contamination. However, recognizing the intricate nature of groundwater quality, as evidenced by varied pH values, demands a multifaceted approach. Localized factors such as geological heterogeneity, land use practices, and hydrological conditions contribute to the site-specific complexities. Ongoing monitoring and targeted remediation efforts are crucial for addressing these localized groundwater contamination issues effectively. Comprehensive investigations incorporating detailed hydrogeological studies, contaminant transport modeling, and source identification are essential for developing sustainable water management strategies tailored to the unique challenges posed by different Bhopal localities.

6. CONCLUSION

In conclusion, the comprehensive evaluation of soil and groundwater samples from various localities in Bhopal has provided valuable insights into the complex interplay of factors influencing water quality. The observed variations in soil pH, heavy metal concentrations, electrical conductivity, and other parameters underscore the heterogeneity of environmental conditions across the selected sites. The correlation between soil contamination and groundwater quality, particularly evident in localities such as Govindapura Industrial are (S2), Hamidia Road (S3), and BHEL area (S6) corresponding to W2, W3, and W6, highlights the potential impact of soil characteristics on groundwater composition.

a) The diverse pH values in both soil and groundwater indicate the significance of site-specific conditions, with alkaline soils potentially contributing to elevated groundwater pH. However, the intricate nature of hydrogeological systems suggests that factors beyond soil pH alone influence groundwater acidity or alkalinity.

b) Elevated heavy metal concentrations in certain soil samples aligning with increased levels in corresponding groundwater samples emphasize a potential pathway of heavy metal migration from soil to groundwater. Anthropogenic activities and complex geochemical processes likely contribute to this contamination, necessitating further investigation for source identification and targeted remediation.

c) The correlation between soil and groundwater electrical conductivity suggests a relationship between soil ion content and groundwater quality. Understanding the mobility of ions within the subsurface is crucial for unraveling the dynamics of soil-water interactions.

d) Spatial variations in other parameters, including Cl-, Mg, Na+, K+, and hardness, highlight the diverse influences on water quality. Groundwater hardness, indicative of Ca2+ and Mg content, varies across localities, providing additional insights into the hydrochemical characteristics of the sampled sites.

Overall, the findings emphasize the need for ongoing monitoring and comprehensive studies to address localized groundwater contamination effectively. Sustainable water management strategies should consider the site-specific complexities, integrating detailed hydrogeological assessments, contaminant transport modeling, and source identification. By combining these approaches, tailored solutions can be developed to safeguard groundwater quality and ensure the environmental sustainability of the studied localities in Bhopal.

7. RECOMMENDATIONS

The following recommendations are suggested:

a) Further analysis and monitoring are essential to understand the dynamics and potential long-term impacts on groundwater quality.

b) Implement remediation measures in areas with significant soil contamination to prevent further deterioration of groundwater quality.

Note that a comprehensive understanding of the local hydrogeological conditions, land use practices, and additional water quality parameters would provide a more accurate assessment of the situation.

References

[1] S. Ramalingam, B. Panneerselvam, and S. P. Kaliappan, “Effect of high nitrate contamination of groundwater on human health and water quality index in semi-arid region, South India,” *Arab. J. Geosci.*, vol. 15, no. 3, 2022, doi: 10.1007/s12517-022-09553-x.

[2] N. Akhtar, M. I. Syakir Ishak, S. A. Bhawani, and K. Umar, “Various natural and anthropogenic factors responsible for water quality degradation: A review,” *Water (Switzerland)*, vol. 13, no. 19, 2021, doi: 10.3390/w13192660.

[3] M. Kumari and S. C. Rai, “Hydrogeochemical Evaluation of Groundwater Quality for Drinking and Irrigation Purposes Using Water Quality Index in Semi Arid Region of India,” *J. Geol. Soc. India*, vol. 95, no. 2, pp. 159–168, 2020, doi: 10.1007/s12594-020-1405-4.

[4] J. Kapelewska *et al.*, “Water pollution indicators and chemometric expertise for the assessment of the impact of municipal solid waste landfills on groundwater located in their area,” *Chem. Eng. J.*, vol. 359, pp. 790–800, 2019, doi: 10.1016/j.cej.2018.11.137.

[5] Y. Opoku-Kwanowaa, R. K. Furaha, L. Yan, and D. Wei, “Effects of Planting Field on Groundwater and Surface Water Pollution in China,” *Clean - Soil, Air, Water*, vol. 48, no. 5–6, pp. 1–9, 2020, doi: 10.1002/clen.201900452.

[6] T. K. Boateng, F. Opoku, and O. Akoto, “Heavy metal contamination assessment of groundwater quality: a case study of Oti landfill site, Kumasi,” *Appl. Water Sci.*, vol. 9, no. 2, pp. 1–15, 2019, doi: 10.1007/s13201-019-0915-y.

[7] Khanoranga and S. Khalid, "An assessment of groundwater quality for irrigation and drinking purposes around brick kilns in three districts of Balochistan province, Pakistan, through water quality index and multivariate statistical approaches," *J. Geochemical Explor.*, vol. 197, pp. 14–26, 2019, doi: 10.1016/j.gexplo.2018.11.007.

[8] O. O. Elemile, D. O. Raphael, D. O. Omole, E. O. Oloruntoba, E. O. Ajayi, and N. A. Ohwavborua, "Assessment of the impact of abattoir effluent on the quality of groundwater in a residential area of Omu-Aran, Nigeria," *Environ. Sci. Eur.*, vol. 31, no. 1, 2019, doi: 10.1186/s12302-019-0201-5.

[9] A. E. M. Celestino, J. A. R. Leal, D. A. M. Cruz, J. T. Vargas, J. D. L. Bashulto, and J. M. Ramírez, "Identification of the hydrogeochemical processes and assessment of groundwater quality, using multivariate statistical approaches and water quality index in a wastewater irrigated region," *Water (Switzerland)*, vol. 11, no. 8, 2019, doi: 10.3390/w11081702.

[10] R. Khanna and S. Gupta, "Agrochemicals as a potential cause of ground water pollution: A review Technical SCIENCE ☼ View project Black Wheat: A Health Promising Crop View project," *Int. J. Chem. Stud.*, no. January 2018, pp. 985–990, 2018, [Online]. Available: https://www.researchgate.net/publication/350874038

[11] K. K. Deshmukh and S. P. Aher, "Assessment of the Impact of Municipal Solid Waste on Groundwater Quality near the Sangamner City using GIS Approach," *Water Resour. Manag.*, vol. 30, no. 7, pp. 2425–2443, 2016, doi: 10.1007/s11269-016-1299-5.

[12] S. J. McGrane, "Impacts of urbanisation on hydrological and water quality dynamics, and urban water management: a review," *Hydrol. Sci. J.*, vol. 61, no. 13, pp. 2295–2311, 2016, doi: 10.1080/02626667.2015.1128084.

[13] O. Oni and O. Fasakin, "The Use of Water Quality Index Method to Determine the Potability of Surface Water and Groundwater in the Vicinity of a Municipal Solid Waste Dumpsite in Nigeria," *Am. J. Eng. Res.*, no. 5, pp. 96–101, 2016, [Online]. Available: www.ajer.org

[14] S. Varol and A. Davraz, "Evaluation of the groundwater quality with WQI (Water Quality Index) and multivariate analysis: a case study of the Tefenni plain (Burdur/Turkey)," *Environ. Earth Sci.*, vol. 73, no. 4, pp. 1725–1744, 2015, doi: 10.1007/s12665-014-3531-z.

[15] D. Han, X. Tong, M. J. Currell, G. Cao, M. Jin, and C. Tong, "Evaluation of the impact of an uncontrolled landfill on surrounding groundwater quality, Zhoukou, China," *J. Geochemical Explor.*, vol. 136, pp. 24–39, 2014, doi: 10.1016/j.gexplo.2013.09.008.

[16] O. F. Schoumans *et al.*, "Mitigation options to reduce phosphorus losses from the agricultural sector and improve surface water quality: A review," *Sci. Total Environ.*, vol. 468–469, pp. 1255–1266, 2014, doi: 10.1016/j.scitotenv.2013.08.061.

[17] M. L. Calijuri, E. D. A. Do Couto, A. D. F. Santiago, R. D. A. Camargo, and M. D. F. M. E Silva, "Evaluation of the influence of natural and antrhopogenic processes on water quality in Karstic region," *Water. Air. Soil Pollut.*, vol. 223, no. 5, pp. 2157–2168, 2012, doi: 10.1007/s11270-011-1012-5.

[18] B. Zhang *et al.*, "Hydrochemical characteristics and water quality assessment of surface water and groundwater in Songnen plain, Northeast China," *Water Res.*, vol. 46, no. 8, pp. 2737–2748, 2012, doi: 10.1016/j.watres.2012.02.033.

[19] D. W. Pollock, R. S. Kookana, and R. L. Correll, "Integration of the pesticide impact rating index with a geographic information system for the assessment of pesticide impact on water quality," *Water, Air, Soil Pollut. Focus*, vol. 5, no. 1–2, pp. 67–88, 2005, doi: 10.1007/s11267-005-7398-6.

[20] G. Zalidis, S. Stamatiadis, V. Takavakoglou, K. Eskridge, and N. Misopolinos, "Impacts of agricultural practices on soil and water quality in the Mediterranean region and proposed assessment methodology," *Agric. Ecosyst. Environ.*, vol. 88, no. 2, pp. 137–146, 2002, doi: 10.1016/S0167-8809(01)00249-3.

[21] S. Mishra, M. S. Chauhan, and S. Sundaramurthy, "Assessment of Groundwater Trends in Bhopal, Madhya Pradesh: A Statistical Approach," *Sustain.*, vol. 15, no. 15, pp. 1–15, 2023, doi: 10.3390/su151511971.

[22] S. C. Panico *et al.*, "Evaluation of Soil Heavy Metal Contamination and Potential Human Health Risk inside Forests, Wildfire Forests and Urban Areas," *Environ. - MDPI*, vol. 10, no. 8, pp. 1–14, 2023, doi: 10.3390/environments10080146.

[23] A. International, U. N. Human, and R. Council, "The Bhopal tragedy: 30 years of injustice for victims and survivors Amnesty International written statement to the 25th session of the UN Human Rights Council (3-28 March 2014)," no. March, 2014.