

S. P. Sinha Ray
Achiransu Acharyya *Editors*

Ground Water Contamination in India

Adverse Effects on Habitats

 Springer

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*Dedicated to
The Members of Centre for Ground Water
Studies*

Foreword

Time has come when groundwater needs an exclusive dealing with its contamination. It is more heartening that not only Hydrogeologists but Engineers, Chemists, Physicists, Architects, Doctors, and even Mathematicians are taking enormous interest in the area of groundwater contamination. No doubt the public concern with water quality, waste disposal, and environmental regulations had the necessary impact on the new research with interdisciplinary approach.

It was a long awaited requirement for a book on *Groundwater Contamination in India—Adverse effects on Habitats*. Most groundwater quality problems today are caused by contamination, over-exploitation, or a combination of both. Rapid urbanization and industrialization in India have resulted in a steep increase in waste generation. Due to a lack of adequate infrastructure and resources, the waste is not properly collected, treated, and disposed off, leading to accumulation and infiltration, causing groundwater contamination. The problem is more severe in and around large cities and industry clusters. In many of these areas, groundwater is the only source of drinking water. Thus, a large population is exposed to the risk of consuming contaminated water.

Groundwater contamination in India also occurs due to natural geogenic sources and substances infiltrating aquifers. Vast tracts of Rajasthan, Gujarat, and Andhra Pradesh are affected by groundwater with fluoride concentrations of greater than 1.5 milligramme per litre. Fluorosis can lead to varying afflictions, from dental problems to severe muscular deformity. The contaminant is found naturally in the rocks and sediments of aquifers, and the depths of its occurrence vary with the formation. Smaller areas of several other states, like Punjab, Uttar Pradesh, Karnataka, Maharashtra, West Bengal, and Madhya Pradesh, also exhibit high fluoride concentrations in groundwater.

Similarly, high arsenic content (greater than 0.01 milligramme per litre) is found primarily in the Alluvial Indo-Gangetic-Brahmaputra basin sediments. It was initially observed that high concentrations of arsenic were only in Bangladesh and West Bengal but later the contaminant was also found to be in high concentrations in north east India. Newer areas are being discovered every year. Symptoms of arsenic

poisoning range from Diffuse Melanosis (darkening of the skin) to Spotted Melanosis (pigmentation) and Keratosis. In the final stage, the affliction can reach the stage of malignancy.

Coastal and inland salinity is found in large tracts of the country. Saurashtra and Kutch in Gujarat and parts of Tamil Nadu, Andhra Pradesh, Orissa, and West Bengal show salt water intrusion into coastal aquifers. Inland salinity is present in Punjab, Haryana, Rajasthan, Gujarat, Madhya Pradesh, Maharashtra, Uttar Pradesh, and some pockets of other states. Besides being harmful to crop productivity and soil quality, high salinity can cause ailments such as kidney stones. High iron concentration in groundwater is found in Eastern and north eastern parts of the country, especially in Bihar, Uttar Pradesh, and West Bengal. Prolonged intake of high iron content water can cause haemochromatosis.

The increasing use of nitrogenous fertilizers in India has led to nitrate contamination of aquifers at levels greater than 40 milligrammes per litre in many parts of the country. The states of Punjab and Haryana are at high risk from nitrate contamination. Other states with areas showing high nitrate levels are Gujarat, Tamil Nadu, West Bengal, and Uttar Pradesh. Consumption of water containing high nitrate levels can cause some types of Cancer. It can also cause the blue baby syndrome, which affects newborn babies. Pesticide contamination of groundwater has raised the alarm in recent times. High pesticide content in groundwater has been reported in intensive agricultural regions such as Punjab and Haryana. The health effects of pesticides are lesser known but suspected to be harmful to humans and animals.

The attempt in this book is to highlight such groundwater contamination in different parts of India which is a matter of great concern in the entire South Asia also. The policy issues to mitigate such menace and mitigation techniques adopted for fluoride and arsenic contamination with case histories will be very useful for the people facing such challenges. The impact of such groundwater contamination on the food chain is also alarming. The most emerging adverse effects of aged microplastics on groundwater regime is another area of grave concern. All these aspects have been dealt with in the book which needs commendation.

As an independent reviewer, I have no hesitation in recommending this book to all workers in the field of Groundwater Science.

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Preface

Groundwater contamination occurs due to naturally existing geogenic sources and also due to anthropogenic substances. The existence of contaminants and transport of substances are highly site-dependent. For instance, vast tracts of Rajasthan, Gujarat, and Andhra Pradesh are affected by groundwater with high fluoride concentrations. Fluorosis can lead to varying degrees of afflictions: from dental problems to severe muscular deformity. High arsenic content is found primarily in sediments of the Alluvial Indo-Gangetic-Brahmaputra basins. Symptoms of arsenic poisoning range from skin pigmentation and cancer. Coastal and inland salinity is found in large tracts of the country. Apart from being harmful to the productivity of crops and soil quality, high salinity can cause ailments such as kidney stones. High iron concentration in groundwater is found in Eastern parts of the country. Prolonged intake of high iron content water can cause haemochromatosis. Increasing use of Nitrogenous fertilizers in India has led to high nitrate contamination of aquifers in many parts of the country. Pesticide contamination of groundwater has raised the alarm in recent times. Adsorption of heavy metal with aged microplastic under varying organic matter content is the latest finding.

This book tries to assess the various adverse effects of groundwater contamination, specifically in India, both at the regional and national levels. The chapters in the book discuss issues related to groundwater contamination, such as the impact of high concentrations of arsenic and fluoride and other heavy metals, issues related to groundwater salinity and its impact on irrigation and livelihood, and spatial analysis of groundwater quality in urban areas along with pollution from aged microplastic. Chapters in the book focus extensively on risk assessment due to groundwater contamination, including cost on human health and livelihood and impact on irrigation and agriculture and on the human food chain. The book also discusses the policies for successful adaptation and mitigation of the problems of groundwater contamination.

In this book, a few chapters have been taken from the various volumes of “Indian Ground Water” to have a better focus on understanding almost the entire gammat of groundwater contamination in different aquifer systems in India.

In finalizing the book, contributions received from Shri Tapan Roy, Shri Ritam Sinha, and Shri Dipanjan Mitra are very noteworthy. Encouragement rendered by Shri Abhijit Ray, President and Dr. Sandhya Bhadury, Secretary, Centre for Ground Water Studies, needs special appreciation. Facilities provided by Shri Raj D. Mirchandani, Capital Publishing Company, New Delhi, at various stages of the publication are gratefully acknowledged.

It is expected that the book will be of interest to students and researchers of environment, agriculture, geography, development studies, environmental policies, and South Asia studies. It will also be useful for policymakers and NGOs working in this field as also other stake holders trying to understand the issues.

Kolkata, India
September 2023

S. P. Sinha Ray
Achiransu Acharyya

About This Book

Deterioration of groundwater quality consequent to large-scale groundwater withdrawal to support agricultural and industrial needs has already emerged as a potential threat to sustainable development of groundwater resources. This has adversely affected drinking water sources and as a result, safe water resources are becoming scarce day by day. This has become a big menace in the rural areas of the Indian subcontinent where 90% of the population depend for their safe drinking water, on groundwater resources. However, it is no longer an issue for India alone. Several countries are facing the same water quality menace and the whole issue has become a deep global concern, as even the food chains due to groundwater-based irrigation have also shown considerable pollution effects.

Contamination of groundwater both geogenic and anthropogenic has resulted in a vulnerable environment scenario. Recent researches have established that pollution of groundwater through plastic wastes is also quite significant. This book has tried to embody some of the groundwater contamination problems which have been successfully mitigated through various remedial measures. These success stories may go a long way in redressal of the problem.

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About the Editors

Dr. S. P. Sinha Ray obtained Ph.D. (Science) degree from Jadavpur University in 1974. He joined Geological Survey of India in 1966, subsequently his service was transferred to Central Ground Water Board in 1972. He retired as Member (SML), Central Ground Water Board in 2002. At present, he is working as Chairman Fluoride Task Force, PHED, West Bengal; Member, Arsenic Task Force, West Bengal; Chairman, Earth Science R&D Committee, DST, Government of West Bengal; Fellow, West Bengal Academy of Science; President Emeritus, Centre for Ground Water Studies.

He has more than 50 years of extensive experience in groundwater exploration, development, and management. By virtue of his long association with the apex body of the country dealing with groundwater resources, he has acquired a very rich experience in the particular subject. Besides having vast knowledge about the subject within the country, he has also gained knowledge and working experience in other countries like Algeria, Bangladesh, the US, South Korea, and Zimbabwe. He has also contributed to various national and international publications.

He attended training on “Groundwater Resources Development” organized by Overseas Technical Cooperation Agency, Japan, Tokyo in 1973 and training on “Computer and Databases” in San Juan, Puerto Rico, by U.S. Geologist Survey in 1992.

He has edited the book *Groundwater Development Issues and Sustainable Solutions* published by Springer Nature, Singapore in 2019 and the book *Water Resources of North-Eastern and Eastern India: Status, Issues and Strategies* published by Geological Society of India, Bangalore in 2021. He has also contributed a few book chapters on different facts of groundwater.

Dr. Achiransu Acharyya is a Senior Faculty member in the Department of Economics at Visva-Bharati (A Central University) situated in Santiniketan, West Bengal where he has been teaching for the last 19 years.

Dr. Acharyya's area of research is mainly agriculture and natural resource economics and economics of water resources. He has several journal and book publications to his credit. He has done several international and national research projects.

He has visited the University of Oregon, USA on a Teaching cum Research Fellowship. He has also visited University of Nijmegen in The Netherlands as Visiting Scholar. He has received the James D. Wolfensohn Award from The World Bank and the Dr. N. A. Mujumdar Prize from the Indian Society of Agricultural Economics. He has worked as a Consultant Economist for the Asian Development Bank. He is the Associate Editor of a reputed Bengali social science journal titled *Anustup*.

Part I
Groundwater Contamination

Chapter 1

Adsorption of Heavy Metal with Aged Microplastic in Groundwater Under Varying Organic Matter Content



Jaswant Singh and Brijesh Kumar Yadav

1 Introduction

From 1950 to 2016, the world produced 460 million metric tonnes of plastic, up from only 1.5 million in 1950 (Hornweg and Perinaz 2012; Law et al. 2020). Approximately 50% of the produced total plastic is used in packaging for consumer goods, which is single-use in nature (Hopewell et al. 2009). As a result, a great amount of plastic trash is ending up in the natural environment, which can cause significant risks to human health (Kehinde et al. 2020). Larger plastic debris degrades into smaller particles after a certain weathering action, UV light-induced degradation, temperature and salinity changes, and mechanical and biological weathering (Zettler et al. 2013). Once reduced to a size less than 5 mm, these plastic debris are referred to as microplastics (MP) (Thompson et al. 2004). MP has been gaining attention due to its omnipresence in the environment. The occurrence of MP has been reported in soil, wastewater, seawater, freshwater, plant biomass, human blood, and even in the atmosphere (Browne et al. 2011; Barnes et al. 2009; Eriksen et al. 2013; Liu et al. 2019; Rillig 2012; Zhang et al. 2020).

MP are easily inhaled by species like zooplankton, fish, and mussels causing asphyxia or even death in these creatures (Cole et al. 2014; Green 2016). MP's cumulative impacts on the food chain can eventually produce unanticipated harm to human health and the surrounding ecological system (Cheung and Fok 2017; Li et al. 2020). MP can also adsorb, transport, and enrich heavy metals and persistent organic contaminations (POPs) because of their hydrophobicity and large specific surface area, which can further aggravate their impacts on the receiving ecosystem (Bouwmeester et al. 2015). A study reported by Ashton et al. (2010) showed the adsorption of heavy metals (Fe, Al, Cu, Mn, Pb, Ag, and Cd) by polyethylene pellets from seawater. Holmes et al. (2012) collected plastic pellets (PE) from beaches

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and studied their metal adsorption capacity. Consequently, MPs are recognized as significant transporters of other contaminants including heavy metals and POPs (Yu et al. 2020; Selvam et al. 2021). It has been shown that chemicals like polychlorinated biphenyls are more toxic to organisms when mixed with MP and exposed to the solution (Barnes et al. 2009; Krause et al. 2021; Wardrop et al. 2016). These effects resemble the “Trojan horse vector effects”, in which MPs convey hazardous chemicals straight into the bodies of animals after its intake (de Sá et al. 2018; Oliveira et al. 2013). Thus, there is a need for systematic investigation of MP with its co-contaminants like heavy metals in soil water environments (Yuan et al. 2022).

The majority of manufactured plastic goods are made from polyethylene (PE), a material used in many everyday items as diverse as fishing gear, plastic bottles, food packaging, toys, and various health and cosmetic products (Chen et al. 2022). At the same time, various studies have identified the heavy metal, Cd, as one of the most dangerous and mobile toxic elements in the environment (Nies 1999). Cd has a long biological half-life and leaches into the soil through water, where it subsequently bio-accumulates in living things and ecosystems (Kubier et al. 2019). According to studies, agricultural land contains a variety of MP, the majority of which contain the toxic metal Cd, which is a common ingredient in pesticides (Liu et al. 2018). Therefore, there is a high possibility for the co-occurrence of Cd and MP in both terrestrial and aquatic ecosystems. The behaviour (fate, bioavailability, and toxicity) of MP/Cd in the environment may be altered after their interactions with each other (Wang et al. 2019). Shallow groundwater resources of such types of problematic sites having significant variations in organic content may get polluted with these pollutants. Therefore, the objective of this study is to understand the adsorption characteristics of Cd by PE-MP in polluted groundwater using microcosm experiments under varying BOD, COD, and initial concentrations of metals.

2 Materials and Methods

2.1 Materials and Chemicals

All the chemicals such as sodium hydroxide (NaOH), cadmium nitrate $\text{Cd}(\text{NO}_3)_2 \cdot 4\text{H}_2\text{O}$, and nitric acid HNO_3 were of analytical purity, supplied through Sigma Aldrich and used directly without further purification. Groundwater samples from four locations (L1, L2, L3, and L4) were collected near the MSW dumpsite of Roorkee, Uttarakhand, India ($29^\circ 54' 00.23''$ N, $77^\circ 51' 48.63''$ E). Here L1 is a tube well located adjacent to the dumpsite, while L2 and L3 are 2 km away on the upstream side of the dumpsite situated in opposite direction and L4 is another tube well situated downstream of the dumpsite. All groundwater samples were filtered using a vacuum filter unit attached with a 0.45 mm Whatman cellulose filter. Naturally aged PE-MP were collected from the same dumpsite directly. The collected plastics were washed

2–3 times repeatedly with distilled water to remove the accumulated unwanted particles. These plastics were reduced to small pieces and ground to convert them into MP of different sizes.

2.2 Practical Experiments

The physiochemical properties of groundwater were analysed prior to the adsorption experiments. In situ parameters such as pH, conductivity, and total dissolved solids were measured using Hanna (H19814) multiparameter probe. Inductively coupled plasma mass spectrometry (ICP-MS) was used to ascertain the presence of other elements in the groundwater.

A microcosm study was carried out using PE-MP in a 250 mL glass made conical flask holding 150 mL groundwater with an initial Cadmium concentration of 20 mg L^{-1} . The pH was kept at 6 and the temperature was maintained at $29 \text{ }^\circ\text{C}$ throughout the experiment. To observe the significant results of the experiments, we added 0.2 g of PE-MP, which was collected directly from the dump site. The initial concentration of Cd was kept dominating the other metal elements found in traces to investigate its interaction with PE-MP. All the solutions were placed into an incubator shaker (REMI CIS-24 Plus) at a speed of 185 rpm for four days taking the samples at an interval of 0.5, 1, 2, 4, 6, 8, 12, 16, 18, 24, 36, 48, and 96 h at a constant temperature of $29 \text{ }^\circ\text{C}$. Thereafter, eight Cd solutions of initial concentration (5–50 ppm) were prepared for isotherm studies. 0.2 g of grounded PE-MP was added to each solution with a constant pH. Based on preliminary experiments, 36 h was chosen as the equilibrium time for the isotherm study. Flame Atomic Absorption Spectrometry (Agilent 200 series AA), outfitted with a Cadmium hollow cathode lamp, was used to measure the Cd concentration. The adsorption of Cd on PE-MP at equilibrium conditions was calculated based using: $Q_e = V(C_0 - C_e)/m$, where Q_e (mg g^{-1}) is the adsorption capacity at equilibrium; C_0 and C_e (mg L^{-1}) are the initial and equilibrium concentrations; V (L) is the volume of adsorption solution; and m (g) is the mass of PE-MP.

3 Results and Discussion

The water quality parameters of samples collected from the site are listed in Table 1. Most of the samples had detected heavy metals (Zn, Ni, Cu, Cd, and Pb) due to leachate movement through the unsaturated zone. Also, high BOD (19–78 mg/L) and COD (47–240 mg/L) were measured in the samples which indicates towards a sizable amount of organic matter present in the groundwater of the study site. The toxic metal Cd was present in all the samples and hence was selected for these experiments. To comprehend the effects of contact time on the Cd absorption with PE-MP, kinetic experiments were conducted. Figure 1 explains about Cd adsorption pattern by the

PE-MP in groundwater. Sample L1 had an adsorption capacity of 0.20 mg/g of heavy metal, while the sample L2 had an adsorption capacity of 0.159 mg/g at its absolute minimum. As shown in Fig. 1, the adsorption process was rapid in the first 5 h, which kept reducing between 5 and 34 h before attaining an equilibrium condition around 36 h. A higher affinity of Cd for MP was observed in the downstream sample (L4) than in the upstream samples (L2 and L3). The results show that metal adsorption is enhanced in water with high BOD and COD. High adsorption of Cd in these samples seems due to the influence of dissolved organic matter which can bind more metals (Refaey et al. 2014).

Figure 2 illustrates the matching of Langmuir and Freundlich adsorption isotherms with the experimental data. According to the Langmuir model, sorption typically takes place at a monolayer of single-molecular sorbent that contains identical sorption sites. It is supposed that there were no barriers between the open sorption sites and the nearby molecules that were occupied by the sorbate. According to the Freundlich model, the adsorption process occurred on a multilayer of the sorbent that had sorption sites with various energies. An empirical model called the nonlinear Freundlich isotherm might describe the heterogeneity of solid surfaces as well as the exponential distribution of the sites and their energies (Freundlich 1907).

According to Aksu and Tunç (2005), the constants K_F and n are indicative parameters of adsorption strength and respectively indicate the predicted adsorption capacity of the adsorbate on the sorbent. Initially, Q_e increased quickly followed by a reduced rate before it became stable.

It is to be noted that the value of Q_e in L1 is more than the rest of the samples, which is compatible with the findings of the adsorption kinetics experiment. The data obtained for the best fit of the isotherm model are listed in Table 2. Although the

Table 1 Main characteristics of the groundwater samples analysed in this work

Parameters	L1	L2	L3	L4
pH	6.4	7.82	7.49	7.3
EC	18.10	2.10	2.45	2.52
TDS	2785	413	395	970
COD	240	47	72	89
BOD	78	19	23	34
Mg	57	2	30	44
Ca	176	6	14	9
Cr	0.34	0.50	0.82	0.12
Mn	7.59	0.48	1.59	0.98
Ni	0.53	0.06	0.09	0.08
Cu	0.65	0.16	0.16	0.19
Cd	0.87	0.25	0.33	0.40
Pb	0.40	0.05	0.00	0.91

Note All the concentrations are in mg/L except pH and EC (mS/cm)

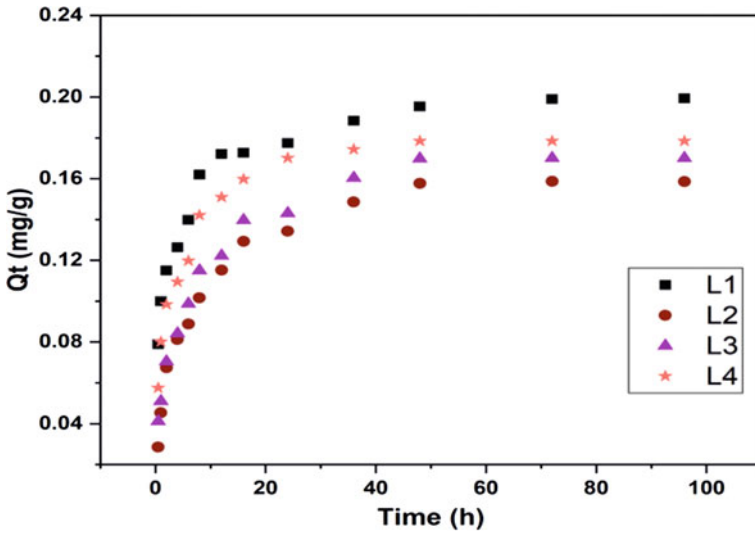


Fig. 1 Adsorption kinetics of Cd onto PE-MP (L1—adjacent to dumpsite, L2 & L3—situated 2 km away from dumpsite in upstream side and L3 is located at 2 km away in the downstream direction)

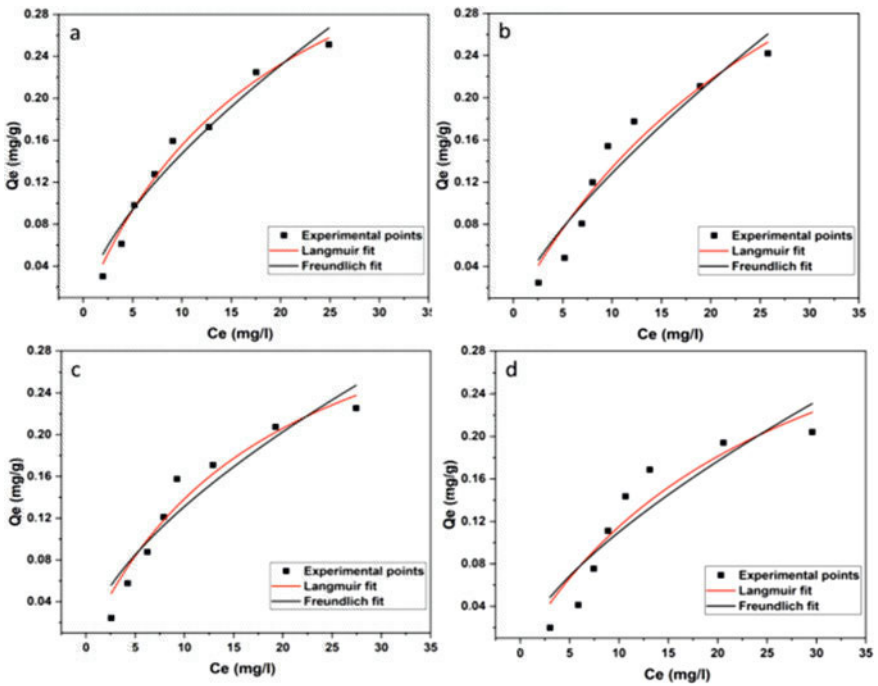


Fig. 2 Adsorption isotherm study of Cd onto PE-MP in a L1, b L2, c L3 and d L4

Table 2 Equilibrium model parameters obtained from isotherm study

	Langmuir isotherm			Freundlich isotherm		
	Q_m (mg/g)	K_L (L/mg)	R^2	N	$K_F \{(\text{mg/g})^*(\text{L/mg})^{1/n}\}$	R^2
L1	0.5782	0.0301	0.98	1.34	0.0203	0.91
L2	0.4035	0.0522	0.95	1.58	0.0308	0.90
L3	0.4270	0.0368	0.93	1.46	0.0227	0.84
L4	0.4607	0.0510	0.88	1.53	0.0327	0.96

Langmuir and Freundlich isotherms provide a reasonable fit to experimental data, the correlation coefficient (R^2) is varying up to some extent. The maximum value of R^2 was obtained from the Langmuir Isotherm for L1, which also contains the high BOD and COD values, indicating the presence of chemical adsorption process. It was also found that PE-MP had a maximum Cd ion adsorption capacity of 0.578 mg/g at room temperature.

4 Conclusion

The interaction of MP with other toxic pollutants, such as metals, has drawn interest in recent years. Studies have shown the adsorption of heavy metals by MPs, but the impacts of organic content (BOD and COD) have not been investigated thoroughly. In the present study, adsorption behaviour of Cd on PE-MP in polluted groundwater of an MSW dumpsite is investigated under varying BOD and COD levels. The outcomes of adsorption experiments demonstrated that Cd is rapidly adsorbed in 2–5 h but achieved equilibrium at a relatively long time of 36 h. The Langmuir model fits more accurately to characterize the adsorption isotherm of PE-MP with Cd. The level of BOD and COD plays a significant role in the adsorption capacity of PE-MP that has been found to increase with higher levels of carbon content. The presence of other elements like calcium and magnesium can cause Cd metal to react with them and needs to be investigated further.

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Conflicts of Interest The authors confirm that there is no known personal or professional conflict of interest that could be seen as having an impact on the work presented here.

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Chapter 2

Groundwater Quality and Contaminations in India



Dipankar Saha

1 Preamble

India is the largest user of groundwater in the world (Saha et al. 2017). The green revolution initiated in the 1960s has given an immense push for groundwater extraction through the installation of millions of irrigation wells around the country (Saha et al. 2017). Besides, the domestic water supply in the rural and suburban areas is almost entirely dependent on underlying aquifers. The recent initiatives by the Government of India under the *Jal Jeevan Mission*, where it is promised that 24×7 pipe water supply will be available at the doorstep of every rural household, is immensely banking on groundwater (https://jaljeevanmission.gov.in/about_jjm#mission). Even in urban areas, traditionally it is believed to be dependent on surface water sources like dams or large-scale extraction from rivers. However, the rising demand for water from the rapidly expanding much exceeds the availability of the water from the present sources, thus gradually dependence on groundwater is increasing. Irrigation consumes more than 90% of total groundwater extraction. The value of groundwater used for irrigation is between 7.6 and 8.3 billion US\$/year and the size of the groundwater-based economy is somewhere between 75 and 80 billion US\$ (Shah et al. 2012).

The large-scale extraction of this resource is creating an undesirable impact on the underlying aquifers in several parts of the country. The impacts are water level decline, wider pre- and post-monsoon fluctuations, jeopardizing the groundwater flow regime, diminishing the yield of the wells and drying up of the shallow wells (Saha and Roy 2018). All these issues impact the drinking water supply and livelihood of the farmers adversely. The groundwater-related discussions generally centre on sustainable use of the resource, involving where and how the demand- and supply-side interventions can be dovetailed judiciously and prudently. However, the groundwater

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contamination created by the geogenic and anthropogenic causes is also spreading fast, capturing new geography and also the deeper aquifer systems. Geogenic contaminations like arsenic, fluoride, salinity, and iron are the most widespread in occurrence and adversely impact the potable water supply. Anthropogenic contamination, on the other hand, is localized in nature around their point of origin, like seepage from urban sewage and landfills, effluent discharge from industries, the mining activities. Excessive use of fertilizers, pesticides, and insecticides in agriculture is creating an impact on wider areas particularly impacting shallow aquifers (Saha et al. 2008). This paper presents a scenario of the groundwater chemistry and contamination issues in the aquifers of India.

2 Broad Hydrogeological Framework

Aquifers are geological formations that can store and yield water to wells. The basic two hydraulic parameters of aquifers are storage and transmissive capacities, which vary widely, depending upon the rock type, extent of weathering and tectonic processes it has undergone. On the basis of the two hydraulic parameters and other aquifer characteristics, these formations are divided into two categories:

1. Soft rock aquifer
2. Hard rock aquifer.

The soft rock aquifer is characterized by primary porosity with good inter-pore space connectivity, which always makes them potential aquifers (Saha et al. 2007). On the other hand, in hard rock aquifers, water remains primarily within the fractures and joints. Such secondary openings yield sufficient water, if they are adequately available, open in nature, and interconnected. The hard rock aquifers generally have lesser potential than the soft rock aquifers (Saha et al. 2013). There is a third group, called semi-consolidated rock aquifer, which occupies a lesser geographical area, where groundwater remains both in the primary porosity, as well as within the fractures and joints.

The geological formations in India are grouped into 14 principal aquifers systems (Fig. 1; Table 1).

- a. **Soft rock aquifer**—The alluvium, the unconsolidated deposits of the Quaternary age, which can be either of fluvial, deltaic, lacustrine, or aeolian origin, come under this group. This unit forms the most potential aquifer system in the Indian subcontinent, covering about 31% geographical area in the country. The most famous belt is Indo-Ganga–Brahmaputra Alluvial Plains. This unit is extensively exploited and also widely affected by geogenic contaminations, like—arsenic, fluoride, and iron (Saha et al. 2007).

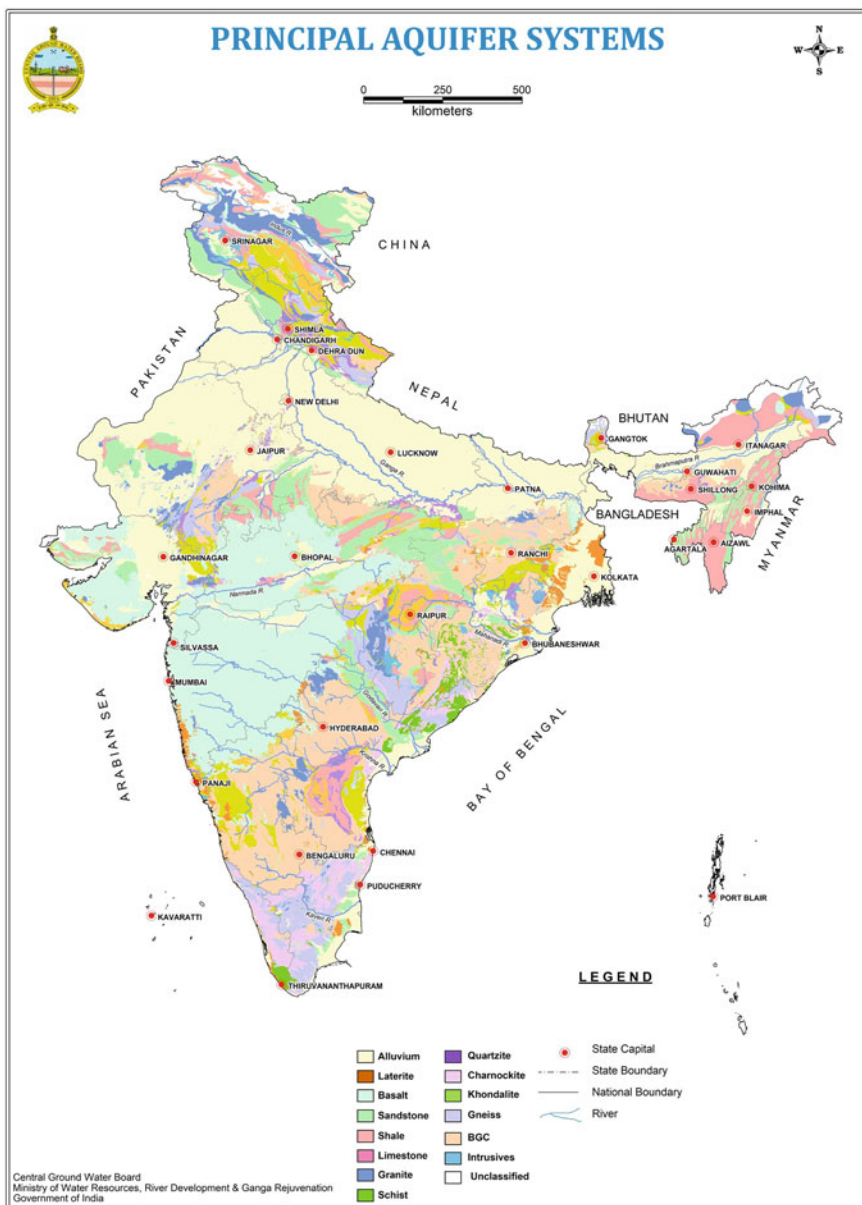


Fig. 1 Principal aquifer systems in India

Table 1 Principal aquifer systems of India

S. No.	Principal aquifer system	In % of total geog. area	Dominant aquifer type
1	Alluvium (including aeolian sediments)	30	Soft rock
2	Laterite	1	Semi-consolidated rock
3	Basalt	16	Hard rock
4	Sandstone	8	Hard and also semi-consolidated rock
5	Shale	7	Hard and also semi-consolidated rock
6	Limestone	2	Hard rock
7	Granite	3	Hard rock
8	Schist	5	Hard rock
9	Quartzite	2	Hard rock
10	Charnockite	3	Hard rock
11	Khondalite	1	Hard rock
12	BGC	15	Hard rock
13	Gneiss	5	Hard rock
14	Intrusives	1	Hard rock

Source Saha and Roy (2018)

- b. **Hard rock aquifer**—Hard rock aquifers cover nearly 70% geographical area of our country. The predominant lithology/rock types are granite or granite gneiss. But this group also includes a wide variety of rocks, like sandstone, quartzite, schist, phyllites, slates, charnockites, khondalites, etc. The weathered zone at the top, generally with 5–15 m thickness forms a good shallow aquifer but is drying up completely because of over-exploitation. The innumerable borewells, used for both drinking and irrigation purposes, extract groundwater from joints and fractures below. Explorations by CGWB have indicated that water-bearing fractures could even be traced down to 350 m bgl. However, the potential fracture systems are restricted mostly within 200 m bgl.
- c. **Semi-consolidated rock aquifer**—This unit mainly comprises shale, sandstone, and limestone. The sedimentary deposits belonging to the Gondwana period and the Tertiary formations are included in this category. Under favourable hydrogeological situations, semi-consolidated aquifers form potential aquifer systems as we find in Tipam sandstone in Tripura (Saha and Sharma 1994).

3 Availability and Utilization of Groundwater Resources

Groundwater resource, which is available within the aquifers at different depths are categorized into two broad groups:

- i. Replenishable/dynamic resource
- ii. Static resource.

The replenishable or dynamic resource is that part of the groundwater remains in the shallow zone of the aquifers, recharged every year by rain. For all our societal needs we primarily depend on this resource. CGWB estimates the blockwise replenishable resource at regular intervals (generally 2 years) for the entire country, in association with the State Governments and the Union Territories. The methodology framed by the Groundwater Estimation Committee, 2015 is followed to estimate the groundwater recharge from rainfall and other sources. Groundwater extraction is worked out separately for irrigation, domestic, and industrial purposes. The latest estimate made in 2020 reveals that the total annual groundwater recharge was 436 billion m³ (bcm), where the annual extractable groundwater resource was worked out to be 398 bcm (CGWB 2020). Annual groundwater withdrawal for the entire country, considering domestic, irrigation, and industrial uses is found to be 245 bcm. Thus, the overall stage of groundwater development in India is worked out as 62%. The estimates were made in each of the 6965 blocks/mandals/firkaas located in areas except the Himalayas. Out of these, 64% of the blocks are found to be safe, where the stage of groundwater development was less than 70%. About 4% of blocks are critical, where extraction is between 90 and 100% of the annual recharge. In about 1114 blocks, comprising 16% of the total, over-exploitation is prevalent, where groundwater extraction is more than the recharge. The over-exploited blocks are mainly confined in Punjab, Haryana, western Uttar Pradesh, Rajasthan, Gujarat, Tamil Nadu, Karnataka, and parts of Maharashtra, Telangana, and Uttar Pradesh.

4 Groundwater Chemistry

Rainfall is the purest form of water. It falls on the surface, enters into the soil, and flows through the vadose zone and the aquifers. On its journey, it constantly interacts with the aquifer matrix. Depending upon the Eh and pH condition, it constantly undergoes rock–water interaction and gets enriched in different constituents. Based on the extent of presence in groundwater, the chemical constituents are classed into: (1) Major constituents, (2) Secondary constituents, (3) Minor constituents, and (4) Trace constituents (Table 2).

Table 2 Major, minor, and trace constituents in groundwater

Constituent classes	Constituents
Major constituents (1.0–1000 mg/L)	Sodium, calcium, magnesium, bicarbonate, sulphate, fluoride, silica
Secondary constituents (0.01–10.0 mg/L)	Iron, strontium, potassium, carbonate, nitrate, fluoride, boron
Minor constituents (0.0001–0.1 mg/L)	Antimony, aluminium, arsenic, cadmium, bromide, barium, iodide, copper, germanium, cobalt, chromium, phosphate, nickel, molybdenum, manganese, lithium, lead, zinc, vanadium, uranium, titanium, selenium, rubidium
Trace constituents (generally less than 0.001 mg/L)	Cerium, gallium, gold, cesium, bismuth, beryllium, lanthanum, niobium, platinum, radium, ruthenium, scandium, thallium, thorium, tin, tungsten, silver, zirconium, yttrium

The most common groundwater facies observed in the country is Ca–HCO₃ when the salinity of the water is less than 750 $\mu\text{s}/\text{cm}$. In cases when the electrical conductivity remains between 750 and 3000 $\mu\text{s}/\text{cm}$, the groundwater generally is of mixed cation and anion type. Groundwater with electrical conductivity above 3000 $\mu\text{s}/\text{cm}$ is generally of Na–Cl. However, it is often found that the hydrochemical facies vary widely.

In a study covering the middle Ganga plain (Saha et al. 2008), the dominant facies are found as Ca–HCO₃, Na–HCO₃, Na–Mg–HCO₃, and Na–Ca–HCO₃. Occasionally Na–Cl–HCO₃ and Na–Cl facies are also reported. It has been observed that Na-dominated facies are found frequently in shallow groundwater and are less frequently observed in deep aquifers. Mg-dominated facies are more widely distributed in the deeper aquifers. While understanding the hydrochemical evolution, the groundwater ranges from “recharging water” with dominant Ca²⁺ and HCO₃⁻ to Na⁺ and Cl⁻ dominated “end point water”. The water is dominantly marked with partial ion exchange, as 50% of the samples are marked by HCO₃-dominant with cation indiscriminate types (Mukherjee et al. 2012). About 15% of the samples are found to be HCO₃-dominant anion phase and Na-dominant cation phase, indicating enrichment of Na⁺ at the expense of Ca²⁺ through the process of ion exchange. It has also been observed that simple dissolution is a dominant process, particularly in shallow aquifers.

Principal component analysis (PCA) has been applied to the chemical analyses data to identify the factors that influence the composition of groundwater. An elaborate study conducted in the arsenic-contaminated middle Ganga plain in the area bordering the states of Bihar and Uttar Pradesh has identified four significant PCs explaining 74% of the total variance of the data set. PC1 accounts for 29% of the variance and is contributed mainly by EC, HCO₃, and Mg. The PC1 indicates a contribution from rainfall infiltration and seepage from surface water bodies. PC2 accounts for 20% of the variance and is characterized by significant positive loading