



## Chemometric appraisal of groundwater and surface water quality for domestic, irrigation and industrial purposes in the coal mining province of Mahan River catchment area

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### ABSTRACT

The global concern about water quality in coal mining operations is a significant issue. It presents detrimental water-related threats, including pollution, acid mine drainage, and habitat destruction. In this study, an attempt has been made to evaluate the water quality for domestic, irrigation and industrial purposes in the coal mining province of Mahan catchment area, with a particular focus on the impact of coal mining activities. 50 samples from pre-monsoon season of 2018, collected from dug well, tube well, mine water and river water were analyzed. The findings indicate that water in the study area exhibits acidic characteristics, with pH values below the desirable range for drinking water. Elevated electrical conductivity, total dissolved solids, sulphate, total hardness and chloride concentrations are observed, particularly around core mining regions. For irrigation suitability, the study reveals that most of the samples are suitable, based on parameters such as sodium percentage (Na%), sodium adsorption ratio (SAR), magnesium hazard (MH), Kelly's index (KI), permeability index (PI), and residual sodium carbonate (RSC). However, majority of the samples collected from core mines show an elevated range of Na% (>80), SAR (>60), MH (>50), KI (>1), PI (>100), RSC (>2.5) and PS (>5) indicating potential soil permeability issues and crop damage, which restrict its suitability for agricultural use. Furthermore, the assessment of water for industrial suitability by analyzing the scaling and corrosion indices, such as the Langelier index (LI), aggressive index (AI), Ryznar index (RI), Puckorius index (PI), and corrosivity ratio (CR) highlights the presence of a corrosive tendency in majority of the water samples, particularly in the mining areas.

**Keywords:** Coal mines; Sustainable water resources management; GIS; Irrigation water quality; Industrial water quality

### 1. Introduction

Global coal production is expected to increase significantly, rising from 9 billion short tons in 2012 to 10 billion short tons by 2050. Major coal-producing nations, including China, India, and Australia, are poised to play a pivotal role in driving this growth. India, ranking as the third-largest coal producer globally, consumed a staggering 1.027 billion tons of coal in 2022–2023. These figures underscore the

massive scale of coal mining activities in India, aligning with the nation's economic development [1]. However, the surge in coal mining activities exacts a considerable toll on the environment, particularly on water resources and quality. This concern extends beyond India and affects regions in Europe, South Africa, China, the USA, and Australia [2].

Prominent challenges associated with coal mining include acid mine drainage (AMD), metal contamination, and elevated sedimentation due to unconsolidated

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materials [3]. Furthermore, coal mining operations often involve the presence of coal washery units, where post-extraction processing includes the use of surfactants and flocculants to reduce impurities [4]. These activities result in the generation of substantial volumes of wastewater, posing a significant risk to both surface and groundwater in the affected regions [5].

In India, the issue of AMD persists notably in the majority of the coalfields, characterized by an abundance of sulfide-enriched coal [6]. However, a common concern across most Indian coal mining areas is the elevated presence of toxic heavy metals in surface water bodies and groundwater. These heavy metals can have detrimental environmental effects and may also pose health risks when they find their way into the food chain or are used as sources of drinking water [7]. These heavy metals are adsorbed by iron and manganese oxyhydroxides in sediments due to their high specific surface area and cation exchange capacity [8]. Open-cast mining activities have been observed to significantly increase downstream sedimentation, up to 100–3,000 times compared to forested areas and 10 times compared to grazing lands [9]. These sediment deposits have a high affinity for metals, which can adversely impact water bodies and aquatic life. The toxicity and potential bioaccumulation of these heavy metals in the food chain further raise concerns [10].

Moreover, coal mining operations create an environment conducive to the mobilization of metals into aquatic ecosystems. Consequently, water resources used for agricultural, irrigation, washing, bathing, or even as drinking water, when contaminated with elevated salt concentrations, solids, metals, or other impurities, can pose serious health risks. Such contamination can affect crop yields and soil properties, particularly with respect to parameters such as water hardness, salinity, and electrical conductivity [11]. Parameters like sodium (Na), magnesium (Mg), calcium (Ca), and bicarbonate ( $\text{HCO}_3$ ) content in irrigation water influence soil permeability [12].

Water quality is of paramount importance for human health and a prerequisite for a healthy society. Ensuring the quality of water resources is essential for environmental sustainability. Numerous statistical methods are available for water quality evaluation, including fuzzy logic, factor analysis, hierarchical cluster analysis, principal component analysis, multivariate and spatial analysis [13].

Apart from these methods, agricultural suitability parameters like sodium percentage (Na%), sodium adsorption ratio (SAR), magnesium hazard (MH), Kelly's index (KI), permeability index (PI), and residual sodium carbonate (RSC) are vital for assessing irrigation water quality and soil health, assisting farmers in optimizing crop productivity. Whereas, on the industrial front, indices such as the Langelier index (LI), aggressive index (AI), Ryznar index (RI), Puckorius index (PI), and corrosivity ratio (CR) play crucial roles in evaluating water properties to prevent issues like scaling and corrosion, ensuring the efficiency and longevity of industrial processes and equipment.

When applied in coal mining operations, these parameters and indices can provide critical insights into the quality of water resources used in mining processes, helping to mitigate issues like scale formation and corrosion in

mining equipment and infrastructure. To effectively use these parameters in the context of coal mining, comprehensive water quality assessments and appropriate water treatment measures are implemented to safeguard equipment and optimize operational efficiency.

The Mahan River catchment area in India is one such region where coal mining activities have been prevalent for several years. Coal mining involves various processes that can directly and indirectly affect water resources, including surface and groundwater systems. The extraction of coal, handling of overburden materials, and discharge of mine water can result in significant alterations to the hydrological regime and water quality. The detrimental impacts of mining on water resources are multifaceted and can manifest in several ways. One of the primary concerns is the depletion of groundwater resources due to excessive water pumping from mining operations. The dewatering of underground mines and open pits can lead to a decline in the water table and the drying up of nearby wells and springs [2]. This can have severe consequences for local communities, particularly those dependent on groundwater resources. Furthermore, coal mining activities often generate large volumes of mine water, which can contain high concentrations of various pollutants, including heavy metals, sediment, and dissolved solids. Improper management of mine water can result in its discharge into nearby water bodies, leading to contamination and degradation of surface water resources. The release of acidic mine drainage, a common byproduct of coal mining, can further exacerbate water quality issues by acidifying water bodies and mobilizing toxic elements [14,15]. The consumption of contaminated water is widely acknowledged as a major threat to human health, resulting in a range of harmful medical conditions [16]. These may encompass diarrhea, cholera, polio, typhoid, and skin issues [17,18].

The hydrological processes within the Mahan River catchment area, including surface runoff, infiltration, and streamflow, can be significantly affected by the alteration of land surfaces due to mining activities. Excavation of coal and associated activities such as land clearing and grading can disrupt natural drainage patterns, leading to changes in the flow regime and erosion of soil and sediment into water bodies. This sedimentation can have detrimental effects on aquatic ecosystems and water quality, reducing the capacity of water bodies to support aquatic life and affecting downstream water users. To mitigate the impacts of coal mining on water resources, it is crucial to implement effective management strategies and regulatory frameworks. This includes measures such as proper mine water treatment and discharge controls, reclamation and restoration of mined areas, and the implementation of water conservation practices. Integrated water resources management approaches, incorporating stakeholder engagement, monitoring programs, and adaptive management strategies, can help ensure sustainable water use in coal mining regions [19].

To assess the impact of mining on water resources, it is crucial to establish a long-term water quality database and consistently monitor relevant parameters. Although numerous studies have investigated mine water quality in various coalfields across India, including Jharia, Neyveli, Raniganj, West Bokaro, Singrauli and Pench [20–28] no such

comprehensive database exists for the Mahan River catchment area, where mine water plays a significant role as a water source.

Simultaneously, it is evident that assessing water quality for multiple purposes is crucial, yet comprehensive studies specifically targeting this objective are lacking. It is also to be noted that there were not many studies conducted with this aim in this study area. Hence, the primary aim of the study are:

- To determine the suitability of water samples by comparing them to WHO permissible limits.
- To determine the suitability of sampled water for agricultural use using parameters such as sodium absorption ratio, sodium percentage, MH, PI, RSC, potential salinity and Kelly's index.
- To determine the suitability of sampled water for industrial use using indices like Langelier index, aggressive index, Ryznar index, Puckorius index, and corrosivity ratio.

The study seeks to create a scientifically-documented record of water quality in the Mahan catchment, equipping authorities with crucial information for formulating more effective management strategies and implementing sustainable water resource management practices.

## 2. Material and methods

### 2.1. Study area

The current investigation focused on evaluating the suitability of domestic, agricultural and industrial use of water in a coal mining region, located in the Surguja district of Chhattisgarh. It is located in the Northern part of Chhattisgarh, bounded by Surajpur and Balrampur in the North, Koriya in west, Korba and Raigarh in South and Jashpur in East. It covers an approximate area of 4,043.299 km<sup>2</sup>.

It is bounded by latitude 22° 37' 18" to 23° 16' 35" and longitude 82° 45' 21" to 83° 41' 45" has an average elevation of 615 m as shown in Fig. 1. The region is characterized by a significant concentration of opencast and underground mining centers. The climate is classified as sub-tropical, with distinct seasons in this area. The summer season extends from March to June, followed by the monsoon season from July to September, the post-monsoon season from October to December, and finally, the winter season from December to March. The maximum temperature typically occurs in May and June, while January experiences the minimum temperature. The annual rainfall in the Surguja district is approximately 1,130 mm, with an average of 73 rainy days throughout the year.

According to the 2011 census data, the population of Surguja stands at 1,972,092. This district is a significant part of the Mahanadi basin, enriched by rivers like Hasdeo and Gej, as well as the Ganga basin, which encompasses rivers such as Rihand, Mahan, Morni, and Piparkanhar.

The district contains rocks that are quite old, ranging from the Archaean to Eocene periods. The basement consists of granitoids and metasediments from the Chota Nagpur Gneissic complex, which lie beneath layers of Gondwana sediments, Lameta beds, and Deccan Traps. Major portion of the district is covered by Chota Nagpur Gneissic Complex and thereafter by Gondwana super group of rocks. Eastern part of the district is dominated by Chota Nagpur Gneissic Complex whereas in western part Gondwana rocks are dominant. Laterites enclosing bauxite pockets extends over a considerable area in the southern part in Mainpat plateau. Kamthi formation, Lameta beds, Archeans and Deccan Trap basalts have scattered exposures in the district (Fig. 2).

The Barakar formation, which includes a soil cover and sandstone of various grain sizes interspersed with shale layers and coal seams, covers a significant percentage of the studied region in terms of hydrogeology. The Barakar sandstones are saturated and act as aquifers. They have

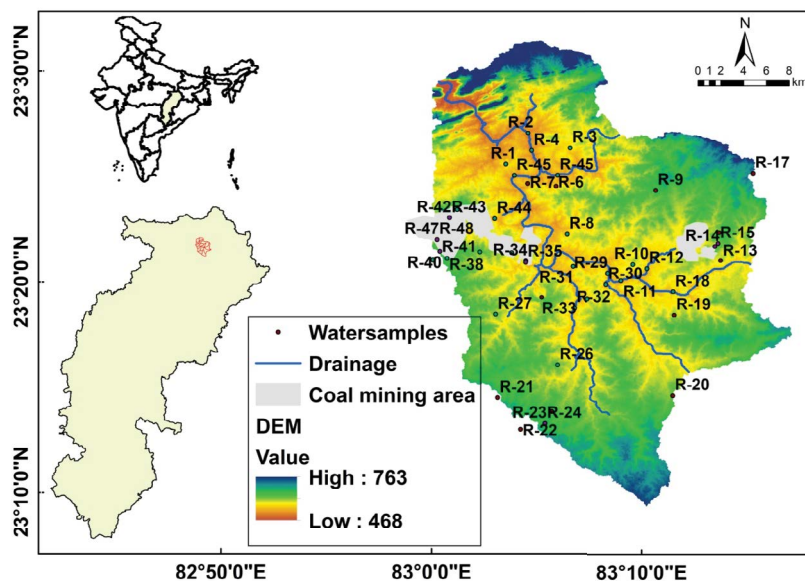


Fig. 1. Geographical representation of the study area.

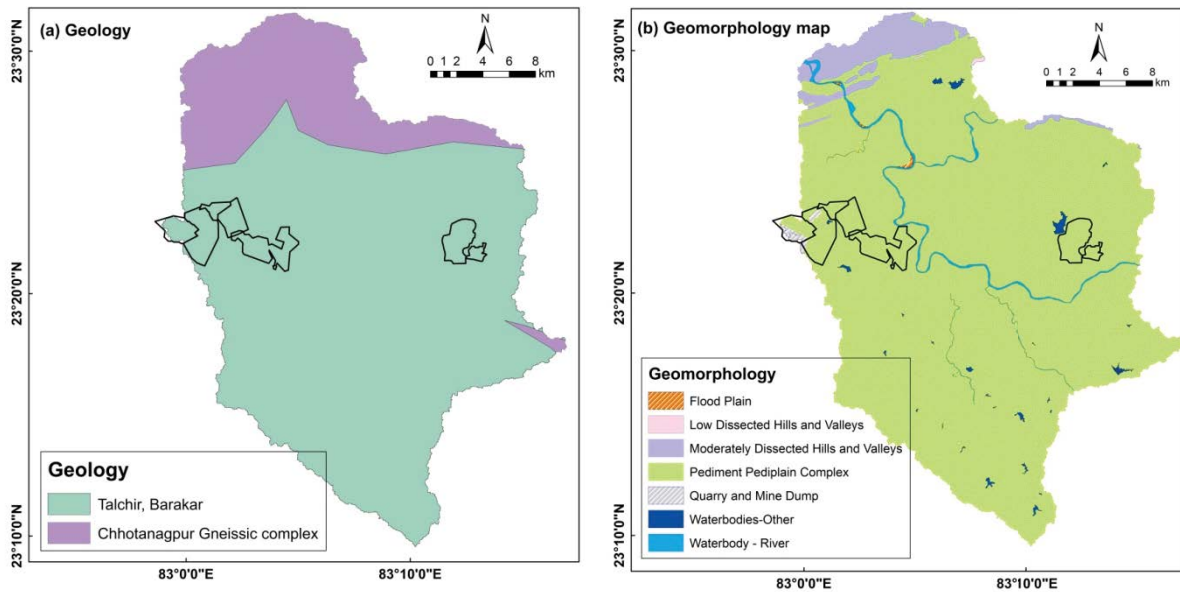


Fig. 2. Figures depicting (a) geology map and (b) geomorphology map.

medium to very coarse grain sizes and multiple gritty pebbly (conglomerate) layers. Shale beds and coal seams serve as aquicludes, resulting in the formation of a multi-layered aquifer system. With an average thickness of 16 m, the formation immediately above the working seam is primarily made up of alluvium and sandstone and functions as an open aquifer. Compact sandstone with secondary porosity makes up the bottom formations, which operate like restricted or semi-confined aquifers. In the study area, aquifer parameters have been assessed, with hydraulic conductivity ( $K$ ) at 0.56 m/d, transmissivity ( $T$ ) at 14 m<sup>2</sup>/d, and a storage coefficient ( $S$ ) of  $3.1 \times 10^{-2}$ . However, certain locations exhibit very high permeability due to localized gritty or pebbly conglomeratic beds [29].

## 2.2. Sampling and analysis

A comprehensive field survey was conducted within the study area. 50 samples were selected for the preliminary survey during the pre-monsoon season of 2018 from various water sources, including dug wells, tube wells, river water, and mine water. The locations were marked with latitudes and longitudes using a portable GPS (Table 1).

Before water sample collection, the removal of stagnant water from wells was achieved by pumping water for approximately 30 min. Subsequently, digital meters were utilized to measure characteristics like pH and electrical conductivity (EC). The collected water was then placed in 1 L polyethylene bottles. To ensure the removal of contaminants, a thorough cleaning process involving three rinses was applied to both the bottles and their caps.

Furthermore, the samples underwent filtration using 0.45- $\mu$ m Millipore filter paper before being transferred to the containers. Nitric acid was employed to acidify the samples intended for cation analysis, thus preventing ion precipitation. Regular EDTA was used in titrimetric to measure  $\text{Ca}^{2+}$  and  $\text{Mg}^{2+}$ . The measurement of  $\text{Na}^{+}$  and  $\text{K}^{+}$  was

conducted using a flame photometer, specifically the Jenway Clinical Flame Photometer-PFP7 model (Mumbai, India).

Additionally, titration methods were applied to measure the concentrations of  $\text{CO}_3^{2-}$  and  $\text{HCO}_3^-$ . The determination of sulfate was carried out using a spectrophotometer, specifically the Optima 2100 DV ICP-OES Spectrophotometer from PerkinElmer (Thane, Maharashtra, India), while the common  $\text{AgNO}_3$  titration method was employed for chloride ( $\text{Cl}^-$ ) measurement. Nitrate was measured using a colorimetric approach.

The World Health Organization (WHO) and the Bureau of Indian Standards (BIS) have set drinking water quality standards, which were used to compare all of the results. Prior to the interpretation of the chemical data, the ionic balance error of each underground water sample was calculated by comparing the total concentration of cations ( $\text{Ca}^{2+}$ ,  $\text{Mg}^{2+}$ ,  $\text{Na}^{+}$ , and  $\text{K}^{+}$ ) to the total concentration of anions ( $\text{CO}_3^{2-}$ ,  $\text{HCO}_3^-$ ,  $\text{Cl}^-$ ,  $\text{NO}_3^-$ , and  $\text{SO}_4^{2-}$ ). Notably, the ionic balance error value was discovered to be lower than the intended threshold of 5% [30].

Complete methodology has been shown in flowchart Fig. 3.

## 3. Results and discussion

### 3.1. Water suitability for domestic purposes

The qualitative evaluation of various water samples and its comparison with both the permissible and desirable limits recommended by World Health Organization (WHO) 2017 are essential aspects of this current research to determine its suitability for domestic purposes [31]. The summary of this analysis are shown in Table 2.

#### 3.1.1. Hydrogen ion (pH)

The pH of water increases as the levels of carbonate and bicarbonate rise in water [32]. This is also significant

Table 1  
Physico-chemical parameters of different water sources in the pre-monsoon season

ID	Location	Source type	pH	EC	TDS	F <sup>-</sup>	Cl <sup>-</sup>	HCO <sub>3</sub> <sup>-</sup>	SO <sub>4</sub> <sup>2-</sup>	NO <sub>3</sub> <sup>-</sup>	Ca <sup>2+</sup>	Mg <sup>2+</sup>	Na <sup>+</sup>	K <sup>+</sup>	TH
R-1	Gonda	DW	6.84	205	158	0.21	8.9	99	3.08	7.13	13.46	15.87	7.1	2.91	98.72
R-2	Mahan River S 7	RW	7.75	220	185	0.23	7.4	102.7	29.21	0.12	20.19	12.06	9.5	3.29	99.92
R-3	Parvatipur	DW	6.44	139	134	0.36	8.4	65.1	2.89	22.31	13.46	8.36	11.2	1.87	67.93
R-4	Mahan River S 6	RW	7.42	270	205	0.24	5.7	82.2	60.29	0.24	25.23	17.75	9.9	3.56	135.85
R-5	Banki River	RW	6.98	137	93	0.06	8.4	51.8	4.63	3.22	10.46	7.35	5.3	1.7	56.29
R-6	Palda	TW	6.4	69	54	0.13	0.9	38.3	1.62	0	4.46	3.86	1.8	3.12	26.98
R-7	Chhatarpur Para/ Patouapara	TW	5.87	106	69	0.18	5.1	21.5	2.58	21.77	6.73	5.64	4.2	1.34	39.95
R-8	Bagrd	DW	6.39	149	100	0.27	7.4	51.8	12.7	0.19	16.82	5.27	3.8	1.87	63.66
R-9	Dharampur	TW	6.02	152	92	0.07	16.7	18.1	1.73	30.34	6.73	10.5	5.4	2.06	59.88
R-10	Maridand	DW	7.34	311	236	0.23	15.4	142.9	14.91	0.95	37.01	10.6	10.9	3.38	135.99
R-11	Mahan River S 2	RW	7.61	160	126	0.24	3.8	85.5	4.84	0.25	11.77	9.25	7.9	2.49	67.35
R-12	Gohangar Nala	RW	7.13	160	116	0.27	5.2	72.1	4.14	3.4	13.46	8.17	6.9	2.01	67.15
R-13	Kotripara	TW	6.89	120	92	0.24	4.1	55.2	5.73	1.32	13.46	5.42	4.7	2.09	55.87
R-14	Mahan II Inlet	MW	7.73	433	341	0.26	6.8	166.5	76.99	2.34	40.37	17.31	23.1	7.32	171.90
R-15	Mahan II Outlet	MW	7.87	434	339	0.25	10.7	159.7	78.53	2.32	37.01	20.32	23.2	7.15	175.84
R-16	Choura	DW	5.93	57	41	0.05	3.4	19.8	1.36	6.58	3.87	2.76	1.8	1.09	20.99
R-17	Silphili	DW	6.23	93	59	0.11	8	26.9	5.88	1.97	6.73	3.7	4.2	1.25	32.00
R-18	Mahan River S 1	RW	7.36	166	129	0.22	3.5	85.5	4.75	0.5	19.87	5.2	6.8	2.31	71.00
R-19	Khargawan	DW	6.12	125	77	0.09	11.2	24.8	0.88	18.9	10.09	3.86	4.4	2.96	41.05
R-20	Kalyanpur	TW	5.9	167	105	0.07	18.8	22.9	0.41	33.72	12.87	5.65	7.5	3.12	55.34
R-21	Karwan	TW	6.2	146	89	0.22	14.8	21.5	1.31	26.89	5.05	8.61	6.5	4.25	47.93
R-22	Hiradabri/ Maheshpur	TW	6.25	122	97	0.2	18.9	24.8	2.66	25.96	10.09	7.49	4.8	2.43	55.93
R-23	Nawapara Inlet	MW	7.61	253	204	0.28	3.7	146.2	6.52	0.98	16.82	17.99	7.2	4.59	115.81
R-24	Nawapara Outlet	MW	7.64	224	212	0.23	1.7	156.8	7.21	0.09	23.55	13.91	4.6	3.98	115.91
R-25	Latori	TW	5.85	102	63	0.07	10.1	20.1	4.03	10.54	6.73	5.64	3.35	2.29	39.95
R-26	Tulsi	DW	6.18	225	135	0.05	30.2	28.9	2.12	33.98	12.65	11.23	12.2	3.87	77.67
R-27	Chikni	DW	7.3	251	182	0.21	11.5	102.4	0	15.84	28.6	7.93	10.2	4.88	104.01
R-28	Bojha	DW	6.33	84	67	0.09	5	34.8	2.21	7.17	6.73	5.64	3.1	2.68	39.95
R-29	Mahan River S 3	RW	7.39	153	129	0.27	4.4	85.5	4.51	0.48	16.82	7.29	7.5	2.67	71.94
R-30	Banki Nala	RW	7.44	177	145	0.32	9	93.7	5.04	0.23	16.82	8.27	9.5	2.38	75.96
R-31	Mayapuri	DW	7.47	407	301	0.13	32.8	136.8	12.91	41.58	30.28	15.66	20.7	9.73	139.91
R-32	Galphuli Nala	RW	7.31	211	175	0.39	6.1	112.5	10.79	1.42	20.55	10.99	7.9	4.41	96.43
R-33	Jhigador	TW	5.98	76	72	0.1	4.3	34.7	0.38	14.58	6.73	3.7	4	3.79	32.00
R-34	Shivani Inlet	MW	7.37	293	225	0.51	7	132.8	29.62	1.17	25.23	10.94	12.1	6.05	107.93
R-35	Shivani Outlet	MW	7.53	290	229	0.48	7.2	128.5	28.66	0.62	35.32	10.65	13.1	4.41	131.97
R-36	Kodasa	DW	7.35	293	251	0.4	8	141	35.42	1.5	31.96	15.61	12.8	4.05	143.90
R-37	Jarhi	DW	6.57	105	93	0.11	7.2	38.1	4.67	18.82	10.09	4.6	3.8	5.52	44.09
R-38	Dugga	DW	6.55	59	55	0.27	2.6	34.8	2.26	0.44	6.73	4.67	2.5	1.14	35.97
R-39	Bhatgaon	DW	6.33	538	395	0.24	11.2	8	268.5	5.39	58.9	23.58	13.2	5.61	243.85
R-40	Bhatgaon Inlet	MW	4.12	769	511	0.47	3.7	0	364.6	1.72	80.7	38.51	14.1	7.3	359.74
R-41	Bhatgaon Outlet	MW	4.09	880	643	0.4	3.2	0	464.1	3.17	102.6	46.63	14.4	8.19	447.71
R-42	Mahan 1 Inlet	MW	4.17	2,861	2,023	2.68	1.5	0	2,105.6	3.35	457.8	160.1	39.92	17.36	1,800.9
R-43	Mahan 1 Outlet	MW	4.04	3,859	2,679	2.69	16.3	0	2238.4	29.49	525.7	165.22	37.2	15.32	1,991.70
R-44	Mashan Nala	RW	4.31	809	655	0.63	8	1.2	476.3	1.31	105.6	40.02	16.28	6.05	427.98
R-45	Mahan River S 5	RW	7.33	317	245	0.3	6.2	75.4	97.1	0.18	35.3	16.48	10.1	3.74	155.87
R-46	Pondi	DW	7.47	1,351	848	0.42	150.1	250.8	217.0	1.34	92.5	25.53	98.1	12.55	335.97
R-47	Mahamaya Inlet	MW	3.36	1,117	848	0.9	6.1	0	642.2	0.51	109.3	64.91	16.2	7.92	539.48
R-48	Mahamaya Outlet	MW	3.33	1,125	901	0.35	7.8	0	680.0	0.99	109.3	79.49	15.5	7.21	599.26
R-49	-	RW	6.32	105	65	0.09	2.5	38.2	7.69	0.46	5.05	5.69	2.3	2.76	35.95
R-50	-	TW	7.05	128	99	0.13	2.2	68.7	1.23	0.14	16.82	3.4	5.5	0.98	55.99

Notes: RW - river water; MW - mine water; DW - dug well; TW - tube well

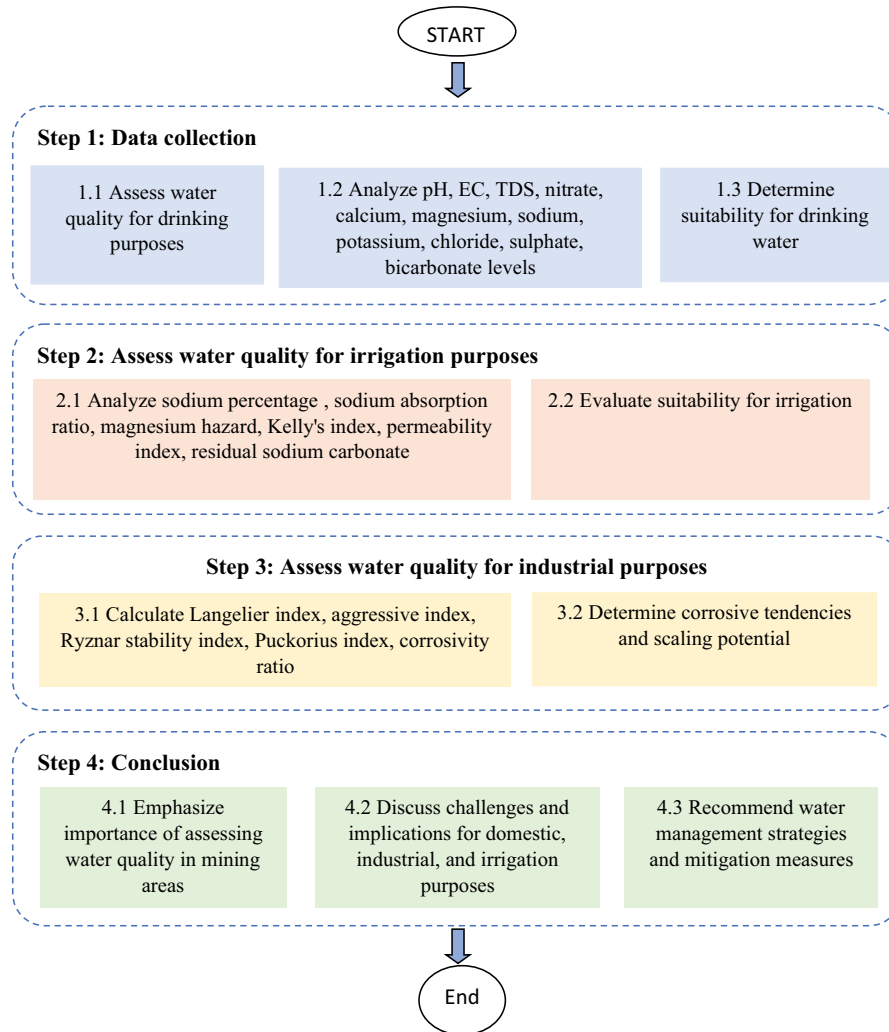


Fig. 3. Flowchart depicting the complete methodology.

Table 2  
Statistical summary of physico-chemical analysis for the sampled water

Parameter	Min.	Max.	Avg.	WHO International Standard (2011)		Samples surpassing the desirable or permissible limit of the WHO
				Desirable limit	Permissible limit	
pH	3.33	7.87	6.45	6.5	8.5	R-40, R-41, R-42, R-43, R-44, R-47, and R-48
EC	57	3,859	420.06	N/A	1,400	R-42 and R-43
TDS	41	2,679	307.74	500	1,000	R-42, R-43, R-44, R-46, R-47, and R-48
NO <sub>3</sub> <sup>-</sup>	0	41.58	8.16	50	75	–
Ca <sup>2+</sup>	3.87	525.72	46.69	75	200	R-42 and R-43
Mg <sup>2+</sup>	2.76	165.22	20.39	30	100	R-42 and R-43
K <sup>+</sup>	0.98	17.36	4.50	N/A	12	R-42 and R-43
Na <sup>+</sup>	1.80	98.10	11.77	N/A	200	–
Cl <sup>-</sup>	0.90	150.10	11.26	200	250	–
SO <sub>4</sub> <sup>2-</sup>	0	2,238.40	160.80	200	250	R-42 and R-43
HCO <sub>3</sub> <sup>-</sup>	0	250.80	66.17	N/A	200	R-46
CO <sub>3</sub> <sup>-</sup>	21.03	1,993	200.11	300	600	R-42 and R-43
Hardness	20.99	1,991.70	200.3	–	500	R-40, R-41, R-42, R-43, R-44, R-46, R-47, and R-48

Notes: Major ions: mg/L; EC: µS/cm; pH: no unit.

in various geochemical equilibrium and solubility analyses. The observed pH values of the range from 3.33 to 7.87, with a mean value of 6.45, indicating an acidic nature of the water (Figs. 4a and 5a). Among the sample stations, R-40, R-41, R-42, R-43, R-44, R-47, and R-48 had the lowest pH values. WHO guidelines recommend a preferred pH range of 6.5–8.5 for drinking water. Out of the total 50 samples, approximately 28% of the samples fall below the desired pH level of 6.5. The acidity of the water near the core mining regions can be explained by the presence of  $\text{CO}_2$  and  $\text{HCO}_3^-$ , which affect the pH level. As stated by Drever and Stillings [33], carbon dioxide dissolves in water, creating carbonic acid ( $\text{H}_2\text{CO}_3$ ), and the release of hydrogen ions results in acidic conditions with pH values below 7. Furthermore, the acidic nature of rainwater, which is a significant source of groundwater replenishment in the area, might also be a contributing factor to the observed low pH values [34].

### 3.1.2. Electrical conductivity

EC provides an approximate measure of the total dissolved substances in water, which depends on factors such as their concentration, temperature and types of ions present [32]. The measured EC values of various water sources range from 57 to 3,859  $\mu\text{S}/\text{cm}$ , with a mean value of 420.06  $\mu\text{S}/\text{cm}$  (Figs. 4b and 5b). Sample stations R-42 and R-43 are characterized by the highest concentrations of EC. The elevated EC values in the vicinity of the core mine sites can be ascribed to the leaching of sulphate and bicarbonate from minerals that contain sulphide and carbonate in the overburden [35]. These minerals contribute to the heightened concentration of dissolved substances in the water, resulting in higher EC values.

### 3.1.3. Total dissolved solids

Total dissolved solids (TDS) refers to the collective amount of mineral constituents that is dissolved in water. In the study region, the measured TDS values range from 41 to 2,679 mg/L, with a mean value of 307.74 mg/L (Figs. 4c and 5c). Sample stations R-42, R-43, R-44, R-46, R-47, and R-48 have TDS values exceeding the recommended limit of 500 mg/L. The rise in TDS within the study area is attributed to several sources, including mine water, overburden dumps, tailing ponds, surface impoundments, industrial effluents, and acid rock drainage. These sources introduce dissolved substances into the water, consequently elevating TDS levels.

### 3.1.4. Nitrate ( $\text{NO}_3^-$ )

The concentration of nitrogen in the study region ranges from 0 to 41.58 mg/L, with a mean value of 9.12 mg/L (Figs. 4d and 5d). It is noteworthy that all the samples in the study area fall within the desirable limit of 50 mg/L set by the WHO, indicating that the nitrogen concentration in the water is within acceptable levels for drinking purposes.

### 3.1.5. Calcium ( $\text{Ca}^{2+}$ )

Hardness in water is primarily caused by a high concentration of calcium. The desirable limit for calcium in drinking

water is 75 mg/L, while the allowable limit is 200 mg/L. In this study, the concentrations of  $\text{Ca}^{2+}$  in water samples ranged from 3.87 to 105.6 mg/L (Figs. 4e and 5e). Sample stations R-42 and R-43 showed the highest  $\text{Ca}^{2+}$  concentrations. The primary source of water hardness in the region may be attributed to ion exchange processes involving silicate minerals.

### 3.1.6. Magnesium ( $\text{Mg}^{2+}$ )

Magnesium is primarily responsible for the permanent hardness of water. In the study region, the concentrations of  $\text{Mg}^{2+}$  in water ranged from 2.76 to 165.22 mg/L (Figs. 4f and 5f). Among the sample stations, R-42 and R-43 exhibited the highest concentrations of magnesium. It is worth noting that approximately 95% of the samples had concentrations below the desirable limit of 30 mg/L.

### 3.1.7. Potassium ( $\text{K}^+$ )

Potassium ( $\text{K}^+$ ) is a naturally occurring chemical component found in water. In comparison to other cations such as sodium, calcium, and magnesium, potassium is typically present in lower concentrations in water. However, in this research study, the collected water samples exhibit a range of 0.98 to 17.36 mg/L for potassium concentration (Figs. 4g and 5g). Sample stations R-42 and R-43 exceeded the limit of 12 mg/L recommended by WHO.

### 3.1.8. Sodium ( $\text{Na}^+$ )

In the current study, the concentration of sodium ( $\text{Na}^+$ ) in water ranges from 1.8 to 98 mg/L (Figs. 4h and 5h). The research findings indicate that all the samples in the study area are within the permissible limit of 200 mg/L as prescribed by WHO.

### 3.1.9. Chloride ( $\text{Cl}^-$ )

In the study area, chloride ions have been identified as the predominant anion in numerous water samples. The concentration of chloride in the water samples ranges from 0.9 to 150.1 mg/L (Figs. 4i and 5i). All the samples in the study area fall within the permissible range, as they have chloride concentrations below 250 mg/L.

### 3.1.10. Sulfate ( $\text{SO}_4^{2-}$ )

Sulphate is an important anion found naturally in minerals. In the study area, sulphate concentrations in water ranged from 0 to 2,238 mg/L (Figs. 4j and 5j). Sample stations R-42 and R-43 exceeded the limit of 200 mg/L recommended by WHO, with the highest concentration in R-43. These stations are located in the core mine area where pyrite oxidation produces acidic mine water with elevated sulphate levels. Mining activities have contributed to these high sulphate concentrations.

### 3.1.11. Bicarbonate ( $\text{HCO}_3^-$ )

Bicarbonate, also known as hydrogen carbonate, plays a crucial role in maintaining the body's acid–base balance.



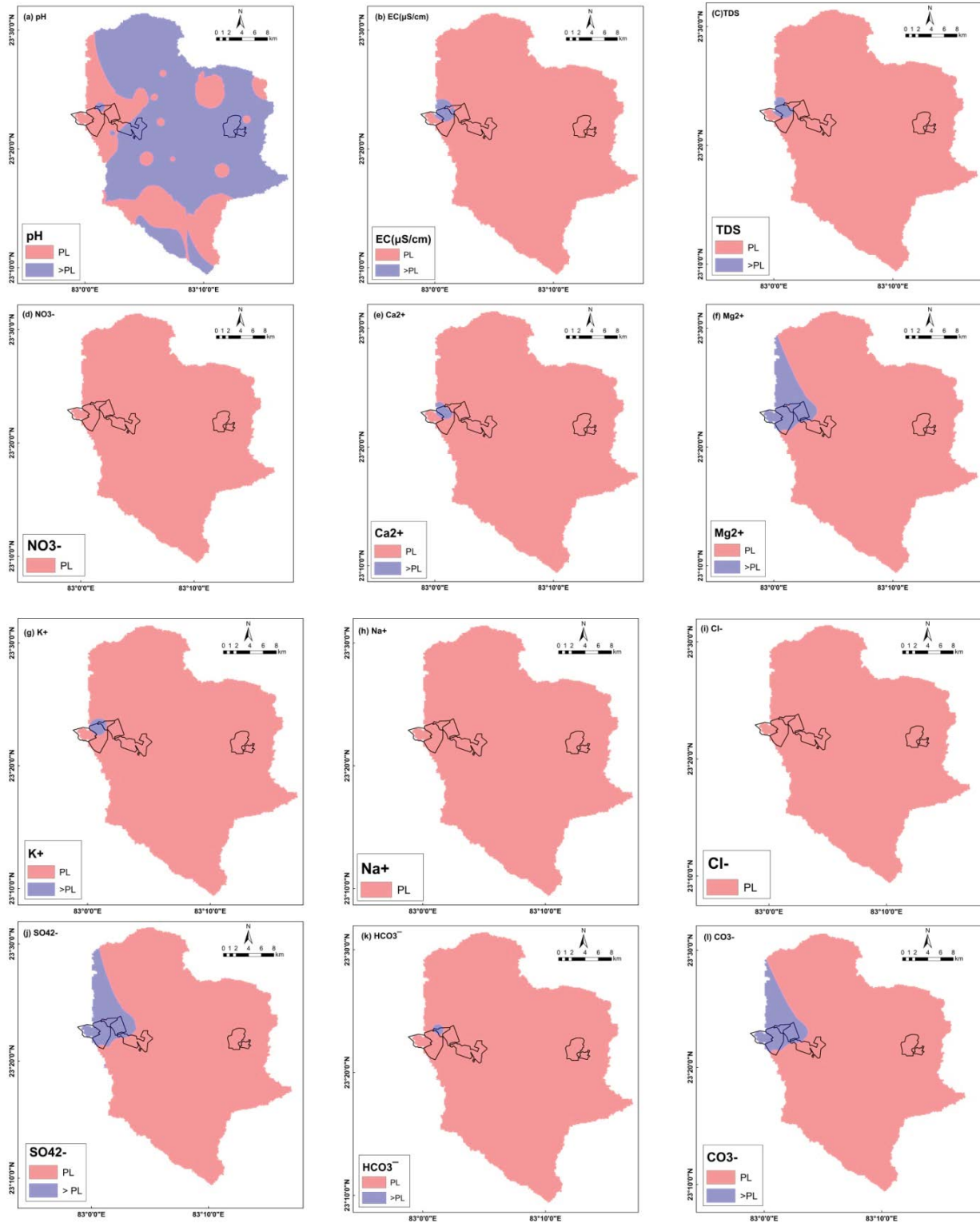


Fig. 4. Spatial distribution map of different ions (a) pH, (b) EC, (c) TDS, (d)  $\text{NO}_3^-$ , (e)  $\text{Ca}^{2+}$ , (f)  $\text{Mg}^{2+}$ , (g)  $\text{K}^+$ , (h)  $\text{Na}^+$ , (i)  $\text{Cl}^-$ , (j)  $\text{SO}_4^{2-}$ , (k)  $\text{HCO}_3^-$  and (l)  $\text{CO}_3^-$ .

It is primarily involved in carbonate equilibrium variations. In the study area, bicarbonate levels in water samples range from 0 to 251 mg/L (Figs. 4k and 5k). The maximum

acceptable concentration of bicarbonate, as per guidelines, is 200 mg/L. It is worth noting that sample station R-46 exceeds the desirable limit for bicarbonate concentration.



### 3.1.12. Carbonate ( $\text{CO}_3^{2-}$ )

The concentration of carbonate in the water samples from different locations ranged from 21.03 to 1,993 mg/L, with an average value of 200.11 mg/L (Table 1). The highest concentration of carbonate was observed at sample locations R-42 and R-43, which are situated in the core mining areas (Figs. 4l and 5l).

### 3.1.13. Hardness

Durfor and Becker [36] proposed that the suitability of water for domestic use can be determined by assessing its water hardness. In this study, the hardness values of the sampled water ranged from 20.99 to 1,991.70 mg/L, with an average value of 200.3 mg/L, as presented in Table 1. The analysis indicated that water at locations R-40, R-41, R-42, R-43, R-44, R-46, R-47, and R-48 exhibited very hard water, as compared to the given permissible level of 500 mg/L. Coal mining exposes water to calcium and magnesium-rich minerals, increasing water hardness. Also, drainage from waste materials like overburden also contributes to higher hardness levels by releasing calcium and magnesium ions.

## 3.2. Evaluation of water quality for irrigation purposes

The suitability of water for irrigation is determined by its ionic concentration and its impact on soil texture and crops [37]. When there is an accumulation of high ion concentrations, the osmotic pressure within plant cells is reduced, preventing water from reaching the branches and leaves. As a result, plant growth is affected, leading to reduced productivity [38].

Common standards for assessing irrigation water suitability include parameters such as SAR, sodium percentage (Na%), MH, PI, RSC, potential salinity (PI), and KI. Table 3 presents a statistical summary of the irrigation water quality parameters specific to the study area.

### 3.2.1. Sodium percentage (Na%)

Na% is a crucial parameter for evaluating irrigation water quality, as emphasized by Wilcox [44]. The Na%

value was calculated using the formula provided in Table 3 [Eq. (1)]. In the study area, Na% ranges from 4% to 87.60%, with an average of 20.84%. Table 4 classifies the samples based on Na% for irrigation suitability. Approximately 54% of the samples are classified as excellent, while 48% fall under the good category. It is important to note that an increase in sodium percentage in water can lead to reduced soil permeability, potentially damaging crops. Fig. 6 shows that most samples are suitable for agriculture, except for samples R-42 and R-43, located in core mining areas. Elevated sodium levels (Na%) in irrigation water result from sodium leaching from coal strata and water contamination through mine discharge. These findings align with similar studies conducted worldwide [45,46], further validating the results obtained in this study.

### 3.2.2. Sodium absorption ratio

Excessive sodium levels in irrigation water can pose a sodium hazard, as it can negatively impact soil permeability and lead to soil compaction [47]. Reddy [48] explains that the SAR is a measure of the ability of irrigation water to penetrate the soil's cation exchange zone. Elevated sodium levels displace calcium and magnesium in the soil, resulting in decreased permeability. Consequently, the estimation of sodium hazard potential in water samples is conducted through SAR assessment.

The SAR values in the study area range from 0.15 to 5.14. SAR values below 20 indicate excellent water quality with minimal sodium hazard, SAR values between 20 to 40 denote good water quality, SAR values between 40 to 60 indicate permissible water quality, and SAR values above 60 suggest poor or inadequate water quality (Table 4). As shown in Fig. 7, few samples, such as R-40, R-41, R-42, R-43, R-44, R-46, R-47, and R-48, are unsuitable for irrigation due to high SAR values. Coal mining can elevate SAR values in irrigation water due to sodium-rich minerals in coal strata, mine discharge, erosion, hydrological changes, and inadequate waste management. These factors collectively increase SAR, potentially leading to soil compaction and reduced soil permeability in agricultural areas.

Table 3  
Methodology adopted for calculating indices for irrigation water quality

Parameter	Formula for calculation	Eq. No	References
%Na	$(\text{Na}^+) \times 100 / (\text{Ca}^{2+} + \text{Mg}^{2+} + \text{Na}^+ + \text{K}^+)$	1	[39]
SAR	$\text{Na}^+ / \sqrt{0.5(\text{Ca}^{2+} + \text{Mg}^{2+})}$	2	[39]
MH	$\text{Mg}^{2+} \times 100 / (\text{Ca}^{2+} + \text{Mg}^{2+})$	3	[40]
KI	$\text{Na}^+ / (\text{Ca}^{2+} + \text{Mg}^{2+})$	4	[41]
PI	$\text{Na}^+ + \sqrt{\text{HCO}_3\text{CO}_3} / (\text{Ca}^{2+} + \text{Mg}^{2+} + \text{Na}^+)$	5	[42]
RSC	$(\text{HCO}_3^- + \text{CO}_3^{2-}) - (\text{Ca}^{2+} + \text{Mg}^{2+})$	6	[43]

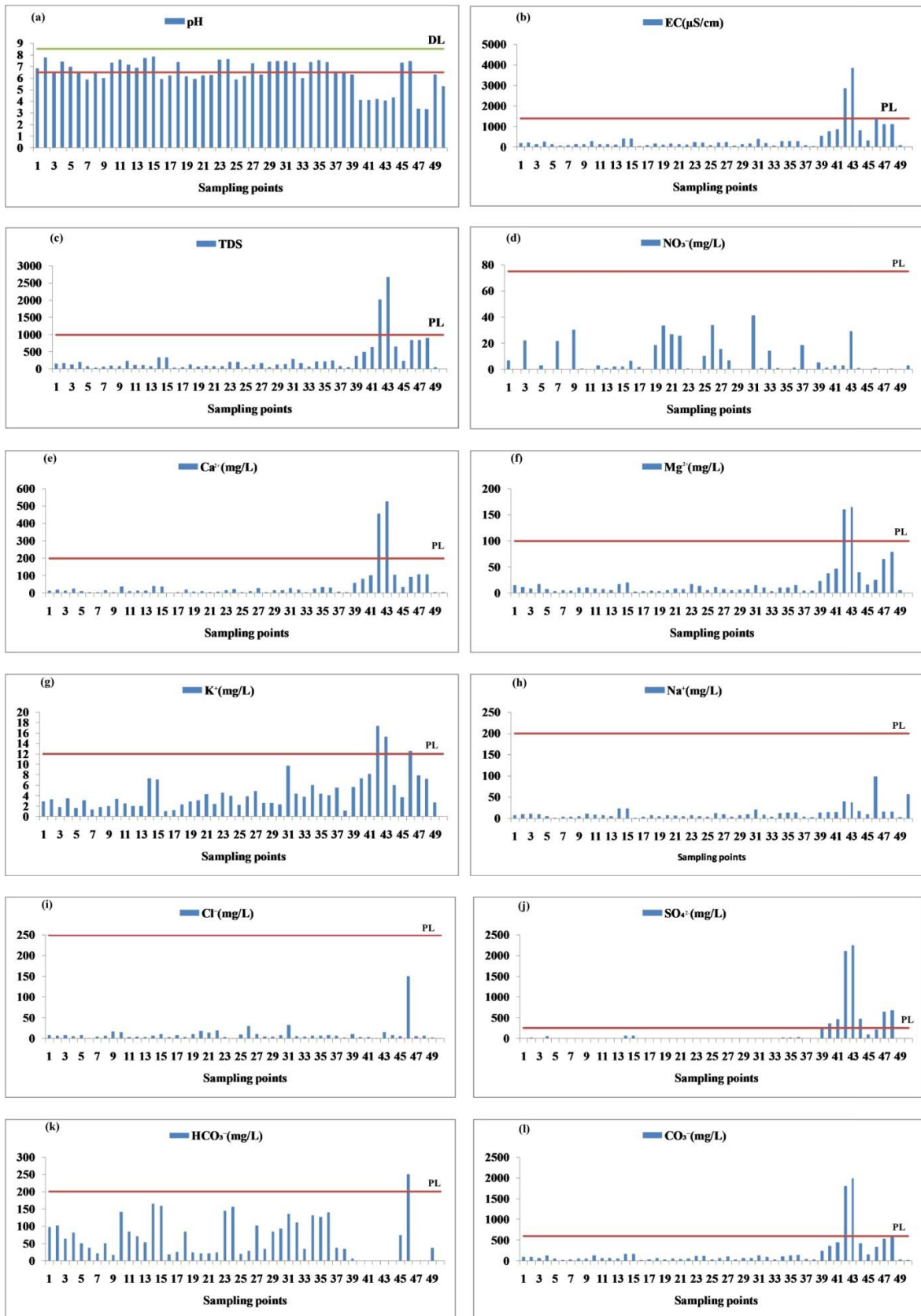


Fig. 5. (a) pH, (b) EC, (c) TDS, (d)  $\text{NO}_3^-$ , (e)  $\text{Ca}^{2+}$ , (f)  $\text{Mg}^{2+}$ , (g)  $\text{K}^+$ , (h)  $\text{Na}^+$ , (i)  $\text{Cl}^-$ , (j)  $\text{SO}_4^{2-}$ , (k)  $\text{HCO}_3^-$  and (l)  $\text{CO}_3^{2-}$ . DL is desirable limit and PL is permissible limit.

Table 4  
Assessment and categorization of irrigation water quality characteristics in the study area

Parameters	Range	Class	No. of samples or % of samples
Na%	<20	Excellent	54%
	20–40	Good	46%
	40–60	Permissible	Sample no. R-46
	60–80	Doubtful	No sample
	>80	Unsafe	Sample no. R-42, R-43 and R-50
SAR	<20	Excellent	100%
	20–40	Good	No sample
	40–60	Permissible	No sample
	60–80	Doubtful	R-40, R-41, R-42, R-43, R-44, R-46, R-47, and R-48
	>80	Unsafe	No sample
MH	<50	Suitable	62%
	>50	Unsuitable	38%
KI	<1	Good	All samples except R-50
	>1	Unsuitable	Sample no R-50
PI	<80	Suitable	66%
	80–100	Suitable	24%
	100–120	Unsuitable	Sample no R-6, R-16, R-17, R-33, R-38 and R-49
RSC	<1.25	Good	32%
	1.25–2.50	Moderate	18%
	>2.50	Unsuitable	50%
PS	<3	Excellent to good	86%
	3–5	Good to injurious	R-41, R-44, R-47 and R-48
	>5	Unsatisfactory	R-42, R-43 and R-46

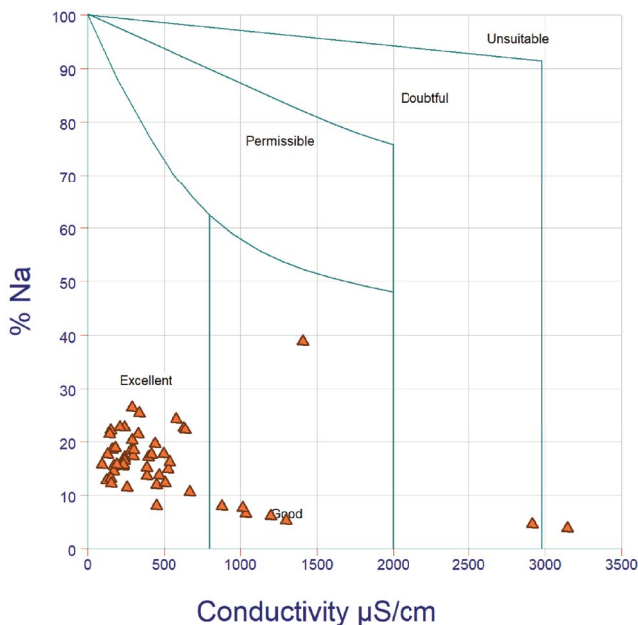


Fig. 6. Wilcox diagram for water sample.

3.2.3. Magnesium hazard

The balance between calcium (Ca) and magnesium (Mg) in water is crucial for maintaining soil quality. Unlike

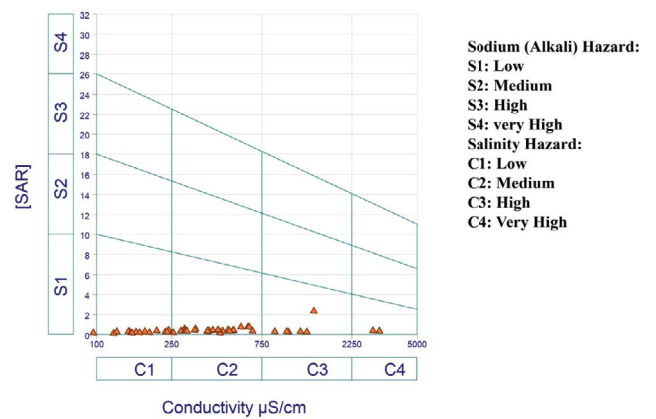


Fig. 7. USSL diagram for irrigation suitability.

increases in  $Ca^{2+}$  concentration, increases in  $Mg^{2+}$  concentration in water behave similarly to sodium (Na), leading to a decline in soil quality due to high salinity [49]. Soil deterioration adversely affects crop yield. The increase in magnesium concentration in water is associated with the presence of exchangeable sodium in the soil. Paliwal et al. (1976) introduced the MH value as an index for assessing irrigation water suitability, as shown in Table 3 [50]. If the MH value exceeds 50, the water is considered harmful and unsuitable for agriculture, as outlined in Table 4. In the current study, 38% of the samples were classified as harmful

and unsuitable for irrigation. The primary reason for the majority of unsuitable water samples originating from core mining areas is the presence of coal strata containing minerals with high magnesium content. When coal mining operations commence, these minerals are exposed to water, which results in the leaching of magnesium ions into the local water sources. Consequently, the water in these mining areas becomes significantly enriched with magnesium, leading to higher MH values and rendering it unsuitable for irrigation due to its detrimental effects on soil quality and crop productivity.

### 3.2.4. Kelly's index

The concentration of sodium (Na) in irrigation water can have detrimental effects on soil, and it can be quantified using KI, as outlined by Kelly and Meyer [41] and presented in Table 3. A KI value less than 1 indicates good quality water suitable for irrigation [51]. In the current study, KI values ranged from 0.04 to 7.06, with a mean value of 0.33. Among the samples, sample number 50 was found to be unsuitable for irrigation due to a high KI value (Table 4).

### 3.2.5. Permeability index

The permeability of soil plays a crucial role in nutrient circulation and the flow of air and moisture to the root zone [52]. Sodium, calcium, magnesium, and bicarbonate levels in irrigation water significantly impact soil permeability [53]. Elevated concentrations of these ions can negatively affect soil permeability, which can be assessed using the PI. The PI allows for the classification of water into three categories: class I (PI < 80), class II (PI = 80–100), and class III (PI = 100–120). Classes I and II water are considered suitable for irrigation, while class III water is not recommended. In the present study, approximately 16% of the samples, particularly from core mining areas, were classified as class III and deemed unsuitable for irrigation (Table 4). This highlights the adverse impact of high ion concentrations on soil

permeability and emphasizes the need for proper water management practices to ensure the use of suitable irrigation water.

### 3.2.6. Residual sodium carbonate

The concentration of carbonate and bicarbonate in irrigation water is a crucial factor to consider, as they can precipitate as carbonate, affecting water quality [54]. RSC is used to assess the effects of carbonate and bicarbonate in irrigation water, with values calculated using the formula provided in Table 3. In this study, 50% of the samples were classified as unsuitable, indicating RSC values exceeding 2.5. This suggests the presence of high carbonate and bicarbonate levels, which can have adverse effects on soil quality and irrigation practices. Proper management strategies are necessary to address these elevated RSC values and ensure the use of suitable irrigation water.

### 3.3. Evaluation of water quality for industrial purpose

The suitability of water for industrial purposes depends on its potential for scaling and corrosion, which result from the interaction of water with metals [55]. Scaling and corrosion indices, such as the LI, AI, RI, Puckorius index (PI), and corrosivity ratio (CR) are used to assess these processes. As scaling and corrosion are complex and interactive, it is important to consider multiple indices to accurately evaluate their impact on metallic equipment. These indices can be calculated using the equations provided in Table 5.

#### 3.3.1. Langelier index

The LI by Langelier [56] is utilized to approximate the degree of calcium carbonate saturation in water, which is a primary cause of scaling. It is an essential tool for water operators in managing internal corrosion and scale deposition [53]. The LI is calculated based on pH, alkalinity, calcium, TDS and water temperature as given in Eq. (7)

Table 5  
Methodology for calculating industrial water quality

Parameter	Formula for calculation	Eq. No.	References
Langelier index (LI)	$\text{pH} - \text{pH}_{\text{sat}}$ $\text{pH}_{\text{sat}} = (9.3 + a + b) - (c + d)$ $a = (\text{Log}10(\text{TDS}) - 1)/10$ $b = -13.12 \times \text{Log}10(T + 273) + 34.55$ $c = \text{Log}10(\text{Ca}^{2+}) - 0.4$ $d = \text{Log}10(\text{Alkalinity})$	7	[56]
Aggressive index (AI)	$\text{pH} + \text{Log}10(\text{Alkalinity} \times \text{Ca}^{2+})$	8	[57]
Ryznar index (RI)	$2\text{pH}_{\text{sat}} - \text{pH}$	9	[58]
Puckorius index (PI)	$2\text{pH}_{\text{sat}} - \text{pH}_{\text{equil}}$ $\text{pH}_{\text{eq}} = 1.465 \times \text{Log}10(\text{Alkalinity}) + 4.54$	10	–
Corrosivity ratio (CR)	$\text{CR} = ((\text{Cl}^-/35.50 + 2(\text{SO}_4^{2-}/96))/2(\text{HCO}_3^- + \text{CO}_3^{2-}/100))$	11	[59]

Notes: pH = actual pH of water;  
 $\text{pH}_{\text{sat}}$  = pH at saturation state of  $\text{CaCO}_3$ ;  
 TDS = total dissolved solids (mg/L);  
 $\text{pH}_{\text{equil}}$  = pH at equilibrium.

Table 6  
Assessment and categorization of industrial water quality characteristics in the study area

Parameters	Range	Class	No. of samples or % of samples
Langelier index (LI)	<-2	High corrosion	46%
	-2 to -0.5	Serious corrosion	42%
Aggressive index (AI)	<10	Moderate corrosion	58%
	>10	Scaling	42%
Ryznar stability index (RI)	<5.5	High scaling	No sample
	5.5–8.5	No significant scaling or corrosion	No sample
	>8.5	Severe aggressiveness/corrosion	All samples
Puckorius index (PI)	<5.5	High scaling	No sample
	5.5–8.5	Low scaling	No sample
	>8.5	Significant corrosion	All samples
Corrosivity ratio (CR)	≤1	Good	88%
	>1	Corrosion	Sample no. R-40, R-41, R-42, R-43, R-47 and R-48

(Table 5). In this study, the LI values ranged from -5.64 to 0, with an average of -1.99. A negative LI indicates a corrosive tendency in the water. Detailed LI classifications can be found in Table 6. Studies have indicated that an LI within the range of -1 to +1 has minimal impact on metallic components, while values outside this range can result in corrosion-related leaks. Specifically, 46% of the samples displayed a high corrosive tendency, while 42% exhibited a serious corrosive tendency. These findings emphasize the need for water operators to implement appropriate corrosion control measures to prevent damage to metallic components caused by corrosive water conditions.

### 3.3.2. Aggressive index

The AI is considered less accurate than the LI but is more practical to use as it excludes water temperature and dissolved solids [57]. It was calculated using Eq. (8) as shown in Table 5. In this study, 42% of the samples exhibited an AI value greater than 10, indicating scaling tendencies on metallic surfaces. The remaining samples showed an AI value below 10, suggesting a moderately corrosive tendency. The AI values ranged from 0 to 11.75, with an average of 8.49 (Table 6). These results indicate a scaling tendency in the water but no corrosive tendency. The high concentration of calcium and magnesium in the water is likely the primary cause of scaling tendencies [58].

### 3.3.3. Ryznar stability index

Rapant et al. [59] and Ryznar [60] introduced the Ryznar stability index (RI) to quantitatively assess calcium carbonate saturation and predict scale formation. The calculation equation for RI is given in Eq.(9) in Table 5. In the present study, RI values ranged from 0 to 15.59. Remarkably, all the samples demonstrated a severe corrosive tendency based on their RI values.

### 3.3.4. Puckorius index

The Puckorius index is a measure of the scaling capacity and corrosive tendency of water, taking into account

buffering capacity and total alkalinity [61]. It was determined by using Eq. (10) as given in Table 5. Unlike the Ryznar stability index, the Puckorius index uses pH equilibrium rather than the actual system pH [62,63]. In this study, the Puckorius index values ranged from 0 to 15.36, with an average of 9.83. Interestingly, all the samples exhibited a Puckorius index value greater than 8.5, indicating a significant corrosive tendency in the study area. These results contrast with the findings of the other indices discussed earlier.

### 3.3.5. Corrosivity ratio

The corrosivity ratio was determined using Eq. (11) provided in Table 5, where the ion concentrations are measured in milligrams per liter (mg/L). A CR value equal to or less than 1 is considered good, indicating non-corrosive water suitable for transportation through metal pipes [59]. However, a CR value exceeding 1 indicates a corrosive nature, making the water unsuitable for industrial or domestic purposes. In this study, seven samples (R-40, R-41, R-42, R-43, R-47, and R-48), particularly from core mining areas, exhibited CR values greater than 1. This shows corrosive tendency in the water, highlighting its unsuitability for transportation through metal pipes and for use in industrial or domestic settings.

## 4. Conclusion

The assessment of water quality for various purposes, including domestic, industrial, and irrigation in the study area, particularly focusing on mining regions, reveals several important findings. The comparison of water samples with WHO standards highlights the suitability of water for domestic purposes, with some parameters falling below the desirable limits. The pH values indicate the acidic nature of water, potentially influenced by  $\text{CO}_2$ ,  $\text{HCO}_3^-$ , and the natural oxidation of pyrite in the mining areas. EC and TDS values indicate the presence of elevated concentrations, particularly around core mining sites, suggesting the influence of mining activities, overburden dumps, and industrial effluents

on water quality. Nitrate concentrations remain within desirable limits, indicating no significant contamination issues. Calcium and magnesium concentrations are within acceptable ranges, while sodium and potassium concentrations are below the permissible limits. However, chloride and sulphate concentrations exceed the desirable limits in some locations, likely due to mine water, overburden dumps, tailing ponds, industrial effluents, and acid rock drainage.

The evaluation of water quality for irrigation purposes reveals that most samples are suitable based on parameters such as sodium percentage (Na%), SAR, MH, KI, PI, and RSC. Sodium percentage (Na%) ranged widely from 4% to 87.60%, with an average of 20.84%, mostly suitable for agriculture, except in core mining regions where elevated Na% resulted from sodium leaching. SAR values varied from 0.15 to 5.14, with high SAR values in some samples, particularly in core mining areas, indicating reduced suitability due to sodium-induced soil permeability issues. MH values highlighted that 38% of samples were unsuitable for irrigation, primarily due to high-magnesium minerals in coal strata. KI mostly met criteria, except for one sample. PI revealed that 16% of samples, mainly from core mining areas, had class III water, unsuitable for irrigation. RSC indicated 50% of samples unsuitable, emphasizing the need for robust water management. Furthermore, the assessment of water corrosiveness and scaling potential highlights a corrosive tendency in some water samples, particularly within the mining areas. The LI, AI, Ryznar stability index, Puckorius index, and corrosivity ratio indicate varying degrees of corrosive tendencies, with some samples exhibiting severe corrosive tendencies. This has implications for the integrity of metal pipes and industrial processes, emphasizing the need for appropriate corrosion control measures. In conclusion, this study underscores the critical importance of assessing and managing water quality in mining areas. It highlights challenges related to water suitability for various purposes, including domestic, industrial, and irrigation needs. Effective water management, encompassing measures to address acidic water, control mining-related contaminants, and prevent corrosion, is essential for ensuring water suitability and sustainability in such regions. Remedial actions for problematic aquifers encompass techniques like artificial recharge, desalination, phytoremediation, enhanced drainage systems, and selecting crop varieties adapted to saline conditions. These actions collectively aim to mitigate water quality issues in coal mining areas, fostering the sustainability of agriculture reliant on these aquifers.

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#### Conflict of interest

There is no conflict of interest.

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