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Investigation of hydrochemistry, origin and suitability of drainage water: A case study in Barapukuria Coal Mine, Bangladesh

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ABSTRACT

Water is an invaluable natural resource for all living organisms, but its quality can be degraded by numerous anthropogenic and geogenic activities. Such issues are especially severe in areas near mining and mineral processing industries. The objective of this study is to evaluate the suitability of drainage water for livestock, drinking, and irrigation purposes around the Barapukuria Coal Mine, Dinajpur, Bangladesh. For this purpose, ten representative water samples were collected from different places of the mine drainage water during the dry season and were analyzed for various geochemical parameters, including pH, TDS, EC, major cations (Na^+, K^+, Ca^{2+}, Mg^{2+}) and anions ($Cl^–$, $HCO_3^–$, $SO_4^{2–}$). These parameters can be used to evaluate whether the water met quality standards set by the EQS, WHO and Bangladesh standards. $Ca^{2+}>Na^+>Mg^{2+}>K^+$ and $HCO_3^->SO_4^{2-}> Cl^-$ are the primary cations and anions trends, where the dominating water type is Ca–Mg–HCO_3. Statistical analysis shows a good correlation between the ions suggesting homogenous water quality, whereas principal component analysis indicates three factors contribute to 84.368% of the entire variation. The water quality index (WQI) reveals that the majority of water samples are of good quality. The Gibbs plot indicates all samples fall into the rock dominance groups. The analysis of irrigation quality parameters, including % Na, SAR, KI, RSBC, MH, TH, and PI, along with Wilcox, USSL, and Doneen diagrams, indicates that the drainage water tends to be of good quality. Regular monitoring of water quality is recommended from the mine area.

Keywords: Hydrochemistry; Drainage Water Quality; Barapukuria Coal Mine; Bangladesh

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INTRODUCTION

Groundwater quality has become a major concern in both underground and open-cut mining operations worldwide. Coal mining activities have an impact on the physical, chemical, and biological aspects of the surrounding ecosystems (Paepae et al., 2021). During mining operations, huge volumes of water are discharged through mine drainage on the ground surface, posing a threat to the quality of surface water resources and environmental degradation (Choubey, 1991; Khan and Rahman, 1992; Allen et al., 1996; Shinde et al., 2013; Ahamed et al., 2016; Devi and Kshetrimayum, 2021). When untreated mine water is released into rivers, streams, and surrounding areas, it can severely affect local agriculture by contaminating soil and water resources (Singh, 1988; Ray and Dey, 2020). Even after mine closures, pollution continues for years, threatening the lives of animals, plants, and humans in the surrounding areas. The presence of metals such as lead, arsenic, and mercury in irrigation water can lead to soil degradation and phytotoxicity, which can reduce crop productivity and food security. Mine drainage water significantly affects hydrology by altering natural water flow patterns and contaminating surface and groundwater (Younger and Robins, 2002). It even can infiltrate the groundwater, leading to reduced availability of clean water for drinking, irrigation, and industrial use.

According to Ray and Dey (2020), mining activities can contaminate water through several processes: seepage during excavation, leaks from wall rock, and runoff from waste dumps and tailings dams. Additionally, discharges from mineral processing plants, pumping operations, intentional flooding or inundation of abandoned mines, hydraulic backfilling, and water sprinkling practices can contribute to water pollution. The mine water may be acidic or non-acidic depending on the content of pyrite in the coal (Tiwary, 2001). The mine water also contains substantial concentrations of sulfate (SO_4), manganese (Mn), aluminum (Al), and iron (Fe) along with several common elements like sodium (Na), magnesium (Mg), potassium (K), and calcium (Ca). The higher concentration of these parameters decreases the drainage water quality because of corrosion, toxicity, incrustation, and other effects from dissolved constituents (Chen et al., 2020). In addition, high levels of hardness, heavy metals, oil and grease in mine water degrades its suitability for domestic use (Tiwary, 2001). Mine wastes primarily contaminate water, which subsequently affects adjacent farmland and bodies of water, as stated by Ribeta et al. (1995) and Meck et al. (2006). Terrestrial and aquatic ecosystems are also significantly impacted (Alam et al., 2011; Kibria et al., 2012).

The Barapukuria coal mine (BCM) is an underground mine that has contributed significantly to the national economy by resolving an ongoing energy crisis (Fardushe et al., 2016). It produces approximately 1750-2356 tons of coal per day from the lower Gondwana deposit according to Barapukuria Coal Mining Company Limited (BCMCL) Yearly Report (2023) which has bituminous to sub-bituminous quality coal. This Gondwana formation in BCM has many joints, faults, weathered zones, bedding fissures, and developed vertical tensile fractures, which are filled with pyrite films and mud (Wardell Armstrong, 1991; Howladar, 2013; Howladar et al., 2017, 2018;). The presence of pyrite contributes to an increase in the acidity of water produced in underground mining by oxidation reaction releasing sulfuric acid when exposed to air and water (Uddin, 2003). Such acidic water containing low pH, and high concentrations of metal, TDS frequently pollutes the surface water (Tiwary, 2001; Fardushe et al., 2016), which may affect human health, soil fertility, aquatic life, and the surrounding terrestrial ecosystem, and it does not meet international standards to be used as drinking water (Kibria et al., 2012; Mohanta et al., 2015).

Howladar et al. (2014) suggested that the water quality of BCM is typically acceptable for irrigation, drinking, and livestock and requires regular monitoring to ensure safety and promote eco-friendly coal production. To date, limited studies have been carried out on the drainage water quality of the mine area. Given this, the present study has been undertaken to evaluate the suitability and utilization of drainage water for livestock, drinking, and irrigation purposes around the Barapukuria Coal Mine, Dinajpur, Bangladesh. This study will help decision-makers in planning future coal mining operations and promoting ecologically sustainable industrial development, especially in regions impacted by mining activities.

STUDY AREA

The study area BCM is located in the northern section of Parbatipur Upazila in the Dinajpur District of Bangladesh. The geographic range of the research region is bounded between 88°55´E to 88°59´E longitude and 25°30´N to 25°35´N latitude (Fig. 1b) Several rivers, including the Khorkhori, Ghirnai, and Jamuna draining this area. These rivers originate locally and are primarily fed by rainwater. The western side of the study area is drained by the Khorkhori River, which flows roughly north to south. Another major river, locally known as the Jamuna, runs to the west of the Khorkhori. On the northeastern side, the Ghirnai River flows through the region, staying mostly dry in the winter but becoming navigable during the rainy season. Before the development of BCM, the local population utilized a variety of water sources for agricultural purposes; now, they use a large volume of coal mine discharge water for irrigation and other agricultural uses (Uddin, 2003). There are about 924 people per square kilometer within the study area. A significant portion of the population sustains their livelihoods through businesses, public services, and agriculture. Despite various challenges, many people currently depend on the Barapukuria Coal Mine to earn their livelihoods (Alam et al., 2011; Howladar et al., 2014).

GEOLOGICAL AND HYDROLOGICAL SETTING

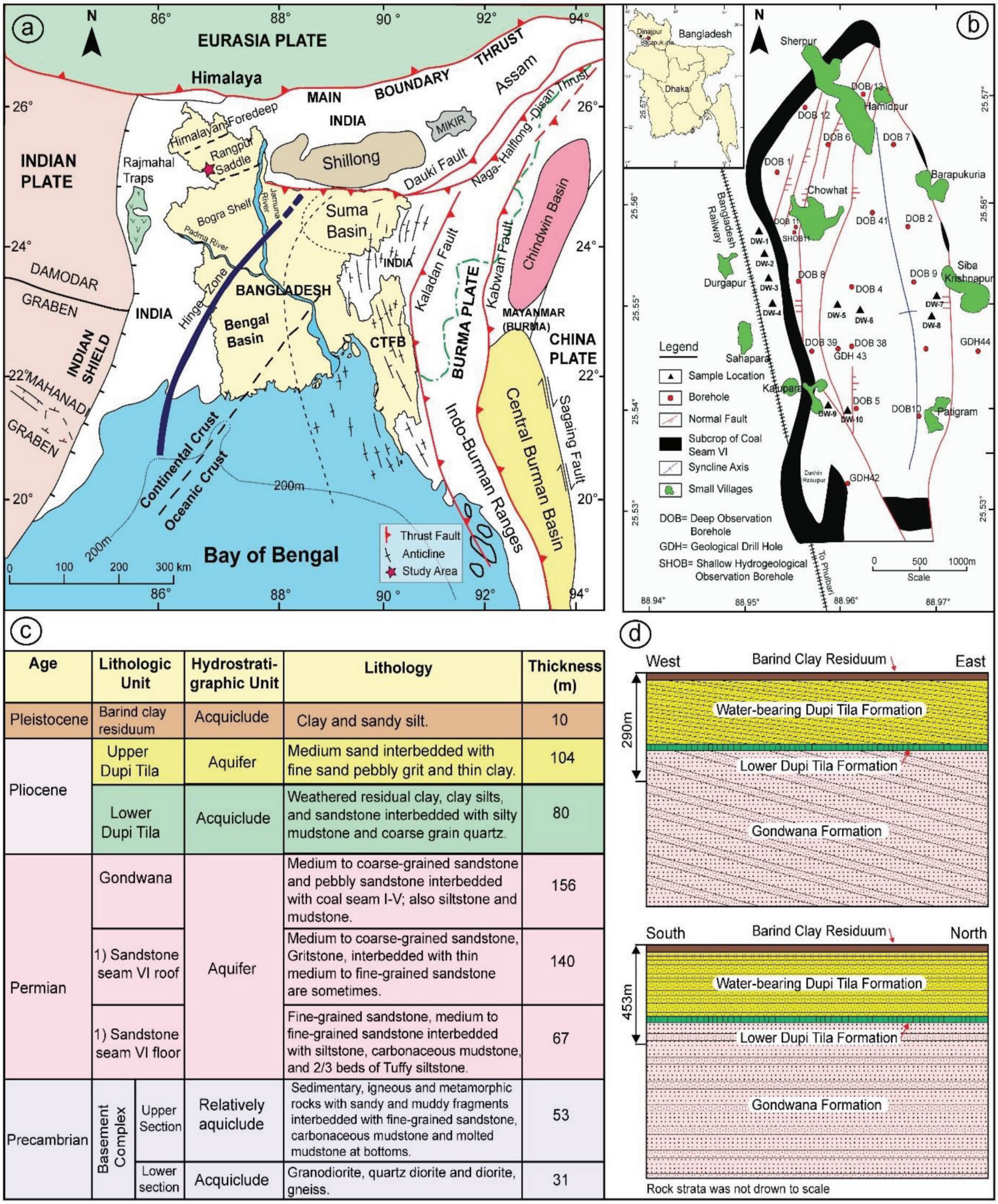
The Gondwana coal basins of Bangladesh include Naogaon, Khalaspir, Dighipara, Jamalganj, Phulbari, and Barapukuria, which are situated in the northwestern part of the country. These basins lie within the Garo-Rajmahal gap, which is known as Rangpur Saddle (Bakr, 1996; Islam and Islam, 2005; Islam, 2009; Howladar et al., 2014). To the west, the Rangpur Saddle is likely connecting the Block of the Rajmahal Hills and Indian Shield. There is the Shillong Massif to the east (Fig. 1a). This block is approximately 96 km wide, and is bounded by N-S, NE-SW, and NW-SE trending faults. The Barapukuria coal basin is narrow, long, shallow, and a faulted asymmetrical syncline. The trend of this basin is approximately N-S direction (Akter et al., 2016). According to Bakr et al. (1996), subsiding basins (graben and half-graben) and elevated ridges (horsts) have been identified from the regional gravity data. The basin area is characterized by flat terrain covered with alluvium and Barind clay residuum of the Pleistocene period (Majumder and Shimada, 2016). Borehole data has been used to prepare the geologic succession (Fig. 1c) of this basin, which shows the sedimentary rocks on the top of the basement complex (Pre-Cambrian) from the Gondwana Group (Guha, 1978). The sedimentary record seems to be severely lacking between the Gondwana Group and Dupi Tila formation (Howladar et al., 2014) as a result of the non-depositional or erosional period that occurred between the Triassic and Pliocene epochs (Khan and Rahman, 1992).

The excessive thickness (an average of 36 m) of coal seam VI of the BCM contains most of the reserves (about 90%) (Wardell Armstrong, 1991; Kibria et al., 2012; Howladar et al., 2017). The Upper Dupi Tila Formation from the study area has a large aquifer that covers hundreds of square kilometers (Fig. 1d). The thickness of this formation ranges from around 100 to 185 meters in the southern portion of the mining area. Since the Gondwana sandstone and Dupi Tila formation are hydraulically connected in coal seam VI, the groundwater inflow is a major concern for the coal mine (Howladar et al., 2014). W.A. Company (1991) suggested that the Dupi Tila aquifer (Upper and Lower sand horizons) is ideal for recharging purposes by using 22 boreholes dataset (Akter et al., 2016). Despite the challenges posed by the geological and hydrogeological context, the drainage water quality is generally suitable for drinking, livestock, and irrigation (Howladar et al*.,* 2014).

METHODOLOGY

Sampling procedure and laboratory analysis

Ten representative water samples (DW-1 to DW-10) were collected from various locations around the BCM area during the dry season to evaluate the suitability of the drainage water for livestock, drinking, and irrigation purposes (Fig 1b). Before collecting samples, clean, dry, and sterilized 500-ml polyethylene bottles were used to get water samples which were carefully rinsed by the pumped water. Then, the



Age	Lithologic Unit	Hydrostrati-graphic Unit	Lithology	Thickness (m)
Pleistocene	Barind clay residuum	Acquiclude	Clay and sandy silt.	10
Pliocene	Upper Dupi Tila	Aquifer	Medium sand interbedded with fine sand pebbly grit and thin clay.	104
	Lower Dupi Tila	Acquiclude	Weathered residual clay, clay silts, and sandstone interbedded with silty mudstone and coarse grain quartz.	80
Permian	Gondwana	Aquifer	Medium to coarse-grained sandstone and pebbly sandstone interbedded with coal seam I-V; also siltstone and mudstone.	156
	1) Sandstone seam VI roof		Medium to coarse-grained sandstone, Gritstone, interbedded with thin medium to fine-grained sandstone are sometimes.	140
	1) Sandstone seam VI floor		Fine-grained sandstone, medium to fine-grained sandstone interbedded with siltstone, carbonaceous mudstone, and 2/3 beds of Tuffy siltstone.	67
Precambrian	Basement Complex Upper Section	Relatively aquiclude	Sedimentary, igneous and metamorphic rocks with sandy and muddy fragments interbedded with fine-grained sandstone, carbonaceous mudstone and molted mudstone at bottoms.	53
	Basement Complex Lower section	Acquiclude	Granodiorite, quartz diorite and diorite, gneiss.	31

Fig. 1: Study area map showing (a) the geologic and tectonic features around the Bengal Basin (after Imam, 2005; Ali et al., 2024); (b) the Structural map of the Barapukuria Coal Basin (after Islam and Hayashi, 2008; Bakr, 1996; Islam, 2009; Ahamed et al., 2016); (c) the Barapukuria Coal Mine hydrostratigraphy (after CMC, 1994; Howladar et al., 2014); and (d) sectional View of water-bearing Dupi Tila Formation and Gondwana Formation (after Islam et al., 2015).

water samples were labeled carefully, sealed and stored in a refrigerator for laboratory analysis. Concentrated Nitric acid (HNO_3) was used to acidify the samples for evaluation of trace elements to prevent any reaction. Again, the samples were acidified with 0.5N HCL to determine the iron concentration. Not acidified samples were used to analyze anions and cations. Until all samples were prepared for analysis, they were stored at 4˚C. All aspects of the sampling procedures, from collection to analysis were performed following the standard methods established by the American Public Health Association (APHA, 2005).

Field measurements of physiochemical parameters such as TDS, EC and pH, were measured using EC/TDS meter (HANNA), HANNA HI 7039P meters, and HANNA meters respectively. The major anions (Cl^-, HCO_3^-, SO_4^{2-}) and cations (Na^+, K^+, Ca^{2+}, Mg^{2+}, Fe^{total}) were determined by following the standard procedures (APHA, 2005) in the lab of Bangladesh Council of Scientific and Industrial Research, Dhaka. An atomic absorption spectrophotometer (AAS, Models: AA240FS and SpectrAA220, Varian, Australia) was used to measure elements such as Fe, Mg, and Ca, while a flame photometer (Model: PFP7, Jenway, UK) was used to measure Na^+ and K^+ ions. An ion chromatograph (IC, Model: SIC10AVP, Shimadzu, Japan) was used to measure the amounts of anions such as Cl^-, HCO_3^-, and SO_4^{2-}.

The results of several laboratory and field analyses of water parameters have been presented in Table 1. The physicochemical parameters of water have been analyzed using MS Excel 2010 and SPSS 21 (IBM SPSS Statistics version 20). Standard formulae (Table 1) were used to determine several irrigation water quality indicators like magnesium hazard (MH), permeability index (PI), potential salinity, residual sodium bicarbonate (RSBC), Kelley's index (KI), total hardness (TH), percentage of sodium (%Na), and sodium adsorption ratio (SAR). Furthermore, while assessing the water quality for irrigational purposes, tools such as the Wilcox diagram, Trilinear diagram, Gibbs plot, and Doneen permeability index plot were used.

Calculation of Water Quality Index (WQI)

The water quality index is an important tool for determining whether groundwater is suitable for consumption or not (Madhav et al., 2018). One way that water quality is depicted is as a ranking system that allows for community control over main factors. To determine the WQI, the WHO uses the Index of the weighted arithmetic method, which considers eight main parameters (Brown et al., 1972; Chaurasia et al., 2018).

Quality Rating/Sub Index (qn): To get the quality rating (q_n), apply the following formula (Brown et al., 1972; Mohamed et al., 2023):

$$q_n = \frac{V_n - V_{io}}{S_n - V_{io}} \times 100 \quad (1)$$

This equation states that for each water quality parameter n, we have V_n, S_n, and V_{io}, where

V_n= estimated value at specific sample location,

S_n= standard allowable value, and

V_{io}= optimum value of pure water (zero value for every parameter other than pH=7).

Unit Weight (W_n): The standard value S_n was used to derive the unit weight, which is inversely related to the parameters (Roy et al., 2021). To simplify the calculation of relative weight, the assigned weight, and the WHO standard value, the following unit weight formula was applied (Howladar et al., 2014), which is summarized in Table 2.

$$W_n = K/S_n \quad (2)$$

For each parameter n, we have W_n, which is its unit weight; K, which is its constant for proportionality and S_n, which is its standard value.

A linear combination of the unit weight and quality rating is used to determine the total water quality index (Aware et al., 2013).

$$WQI = \sum \frac{q_n \times W_n}{W_n} \quad (3)$$

Table 1: Analyzing the water samples using water quality indices to determine their suitability for irrigation (Kundu et al., 2019).

SN	References	Water Quality Indices
i	Richards, 1954	$SAR = Na^+/\sqrt{Ca^{2+} + Mg^{2+}}$
ii	Wilcox, 1955	$\%Na = (Na^+ + K^+) \times 100/(Na^+ + K^+ + Ca^{2+} + Mg^{2+})$
iii	Kelley, 1963	$KI = Na^+/(Ca^{2+} + Mg^{2+})$
iv	Szabolcs & Darab, 1964	$MH = Mg^{2+}/(Ca^{2+} + Mg^{2+})$
v	Doneen, 1964	$PI = (Na^+ + \sqrt{HCO^-{}_3}) \times 100/\ (Na^+ + Ca^{2+} + Mg^{2+})$
vi	Gupta, 1987	$RSBC = HCO_3{}^- - Ca^{2+}$
vii	Sawyer & McCarty, 2003	TH (as $CaCO_3$) = $(Ca^+ + Mg^+) \times 50$

Every parameter is calculated in mg/L for equation (vii), and for equations (i - vi), all values are calculated in meq/L

RESULTS AND DISCUSSION

Physiochemical parameters of water samples

Several physicochemical parameters were investigated, including pH, total dissolved solids (TDS), electrical conductivity (EC), major cations (Na^+, K^+, Ca^{2+}, Mg^{2+}) and anions (Cl^-, HCO_3^-, SO_4^{2-}). Based on the obtained result, this study evaluates the drinking water and public health quality by comparing the physical and chemical parameters of groundwater and surface water with the standards recommended by the World Health Organization (WHO, 2011) and the Environmental Quality Standard for Bangladesh (EQS, 1993), as shown in Table 3.

The degree to which the hydroxyl and hydrogen ions concentrations in water are indicated by the pH value (Prasanth et al., 2012). The World Health Organization (1997) specifies a pH between 6.5 and 8.5 for drinking water. The pH concentrations found in the samples under investigation are within the acceptable range of 6.72 to 7.95, with a standard deviation of 0.41 and a median of 7.19 (Table 4). The concentration of organic compounds and inorganic salts in water can be determined by the Total Dissolved Solids (TDS). The TDS in the mine drainage water was found between 133.76 and 361.60 mg/L, a mean of 218.82 mg/L which is within the permissible limits of 500-1500 mg/L. Many factors, including temperature, ion type, and concentration, affect the electrical conductivity (EC) of water (Iwalewa, 2012). A higher EC value indicates that there are more ions in the water sample. The acceptable EC level for drinkable water, as stated by the World Health Organization (1997), is 1500 μS/cm. The present research provides permissible limits with an average of 342 μS/cm, between 209 and 565 μS/cm.

Table 2: Physiochemical parameters, WHO water quality standard (2011) and their relative weight.

Parameters	WHO Standards (2011)	Weight	Relative Weight (W_n)
TDS	500	5	0.121951
TH	100	3	0.073171
pH	6.5-8.5	4	0.097561
EC	500	4	0.097561
Ca^{2+}	75	3	0.073171
Na^+	200	3	0.073171
Mg^{2+}	50	3	0.073171
Fe^{total}	0.3	3	0.073171
K^+	10	2	0.048780
Cl^-	250	5	0.121951
HCO_3^-	500	1	0.024390
SO_4^{2-}	250	5	0.121951

Table 3: An analysis of potential adverse effects is conducted by comparing drainage water samples to the standards established by the (WHO, 2011), Environmental Quality Standard (EQS, 1993) and Bangladesh Standard for safe drinking purposes (Howladar et al., 2017; Singaraja, 2017; Rahman et al., 2023).

Parameters	WHO standard	EQS standard	Bangladesh standard	Mine drainage water in the study area	Undesirable effects
pH	6.5-8.5	6.5-8.5	8.5	6.72-7.95	Permissible limits.
TDS	1000	1000	500	133.76-361.60	Each sample has a normal taste and is below the permissible limits.
EC	1000	1000	1000	209-565	Permissible limits.
Ca^{2+}	75-200	-	75	19.20-59.40	Scale formation.
Mg^{2+}	50-150	30-50	30	5.92-24.80	Below permissible limits.
Na^+	200	200	200	12.70-32.10	Permissible limits.
Fe^{total}	0.3-1	0.3-5	0.5	0.47-11.10	Permissible limits but some samples exceed the limits.
K^+	12	12	12	1.14-13.11	Permissible limits but only two samples exceed the limits.
Cl^-	200-600	150-600	250	0.99-8.10	Each sample has a normal taste and is below the permissible limits.
SO_4^{2-}	400	400	200	7.94-38.40	Below permissible limits.
HCO_3^-	200	-	200	127.60-225.10	Permissible limits but some samples exceed the limits.

Table 4: The physicochemical parameters of the mine drainage water around the BCM area are expressed in (mg/L) except EC.

Sample no.	pH	TDS	EC (µs/cm)	Na^+	K^+	Ca^{2+}	Mg^{2+}	Fe ^{total}	Cl^-	HCO_3^-	SO_4^{2-}
DW-1	7.09	188.80	295	19.80	6.24	27.60	5.92	1.88	2.16	128.50	16.30
DW-2	7.14	184.32	288	18.50	5.50	28.40	6.26	2.22	2.53	127.60	7.94
DW-3	6.72	338.56	529	23.20	12.20	48.40	17.80	0.95	0.99	150.40	12.20
DW-4	7.45	166.40	260	12.70	1.14	19.20	7.44	0.47	0.99	136.50	38.40
DW-5	7.08	361.60	565	32.10	10.00	59.40	24.80	11.10	7.46	144.30	25.50
DW-6	7.95	172.16	269	12.90	4.26	30.40	8.72	0.76	3.39	147.20	19.20
DW-7	7.24	136.96	214	17.53	5.50	45.20	14.50	1.42	6.22	215.00	14.10
DW-8	7.75	178.56	279	18.20	8.40	50.25	22.00	1.14	8.10	225.10	11.90
DW-9	6.90	327.04	511	13.54	13.11	35.80	21.52	1.50	4.16	217.60	16.75
DW-10	7.82	133.76	209	25.14	12.28	47.10	19.24	1.42	6.33	203.46	12.60
Min.	6.72	133.76	209	12.70	1.14	19.20	5.92	0.47	0.99	127.60	7.94
Max.	7.95	361.60	565	32.10	13.11	59.40	24.80	11.10	8.10	225.10	38.40
Mean	7.31	218.82	342	19.36	7.86	39.18	14.82	2.29	4.23	169.57	17.49
Median	7.19	181.44	283.50	18.35	7.32	40.50	16.15	1.42	3.78	148.80	15.20
SD.	0.41	87.57	136.82	6.11	3.98	12.71	7.22	3.14	2.64	40.35	8.77

Abundances of different ions

This study has analyzed the concentration of various geochemical parameters including major cations (Na^+, K^+, Ca^{2+}, Mg^{2+}) and anions ($Cl^–$, $HCO_3^–$, $SO_4^{2–}$) together with their corresponding WHO (1997) recommended values which are tabulated in Table 3 and Table 4. Sodium ions (Na^+) are present in groundwater because most rocks and soils are sodium compounds. The reason for this is that salt dissolves quite quickly. The average sodium concentration in the samples is 19.36, with a median of 18.35 and a standard deviation of 6.11 mg/L (Table 4). This value falls within the permissible limits of 200 mg/L (Table 3). However, the concentration of potassium (K^+) is much lower than that of Na, Mg and Ca. Potassium concentrations range between 1.14 and 13.11 mg/L, averaging 7.86 mg/L. Only two samples surpass the 12 mg/L limit, while the majority of samples remain within it. Typically, water becomes harder when divalent cations, especially calcium (Ca^{2+}) are present. In most natural water, calcium is the fifth most common element. The calcium concentration varies from 19.20 to 59.40 mg/L, which is below the permissible limits of 75-200 mg/L. The element magnesium (Mg^{2+}) is generally present in all naturally occurring waters and is common to the Earth's crust. It is an essential component of water hardness as well. Table 3 shows that drinking water has an average magnesium content of 14.42 mg/L, falling within the World Health Organization's permissible level between 5.92 and 24.80 mg/L. Generally, the occurrence of iron (Fe^t) in water is a consequence of the mineral oxidation process that contains high levels of iron (Ganguli et al., 2021). This oxidation process has a substantial impact on the chemical characteristics and the use of iron. Iron concentrations in the studied samples vary between 0.47 and 11.10 mg/L. While most of the samples fall within the acceptable range, only two samples are above the allowable limits of 0.3-1 mg/L.

Several factors can contribute to the formation of chloride (Cl^-), including weathering, salt in precipitation carried by the wind, intrusion of saltwater, discharge of municipal effluents, and industrial and household wastes (Karanth, 1987; Prasanth et al., 2012). All of the samples that were examined have chloride concentrations that are below the acceptable limits of 200-600 mg/L; On average, these values are 4.23 mg/L, ranging from 0.99 to 8.10 mg/L. In terms of Bicarbonate ($HCO_3^–$), it is a common water-soluble mineral that forms when carbon dioxide interacts with carbonate rocks like limestone and dolomite (Chaurasia et al., 2018). Typically, alkaline conditions are formed by the presence of bicarbonate. Most of the samples fall within the acceptable limits, but some samples exceed the limits, ranging from 127.60 to 225.10 mg/L. The median and standard deviation are 148.80 and 40.35 mg/L respectively. Sulfate ($SO_4^{2–}$) is one of the most important anions that occurs as the inorganic sulfate salts and dissolved gas (H_2S). The acceptable range of sulfate concentration is 200-400 mg/L for drinking water, (Table 4). All samples fall below the allowed limit of sulfate, ranging from 7.94 to 38.40 mg/L in the study region, with an average of 17.49 mg/L.

Statistical Interpretation

For statistical interpretation of the water samples to evaluate their quality, various statistical tools have been used as discussed below:

Pearson correlation coefficient

One of the most useful methods for understanding the strength and direction of linear relationships between dependent and independent variables is the correlation coefficient (r). This method has been applied to correlate the physiochemical parameters of drainage water from the BCM industry, as shown in Table 5. The values of the correlation coefficient

(r) range from -1 to 1, with a positive value suggesting a positive connection and a negative value indicating a negative correlation of variables. If the value of r is zero, then there is a negligible connection between the variables (Popoola et al., 2019). Regarding the r values of >0.7, 0.5-0.7 and < 0.5, Saleem et al. (2012) classified the correlation as strong, moderate, and weak respectively.

In terms of pH, there is a moderately negative correlation between TDS and EC, suggesting that as pH decreases, TDS and EC tend to increase, indicating a potential association between acidity and higher mineral content or ion conductivity in the water. However, pH has a weak negative correlation with Fe^{total}, Mg^{2+}, Ca^{2+}, K^+, and Na^+ in the Pearson correlation matrix, which implies that lower pH conditions may slightly decrease the concentrations of certain elements, reflecting a subtle tendency for reduced levels of these specific ions (Ravikumar et al. 2013). The correlation between Cl^-, HCO_3^-, and SO_4^{2-} is moderately positive. In contrast to the moderate correlations shown for K^+, $Mg^{2+,}$ and Fe^t, EC and TDS show a strong positive association, suggesting that EC is responsible for the inorganic pollution load and the dissolving of salts and in water (Wagh et al., 2018). In addition, significant correlation pairs were found between Na-Ca, Na-Fe, K-Mg, Mg-Cl, Ca-Cl, and Ca-Mg. Typically, SO_4^{2-} shows a weakly positive relationship with pH, EC, TDS, and Fe^t, whereas the others show a negative correlation. This indicates that there is a subtle tendency for the water to become slightly alkaline. In contrast to the other ions, K^+ displays a negative connection with SO_4^{2-}, indicating an inverse relationship between the concentrations of these two ions. Unlike the other variables, which are only weakly correlated, HCO3⁻ and Cl^- have a moderate positive correlation.

The majority of the ions present in the water samples within the research area exhibit a good positive relationship. As the TDS value increases, the ionic concentrations of all samples also increase in drainage water, which means that the drainage water may pose risks to human health if the water is used for drinking or irrigation purposes (Fig. 2). Therefore, the observed positive correlation among the studied water parameters suggests that human activities, particularly anthropogenic and industrial activities, can contribute to the pollution of the evaluated groundwater parameters in the research region.

Table 5: Major physiochemical characteristics of the drainage water samples and their correlation coefficient matrices.

Parameters	pH	EC	TDS	Na^+	K^+	Ca^{2+}	Mg^{2+}	Fe^{Total}	Cl^-	SO_4^{2-}	HCO_3^-
pH	1										
EC	-0.701*	1									
TDS	-0.701*	**1.000****	1								
Na^+	-0.232	0.420	0.420	1							
K^+	-0.340	0.586	0.586	0.511	1						
Ca^{2+}	-0.090	0.418	0.418	**0.756***	0.664*	1					
Mg^{2+}	-0.108	0.545	0.545	0.528	**0.773****	**0.867****	1				
Fe^{Total}	-0.251	0.560	0.560	**0.762***	0.223	0.554	0.46	1			
Cl^-	0.366	-0.049	-0.049	0.418	0.331	**0.734***	**0.70***	0.443	1		
SO_4^{2-}	0.085	0.078	0.078	-0.150	-0.473	-0.320	-0.13	0.211	-0.221	1	
HCO_3^-	0.221	-0.128	-0.12	-0.110	0.454	0.453	0.63	-0.22	0.66*	-0.30	1

Note: Data with a high correlation coefficient (around 1) is highly correlated, moderately correlated (between 0.45 and 0.75), and weakly correlated (below 0.45). The correlation is significant at both the 0.05 and 0.01**(2-tailed) levels.*

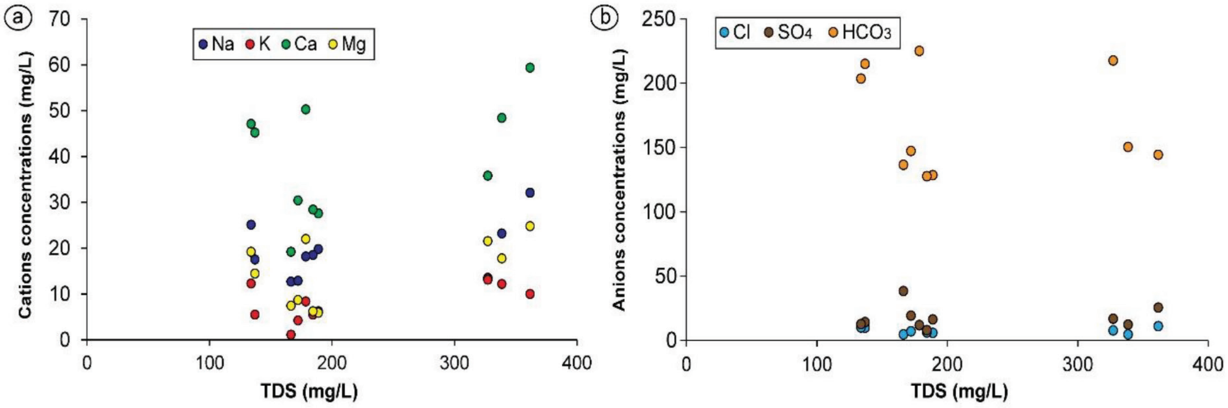


Fig. 2: A scatter plot showing the (a) major anions and (b) cations concentrations relative to the TDS.

Box and Whisker Plot

The Box and Whisker plot shows the concentration variations for major anions (Cl$^-$, SO$_4^{2-}$, HCO$_3^-$) and cations (Na$^+$, K$^+$, Ca^{2+}, Mg$^{2+)}$ in mine drainage water (Fig. 3). HCO$_3^-$ and Ca^{2+} are the most significant anions and cations in this context (Jun et al., 2015). Magnesium (Mg), sodium (Na), and sulfate (SO$_4^2$) concentrations are very high in some of the water samples. In general, the major anions are HCO$_3^-$ > SO$_4^{2-}$ > Cl$^-$ in order of relative abundance, whereas minor cations are Ca^{2+} > Na$^+$ > Mg^{2+} > K$^+$. The predominant components of the TDS are Na$^+$, Ca^{2+} and HCO^3. Two outliers denoted as SO$_4^{2-}$ and K$^+$, are responsible for the abruptly elevated levels observed in the water samples.

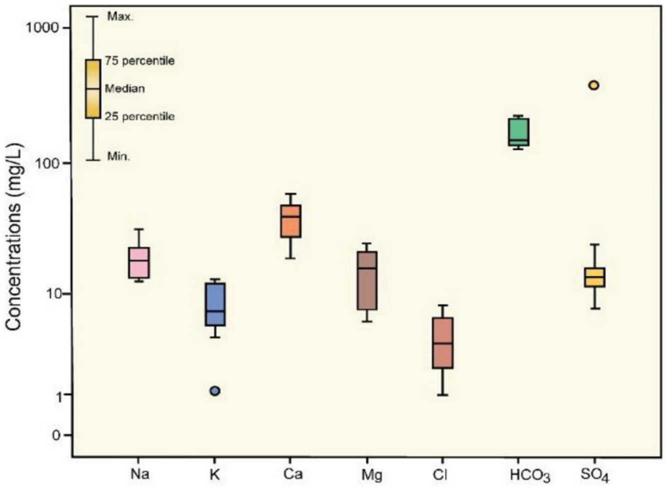


Fig. 3: The variation in concentrations of the major ions shown in the Box and Whisker plots.

Principal Component Analysis

Principal Component Analysis (PCA) is a statistical technique widely used to simplify complex datasets by transforming a large set of correlated variables into a smaller set of uncorrelated variables (Bodrud-Doza et al., 2016). For the assessment of groundwater quality, PCA was applied to the dataset using Varimax rotation with Kaiser Normalization (Kaiser, 1960; Panda et al., 2006; Jun et al., 2015). This method effectively simplifies the intricate hydrochemical interactions within the area, including ion exchange, material leaching, agricultural fertilizer, the impact of domestic sewage, and mineral weathering, by reducing the dataset to a select few key components. Kaiser (1960) suggested the use of only the factors along with eigenvalues exceeding one. Three factors are extracted for groundwater quality data sets utilizing eigenvalues of more than 1. According to Unmesh et al. (2006), the factor loading is categorized as weak (<0.50), moderate (0.75-0.50), and strong (>0.75). Moreover, factor scores can be associated with the intensity of the particular process description. Factor loading close to ±1 suggests a strong correlation, while those near zero indicate little to no contribution. Varimax rotation is often applied to maximize the clarity of these loadings, making it easier to identify the most influential factors.

PCA shows that the first three factors (PC1, PC2, and PC3) accounted for 84.368% of the total variance in the study area (Table 6; Fig. 4a, 5b). PC1 with 45.437% of the total variance displays strong loading for Na$^+$, K$^+$, Ca^{2+}, Mg^{2+} and moderate loading for EC, TDS, and Cl$^-$, whereas the rest of the parameters have weak loading. This indicates the joint involvement of ions in the water. The pH has a weak loading on PC1, and its negative loading indicates a minor bipolar influence, supporting the idea that limestone dissolves well under acidic (low pH) conditions (Esdras et al., 2017). The positive correlation between Ca^{2+} and Mg^{2+} suggests that carbonate dissolution occurs in certain locations. PC2 with 25.135% of the total variance displays a strong loading of HCO$_3^-$ and a moderate loading of pH, suggesting the alkaline nature of the groundwater (Tanvir Rahman et al., 2017). PC3 with 25.135% of the total variance shows moderate loading for Fe^{total} and SO$_4^2$, whereas others have weak loading. It indicates the weathering of rock and anthropogenic impacts on the water contaminations.

Table 6: Principal component analysis using Varimax rotation on the water samples.

Parameters	PC1	PC2	PC3
pH	-0.397	0.690	0.406
EC	0.743	-0.596	-0.153
TDS	0.743	-0.596	-0.153
Na$^+$	**0.756**	-0.069	0.382
K$^+$	**0.814**	0.117	-0.447
Ca^{2+}	**0.886**	0.333	0.124
Mg^{2+}	**0.895**	0.307	-0.022
Fe^{Total}	0.680	-0.273	0.622
Cl$^-$	0.552	0.717	0.338
SO$_4^{2-}$	-0.225	-0.396	0.572
HCO$_3^-$	0.316	**0.781**	-0.339
Eigenvalue (%)	4.998	2.765	1.518
% of variance	45.437	25.135	13.795
Cumulative %	45.437	70.572	84.368

Bold values indicate strong (>0.75) and positive factor loadings.

Hydrochemical facies

Hydrochemical facies are zones within a groundwater system by unique combinations of cation and anion concentrations (Piper, 1953; Lloyd, 1965; Madhav et al., 2018). These facies help to explain the origin and distribution of groundwater types. The geochemical evolution of groundwater and its relationship with dissolved ions can be effectively understood by using graphical representations such as Piper's Trilinear and Expanded Durov diagrams (Piper, 1953). These diagrams are reliable tools for analyzing water quality and enable comparing and classifying different water types based on their major dissolved constituents. Moreover, the hydrochemical characteristics of groundwater are significantly affected by factors such as lithology, regional water flow patterns, and residence time (Nayak et al., 2023). Based on their chemical composition, groundwater can be categorized as bicarbonate, sulfate, and chloride-containing water. This study uses a Piper diagram to illustrate the distribution of cation and anion percentages expressed in milligrams per liter (mg/L) in groundwater. The Piper diagram presents the hydrochemical data in two triangular fields and an upper diamond-shaped field, allowing for the visualization of clusters among similar groundwater sample groups. Here, alkali cations (Na^+ and K^+) have been classified as primary constituents, while alkaline earth cations (Ca^{2+} and Mg^{2+}) are considered secondary constituents. Strong acidic anions (SO_4^{2+} and Cl^-) are categorized as saline constituents, and HCO_3^- is regarded as a weak acid. The chemical character of the water has been determined by the balance between these cations and anions. The analysis shows that weak acids generally exceed strong acids in all samples, and secondary constituents surpass primary constituents. According to the Piper diagram (Fig. 5a), the most common ions are bicarbonate (HCO_3^-), alkaline earth (Mg^{2+} and Ca^{2+}) and the majority of water type is Ca-Mg-HCO_3. As a result, there was no discernible change in geochemical faces in water samples, which aligns with the findings of (Howladar et al., 2014; Nayak et al., 2023). In addition, the presence of bicarbonates and calcium in groundwater samples may have resulted from the natural dissolution of carbonate minerals.

The Expanded Durov diagram is another important graphical tool that distinctly classifies the combinations of major cations and anions based on their concentrations in mg/L. In this diagram, the total percentages of cations and anions equal 100%. It offers a clearer representation of hydrochemical types and related processes (Lloyd, 1965). Based on this analysis, the water types of the study area are categorized as calcium-bicarbonate and magnesium-bicarbonate, indicating that the shallow, recently recharged water in this region, similar to other floodplain areas of Bangladesh (Fig. 5b; Hossain et al., 2010; Howladar et al., 2014).

Gibbs plot is a widely used graphical method for the hydrochemical classification of water samples. According to Gibbs (1970), it helps in identifying the dominant processes controlling water chemistry, such as rock-water interaction, evaporation, or precipitation dominance. The concentration of dissolved ions in groundwater samples is significantly influenced by lithology, geochemical reactions, and the solubility of interacting rocks. The functional sources of dissolved ions can be effectively evaluated by plotting samples based on the variation in the ratio of Total Dissolved Solids (TDS) against the cation [Na/(Na+Ca)] or the anion ratio [Cl/(Cl+HCO_3)]. The analysis of the Gibbs plot shows that all the samples of the study area originate from rock dominance sources (Fig. 6a and 6b). This indicates the weathering of rocks and minerals mainly controls the water chemistry. The waters usually have low to moderate TDS and ionic ratios reflecting the dissolution of silicate and carbonate minerals. This rock–water interface is the key factor in alluvial plains that controls the groundwater chemistry (Madhav et al., 2018).

Application of Water Quality Index

The water quality index (WQI) is a unique rating that provides a single value for assessing water quality, enabling the identification of suitable treatment techniques to address specific issues (Esdras et al., 2017). Water can be divided into five categories based on WQI: unsuitable (>300), very poor (200-300), poor (100-200), good (50-100) and excellent (<50) for human usage (Howladar et al., 2014; Boateng et al., 2016). Most of the drainage water samples around the mine fall under the good category, ranging from 35.84 to 88.22, with an average of 69.94 (Table 7). The graphical representation of the water quality index for different water samples (DW-1 to DW-10) shows that none of the samples showed water of poor quality (Fig. 7). Only one sample (DW-4) has excellent water type, with a WQI of 35.84. Additionally, the sample DW-6 is slightly over 50, which classifies it within the range of good water quality. The WQI of DW-5 indicates the highest peat at 88.22, whereas DW-4 has the lowest index with only 35.84.

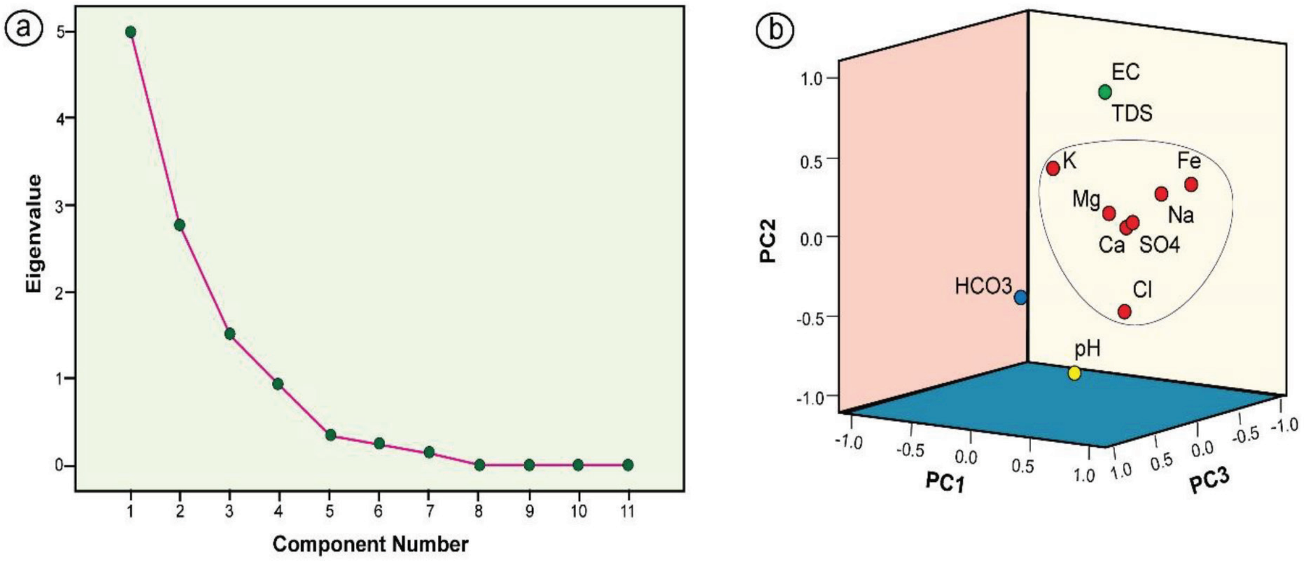


Fig. 4: Principal component analysis showing (a) screen plot of the distinctive roots with eigenvalues (b) principal component (PC1, PC2, and PC3) plot in rotated spaces.

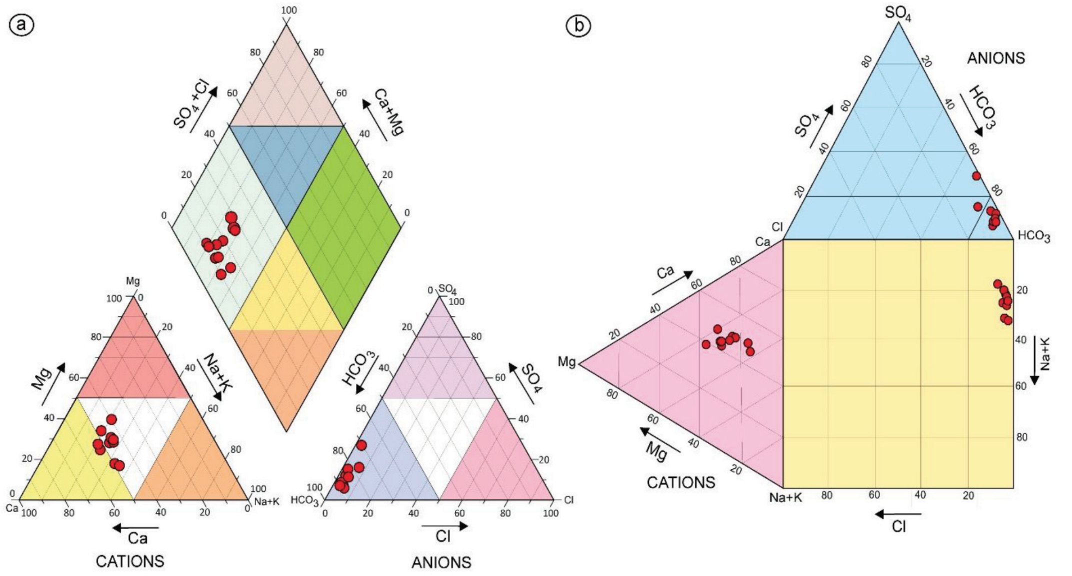


Fig. 5: (a) Piper trilinear (b) Durov plots depicting the proportion of anion and cations of mine drainage water of BCM.

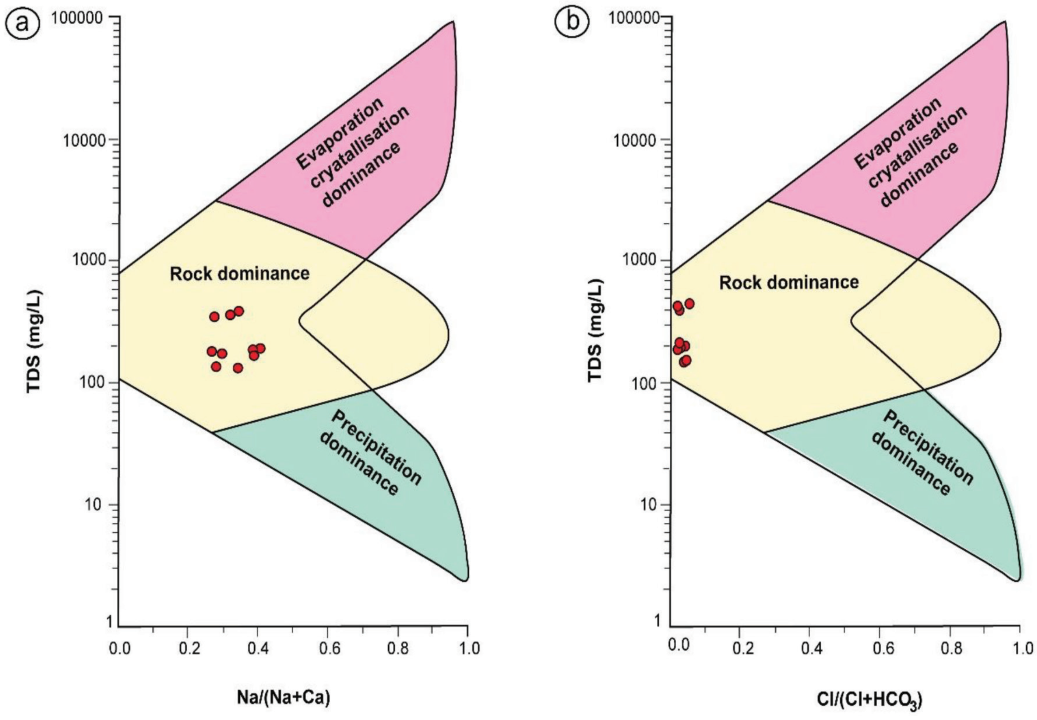


Fig. 6: Gibbs diagram showing the relationship of (a) Na/(Na+Ca) vs TDS. and (b) Cl/(Cl+ HCO3) vs. TDS.

Quality of water for livestock

Around BCM, groundwater, ponds, rivers, and canals are the primary sources of drinking water for regular livestock. Therefore, the assessment of water quality is crucial for livestock management. According to Howladar et al. (2014), most animals may safely consume water with a slightly high concentration of dissolved solids (about 10 mg/L), with sodium chloride being the primary ingredient. If the magnesium ion is <250 mg/L and the salinity is <1,500 mg/L, the water is considered safe for livestock consumption (Ayers and Wescot, 1994). Bhardwaj and Singh (2011) have suggested that the excessive amount of salinity for livestock can have a deteriorating effect on animals, it is likely to cause many health difficulties and ultimately death. The research area's drainage water has a TDS content of 133.76 to 361.60 mg/L, on average 218.82 mg/L, considered acceptable for animal consumption according to the Environmental Studies Board (1972).

Irrigation suitability

The mining activities at BCM directly affect water quality, soil fertility, land morphology, and the surrounding environment (Uddin, 2003; Islam and Islam, 2005; Howladar et al., 2014; Mohanta et al., 2015; Fardushe et al., 2016). As a result, the current study uses several significant measures, including % Na, SAR, KI, RSBC, MH, TH, and PI, to determine the quality of water for agricultural purposes. A detailed description of these parameters has been provided below:

Percent Sodium (%Na)

The percentage of sodium is a crucial component in assessing the risk of sodium hazards (Devi and Kshetrimayum, 2021). A common method of determining the suitability for irrigation is to use the percentage of sodium in all-natural waters (Wilcox, 1955). The average percentage within the research area is 25.52%, ranging between 18.91% and 35.39%. All samples show excellent to good conditions for irrigation, according to the Wilcox diagram (Fig. 8a; Table 8).

Sodium Adsorption Ratio (SAR)

This is another crucial factor for determining whether water is permissible for irrigation since the level of sodium may decrease the structure and permeability of the soil (Richards L.A, 1954; Todd, 2005; Devi and Kshetrimayum, 2021). An increasing SAR concentration raises the sodium hazard risk in plant development (Islam and Islam, 2005). The values of SAR in the research region are all below the permitted range, ranging between 0.44 and 0.89 meq/L, with an average of 0.68 meq/L (Table 8). By plotting SAR vs EC, the United States Salinity (USSL) was shown to evaluate irrigation waters (Fig. 8b). According to the USSL (1954), except for two samples that exhibit low sodium type, most of the samples have a medium salinity. As a result, the type of water is usable for irrigation purposes on all kinds of soil as it has a medium salinity and low sodium content (Fig. 8b).

Table 7: Calculated Water Quality Index and their classification of the studied samples.

Sample no.	Type of water	WQI
DW-1	Good	72.48
DW-2	Good	80.42
DW-3	Good	69.63
DW-4	Excellent	35.84
DW-5	Good	88.22
DW-6	Good	50.95
DW-7	Good	68.22
DW-8	Good	73.24
DW-9	Good	82.51
DW-10	Good	77.94
Average	**Good**	**69.94**

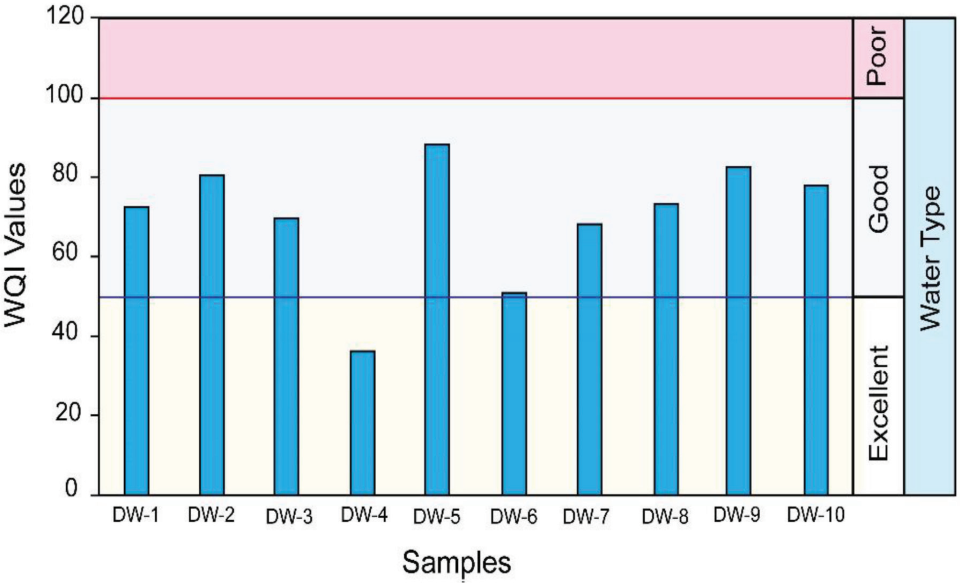


Fig. 7: Graphical representation of water quality index (WQI) variation in the study area.

Kelley Index (KI)

The KI value is determined through a comparison of the sodium concentration with that of calcium and magnesium, as per Kelley's method (Kelley, 1963). While SAR is more often used to calculate salt hazards, KI is also utilized for this purpose. If the KI value is higher than one, it means that the water is too salty to be used for irrigation. Irrigation may be performed on samples with KI < 1. Between 0.17 to 0.46 (meq/L), the KI value is 0.29 (meq/L) on average, suggesting suitability for agriculture in the research area (Table 8).

Residual Sodium Bicarbonate (RSBC)

The water can be classified using residual sodium bicarbonate (Alaya et al., 2014; Gupta and Gupta, 1997). The levels of >10, 5-10, and <5 meq/L, are regarded as being unacceptable marginal and safe respectively. RSBC concentration in the investigated area is between −0.60 and 1.78 (meq/L), 0.83 (meq/L) on average, suggesting that the irrigation water meets the quality standards (Table 8). RSBC demonstrates that there is an excess of HCO_3^- in the water, as shown by the negative water values and the high concentration of HCO_3^- relative to Ca^{2+}.

Magnesium Hazard (MH)

The index of magnesium hazards is a ratio that was proposed by Szabolcs and Darab (1964) and Paliwal (1972). Damage to agricultural harvests occurs when the hazard value of magnesium exceeds 50% as a result of an increase in soil acidity; nevertheless, less than half of the affected area is still appropriate for irrigation and shows no negative effects. Table 8 shows that in the study area, the MH value on average is 36.90% and varies between 26.13 and 49.78%, indicating that it is appropriate for irrigation.

Total Hardness (TH)

This is basically used to assess water suitability for various uses, including agriculture, homes, and industries (Sawyer and McCarty, 2003; Ravikumar et al., 2013). When magnesium (Mg^{2+}) and calcium (Ca^{2+}) are present, the hardness of water increases. The overall hardness values within the study area are 158.73 mg/L on average, with a range of 78.52 to 250.26 mg/L (Table 8). An estimated 60% of samples are hard, with 40% rated as moderately hard. Based on Fig. 9a, which illustrates the correlation between TDS and TH, only a tiny percentage are soft-fresh water, whereas the majority of the water samples are hard-fresh water.

Permeability Index (PI)

Doneen (1964) developed a categorization of water suitability based on PI for agricultural purposes. The water can be classified as I, II, and III classes. If the permeability index is 75% or higher, the water type is considered Class I and Class II (Ghalib, 2017). In contrast, Class III type of water has a permeability of 25% indicating that it is not suitable for agricultural purposes. The drainage water within the research area was found to be within Class I and II categories; the PI value is between 45.84 and 96.50, on average 67.15 suggesting good for irrigation (Fig. 9b; Table 8).

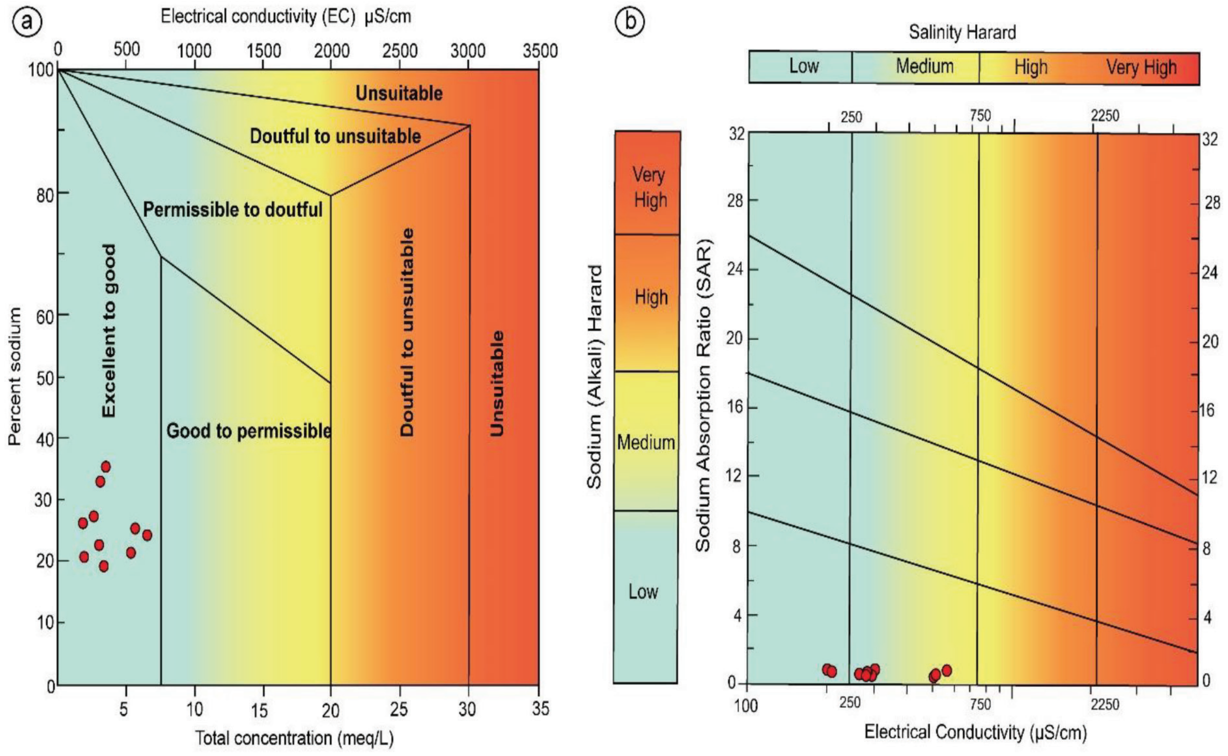


Fig. 8: Classification of Irrigation water quality according to (a) total concentration and percent sodium (after Wilcox, 1955); (b) salinity and sodium hazard (after USSL, 1954; Nakhaei et al., 2016).

Comparison with previous studies

The drainage water quality around the BCM area exhibits a notable variation when compared to previous studies and established standards (Table 9). This study presents an average pH value of 7.31, which falls within the acceptable range of 6.5-8.5 set by WHO and EQS. This result aligns closely with the findings of Howladar et al. (2014) and Fardushe et al. (2016), who reported pH values of 7.48 and 7.47, respectively. The mean value of TDS is 218.82 mg/L, which is lower than 445.1 mg/L, according to Zakir et al. (2013), yet still within the permissible limits of 1000 mg/L. EC values ranged from 342 µS/cm in this study to 445.1 µS/cm in Zakir et al. (2013), indicating a relatively stable water quality. The concentrations of Na^+ and K^+ in this study are 19.36 mg/L and 7.86 mg/L, which are comparable to the values in Howladar et al. (2014) and fall within the permissible limits. Ca^{2+} and Mg^{2+} concentrations are 39.18 mg/L and 14.82 mg/L, respectively, which are significantly lower than those reported by Howladar et al. (2014), indicating variations in mineral leaching influenced by mining activities. Additionally, iron (Fe^{total}) level is 2.29 mg/L in this study, which is higher than reported in other studies, but remains below the WHO limits. Chloride (Cl^-) and Bicarbonate (HCO_3^-) levels are measured at 2.29 mg/L and 169.57 mg/L

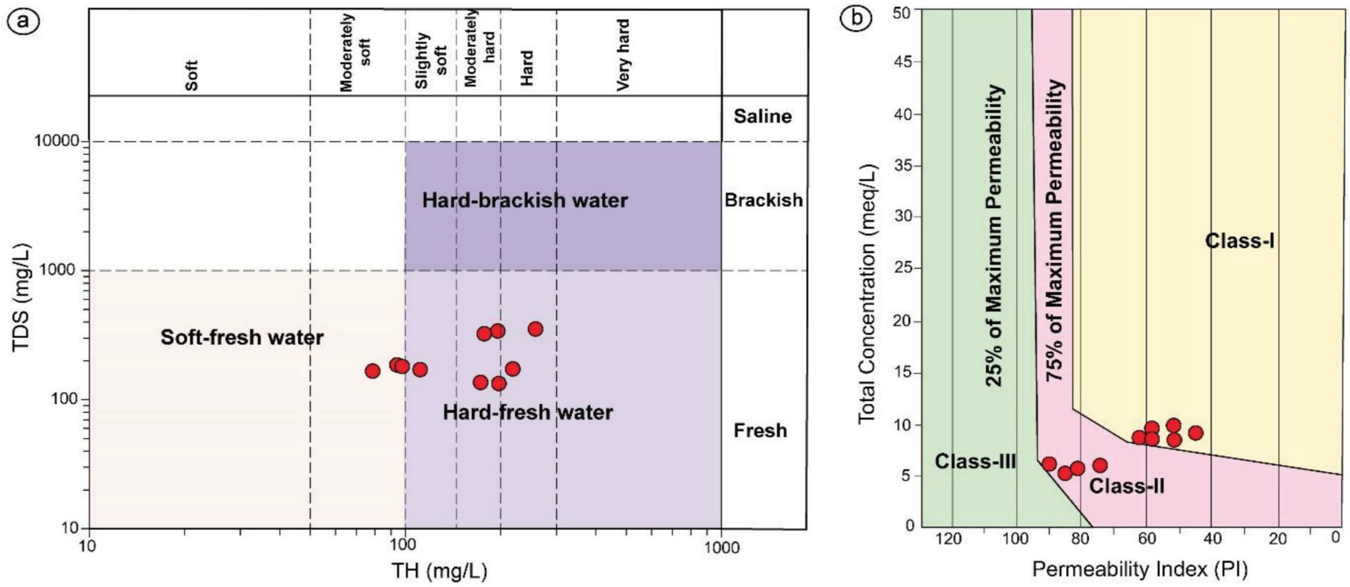


Fig. 9: Classification of irrigation water quality based on (a) total hardness and total dissolved solids (after Sawyer and McCarty, 2003; Eyankware et al., 2020) and (b) permeability index and total concentration (after Doneen, 1964).

Table 8: Parameters measuring (in meq/L) the quality of BCM mine drainage water for irrigation purposes.

Sample no.	%Na	SAR	KI	RSBC	MH	TH	PI
DW-1	35.3853	0.8921	0.4620	0.7302	26.1318	93.2228	84.8568
DW-2	32.8555	0.8187	0.4165	0.6755	26.6616	96.6179	82.2527
DW-3	25.4059	0.7246	0.2601	0.0514	37.7552	194.0050	52.7627
DW-4	27.0273	0.6235	0.3518	1.2805	38.9910	78.5196	96.5048
DW-5	24.8196	0.8827	0.2790	-0.5975	40.7792	250.2550	45.8443
DW-6	23.0722	0.5309	0.2511	0.8971	32.1154	111.7308	75.6459
DW-7	20.7564	0.5807	0.2211	1.2705	34.6016	172.4415	62.6948
DW-8	18.9066	0.5388	0.1833	1.1842	41.9307	215.9038	53.0956
DW-9	20.6288	0.4416	0.1656	1.7822	49.7846	177.8758	59.7630
DW-10	26.3579	0.7798	0.2780	0.9865	40.2531	196.6871	58.0878
Min.	18.9066	0.4416	0.1656	-0.5975	26.1318	78.5196	45.8443
Max.	35.3853	0.8921	0.4620	1.7822	49.7846	250.2550	96.5048
Mean	25.5215	0.6813	0.2868	0.8260	36.9004	158.7259	67.1508
Median	25.1127	0.6740	0.2690	0.9418	38.3731	175.1587	61.2289
SD.	5.280543	0.159607	0.096355	0.6779	7.239324	59.32681	16.63498

respectively, significantly lower than the values reported by Howladar et al. (2014) and Howladar et al. (2017), indicating within the permissible limits (200-600 mg/L). Sulfate (SO_4^{2-}) levels were 17.49 mg/L, lower than the values reported by Howladar et al. (2014) and Zakir et al. (2013). Sulfate (SO_4^{2-}) level in this study is 17.49 mg/L, lower than the values found by Zakir et al. (2013) and higher than those reported by Howladar et al. (2014) and Howladar et al. (2017), yet still below the acceptable limits. The Piper diagram (Fig. 5a) in this study shows that the dominant ions are bicarbonate (HCO_3^-) and alkaline earth ions (Mg^{2+} and Ca^{2+}), with the primary water type being Ca-Mg-HCO_3. In comparison, Howladar et al. (2014) classify the waters of the study area as calcium-bicarbonate, magnesium-bicarbonate and Ca–HCO_3 type.

This classification aligns with the findings of the present study, suggesting that the shallow, recently recharged waters in floodplain areas of Bangladesh. Overall, the findings suggest that while the water quality around Barapukuria remains within permissible limits for many parameters, continuous monitoring is essential to mitigate any potential health risks associated with mining activities.

The analysis of irrigation water parameters around the Barapukuria coal mine area shows that sodium percentage (%Na) is 25.52%, slightly higher than Howladar et al. (2014) at 23.82% but lower than Zakir et al. (2013) at 41.70%. The Sodium Adsorption Ratio (SAR) of 0.68 aligns closely with Howladar et al. (2014) at 0.61, indicating good irrigation quality, while being significantly lower than Howladar et al. (2017) at 4.88. The Residual Sodium Bicarbonate (RSBC) value of 0.83 is comparable to Zakir et al. (2013) at 0.80. Additionally, the Magnesium Hazard (MH) and Total Hardness (TH) values in this study (36.90 and 158.73, respectively) are consistent with previous findings. Therefore, the irrigation water quality around the Barapukuria coal mine remains largely suitable for agricultural use.

A comparative analysis of drainage water quality between the Barapukuria Coal Field in Bangladesh and various coal fields in India reveals notable differences across several parameters (Table 9). The pH level in Barapukuria is 7.31, which falls within the acceptable range of 6.5 to 8.5. In contrast, the Jharia and Raniganj coal fields in India exhibit higher pH values, ranging from 7.0 to 8.1, while the Northeastern coal fields show an alarming range of 2.3 to 2.7, which is significantly below acceptable standards. TDS in Barapukuria averages 218.82 mg/L, considerably lower than the TDS levels recorded in the Indian coal fields, where values can reach as high as 1212 mg/L in Jharia and 2518 mg/L in Northeastern Assam. This indicates that water quality in Barapukuria is better in terms of salinity. Additionally, EC in Barapukuria is measured at 342 µS/cm, which is within permissible limits and lower than the levels found in Indian coal fields, suggesting less mineralization in the water. Concentrations of sodium (Na^+) and calcium (Ca^{2+}) in Barapukuria are also within acceptable ranges, with Na^+ at 19.36 mg/L, while Ca^{2+} reaches 39.18 mg/L, both of which are lower than those observed in some of the Indian coal fields. This comparison suggests that the water quality in the Barapukuria Coal Field is generally more suitable compared to that in the Indian coal fields according to the established standards.

Table 9: Comparison of drainage water quality parameters in the Barapukuria coal field, Bangladesh, and various coal fields in India (Ray and Dey, 2020).

Barapukuria Coal Field in Bangladesh												
References		pH	TDS	EC (µS/cm)	Na^+	K^+	Ca^{2+}	Mg^{2+}	Fe_{total}	Cl^-	HCO_3^-	SO_4^{2-}
This Study		7.31	218.8	342	19.36	7.86	39.18	14.82	2.29	4.23	169.57	17.49
Howladar et al. (2017)		6.82	116	156.60	7.7	3.10	30	15	0.60	5.32	180.15	1.33
Fardushe et al. (2016)		7.48	169	324	-	-	-	-	1.44	-	-	-
Howladar et al. (2014)		7.47	204.9	320.2	19.68	11.10	51.76	16.04	1.19	12.14	208.76	14.22
Zakir et al. (2013)		7.16	445.1	304.3	21.82	8.20	30.83	12.77	0.97	25.24	2.10	23.91
Various Coal Fields in India												
Ray and Dey (2020)	Jharia	7.9	429.33	-	-	-	102.2	180.91	15.7	14.97	-	704.48
	Jharia	8.1	1112	-	-	-	120.24	128.64	12.5	37.43	-	457.31
	Jharia	8	1212	-	-	-	124.24	123.78	15	19.65	-	549.48
	Raniganj	8.1	570	-	-	-	68	53	1	35	-	75
	Raniganj	7	990	-	-	-	162	98	16	29	-	376
	Raniganj	7.8	880	-	-	-	118	90	15	150	-	368
	Northeas-tern (Assam)	2.7	2518	-	-	-	2040	108	350	1.1	-	3050
	Northeas-tern (Assam)	2.3	1662	-	-	-	95	63	120	0.6	-	1662

CONCLUSIONS

The drainage water quality of the Barapukuria Coal Mine has been evaluated for drinking, livestock, and irrigation suitability. The physicochemical parameters including pH, TDS, EC, major cations (Na^+, K^+, Ca^{2+}, Mg^{2+}) and anions (Cl^-, HCO_3^-, SO_4^{2-}) were investigated for drinking purposes. The analysis reveals that the majority of the values fall within the acceptable limits established by the WHO, EQS, and Bangladesh standards, with the exception of Mg^{2+} and total Fe. The order of anions and cations concentration is $HCO_3^- > SO_4^{2-} > Cl^-$ and $Ca^{2+} > Na^+ > Mg^{2+} > K^+$, respectively. Statistical analysis shows that most ions exhibit a good positive correlation, with minimal deviation from their mean values suggesting these ions likely originate from the same source, likely shallow, recently recharged groundwater. This pattern is typical of floodplain regions in Bangladesh, where uniform recharge processes lead to consistent ion concentrations. Principal component analysis (PCA) shows that the first three factors accounted for 84.368% of the total variance. The PCA results suggest that the water quality in the mining area is mainly affected by rock weathering, ion dissolution, and anthropogenic activities. The Expanded Durov and Piper's trilinear diagrams reveal that the majority of water type is Ca-Mg-HCO_3. The analysis of the Gibbs plot demonstrates all the samples are from rock dominance source, which controls the chemistry of groundwater. Water Quality Index analysis reveals that the entire mine drainage water samples are mainly good quality types. The analysis of irrigation water parameters such as % Na, SAR, TH, MH, RSBC, and PI show that overall drainage water quality is good for irrigation. The Wilcox diagram indicates that the water quality falls within the excellent to good category, while the US Salinity diagram reveals a medium salinity level with low sodium content. The water is suitable for irrigation in most soil and crops with minimal risk. Therefore, it is recommended to regularly monitor water quality and develop hydrological models to predict the impacts of mining activities on both groundwater and surface water quality in the BCM.

AUTHOR'S CONTRIBUTIONS

Sohag Ali: Writing review and editing, Writing original draft, Methodology, Formal analysis, Data curation, Conceptualization; **Numair Ahmed Siddiqui:** Writing - review and editing, Supervision, Resources, Project administration, Funding acquisition; **Md. Yeasin Arafath:** Writing - review and editing, Formal analysis; **Md. Abdullahil Kafi:** Writing - review and editing, Investigation, Formal analysis; **Mohamed A.K. El-Ghali:** Writing review and editing, Formal analysis; **AKM Eahsanul Haque:** Writing - review and editing, Formal analysis; **Md. Inzaman-Ul-Haque Rimon:** Writing - review and editing, Methodology, Conceptualization; **Farfour Mohammed:** Writing - review and editing, Formal analysis. All authors read and approved the final manuscript.

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