Environmental Science and Pollution Research
https://doi.org/10.1007/s11356-023-27606-w

RESEARCH ARTICLE

Monitoring the dynamics of acid mine drainage affected stream surface water hydrochemistry at Jaintia Hills, Meghalaya, India

Mautushi Das[1] · **Khikeya Semy**[2]

Received: 23 August 2022 / Accepted: 9 May 2023

Abstract

Streams are pristine natural life-thriving water sources for people living in the mountainous proximity of NE India, where water scarcity is a common occurrence in most villages and towns. In the last few decades, factors like coal mining had drastically reduced the usability of stream water in the region; as such, an attempt has been made to assess the spatiotemporal variation of stream water chemistry affected by acid mine drainage (AMD) at Jaintia Hills, Meghalaya. The water variables were subjected to a multivariate statistical technique of principal component analysis (PCA) to understand their condition at each sampling point while comprehensive pollution index (CPI) and water quality index (WQI) was incorporated to assess the quality status. Maximum WQI was recorded in S4 (541.14) during summer, while minimum value was estimated in winter at S1 (14.65). Throughout the seasons, the WQI revealed "Good" quality in S1 (unimpacted stream), while the impacted streams (S2, S3, and S4) exhibited a "Very poor" to "Water unsuitable for drinking" status. Similarly, in S1, the CPI showed a ranged value of 0.20 to 0.37, presenting a water quality status of "Clean to Sub-Clean," whereas, CPI of the impacted streams indicated "Severely polluted" status. In addition, PCA bi-plot presented higher affinity of free CO_2, Pb, SO_4^{2-}, EC, Fe, and Zn in AMD-impacted streams than in unimpacted streams. The result demonstrates the environmental issues induced by coal mine waste and in particular, stream water being severely affected by AMD in mining areas of Jaintia Hills. Thus, measures to stabilized the mine repercussions and cumulative effects on the water bodies need to be formulated by the government, as stream water will remain the primary water source for the tribal communities in this region.

Keywords Jaintia Hills · AMD-impacted streams · PCA · WQI · CPI

Introduction

The hydrology of a water body depends on its physical and chemical processes involving regional geology, biological characteristics, climate, and human activities (Fukushima et al. 2000). The water quality of a stream has considerable importance for the reason that these water resources are generally used for multiple purposes, from irrigation to daily domestic usage. However, pollution of water sources generated from various anthropogenic activities has drastically increased over the years, resulting in a shortage of potable water (Das et al. 2022).

Scientific studies conducted by workers, such as Equeenuddin et al. (2010), Chaulya et al. (2011), Singh et al. (2012), Nigam et al. (2015), and Kumar and Singh (2016) have reported the deterioration effect of coal mining activities on water quality. Various organic and inorganic wastes are produced during coal excavation and water pollution caused by the disposal of wastewater is one of several environmental issues associated with mining. Since mining accelerates heavy metal accumulation in the terrestrial and aquatic interface, mine spoils rich in heavy metals released from mining sites have often obscured the natural loading of metals to stream water and sediments (Wilson et al. 2005). Moreover, mining activities around the world have left many rivers and streams contaminated with toxic metals (Gurrieri 1998). Acid mine drainage (AMD) is formed when pyritic minerals from overburdened mine spoils are exposed to atmospheric, hydrological, or biological

Responsible Editor: Xianliang Yi

✉ Khikeya Semy
khikeyasemy@gmail.com

[1] Department of Botany, University of Science and Technology Meghalaya, Ri-Bhoi 793101, India

[2] Department of Botany, Don Bosco College, Kohima 797001, Nagaland, India

weathering (oxygen, water and chemoautotrophic bacteria) which later gets oxidized, resulting in sulfuric acid formation. In the long run, AMD can influence the dissolution of metal ions, elevate sulfate contents, cause high acidity, and increase electrical conductivity (Sahoo and Sahu 2020). In addition, mining exerts a notable influence on energy and matter cycles of the natural environment, so it is important to analyze the dispersion and distribution of toxic elements and other environmental variables when their concentrations are beyond their natural biochemical background (Oliveira et al. 2002).

In the tribal dominant state of Meghalaya, NE India, coal mining is primarily controlled by private ventures or communities, and it is the most exploited fossil fuel in the Jaintia Hills. In recent decades, environmental issues triggered by coal mining activities started to surface through indications, such as the rapid loss of forest cover, reduction in crop productivity, poor soil and water quality, and impairment of local population health. However, no major studies were undertaken in the currently studied locations inspite of mining effects being observed in the vicinity for years. Thus, a thorough seasonal assessment was needed in either one of the environmental qualities to be cognizant of the locality pollution case. Among the natural resources, stream water is profoundly one of the most important but vulnerable assets of nature in the mountainous region, as they serve as a commodity for daily household usage and in aiding the economic sectors of the tribal inhabitants. Moreover, streams are the only source of fresh water during the dry seasons and their utilization becomes a necessity even when streams are polluted. Hence, the current research aims to assess the physical and chemical properties of the stream water at Jaintia Hills and provide a more complete logical evaluation of coal mine drainage problems in Meghalaya, northeast India.

Materials and methods

Study area

The Jaintia Hills district, covering an area of 3891 km^2, is situated in the eastern part of Meghalaya and lies between 25° 02′ N to 25° 45′ latitude and 91° 58′ E to 92° 50′ E longitude. The area is bounded in the north and east by the state of Assam, west by the East Khasi Hills, and south by Bangladesh. Coal and limestone mining had been the two major non-renewable natural and economic resources of Meghalaya for generations; other employment activities include stone quarries, pine plantations, agriculture, orchard farming, and tourist recreational spots. Though many areas of NE India are yet to be explored for their natural resources, the minerals and fossil fuels of Meghalaya have been extensively explored. To study the impact of coal mining on water quality in the area, three AMD-impacted streams and one anthropogenically unimpacted stream was selected (Fig. 1). The characteristic features of the sampling streams are described and presented in Table 1.

Water sampling and analysis

Water sampling was carried out at all selected sites in the first week of every month from April 2021 to March 2022, covering the seasons of spring, summer, autumn, and winter. In total, 240 surface water samples (60 samples for each season) were collected in 1L polyethylene bottles, kept in an ice box and brought to the laboratory for further analysis. In situ parameters like pH, dissolved oxygen (DO), electrical conductivity (EC), and turbidity were recorded using the Deluxe water analysis Kit (Model-191E). Standard procedures of Trivedy and Goel (1986) and APHA (2005) were followed to analyze the parameters Calcium (Ca^{2+}), free CO_2, chloride (Cl^-), nitrate (NO^{3-}), phosphate (PO_4^{2-}), sulfate (SO_4^{2-}), and silica (SiO_2). The heavy metals iron (Fe), lead (Pb), zinc (Zn), and manganese (Mn) were determined using a Perkin Elmer Atomic Absorption Spectrophotometer (Perkin Elmer, Analyst 700). Water current (WC) in different streams was measured by a digital flow rate meter (Water Sparks, DFM01).

Statistical analyses

The variations recorded for the water parameters in different sites and seasons were analyzed statistically using one-way analysis of variance (ANOVA) followed by Duncan's multiple range test (DMRT) ($p < 0.05$), employing the software

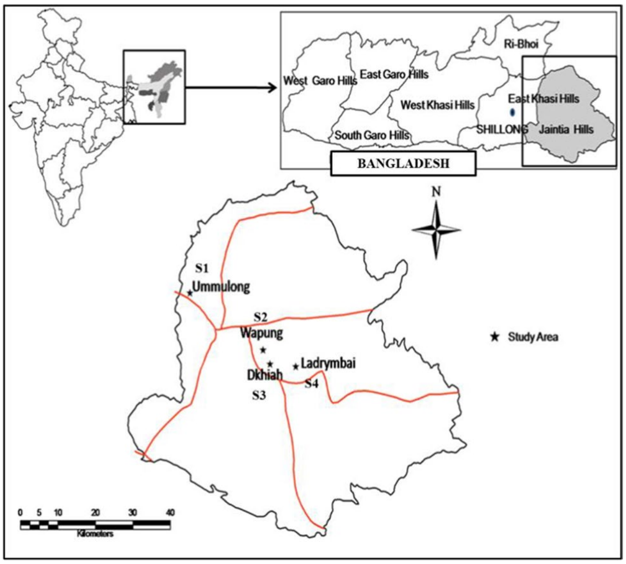

Fig. 1 Study area map with sampling locations at Jaintia Hills

Table 1 Characteristic features of the sampling streams and their coordinates

Sampling point	Stream code	Characteristics of the streams and catchment area	Coordinates
Stream 1	S1	Unimpacted stream: located in Ummulong, not affected by coal mining or any anthropogenic activities; depth: 10–100 cm, width: 2–5 m; disturbance limited only to environmental factors like wind, erosion, atmospheric temperature and weather	25° 31′ 21″ N 92° 08′ 15″ E
Stream 2	S2	AMD-impacted stream: located in Wapung, abandoned coal mine for 7 years; depth: 5–15 cm, width: 2–5 m; human settlement and farming	25° 24′ 30″ N 92° 18′ 56″E
Stream 3	S3	AMD-impacted stream: located in Dkhiah, receives acid mine water through seepage from huge coal storage; depth: 10–20 cm, width: 4–5 m; human settlement, domestic waste disposal area and roads	25° 23′ 16″ N 92° 19′ 28″ E
Stream 4	S4	AMD-impacted stream: located in Ladrymbai, receives waste from active coal mines; depth: 4–12 cm, width: 2–6 m; stone quarries and roads	25° 22′ 27″ N 92° 23′ 56″ E

SPSS version 21. Principal component analysis (PCA) was performed by the statistical package RStudio Version 1.3.1093 to determine the minimum data set (MDS) and evaluate site-specific physicochemical affinity of the streams at varying seasons.

Weighted water quality index (WQI) was estimated following Tyagi et al. (2014) using the given expression:

$$q_i = \left(C_i/S_i\right) \times 100$$

where q_i = quality rating scale; C_i = concentration of i^{th} parameter and S_i = standard value of $i.^{th}$ parameter (Yisa and Jimoh 2010)

The relative weight was enumerated as follows:

$$w_i = 1/S_i$$

Water quality was then evaluated by the following:

$$WQI = \sum q_i w_i / \sum w_i$$

water quality rating and grading based on computed WQI result: < 50 = excellent; 50–100 = good water; 101–200 = poor water; 201–300 = very poor water, > 300 = water unsuitable for drinking.

Comprehensive pollution index (CPI) is used to categorize the status of seasonal water quality (Zhao et al. 2012) and the following equation was formulated as follows:

$$\mathrm{CPI} = \frac{1}{n}\sum_{i=1}^{n} Mi/Si$$

where n is the number of parameters, Si is the standard permissible limit for the i^{th} water quality parameter, and Mi is the monitored value for each water quality parameter.

The proposed guidelines of various governments for a general discharge of an environmental pollutant were taken into consideration to determine the standard permissible limit for each parameter (CPCB 2011; BIS 2012; WHO 2012). Accordingly, CPI graded the water quality as, CPI ≤ 0.20 = clean; 0.21–0.40 = sub-clean; 0.41–1.00 = slightly polluted; 1.01–2.0 = moderately polluted, and ≥ 2.01 = severely polluted.

WQI employs aggregation techniques to convert large amounts of water quality data into a single value or index. The quality model has been used globally to evaluate water quality (surface water and groundwater) using local water quality criteria. It has become a popular tool due to its generalized structure and ease of use, since its development in the 1960s (Etim et al. 2012). Some issues with the WQI model include the fact that it is typically developed based on site-specific guidelines for a specific region, and thus not generic. In contrast, if inappropriate weightings are used, i.e., a parameter is given more importance than it deserves, it can have a negative impact on model evaluation (Md. Uddin et al. 2021).

Results and discussion

Result

Physical and chemical water properties of the streams

The spatiotemporal variation of the stream water variables with DMRT ($p < 0.05$) among the sites are presented in Table 2. pH ranged from 2.89 to 4.05 in coal mine–impacted streams, with both the minimum and maximum value in S2 during spring and summer, whereas in the unimpacted stream, it varies from 6.05 (summer) to 7.51 (autumn). Analysis of variance showed significant variations in pH between sites during spring, summer, and autumn at $p < 0.001$. As recorded in winter, a significant difference was observed between S1 and the entire AMD-impacted stream, but such validation was not assessed between groups of S2, S3, and S4. EC showed higher values in mine-impacted streams and ranged from 190 µS/cm in S4 (summer) to 1092 µS/cm in S3 (spring), while in the unimpacted stream, the value varies from 30 µS/cm (summer) to 203.33 µS/cm (autumn). In S1, DO was high and ranged

Table 2 Seasonal variation of the physical and chemical stream water properties and Duncan's multiple range test ($p < 0.05$) for sampling sites

		Spring			Summer			Autumn			Winter		
Parameter	Sites	Mean ± S.D	*F*	*p*	Mean ± S.D	*F*	*p*	Mean ± S.D	*F*	*p*	Mean ± S.D	*F*	*p*
pH	S1	6.31 ± 0.14^{c}	197.22	.000	6.05 ± 0.03^{a}	695.31	.000	7.51 ± 0.24^{c}	274.92	.000	6.10 ± 0.6^{a}	122.08	9.81
	S2	2.89 ± 0.15^{a}			4.05 ± 0.01^{b}			3.33 ± 0.02^{a}			3.83 ± 0.11^{b}		
	S3	3.67 ± 0.05^{b}			3.32 ± 0.05^{c}			3.75 ± 0.01^{ab}			3.52 ± 0.15^{b}		
	S4	3.36 ± 0.40^{b}			3.47 ± 0.04^{d}			3.61 ± 0.01^{ab}			3.53 ± 0.9^{b}		
EC	S1	73.33 ± 5.7^{a}	19.34	.001	30 ± 5.77^{a}	94.53	.000	203.33 ± 8.81^{a}	245.49	.000	56.67 ± 12.01^{a}	9.813	.005
	S2	620 ± 26.45^{b}			236.67 ± 12.09^{b}			343.31 ± 18.55^{b}			220 ± 15.27^{a}		
	S3	1092.6 ± 81.1^{c}			726.67 ± 18.01^{c}			623.33 ± 8.81^{c}			754 ± 40.98^{b}		
	S4	273.3 ± 14.52^{a}			190 ± 5.77^{b}			756.67 ± 23.33^{d}			730 ± 32.07^{b}		
DO	S1	6.73 ± 0.60^{b}	5.401	.02	8.81 ± 1.02^{b}	4.63	.037	9.73 ± 1.39^{b}	8.23	.008	8.94 ± 1.05^{a}	1.16	.38
	S2	3.29 ± 0.47^{ab}			4.92 ± 1.38^{ab}			4.47 ± 0.26^{a}			4.81 ± 2.69^{a}		
	S3	2.24 ± 0.47^{a}			4.73 ± 0.45^{a}			4.34 ± 0.60^{a}			5.39 ± 1.14^{a}		
	S4	2.49 ± 0.35^{a}			4.60 ± 0.34^{a}			4.68 ± 1.20^{b}			5.70 ± 0.68^{a}		
Free CO_2	S1	14 ± 2.00^{a}	22.39	.000	6.67 ± 1.76^{a}	7.102	.012	12.67 ± 1.76^{a}	168.92	.000	8.33 ± 5.81^{a}	66.3	.000
	S2	51.33 ± 1.76^{b}			22 ± 5.03^{b}			33.33 ± 2.40^{b}			28.81 ± 2.60^{a}		
	S3	73.31 ± 9.33^{c}			27.67 ± 3.84^{b}			110.67 ± 5.81^{c}			52.67 ± 3.7^{b}		
	S4	61.33 ± 4.80^{bc}			20.30 ± 1.19^{b}			39.33 ± 1.15^{b}			117.33 ± 9.3^{c}		
Cl^-	S1	33.09 ± 2.36^{a}	1.56	.27	23.63 ± 6.25^{a}	10.45	.004	37.82 ± 2.36^{a}	51.82	.000	35.45 ± 4.09^{a}	79.69	.000
	S2	37.82 ± 2.36^{a}			56.73 ± 8.76^{b}			56.73 ± 8.18^{a}			78 ± 7.09^{b}		
	S3	44.91 ± 6.25^{a}			$40.18 \pm 4.72a^{b}$			54.37 ± 13.16^{a}			51.75 ± 3.86^{ab}		
	S4	35.45 ± 4.09^{a}			87.39 ± 1.93^{c}			180.36 ± 9.45^{b}			222.43 ± 16.8^{c}		
SO_4^{2-}	S1	4.17 ± 0.01^{a}	749.8	.000	17.33 ± 2.67^{a}	62.07	.000	17.20 ± 2.90^{a}	7.75	.009	24.11 ± 0.37^{a}	306.9	.000
	S2	182 ± 2.00^{c}			72.32 ± 0.15^{b}			33.59 ± 0.09^{ab}			54.08 ± 0.64^{b}		
	S3	180.67 ± 1.15^{c}			93.53 ± 0.31^{c}			72.71 ± 6.14^{c}			89.98 ± 3.19^{c}		
	S4	67.67 ± 6.27^{b}			36 ± 8.32^{d}			49.97 ± 6.76^{bc}			40.84 ± 0.02^{d}		
Ca^{2+}	S1	7.01 ± 0.74^{c}	11.56	.003	5.60 ± 0.28	4.65	.037	4.77 ± 0.28^{a}	1.383	.317	14.59 ± 2.34^{a}	.55	.65
	S2	4.21 ± 0.48^{ab}			3.36 ± 0.84			2.80 ± 0.56^{a}			13.12 ± 3.02^{a}		
	S3	4.76 ± 0.28^{b}			4.76 ± 0.28			5.33 ± 1.56^{a}			13.17 ± 3.75^{a}		
	S4	3.08 ± 0.28^{a}			2.80 ± 0.74			8.97 ± 4.04^{a}			17.86 ± 2.63^{a}		
NO^-_3	S1	0.67 ± 0.007^{c}	473.77	.000	0.25 ± 0.001^{a}	246.28	.000	0.33 ± 0.001^{a}	579.74	.000	0.08 ± 0.001^{a}	608.7	.000
	S2	0.17 ± 0.001^{a}			0.24 ± 0.001^{a}			1.33 ± 0.009^{b}			0.09 ± 0.001^{b}		
	S3	0.18 ± 0.001^{a}			0.36 ± 0.002^{b}			0.68 ± 0.001^{c}			0.19 ± 0.002^{c}		
	S4	0.57 ± 0.023^{b}			0.43 ± 0.002^{c}			0.42 ± 0.001^{d}			0.12 ± 0.001^{d}		
PO_4^{2-}	S1	2.41 ± 0.003^{a}	440.61	.000	0.05 ± 0.009^{b}	27.31	.000	0.12 ± 0.001^{a}	512	.000	0.12 ± 0.001^{a}	.965	.45
	S2	1.89 ± 0.003^{b}			0.01 ± 0.002^{a}			0.14 ± 0.001^{b}			0.44 ± 0.003^{a}		
	S3	0.34 ± 0.002^{c}			0.027 ± 0.001^{ab}			0.13 ± 0.002^{c}			0.15 ± 0.01^{a}		
	S4	1.57 ± 0.005^{d}			0.11 ± 0.001^{c}			0.09 ± 0.001^{d}			0.16 ± 0.001^{a}		

Table 2 (continued)

Parameter	Sites	Spring			Summer			Autumn			Winter		
		Mean ± S.D	*F*	*p*	Mean ± S.D	*F*	*p*	Mean ± S.D	*F*	*p*	Mean ± S.D	*F*	*p*
Turb	S1	1.75 ± 0.36^{a}	20.14	.000	2.02 ± 0.54^{a}	.11	.953	1.13 ± 0.43^{a}	1.042	.425	3.19 ± 0.01^{a}	34.73	.000
	S2	3.69 ± 1.25^{a}			11.86 ± 0.81^{a}			2.35 ± 0.56^{a}			22.01 ± 2.4^{b}		
	S3	10.30 ± 0.98^{b}			8.69 ± 0.62^{a}			2.77 ± 0.88^{a}			22.39 ± 2.66^{b}		
	S4	3.06 ± 0.46^{a}			12.28 ± 0.72^{a}			2.21 ± 0.96^{a}			4.36 ± 0.39^{a}		
SiO_2	S1	3.19 ± 0.005^{a}	7.17	.012	2.64 ± 0.21^{a}	7.59	.010	3.41 ± 0.24^{a}	6.73	.014	1.55 ± 0.02^{a}	27.01	.000
	S2	15.89 ± 3.68^{b}			15.17 ± 6.08^{b}			19.67 ± 0.14^{b}			4.55 ± 0.47^{b}		
	S3	22.29 ± 0.75^{c}			20.47 ± 0.19^{b}			20.03 ± 1.61^{b}			7.66 ± 0.30^{c}		
	S4	24.99 ± 2.31^{c}			20.41 ± 0.14^{b}			14.69 ± 5.74^{b}			3.65 ± 0.79^{b}		
WC	S1	0.23 ± 0.04^{a}	.232	.872	1.51 ± 0.26^{b}	7.32	.011	0.44 ± 0.04^{a}	.354	.788	0.33 ± 0.01^{a}	.612	.626
	S2	0.27 ± 0.04^{a}			1.06 ± 0.14^{ab}			0.51 ± 0.11^{a}			0.41 ± 0.07^{a}		
	S3	0.25 ± 0.02^{a}			0.60 ± 0.03^{a}			0.53 ± 0.05^{a}			0.29 ± 0.04^{a}		
	S4	0.28 ± 0.06^{a}			0.97 ± 0.12^{a}			0.45 ± 0.05^{a}			0.36 ± 0.02^{a}		
Mn	S1	0.09 ± 0.05^{a}	2.23	.162	0.09 ± 0.001^{a}	18.22	.001	0.12 ± 0.08^{a}	4.49	.040	0.15 ± 0.05^{a}	1.78	.23
	S2	0.11 ± 0.01^{a}			0.14 ± 0.005^{a}			0.15 ± 0.03^{a}			0.54 ± 0.08^{a}		
	S3	0.18 ± 0.06^{a}			0.18 ± 0.002^{a}			0.39 ± 0.06^{b}			0.71 ± 0.04^{a}		
	S4	0.27 ± 0.06^{a}			0.39 ± 0.01^{b}			0.16 ± 0.01^{a}			0.24 ± 0.01^{a}		
Pb	S1	0.01 ± 0.003^{a}	4.84	.033	0.014 ± 0.003^{a}	13.94	.002	0.017 ± 0.003^{a}	34.17	.000	0.019 ± 0.001^{a}	50.67	.000
	S2	0.17 ± 0.06^{a}			0.06 ± 0.01^{b}			0.29 ± 0.036^{b}			0.33 ± 0.05^{b}		
	S3	0.80 ± 0.03^{b}			0.08 ± 0.005^{c}			0.39 ± 0.02^{c}			0.31 ± 0.05^{b}		
	S4	0.18 ± 0.01^{b}			0.04 ± 0.006^{b}			0.23 ± 0.03^{b}			0.29 ± 0.01^{b}		
Zn	S1	0.03 ± 0.006^{a}	84.22	.000	0.034 ± 0.006^{a}	244.87	.000	0.031 ± 0.006^{a}	12.96	.002	0.02 ± 0.001^{a}	46.82	.000
	S2	0.94 ± 0.04^{b}			0.76 ± 0.001^{b}			0.55 ± 0.24^{b}			1.18 ± 0.01^{c}		
	S3	0.37 ± 0.05^{c}			0.59 ± 0.03^{c}			0.76 ± 0.11^{b}			1.44 ± 0.14^{c}		
	S4	1.13 ± 0.08^{d}			0.36 ± 0.02^{d}			1.21 ± 0.015^{c}			0.60 ± 0.11^{b}		
Fe	S1	0.27 ± 0.14^{a}	6.66	.014	0.26 ± 0.04^{a}	966.45	.000	0.19 ± 0.08^{a}	550.25	.000	0.21 ± 0.06^{a}	669.7	.000
	S2	10.49 ± 3.5^{ab}			3.70 ± 0.18^{b}			18.35 ± 0.12^{b}			9.74 ± 0.24^{b}		
	S3	19.39 ± 1.08^{b}			9.57 ± 0.08^{c}			18.43 ± 0.05^{b}			8.07 ± 0.03^{c}		
	S4	15.65 ± 5.2^{b}			5.66 ± 0.04^{d}			22.63 ± 0.48^{c}			18.56 ± 0.22^{d}		

All the parameters are expressed in mg/l except for pH, EC (µS/cm), Turb. (NTU), and WC (m^3/s) from 6.73 mg/l in winter to 9.73 mg/l during autumn, which covers the post-monsoon period. DO showed a significant difference between sites in spring and autumn at $F = 5.401$; $p = 0.02$ and $F = 8.23$; $p = 0.008$, respectively. Turbidity, which measures the cloudiness or haziness of a fluid caused by individual particles (suspended solids), was higher in AMD streams (2.21–22.39 NTU) as compared to unimpacted stream (1.13–3.19 NTU). A significant difference at $p < 0.001$ between sites was recorded for spring and winter. The maximum SiO_2 content was obtained during spring in S4 (24.99 mg/l) while the minimum was detected in S1 during winter (1.55 mg/l). Throughout the season, S1 presented a statistical difference at $p < 0.05$ level for S2, S3, and S4. Free CO_2 ranged from 6.6 to 8.33 mg/l in the unimpacted stream and 20.30 to 117.33 mg/l in impacted streams. Maximum free CO_2 was recorded in S4 (active mining–impacted stream) during winter followed by S3 (autumn) located near the coal storage area. A significant statistical difference ($p < 0.05$) in free CO_2 was observed between sites at all seasons. Comparatively, higher Cl^- concentration was detected in the impacted streams with both the minimum (35.45 mg/l) and maximum value (222.43 mg/l) in S4 during spring and winter. A significant temporal and spatial variation of Cl^- at $p < 0.05$ between sites was observed at all seasons except in spring. Highest Ca^{2+} content was obtained during winter in S4 (17.86 mg/l) and lowest during autumn in S2 (2.80 mg/l). Ca^{2+} values was significantly different between sites during spring and summer at $F = 11.56$; $p = 0.003$ and $F = 4.65$; $p = 0.037$, respectively. Maximum and minimum SO_4^{2-} were noted during spring in S2 (182.20 mg/l) and S1 (4.17 mg/l), while a statistically significant difference ($p < 0.05$) was observed in all the sampling sites at varying seasons. NO^{-}_{3} content, in general, was low and showed site variation with a significant value of $p < 0.001$. Highest NO^{-}_{3} content was recorded in S2 during autumn (1.33 mg/l) and the lowest during winter at S1 (0.08 mg/l). In S1, maximum PO_4^{2-} was obtained during spring (2.41 mg/l) and minimum in summer (0.05 mg/l). AMD-affected streams also showed a similar trend where PO_4^{2-} concentration varies from 0.01 to 1.89 mg/l, while a significant difference between sites during spring ($F = 440.61$; $p < 0.001$), summer ($F = 27.31$; $p < 0.001$), and autumn ($F = 512$; $p < 0.001$) was noted. Analogous to the other physicochemical water parameters, spatial variation was also noted in the seasonal concentration of the metals. Fe was significantly different at $p < 0.05$ between sites in all seasons and its value ranges from 0.19 to 22.63 mg/l with the lowest estimated value recorded in S1 and the highest in S4. Pb concentration in the AMD-impacted stream varies from 0.01 to 0.80 mg/l with the minimum in S1 and maximum in S3. Analysis of variance showed a significant difference between sites for spring ($F = 4.84$; $p = 0.033$), summer ($F = 13.94$; $p = 0.002$), autumn ($F = 34.17$; $p < 0.001$), and winter ($F = 50.67$; $p < 0.001$). In general, SI showed low Zn content in all the seasons (0.02 to 0.034 mg/l) while in AMD-affected streams, it varied from 0.37 to 1.44 mg/l. The four sampling sites showed a significant difference throughout the seasons at $F = 84.22$; $p < 0.001$ for spring, $F = 244.87$; $p < 0.001$ for summer, $F = 12.96$; $p = 0.002$ for autumn, and $F = 46.82$; $p < 0.001$ for winter. Similarly, Mn also presented a significant difference at $p < 0.05$ between sites in all the studied seasons, with the maximum amount recorded from S3 during winter (0.17 mg/l) and the minimum from S1 in spring (0.09 mg/l) (Figs. 2, and 3).

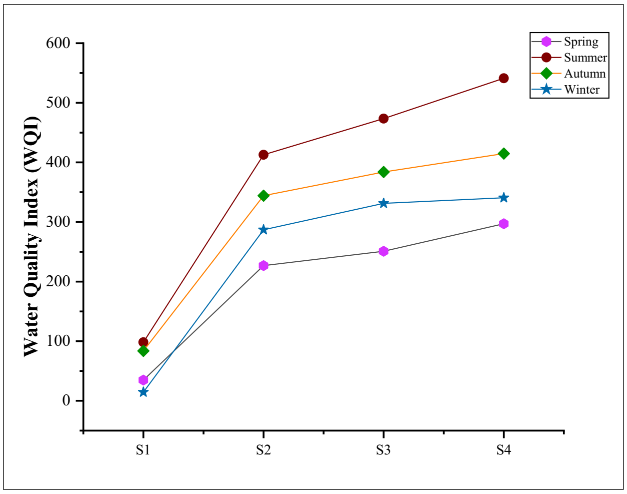

Fig. 2 Seasonal variation in the WQI of the sampling streams at Jaintia Hills

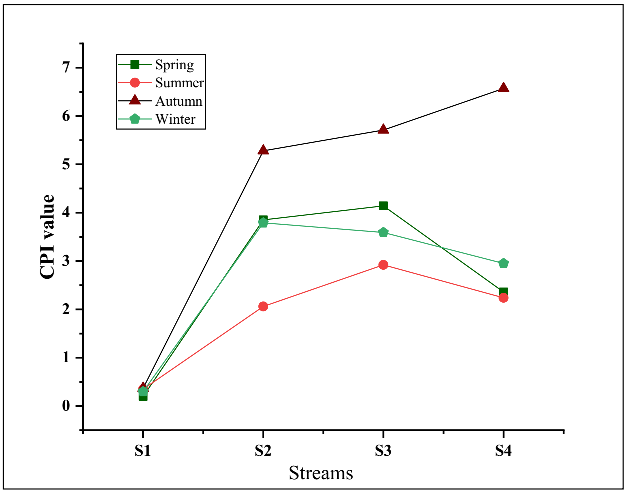

Fig. 3 Comprehensive pollution index (CPI) at varying seasons in the sampling streams

PCA and MDS

PCA was performed with 16 active environmental variables, 240 surface water samples, obtained from four streams in different seasons, in order to assess the relationship between the water quality parameters and the seasons of spring, summer, autumn, and winter. The factor loading, explained variance % and the cumulative variance % of the PCA axes are shown in Table 3. The PCs having an eigenvalue greater than or equal to one were considered for the statistical analysis (Fig. 4). PCA ordination plot of environmental variables, seasons, and sites accounts to a total variability of 81% where maximum variance was explained by PC1 (27%) followed by PC2 (22%), PC3 (19%), and PC4 (13%) of the total inertia. The loaded principal components were used to identify MDS of parameters among the measured variables that could best represent the water attributes when it was run on the normalized data matrix. It is assumed that the variables of greater factor loading and PC with very high eigenvalues (> 1) (Mandal et al. 2008) accounting for at least 5% of the variation in the dataset are those that can accurately represent the system's functionality (Nabiollahi et al. 2017). Variables with absolute values that are within 10% of the highest factor loading for each principal component under consideration are regarded as highly weighted factors and were thus retained for MDS (Semy et al. 2021).

In compliance with the factor loadings and score of the variables, the initial factor represented by PC1 depicted a strong positive score for Fe and Cl^-, a moderate score for EC, free CO_2, and Zn. In PC2, a strong positive record was obtained only for SO_4^{2-}, while free CO_2, Pb, Zn, and Fe manifested very weak factor loadings. The third factor (PC3) provided a seemingly strong positive specificity for Mn, turbidity, and a moderate affinity for Ca^{2+}. Meanwhile, in the last factor (PC4), PO_4^{2-} has a categorically higher positive score than the other variables, with minimums for turbidity and SiO_2. PCA results visualized using a bi-plot representing dominant individual variables, seasons, and sites are depicted in Fig. 5. The bi-plot was used to further explore the extent of environmental variable pollution and for source identification. During winter,

Table 3 Factor loadings of the component matrix representing the 16 environmental variables

	PC1	PC2	PC3	PC4
pH	−0.73	−0.53	−0.21	−0.05
EC	0.68	0.58	0.19	−0.02
DO	−0.31	−0.72	0.00	−0.51
Free CO_2	0.74	0.15	0.41	−0.02
WC	−0.33	−0.24	−0.27	−0.61
Cl^-	0.90	−0.28	−0.10	0.07
SO_4^{2-}	0.20	0.82	0.25	0.24
Ca^{2+}	0.38	−0.65	0.58	−0.08
NO^-_3	−0.14	−0.17	−0.64	0.11
PO_4^{2-}	−0.29	−0.10	−0.17	0.87
Mn	0.01	−0.07	0.91	0.07
Pb	0.31	0.28	−0.05	0.72
Zn	0.74	0.15	0.41	0.29
Fe	0.88	0.33	−0.05	0.12
Turb	0.10	−0.03	0.96	0.02
SiO_2	0.12	−0.11	−0.11	0.00
Eigen value	4.31	3.53	3.10	2.09
Variability %	0.27	0.22	0.19	0.13
Cumulative %	0.27	0.49	0.68	0.81

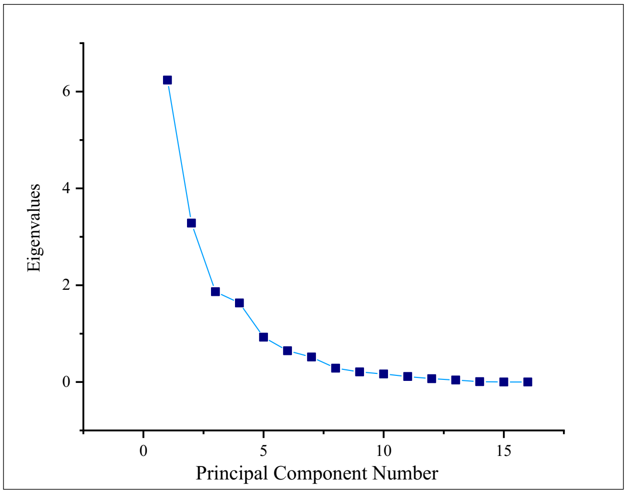

Fig. 4 Scree plot of eigenvalues representing the selected PCs

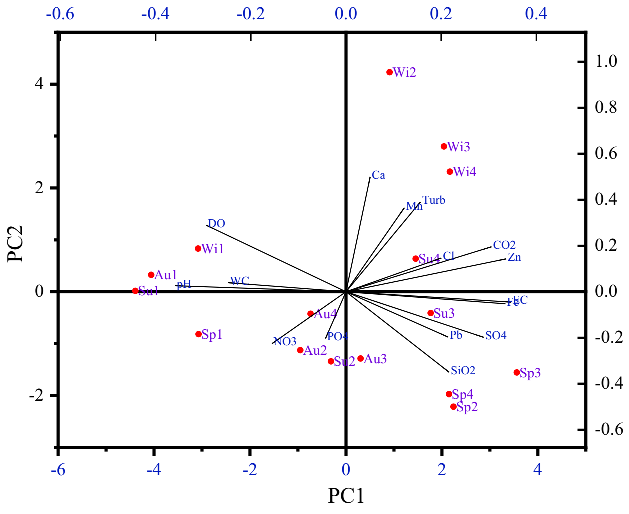

Fig. 5 PCA bi-plot of the water quality parameters in relation to the sampling streams during spring (Sp), summer (Su), autumn (Au), and winter (Wi)

S1 has high affinity with DO, S3 with Ca^{2+} and turbidity, S4 with turbidity and Mn. In spring, S3 formed the main site for $SO_4{}^{2-}$ content, while S2 and S4 with SiO_2. In autumn, observation points out that S1 is inclusive to pH, S3 to $PO_4{}^{2-}$ while S2 and S4 to $NO^-{}_3$.

In PC1, Cl^- an anion salt found in natural water bodies including runoffs from sewage and domestic discharge was recognized for MDS. In PC2, $SO_4{}^{2-}$ one of the primary parameters responsible for the deterioration of water quality in the coal mine–impacted region (James et al. 2000) was selected. From PC3, turbidity, a crucial variable for easily identifying the potability of drinking water was chosen, while in PC4, $PO_4{}^{2-}$ a nutrient water parameter that is mostly derived from inorganic fertilizers used in agricultural and farm waste was selected for MDS.

WQI and CPI

WQI of the streams showed significant site variation, depicting the impacts of different coal mine landuse patterns on the stream water quality status at varying seasons. As presented in Fig. 2, maximum WQI in autumn was acquired at S4 (414.76) with the minimum at S1 (83.80); similarly, the WQI of winter was lowest in S1 (14.65) followed by S2 (287.02), S3 (331.24), and S4 (340.75). Spring recorded the lowest WQI value in S1 (34.87) followed by S2 (226.83), S3 (250.88), and S4 (297.04). Comparatively, higher WQI was detected during summer in all the sampling points with a value of 98.23 (S1), 412.71 (S2), 473.44 (S3), and 541.14 (S4). The examined WQI points out that during spring, S1 exhibited "Good water" quality while the AMD-impacted stream of S2, S3, and S4 showed "Very poor water" status. Summer presented "Good water" in S1 and "Water unsuitable for drinking" in the samples of S2, S3, and S4. Correspondingly, during autumn season, a "Good water" status was observed in the unimpacted stream of S1 but such a result was not validated in S2, S3, and S4 as the WQI was rated 'Very poor." Similarly, in spring, S1 presented "Excellent water" quality while S2, S3, and S4 were categorized as having "Very poor" to "Water unsuitable for drinking" status. As presented in Fig. 3, variation in the CPI water quality value at different streams and seasons were observed. The maximum CPI during spring was detected in S3 (4.14), followed by S2 (3.85), S4 (2.36), and S1 (0.20). In summer, the highest CPI value of 2.92 was procured in S3 and lowest in S1 (0.35). Similarly, during autumn (0.37) and winter (0.30), the minimum CPI was estimated in S1, while the maximum was recorded at S4 (6.57) and S2 (3.79), respectively. Corresponding to the WQI status, the CPI also showed "Clean to sub-clean" water quality status in S1 while the impacted streams recorded "Severe pollution."

Discussion

Physicochemical variables of the stream water

Stream water properties often depict the health of the environment and its disturbance by external pressure can be investigated by analyzing the changing water variables. As evident from the study, a trend of water acidity induced by AMD drainages on impacted streams attributed to pyrite waste and other toxic heavy metals from coal mines is reported in recent years by Semy and Singh (2021) in NE India. Significant temporal and spatial variations of EC at $p < 0.05$ were observed between sites at each season, which could have arisen due to fluctuation of inorganic dissolved solids such as Ca^{2+}, Cl^-, $NO^-{}_3$, $SO_4{}^{2-}$, Fe, and Mg in the stream water at varying seasons of the year. In general, coal mine drainage–affected sites showed minimum DO compared to the affected stream in all sampling seasons, which indicates the degradation of water quality due to high organic waste and microbial activities (Debrah et al. 2010). The runoff of coal waste into the AMD streams, followed by the decomposition of organic matter, could have enhanced the rate of microbial respiration and elevated the free CO_2 in the impacted water bodies. Cl^- is seen as a common and naturally occurring element present in most waterways, but it may also be formed from inorganic fertilizers and sewage discharge from the catchment areas. A high concentration of $SO_4{}^{2-}$ in majority of the AMD stream water samples suggests sulfide oxidation from pyrites (FeS_2) or reactions involving carbonic acid weathering processes could have altered the water chemistry (Neogi et al. 2017). As recorded, the heavy metals were comparatively higher in AMD-affected streams compared to the unimpacted stream, which conforms to the work of Tiwary (2001) in NE India. Seasonally, the amount of heavy metals in the streams was higher during the summer and autumn periods, and this phenomenon may be explained by the increasing volume of the mine water discharge, which thereby concentrated the metals in the AMD streams. Studies have also reported that high levels of metals (especially Fe, Mn, Pb, and Ni) in the mine water during rainy seasons were attributed to leachate water from overburden dump materials and coal mine waste effluents (Mondal et al. 2013; Sun et al. 2014).

Pollution loads and stream water quality

The determined results demonstrated through the PCs indicate inorganic pollution factors, including heavy metal elements, to the variability of the stream water. During summer, the environmental variables showed a higher affinity with the anthropogenically impacted streams. The geology and locations of all the coal mine-impacted streams showed salient contrariety, such as active mining, mine abandoned for 7 years and coal storage area, which influenced the wastewater chemistry and its subsequent impact on the receiving waterways. In addition, the impacted streams indicate that most of the water variables that are considered harmful to water quality, like acidic pH, high SO_4^{2-}, EC, free CO_2, turbidity, Zn, Fe, and Pb, accumulated in greater concentrations compared to the freshwater stream. Some of the parameters, like EC, DO, free CO_2, Mn, Pb, and Fe in streams located in S2, S3, and S4 were beyond the permissible limit of drinking water recommended by BIS/WHO. On the other hand, the unimpacted stream has no exposure to anthropogenic disturbances, and thus the water parameters were all within the standard limit of BIS/WHO throughout the seasons. Site-wise, the active coal mine and coal storage AMD stream was dominated by Cl^-, free CO_2, Pb, SO_4^{2-}, EC, Fe, and Zn compared to other variables due to its heavy coal waste drainage system polluting the streams; moreover, these variables represent contaminants in mining areas (Khan et al. 2013). Interestingly, the abandoned mine AMD stream displayed lower dominance for metal elements, including other parameters like SO_4^{2-} and EC. This could be due to the rejuvenating state of the abandoned stream, as its environment naturally restores the degraded gradient into its original form or develop a new condition over a period of time to replenish the deteriorated hydro-system. Through experimental work and visual observation, the annual water discharge, elemental flux, and total solute transfer from mines at each impacted station have played major roles in affecting its site-specific water chemistry. Acidity in the impacted streams is however due to the high reactivity of pyrite from coal because even a low fraction of sulfide minerals in coal or mine wastes has the potential to generate sulfuric acid and create significant environmental degradation (Neogi et al. 2017). SiO_2 was also higher in the impacted streams and this represents the rates of dissolution of the silicate minerals, which often developed from weathering of coal rocks and incongruently generate a variety of solid or dissolved substances (Sarin et al. 1989). As stated by Banks (2004), the considerable variation in the mine water chemistry can be attributed to factors such as the rate of circulation of water and oxygen, the neutralization potential of host rocks and ambient groundwater, and the mineral content of sulfides. Earlier work in the region conducted by Singh (2005) and Das and Ramanujam (2011) have reported that the rivers, streams, and springs of the coal mine–affected area are mostly characterized by low pH, high conductivity, elevated concentrations of sulfates, Fe, and many toxic heavy metals with very low dissolved oxygen. Similarly, in the study, all these parameters characterized the degradation of water quality and coherently point out the deteriorated state of AMD stream water.

As indicated by WQI and CPI, the stream unaffected by anthropogenic activities (S1) rendered good water quality that could be used for drinking and domestic purpose throughout the four seasons. The stream located in the abandoned coal mine area (S2) exhibits that the hydrochemistry is majorly affected during summer, followed by autumn and decreases with the coming of the dry winter months. Similarly, the stream located in the coal storage area (S3) presented maximum deteriorated water quality during summer with a minimum in winter. However, the stream situated near the active mines (S4) recorded the worst water quality among the streams, with the highest value in summer followed by autumn, winter, and spring. As observed during the seasonal study, periodic rainfall has a major impact on the water quality, as maximum rainfall in the summer and autumn seasons correlates to greater substandard water quality status because of surface runoffs that carry coal waste, forest litter, and debris into the streams. Due to this, the hydrochemistry is altered, which could worsen the water quality and reduces its usability (Paliwal et al. 2007). Coinciding with the current demonstrated results, Singh et al. (2012) and Tiwari et al. (2016) have also reported that mine drainages hamper the quality of the water bodies to the extent where aquatic ecosystem function is impeded by the drastic alteration of water properties.

Conclusion

Assessment of water quality is a timely requirement amid emerging public health problems in the context where the availability of safe potable water is at risk due to various anthropogenic activities. The current study evaluated the overall suitability of drinking water from an unimpacted stream (S1) and AMD-impacted streams (S2, S3, and S4) using combined water quality parameters and demonstrated using the WQI and CPI. Throughout the seasons, the AMD stream water of Jaintia Hill was acidic with an elevated amount of heavy metals, while the concentrations of free CO_2, turbidity, SO_4^{2-}, and EC were also comparatively higher than the anthropogenically unimpacted stream. Water quality in S1 showed “Good” to “Excellent” quality status while the AMD-impacted streams rendered “Very poor quality” which can be detrimental, even fatal, for the local population relying on the stream water. In addition, the active mine stream presented more affinity towards SO_4^{2-}, EC, Zn, free CO_2, and turbidity, demonstrating the deteriorating effects of coal mining on stream water, while unimpacted streams have lower affinity to the physicochemical variables compared to impacted streams. The present work underlines that the AMD streams can have contrasting impacts on the environment depending on site-specific land use patterns. Heavy metals, including chemical variables, can be removed from the contaminated stream water using scientific techniques like chemical precipitation, ion exchange, adsorption, membrane filtration, reverse osmosis, solvent extraction, and electrochemical treatment. However, it is neither economical nor convenient for a significant public water supply. Therefore, developing a robust stream system management, regulating coal mine waste, and allowing the river to regenerate naturally without being interfered by extreme anthropogenic activities would be the most reasonable, cost-effective, and conventional ways to treat AMD-impacted streams. Overall, the study provided crucial information on the nature and source of pollution that will impart quality ideas to the local population and advocate sustainable mining laws for implementing management guidelines to prevent further degradation of AMD-impacted streams and the environment of Jaintia Hills.

Author contribution Khikeya Semy: field work, experiments and construction of manuscript; Mautushi Das: supervision of the work, reviewing, and editing of manuscript.

Data availability Data made available on reasonable request.

Declarations

Ethics approval Not applicable.

Consent to participate All the authors agreed to partake on the research conducted.

Consent for publication The authors agree to publish the paper based on the research conducted.

Competing interests The authors declare no competing interests.

References

APHA (2005) American Public Health Association, Standard Methods for the Examination of Water and Wastewater, Method 1020

Banks D (2004) Geochemical processes controlling mine water pollution. In: Groundwater management in mining areas, proceedings of the 2nd Image-Train Advanced Study course, pp. 17–44

Bureau of Indian Standards, BIS 10500 (2012) Manak Bhavan. New Delhi, India

Central Pollution Control Board (CPCB) (2011) Report on status of quality in India. Central Pollution Control Board, Monitoring of Indian National Aquatic, Resources

Chaulya SK, Kumar A, Mandal A, Tripathi N, Singh RS, Mishra PK, Bandyopadhyay LK (2011) Assessment of coal mine road dust properties for controlling air pollution. Int J Environ pro 1(2):1–7

Das M, Ramanujam P (2011) Metal content in water and in green filamentous algae Microspora quadrata Hazen. From coal mine impacted streams of Jaintia Hills district, Meghalaya. India. Int J Bot 7(2):170–176

Das M, Semy K, Kuotsu K (2022) Seasonal monitoring of algal diversity and spatiotemporal variation in water properties of Simsang river at South Garo Hills, Meghalaya. India Sustain Water Res Manage 8:16

Debrah CA, Obiri-Danso K, Ephriam JH (2010) Effect of acid mine drainage on creeks or streams in a mining community in Ghana and treatment options. Int J Environ Sci Develop 1(5):399–403

Equeenuddin SM, Tripathy S, Sahoo PK, Panigrahi MK (2010) Hydrogeochemical characteristics of acid mine drainage and water pollution at Makum Coalfield, India. J Geochem Explor 105:75–80

Etim EE, Akpan IU, Andrew C, Edet EJ (2012) Determination of water quality index of pipe borne water in Akwa Ibom State. Nigeria Int J Chemical Sci 5(2):179–182

Fukushima K, Nakajima R, Sato A, Sakurai T (2000) Relationships between stream water chemistry and catchment geology in a mountainous region in Nagano Perfecture, Japan II: mid to southern part along the Median Tectonic Line. Limno 1:117–127

Gurrieri JT (1998) Distribution of metals in water and sediment and effects on aquatic biota in the upper Stillwater River basin, Montana. J Geochem Explor 64:83–100

James I, Sams III, Beer KM (2000) Effects of coal-mine drainage on stream water quality in the Allegheny and Monongahela River basins—sulfate transport and trends. National water-quality assessment program, Lemoyne, Pennsylvania. Water-resources investigations report 99–4208.

Khan I, Javed A, Khurshid S (2013) Physico-chemical analysis of surface and groundwater around Singrauli coal field, district Singrauli, Madhya Pradesh. India Environ Earth Sci 68(7):1849–1861

Kumar A, Singh PK (2016) Qualitative assessment of mine water of the western Jharia coalfield area, Jharkhand, India. Curr World Environ 11(1) https://doi.org/10.12944/CWE.11.1.37

Mandal UK, Warrington DN, Bhardwaj AK, Bar-Ta A, Kautsky L, Minz D (2008) Evaluating impact of irrigation water quality on a calcareous clay soil using principal component analysis. Geoderma 144:189–197

Md. Uddin G, Nash S, Olbert AI (2021). A review of water quality index models and their use for assessing surface water quality. Eco Indica 122

Mondal GC, Singh AK, Singh TB, Tewary BK, Sinha A (2013) A hydrogeochemistry and quality assessment of mine water of West Bokaro Coalfields, Hazaribag. Jharkhand India J Mater Sci Eng 3(8):540–549

Nabiollahi K, Taghizadeh-Mehrjardi R, Kerry R, Moradian S (2017) Assessment of soil quality indices for salt-affected agricultural land in Kurdistan Province. Iran Eco Indi 83:482–494

Neogi B, Singh AK, Pathak DD, Chaturvedi A (2017) Hydrogeochemistry of coal mine water of North Karanpura coalfields, India: implication for solute acquisition processes, dissolved fluxes and water quality assessment. Environ Earth Sci 76:489

Nigam GK, Sahu RK, Sinha J, Sonwanshi RN (2015) A study on physico-chemical characteristics of open cast mine water. J Indust Poll Cont 31(2):191–200

Oliveira SJM, Farinha S, Matos XJ, Avila P, Rosa C, Machado CJM, Daniel FS, Martin L, Leite MRM (2002) Diagnóstico Ambiental das principais áreas mineiras degradadas do país. Boletimde Minas Lisboa 39(2):67–85

Paliwal R, Sharma P, Kansa A (2007) Water quality modelling of the river Yamuna (India) using QUAL2E-UNCAS. J Environ Manage 83(2):131–144

Sahoo BP, Sahu HB (2020) Assessment and characterization of mine waste and fly ash material for effective utilization in opencast coal mines. Int J Recent Technol Eng 9(1):2490–2500

Sarin MM, Krishnaswamy S, Dilli K, Somayajulu BLK, Moore WS (1989) Major ion chemistry of the Ganga-Brahmaputra river system: weathering processes and fluxes to the Bay of Bengal. Geochim Cosmochim Acta 53:997–1009

Semy K, Singh MR (2021) Quality assessment of Tsurang River water affected by coal mining along the Tsurangkong Range, Nagaland. India Appl Water Sci 11:115

Semy K, Singh MR, Vats N (2021) Evaluation of soil quality of a coal mine affected forest at Changki, Nagaland, India. J Environ Eng Landscape Manage 29:381–390

Singh AK, Mahato MK, Neogi B, Tewary BK, Sinha A (2012) Environmental geochemistry and quality assessment of mine water of Jharia coalfield. Environ Earth Sci 65(1):49–65

Singh OP (2005) Mining environment. Prblems and Remedies. (Eds.), Regency Publications, New Delhi.

Sun L, Gui H, Peng W (2014) Heavy metals in groundwater from the Wolonghu coal mine, northern Anhui Province, China and their hydrological implications. Water Practice Technol 9(1):79–87

Tiwari AK, Singh PK, Mahato MK (2016) Environmental geochemistry and a quality assessment of mine water of the west Bokaro coalfield, India. Mine Water Environ 35:525–535. https://doi.org/10.1007/s10230-015-0382-0

Tiwary RK (2001) Environmental impact of coal mining on water regime and its management. Water Air Soil Poll 132:185–199

Trivedy RK, Goel PK (1986) Chemical and biological method for water pollution studies. Environ Pub 6:10–12

Tyagi S, Singh P, Sharma B, Singh R (2014) Assessment of water quality for drinking purpose in district Pauri of Uttarkhand India. Appl Ecol Environ Sci 2(4):94–99

WHO (2012) World health statistics. WHO Library Cataloguing-in-Publication Data (NLM classification: WA 900.1.

Wilson B, Lang B, Pyatt FB (2005) The dispersion of heavy metals in the vicinity of Britannia mine, British Columbia, Canada. Ecotoxico Environ Saf 60:269–276

Yisa J, Jimoh T (2010) Analytical studies on water quality index of river Landzu. Am J Appl Sci 7(4):453–458

Zhao Y, Xia XH, Yang ZF, Wang F (2012) Assessment of water quality in Baiyangdian Lake using multivariate statistical techniques. Procedia Environ Sci 13:1213–1226