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Physicochemical Baseline and Thermal Pollution of Canal Water Adjacent to the Barapukuria Coal Mine, Dinajpur, Bangladesh

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ABSTRACT

Background: Untreated effluent from the Barapukuria coal mine, the only operating underground coal mine in Bangladesh, enters adjacent canals used by local communities, yet no station-resolved baseline exists for the receiving canal.

Objective: This study established a pre-monsoon (March 2023) physicochemical baseline of the canal in Dinajpur, northern Bangladesh, to evaluate compliance with the Bangladesh Environment Conservation Rules (ECR) 1997 and World Health Organization (WHO) guidelines.

Methods: Five stations (W1 upstream to W5 downstream) were sampled at 200 m intervals and measured in triplicate for temperature, colour, odour, pH, dissolved oxygen (DO), electrical conductivity (EC) and total dissolved solids (TDS); data were analysed using one-way ANOVA, Tukey HSD, Pearson correlation, principal component analysis (PCA) and a weighted-arithmetic Water Quality Index (WQI).

Results: pH (7.08 ± 0.34), DO (5.16 ± 1.55 mg L⁻¹) and TDS (430 ± 125 mg L⁻¹) remained within limits, whereas temperature peaked at 31.7 °C, exceeding the 28 °C ECR aquatic-life limit, and EC fell to 176 µS cm⁻¹, indicating mineral-poor water. All parameters differed among stations ($p < 0.001$; $\eta^2 = 0.94\text{--}0.99$); PCA explained 92.1% of variance and isolated the discharge point; WQI (66.1–81.5, “Good”) deteriorated downstream.

Conclusion: The canal is chemically compliant but thermally stressed and mineral-poor, warranting industrial cooling, sedimentation control and multi-season monitoring to protect downstream aquaculture and agriculture.

Introduction

Globally, the quality and availability of surface and groundwater are increasingly threatened by mining, which mobilises acidity, salinity and trace elements into aquatic systems through excavation, dewatering and the weathering of exposed waste rock.^{1,2} Coal mining is particularly water-intensive, and where treatment infrastructure is absent the receiving waters carry the full burden of effluent discharge, degrading drinking, fisheries and irrigation supplies on which rural communities depend.^{2,3} Establishing reliable physicochemical baselines is therefore the first step toward evidence-based water governance in mining landscapes.

The contaminant pathways from coal operations are well characterised. Sulphide oxidation can generate low-pH water enriched in sulphate, iron, manganese and toxic metals, while solid and liquid wastes, thermal loading from mine-water pumping and suspended coal particulates alter the physical and chemical character of receiving channels.^{4,5} Because discharge enters at discrete outfalls, impacts typically follow a longitudinal gradient, with maximum degradation near the discharge point and partial recovery downstream as dilution proceeds.^{5,6} Spatial and temporal profiling is therefore essential to delineate the extent of a contaminant plume.

Contemporary mine-water assessment couples field and laboratory measurement of physicochemical parameters with index and multivariate analysis. The weighted-arithmetic Water Quality Index condenses

several parameters into a single interpretable score for management,^{7,8} while principal component analysis and correlation matrices help separate natural mineralisation from anthropogenic loading.^{8,9} Measured concentrations are then benchmarked against national and international standards to judge fitness for use.^{9,10}

In Bangladesh, surface-water quality is regulated under the Environment Conservation Rules (ECR) 1997, which set use-specific thresholds: a pH range of 6.5–8.5, dissolved oxygen of 4.5–8.0 mg L⁻¹, electrical-conductivity limits of 700 $\mu\text{S cm}^{-1}$ for drinking and 800–1000 $\mu\text{S cm}^{-1}$ for fisheries, and a temperature limit of 28 °C for sustaining aquatic life.¹¹ These are complemented by the WHO drinking-water guidelines, which recommend pH 6.5–8.5, a guideline temperature near 25 °C and a desirable total dissolved solids concentration below 1000 mg L⁻¹.¹² For the regional readership, the Indonesian Government Regulation PP No. 22/2021 applies broadly comparable Class-II surface-water criteria (pH 6–9, DO $\geq$ 4 mg L⁻¹, TDS $\leq$ 1000 mg L⁻¹).

The Barapukuria coalfield in Dinajpur district, northern Bangladesh, is the country's principal coal-production base, covering roughly 6.68 km² and mined by the multi-slice longwall method. The mine lacks a structured wastewater-utilisation protocol, so effluent enters local canals essentially untreated, and prior work has documented elevated trace metals and physicochemical degradation in the area's mine water, groundwater and soils.^{13–15} An earlier baseline survey reported a marked thermal gradient and mineral variability across local water sources.¹⁶ Despite this attention, a specific gap remains: no study has provided a station-resolved, longitudinally profiled physicochemical baseline of the canal that directly receives the mine discharge, nor applied inferential statistics and a Water Quality Index to that canal.

Accordingly, this study makes three contributions. First, it provides the first station-resolved, longitudinally profiled physicochemical baseline of the canal receiving Barapukuria discharge, with a designated upstream control (W1), discharge point (W3) and downstream-recovery zone (W5). Second, it upgrades the descriptive tradition of regional mine-water studies into an inferential and multivariate assessment combining ANOVA, correlation, PCA and an uncertainty-quantified WQI. Third, it reframes the problem at Barapukuria: because the coal is low-sulphur ($\approx$ 0.5%) high-volatile bituminous, the canal lacks the acidic, metal-rich signature of classic acid mine drainage, and the dominant stressors are instead thermal loading and physical degradation. We hypothesised that, while chemical indicators (pH, EC, TDS, DO) would largely remain within national standards, the physical character of the canal water — temperature, colour and odour — would be significantly degraded by continuous mine discharge, evaluating compliance against ECR 1997 and WHO guidelines.^{11,12}

Materials and Methods

Study Design and Setting

This study used an environmental-monitoring design integrating primary field and laboratory data with secondary documentary context. The research focused on the canal adjacent to the Barapukuria Coal Mine in the Parbatipur/Phulbari area of Dinajpur district, northern Bangladesh, located between latitudes 25°31'N and 25°35'N and longitudes 88°57'E and 88°59'E, as shown in Figure 1. Coordinates were verified against Survey of Bangladesh Topographic Sheet No. 78c/14. The coalfield spans approximately 6.68 km² and lies within flat agricultural floodplains about 45 km east of Dinajpur City.^{15,16}

Materials, Samples, and Data Sources

Water samples were collected from the canal into which wastewater is discharged directly from the Barapukuria mine drainage system. To resolve the longitudinal impact of the point-source discharge, samples were taken at 200 m intervals along the canal to construct a longitudinal profile.^{5,6} A total of five stations (W1–W5) were sampled in March 2023, representing the pre-monsoon season; their exact coordinates, sampling times and codes are listed in Table 1, and their spatial arrangement is shown in Figure 1. Station W1, at the head of the canal, served as the upstream control capturing regional water characteristics before mining influence; W3 was located at the direct discharge point representing the zone of maximum impact; and W5 represented the downstream-recovery zone. During sampling the mine was actively discharging effluent, so the data represent water quality under direct industrial influence. Each sample container was labelled with collection date and location. Water temperature was recorded on-site, and colour and odour were observed directly to capture these transient physical characteristics. pH and dissolved oxygen (DO) were measured immediately in the field using calibrated portable instruments. For the remaining analyses, specimens were stored in an insulated cooler with ice packs and transported to the laboratory of the Department of Geography and Environment, Jagannath University, for determination of electrical conductivity (EC) and total dissolved solids (TDS). Bottles were rinsed three times with target water before collection to ensure chemical equilibrium and prevent cross-contamination. DO was determined by the electrometric (membrane-electrode) method using a digital DO meter (Model D, 46974, Taiwan); pH by the electrometric method using a digital pH meter (Model pH Scan 1/2, Malaysia) calibrated with pH 4.0, 7.0 and 10.0 buffers; and EC and TDS by the conductometric method using a digital EC/TDS meter (Model HM, Germany) calibrated with standard reference solutions, with TDS obtained from EC using a site-specific conversion factor and cross-checked gravimetrically. All determinations followed recognised standard methods for the examination of water.⁹

Experimental Variables and Analytical Procedures

Strict QA/QC procedures were followed. All portable instruments were calibrated daily before use against certified standards. At each station, measurements were

performed in triplicate and the mean recorded to minimise random error; the triplicate structure also provided the replication required for inferential testing. Analytical precision, expressed as the mean relative standard deviation of triplicate readings, was below 4% for every parameter, confirming high measurement repeatability. Reagent blanks and re-calibration checks were interspersed through the sampling sequence to confirm instrument stability. Measured values were benchmarked primarily against the Bangladesh Environment Conservation Rules (ECR) 1997 and the WHO drinking-water guidelines,^{11,12} with the Indonesian Government Regulation PP No. 22/2021 Class-II criteria included as a regional cross-reference. Use-specific thresholds for drinking, fisheries and irrigation were applied where defined.^{11,17}

Data Analysis

Data were organised in Microsoft Excel and analysed in Python 3.11 (SciPy and scikit-learn libraries). Descriptive statistics (mean, standard deviation, range and coefficient of variation) were computed per parameter. Normality and homogeneity of variance were screened with the Shapiro–Wilk and Levene tests prior

to parametric testing. One-way analysis of variance (ANOVA) compared stations for each parameter using the triplicate analytical replicates as the error term, with the eta-squared (η^2) effect size and Tukey HSD post-hoc tests (compact-letter display); the analysis therefore tests analytical, not temporal, separability. Pearson correlation quantified inter-parameter relationships using the five station means, and an exploratory multiple regression examined DO as a function of temperature and EC. Principal component analysis (PCA) on standardised parameters summarised the multivariate structure.^{7,8} A weighted-arithmetic WQI was computed per station using unit weights $w_i = K/S_i$ with $K = 1/\sum(1/S_i)$, quality ratings $q_i = 100(V_i - V_0)/(S_i - V_0)$, and $WQI = \sum w_i q_i$, where S_i are the standard values (DO 6.0 mg L⁻¹, pH 8.5, EC 1000 μ S cm⁻¹, TDS 1000 mg L⁻¹, temperature 25 °C) and V_0 the ideal values (DO 14.6 mg L⁻¹, pH 7.0, others 0);^{7,10} analytical uncertainty was propagated through the index by Monte Carlo simulation (20,000 draws per station). Significance was set at $\alpha = 0.05$ and exact p-values are reported to three decimal places. Spatial mapping used ArcGIS and Google Earth Pro.

Table 1. Locations, timing, and code of collected water samples

Sample no.	Latitude	Longitude	Collection time	Sample code
Sample-1	25° 32' 30.912" N	88° 57' 21.852" E	12:43 pm	W1
Sample-2	25° 32' 30.804" N	88° 57' 22.752" E	12:58 pm	W2
Sample-3	25° 32' 29.22" N	88° 57' 25.74" E	1:18 pm	W3
Sample-4	25° 32' 34.728" N	88° 57' 27.288" E	1:37 pm	W4
Sample-5	25° 32' 33.288" N	88° 57' 24.732" E	1:56 pm	W5



Figure 1. Study area and water-sample collection locations (W1–W5) on an OpenStreetMap base; inset shows the location within Bangladesh. Map data © OpenStreetMap contributors.

Results

Sampling Overview and Physical Character

Five stations were profiled along the canal under active mine discharge (Table 1). Physical observations, summarised in Table 2, showed a clear longitudinal degradation: the upstream stations W1 and W2 displayed olive-green and light-green tints and were rich

in water hyacinth, whereas W3, W4 and W5 — adjacent to the drain — appeared blackish. Most samples were odourless, but W4 and W5 exhibited slight odour associated with a decomposing animal carcass near W4 and stagnant organic matter near W5 (Table 2). The blackening from the discharge point downstream indicates water unsuitable for domestic, agricultural and aquaculture use.

Table 2. Colour and odour of collected water samples

Sample code	Colour	Odour
W1	Olive green	Odourless
W2	Light green	Odourless
W3	Blackish	Odourless
W4	Blackish	Slight
W5	Blackish	Slight

Temperature

Water temperature ranged from 26.2 °C at the upstream control W1 to 31.7 °C at the mixing zone W4, with a mean of 28.8 ± 2.1 °C, as detailed in Table 3 and illustrated in Figure 2. All stations exceeded the WHO guideline value of 25 °C. Against the ECR 1997 aquatic-life limit of 28 °C, W1, W2 and W5 were within or near the threshold, whereas W3 (29.8 °C) and especially W4 (31.7 °C) exceeded it. Temperature differed significantly among

stations ($F(4,10) = 102.050$, $p < 0.001$, $\eta^2 = 0.976$; Table 4), and the Tukey grouping in Figure 2 confirmed W4 as the hottest, statistically distinct station. The elevation of about 9.7 °C between regional cool groundwater (~22 °C) reported for the same coalfield¹⁶ and the W4 peak identifies industrial effluent, rather than ambient solar heating alone, as the primary driver of the thermal exceedance, which peaks at the high-intensity mixing zone before partial downstream dilution.

Table 3. Physicochemical parameter values by station and comparison with ECR 1997 and WHO standards

Parameter (unit)	W1	W2	W3	W4	W5	Mean ± SD	ECR 1997	WHO	Status
Temperature (°C)	26.2	27.5	29.8	31.7	28.8	28.8 ± 2.1	28	25	Exceeds
DO (mg L ⁻¹)	6.9	6.5	3.1	4.8	4.5	5.16 ± 1.55	4.5–8.0	4–6	W3 below
EC (µS cm ⁻¹)	250.0	231.7	354.9	270.0	176.0	256.5 ± 65.2	700	1000	Within
pH	7.3	7.2	6.5	7.1	7.3	7.08 ± 0.34	6.5–8.5	6.5–8.5	Within
TDS (mg L ⁻¹)	600	450	250	400	450	430 ± 125	2100	1000	Within

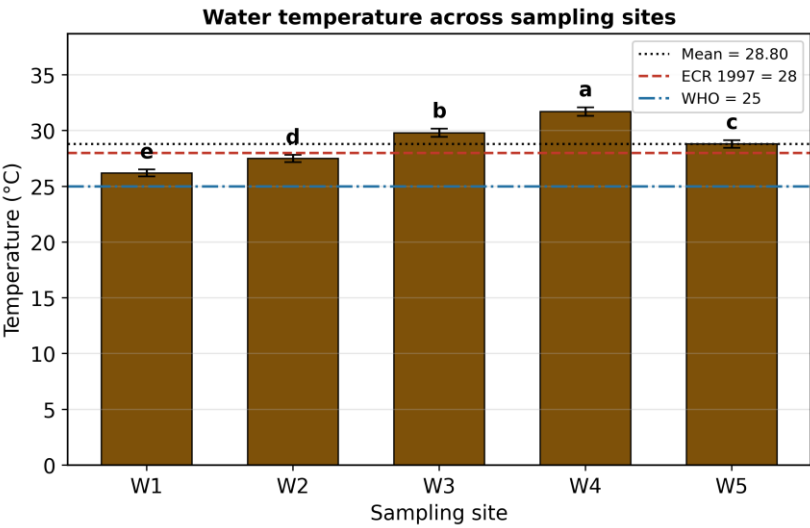


Figure 2. Water temperature by station with mean and ECR/WHO thresholds (Tukey letters). Bars sharing the same lowercase letter (a–e) do not differ significantly among stations (Tukey HSD, $p > 0.05$); different letters denote significant differences.

Dissolved Oxygen

Dissolved oxygen ranged from 3.1 mg L⁻¹ at the discharge point W3 to 6.9 mg L⁻¹ at the upstream control W1, averaging 5.16 ± 1.55 mg L⁻¹ (Table 3; Figure 3). Most stations met the ECR 1997 range (4.5–8.0 mg L⁻¹) and the WHO range (4–6 mg L⁻¹), but W3 fell to 3.1 mg L⁻¹, below the ECR floor and the 5.0 mg L⁻¹ threshold at

which aquatic ecosystems begin to experience stress. DO differed significantly among stations ($F(4,10) = 443.987$, $p < 0.001$, $\eta^2 = 0.994$; Table 4). The depression at the discharge point is consistent with the high oxygen demand exerted by organic and inorganic matter in mine effluent and with the inverse temperature–oxygen relationship,^{19,20} and DO recovered partially downstream at W4 and W5 (Figure 3).

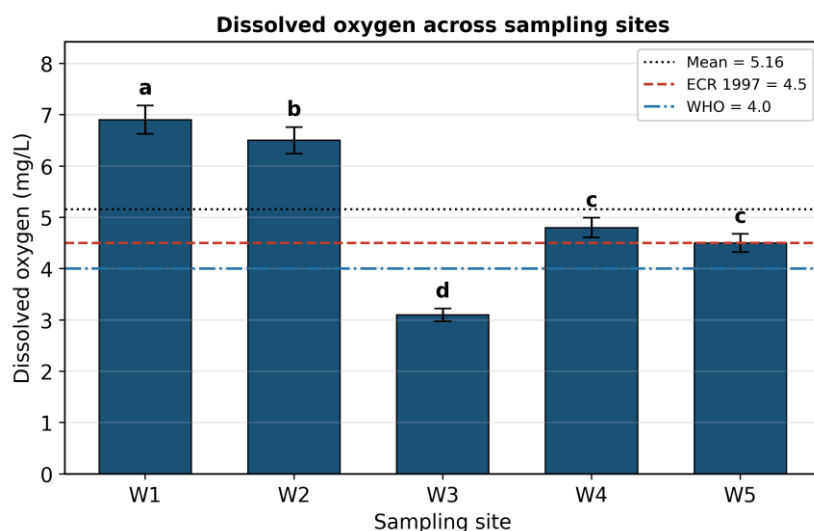


Figure 3. Dissolved oxygen by station with ECR and WHO thresholds (Tukey letters). Bars sharing the same lowercase letter (a–e) do not differ significantly among stations (Tukey HSD, $p > 0.05$); different letters denote significant differences.

Electrical Conductivity

Electrical conductivity averaged 256.5 ± 65.2 $\mu\text{S cm}^{-1}$, ranging from 176 $\mu\text{S cm}^{-1}$ at W5 to 354.9 $\mu\text{S cm}^{-1}$ at the discharge point W3 (Table 3; Figure 4). All values lay far below the ECR drinking limit of 700 $\mu\text{S cm}^{-1}$ and the WHO value of 1000 $\mu\text{S cm}^{-1}$. Conductivity differed significantly among stations ($F(4,10) = 274.429$, $p <$

0.001, $\eta^2 = 0.991$; Table 4). The low values, particularly the 176 $\mu\text{S cm}^{-1}$ at W5, indicate mineral-poor water; in an agricultural context this nutrient deficiency may limit optimal plant growth even though the water is chemically safe.¹⁷ The elevated EC at W3, visible in Figure 4, reflects ionic enrichment at the immediate point of effluent entry.

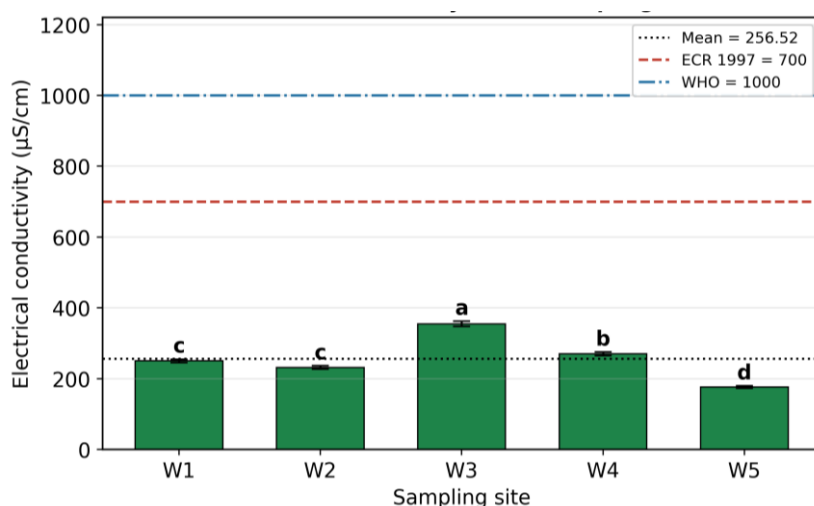


Figure 4. Electrical conductivity by station (Tukey letters). Bars sharing the same lowercase letter (a–e) do not differ significantly among stations (Tukey HSD, $p > 0.05$); different letters denote significant differences.

pH

The pH of all samples ranged from 6.5 at the discharge point W3 to 7.3 at W1 and W5, averaging 7.08 ± 0.34 , indicating near-neutral to marginally alkaline water (Table 3; Figure 5). Every station fell within the ECR 1997 and WHO range of 6.5–8.5. Although pH differed statistically among stations ($F(4,10) = 39.831$, $p < 0.001$,

$\eta^2 = 0.941$; Table 4), the absolute variation was small, and as the Tukey letters in Figure 5 show, W3 alone formed a distinct lower group, reflecting a mild acidifying influence at the discharge point. The near-neutral character is consistent with the low-sulphur (0.5%) bituminous coal at Barapukuria, which limits classic acid-mine-drainage acidification.^{13,15}

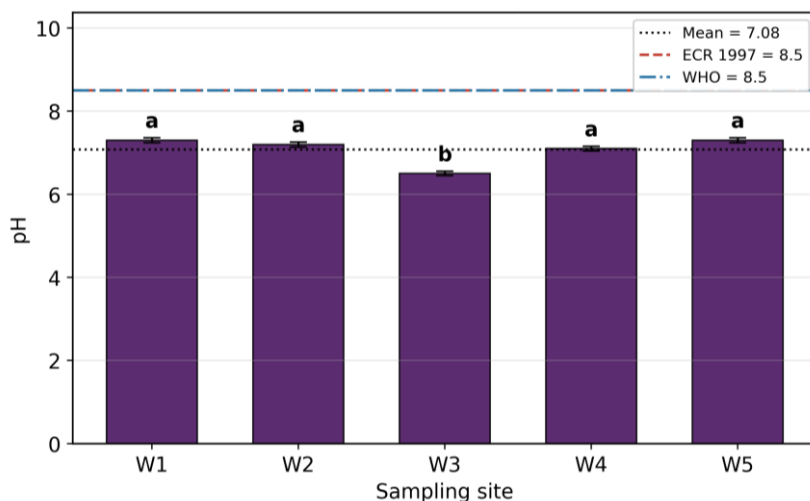


Figure 5. pH by station (Tukey letters). Bars sharing the same lowercase letter (a–e) do not differ significantly among stations (Tukey HSD, $p > 0.05$); different letters denote significant differences.

Total Dissolved Solids

Total dissolved solids ranged from 250 mg L⁻¹ at W3 to 600 mg L⁻¹ at W1, averaging 430 ± 125 mg L⁻¹ (Table 3; Figure 6). All values were far below the ECR 1997 surface-water maximum of 2100 mg L⁻¹ and the WHO value of 1000 mg L⁻¹. TDS differed significantly among

stations ($F(4,10) = 453.348$, $p < 0.001$, $\eta^2 = 0.995$; Table 4). Water containing less than 500 mg L⁻¹ dissolved solids is generally considered suitable for household and industrial use; the moderate TDS levels shown in Figure 6 render the canal acceptable for fisheries and, at several stations, for irrigation.^{17,18}

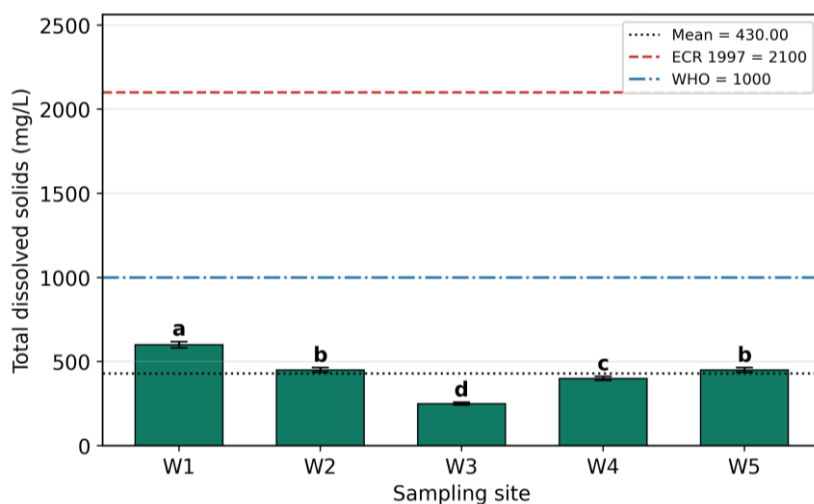


Figure 6. Total dissolved solids by station (Tukey letters). Bars sharing the same lowercase letter (a–e) do not differ significantly among stations (Tukey HSD, $p > 0.05$); different letters denote significant differences.

Multivariate Structure and Water Quality Index

Pearson correlation, displayed in Figure 7, revealed a coherent quality gradient: DO correlated positively with TDS ($r = 0.887$, $p = 0.045$) and pH with TDS ($r = 0.881$, $p = 0.048$), while EC correlated negatively with pH ($r = -0.904$, $p = 0.035$). Temperature correlated negatively with DO ($r = -0.714$, $p = 0.175$), the expected thermal

oxygen-depression signal.¹⁹ An exploratory multiple regression of DO on temperature and EC was non-significant ($R^2 = 0.581$, $F(2,2) = 1.385$, $p = 0.419$) and is reported as indicative only, given the limited degrees of freedom at five stations. Principal component analysis (Figure 8) extracted two components explaining 92.1% of variance (eigenvalues 4.68 and 1.07). PC1 (74.9%) contrasted high DO, pH and TDS against high

temperature and EC, separating the upstream control stations (W1, W2; positive scores) from the discharge point (W3; strongly negative score), while PC2 (17.2%) represented a thermal/ionic axis aligning W4 and W5; the site scores are listed in Table 5. The weighted-arithmetic Water Quality Index (Table 5; Figure 9) placed all stations in the “Good” band but deteriorated monotonically downstream, from 66.1 at W1 to 81.5 at W5 (mean 72.3). Propagating triplicate uncertainty

through the index gave tight estimates (W1 66.1 ± 2.2 to W5 81.5 ± 1.8 ; Table 6), so the ~15-unit downstream increase greatly exceeds the ~2-unit measurement uncertainty and represents a real signal. The sub-indices in Table 6 show that the index is governed mainly by dissolved oxygen and, at the discharge point, by the pH sub-index, tying the trend directly to the oxygen depression that defines the discharge zone.

Table 4. One-way ANOVA and Tukey HSD results by parameter

Parameter	F (4,10)	p	η^2	Tukey grouping (high→low)
Temperature	102.050	<0.001	0.976	W4 > W3 > W5 > W2 > W1
DO	443.987	<0.001	0.994	W1 > W2 > W4 = W5 > W3
EC	274.429	<0.001	0.991	W3 > W4 > W1 = W2 > W5
pH	39.831	<0.001	0.941	W1 = W2 = W4 = W5 > W3
TDS	453.348	<0.001	0.995	W1 > W2 = W5 > W4 > W3

Table 5. Water Quality Index and PCA site scores

Site	WQI	Category	PC1 score	PC2 score
W1	66.1	Good	+2.25	-1.05
W2	66.6	Good	+1.16	-0.34
W3	71.1	Good	-3.30	-0.80
W4	76.4	Good	-0.89	+0.97
W5	81.5	Good	+0.78	+1.23

Table 6. WQI parameter sub-indices and uncertainty-propagated index per station

Site	DO sub	pH sub	EC sub	TDS sub	Temp sub	WQI (mean $\pm$ SD)
W1	45.73	7.21	0.08	0.18	12.85	66.1 ± 2.2
W2	48.11	4.81	0.07	0.14	13.48	66.6 ± 2.1
W3	68.30	-12.02	0.11	0.08	14.61	71.1 ± 1.5
W4	58.20	2.40	0.08	0.12	15.54	76.4 ± 1.8
W5	59.98	7.21	0.05	0.14	14.12	81.5 ± 1.8

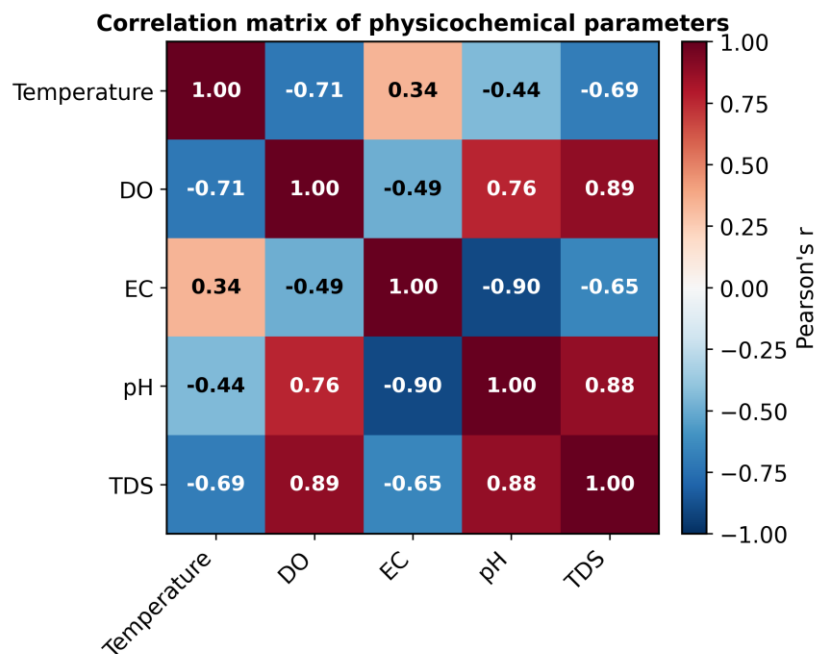


Figure 7. Pearson correlation matrix of physicochemical parameters.

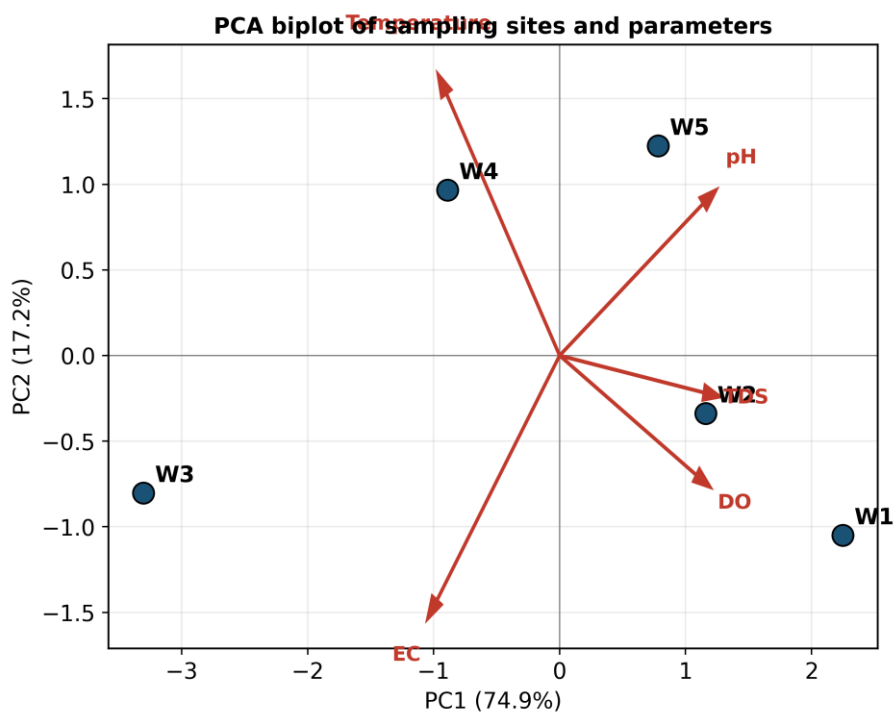


Figure 8. PCA biplot of sampling stations and parameters (PC1 74.9%, PC2 17.2%).

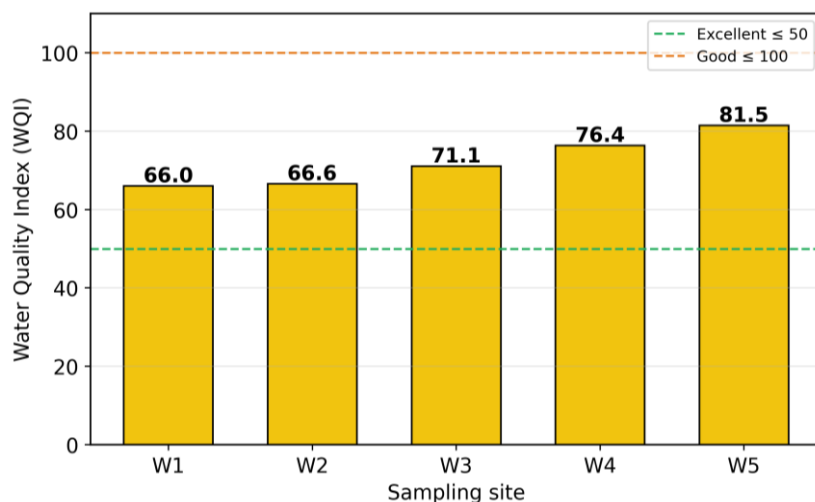


Figure 9. Weighted-arithmetic Water Quality Index by station.

Discussion

The single most important message of this study is a reframing. Coal-mine water research is dominated by the acid-mine-drainage paradigm, in which sulphide oxidation produces low-pH, high-conductivity, metal-laden water.⁴⁻⁶ The Barapukuria canal departs from that paradigm: the near-neutral pH (6.5–7.3), modest conductivity (176–354.9 $\mu\text{S cm}^{-1}$) and absence of acidification documented in Table 3 reflect the low-sulphur bituminous coal of the basin.^{13,15} The binding stressors here are instead thermal loading and physical degradation, which call for cooling and sedimentation rather than the neutralisation and metal-precipitation responses calibrated to acid mine drainage. Recognising this distinction is essential for designing an appropriate management response and represents the study's principal conceptual contribution.

This pre-monsoon baseline shows that the Barapukuria coal-mine canal is chemically compliant yet physically degraded. As summarised in Table 3, pH (7.08 ± 0.34), DO ($5.16 \pm 1.55 \text{ mg L}^{-1}$) and TDS ($430 \pm 125 \text{ mg L}^{-1}$) remained within ECR 1997 and WHO limits at essentially all stations, whereas temperature exceeded the aquatic-life threshold — peaking at 31.7°C at the W4 mixing zone — and EC fell as low as $176 \mu\text{S cm}^{-1}$, signalling mineral-poor water. The significant among-station differences for every parameter (Table 4) and the PCA separation of the discharge point W3 (Figure 8) demonstrate that the discharge imposes a measurable longitudinal structure on the canal rather than a uniform change.

The thermal anomaly merits closer mechanistic attention because it determines the appropriate intervention. Elevated temperature reduces dissolved-oxygen solubility, accelerates microbial respiration and organic decomposition, and raises the metabolic oxygen demand of ectothermic organisms precisely where oxygen supply is lowest.^{19,20} The co-location of the thermal peak and the oxygen minimum at the discharge zone, evident when Figure 2 and Figure 3 are compared, therefore describes a compounding stress more severe

than either parameter implies in isolation, and it is consistent with the slow-moving, dark-coloured canal absorbing short-wave radiation efficiently from the discharge point downstream. This explains the local perception of declining aquatic life along the canal.

The dissolved-oxygen pattern is consistent with effluent-driven oxygen demand. The minimum of 3.1 mg L^{-1} at W3 (Figure 3) falls below the 5.0 mg L^{-1} stress threshold and the ECR floor, indicating localized hypoxia where organic and inorganic effluent loads consume oxygen.²¹ The strong DO–TDS correlation ($r = 0.887$; Figure 7) and the negative Temperature–DO association together describe a coupled thermal–oxygen–solute system in which the hottest, most impacted station is also the most oxygen-depleted. Partial DO recovery at W4 and W5 reflects downstream re-aeration and dilution, mirroring longitudinal recovery patterns reported for industrial channels receiving point-source effluent.²¹

The near-neutral pH and low EC reflect the geochemical setting. The low-sulphur bituminous coal at Barapukuria limits sulphide oxidation, so the canal avoids the strongly acidic, metal-laden signature of acid mine drainage reported for high-sulphur coalfields elsewhere.^{4-6,22} Instead, the dominant stressors are thermal loading and ionic dilution. The low EC and TDS (Table 3) — while reassuring for potability — indicate a nutrient-poor matrix that, in an irrigation context, may constrain crop productivity, a trade-off also noted in mineral-poor mine-influenced waters.^{17,18}

The values reported here sit coherently within the regional literature. The conductivity range ($176\text{--}354.9 \mu\text{S cm}^{-1}$) overlaps earlier measurements from the same coalfield, and the near-neutral pH matches the slightly alkaline mine water documented in recent Barapukuria assessments.^{13,14,15,16} Internationally, the contrast with acidic systems is instructive: studies of high-sulphur coalfields report pH values well below 4 and conductivities of thousands of microsiemens per centimetre with substantial dissolved-metal loads,^{2,4,22} none of which is observed here. The Water Quality Index values (66.1–81.5, “Good”; Table 5) are broadly

comparable to those reported for moderately impacted mine-adjacent waters,^{7,8,10} but the index masks the physical degradation that dominates here — a recognised limitation of chemistry-weighted indices when applied to thermally and aesthetically impaired waters.¹⁰

For fisheries, the combination of temperatures above the 28 °C aquatic-life threshold at the discharge zone (Figure 2) and dissolved oxygen falling to 3.1 mg L⁻¹ at W3 (Figure 3) indicates conditions marginal to unsuitable for sensitive species, particularly during the warm pre-monsoon period sampled here.^{19,21} For agriculture, the picture is mixed: pH and TDS are within irrigation criteria, but the low conductivity signals a nutrient-poor matrix providing little dissolved-mineral benefit to crops, echoing suitability assessments of Bangladeshi surface waters that pass potability but fail irrigation criteria.^{17,23} These use-suitability assessments are explicitly bounded to the pre-monsoon dry season; monsoon dilution and post-monsoon recovery could shift both the thermal and ionic status,²¹ and only multi-season monitoring can establish year-round suitability.

From a regulatory standpoint, the canal complied with ECR 1997 for pH, DO (except W3), EC and TDS, but failed the temperature criterion at 40% of stations (W3 and W4), and every station exceeded the WHO temperature value.^{11,12} Against the Indonesian PP No. 22/2021 Class-II benchmark, DO at W3 (3.1 mg L⁻¹) likewise fell below the 4 mg L⁻¹ minimum. The results support a tiered, site-specific action plan. The first and most binding constraint is thermal: a heat-exchange or cooling-retention pond sized to provide sufficient residence time to bring discharge below 28 °C before it enters the canal. The second priority is physical: sedimentation tanks to capture the suspended coal particulates responsible for the blackening observed from W3 downstream (Table 2). The third priority is surveillance: a monitoring programme extended to biochemical and chemical oxygen demand, nutrients and priority trace metals, sampled quarterly across seasons with adequate replication.^{14,18}

The study has notable strengths. It provides the first station-resolved, longitudinally profiled baseline for the specific canal receiving Barapukuria discharge; it applies a coherent QA/QC protocol with triplicate measurement; and it upgrades a descriptive survey into an inferential and multivariate assessment with effect sizes, PCA and an uncertainty-quantified Water Quality Index, yielding interpretable, management-ready outputs.

Several limitations temper interpretation. The assessment covers a single pre-monsoon season and a single medium (water), so seasonal dynamics and sediment storage are not captured.²¹ The five stations, although adequate to resolve the discharge gradient, constrain the statistical power of the inferential tests, so the correlation and regression results are reported as indicative and the ANOVA tests analytical rather than temporal separability. Heavy metals, nutrients, biochemical oxygen demand and chemical oxygen

demand were not measured, so the chemical compliance reported here is partial.^{13,14} Multi-season monitoring with metal and sediment analysis is needed to convert this baseline into a comprehensive environmental-management plan.

Conclusion

This pre-monsoon baseline establishes that the canal adjacent to the Barapukuria coal mine is chemically compliant but physically stressed. pH (7.08 ± 0.34), DO (5.16 ± 1.55 mg L⁻¹) and TDS (430 ± 125 mg L⁻¹) met ECR 1997 and WHO limits, whereas temperature peaked at 31.7 °C — exceeding the 28 °C aquatic-life limit at the W3–W4 mixing zone and the 25 °C WHO value at all stations — and electrical conductivity fell to 176 μ S cm⁻¹, indicating mineral-poor water. All parameters varied significantly among stations ($p < 0.001$; $\eta^2 = 0.94\text{--}0.99$), PCA explained 92.1% of variance and isolated the discharge point, and the Water Quality Index (66.1–81.5, “Good”) deteriorated downstream, with 40% of stations exceeding the ECR temperature limit. We recommend that mine authorities install industrial cooling or heat-exchange ponds and sedimentation tanks before discharge, and that local agencies adopt multi-season monitoring with heavy-metal and sediment analysis to safeguard the canal ecosystem and downstream agricultural productivity.

Declarations

Ethical Approval. This study involved environmental water sampling only and did not involve human participants, animals, or sensitive personal data; formal ethics-committee approval was therefore not required. The fieldwork respected local customs, traditions, and community values.

Conflict of Interest. The authors declare no conflict of interest.

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Data Availability. All data generated or analysed during this study are included in this article. Additional data are available from the corresponding author on reasonable request.

Use of Artificial Intelligence. During the preparation of this work, the authors did not use AI-assisted tools. The authors reviewed and edited all content and take full

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