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Hydrogeochemical and Microbial Assessment of Surface Mining Impacts on Water Resources in Rayfield, Jos Plateau, Nigeria

Adesola, S. L.[1], Mallo, J.S.[1], Ajang, B.I[2] & Patrick, J.Y.[1]

[1]Department of Mining Engineering, University of Jos
[1]Department of Mining Engineering, University of Jos
[2]Department of Minerals and Petroleum Resources Engineering, Plateau State Polytechnic Barkin Ladi
[1]Department of Mining Engineering, University of Jos

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ABSTRACT

Surface mining remains a critical driver of economic development in mineral-rich regions; however, its environmental implications particularly on water resources pose significant risks to public health and ecosystem sustainability. This study evaluates the impact of surface mining operations on surface and groundwater systems in Rayfield Resort and surrounding communities in Jos South Local Government Area, Plateau State, Nigeria. Eleven water sampling stations (WS1–WS11), including mine pits, boreholes, and hand-dug wells, were monitored over a 12-month period. Comprehensive physicochemical, hydrogeochemical, heavy metal, and microbial analyses were conducted following ISO standards. Pollution indices, including Contamination Factor (CF), Pollution Index (PI), and Nemerow Pollution Index (NPI), were employed to assess contamination levels. Results indicate circum-neutral pH (6.27–7.43), low TDS (47–386 mg/L), but elevated turbidity (5.11–23.54 NTU) and TSS (73–302 mg/L) across all stations. Heavy metals, particularly cadmium, lead, and arsenic, exceeded WHO/NSDWQ limits in several locations, with hotspots identified at WS8, WS9, WS10, and WS11. Microbial analysis revealed the presence of E. coli in all samples, rendering water unsafe for direct consumption. The findings suggest that contamination is primarily driven by runoff-mediated particulate transport and anthropogenic inputs rather than classical acid mine drainage. The study recommends integrated mitigation strategies including sediment control, targeted metal removal, and universal disinfection systems. These results contribute to sustainable mining practices and align with global water safety and environmental protection goals.

1. Introduction

1.1 Background

Water is a critical natural resource essential for human survival, agriculture, and industrial development. However, its quality is increasingly threatened by anthropogenic activities, particularly mining. Surface mining operations disrupt geological formations, expose mineralized rocks, and generate waste materials that can degrade water systems through sedimentation and chemical contamination.

The Jos Plateau in Nigeria has a long history of tin mining, with extensive artisanal and mechanized activities altering the natural landscape. In Rayfield, mining has led to the formation of artificial ponds, exposure of mineralized rocks, and increased runoff, all of which influence water quality. Communities in this region rely heavily on untreated surface and groundwater for domestic and agricultural use, making water contamination a significant public health concern.

Previous studies have highlighted heavy metal contamination and sediment-related pollution in mining areas; however, there is limited integrated analysis combining hydrogeochemistry, microbial assessment, and multivariate statistics in this region. This study aims to bridge this gap by providing a comprehensive evaluation of water quality using physicochemical analysis, pollution indices, and advanced statistical techniques.

The specific objectives are to assess water quality parameters, determine contamination levels, evaluate suitability for domestic and agricultural use, and identify the dominant processes controlling water quality.

1.2 Problem Statement

Despite extensive mining in the region, there is limited empirical data quantifying the extent of water contamination. Existing regulatory frameworks are weak, and environmental monitoring remains insufficient. Consequently, local populations are exposed to potentially hazardous water without adequate treatment or awareness.

1.3 Aim and Objectives

1.3.1 Aim:

To evaluate the impact of surface mining on local water resources in Rayfield, Jos Plateau.

1.3.2 Objectives:

- Assess physicochemical characteristics of water sources
- Determine heavy metal concentrations and contamination levels
- Evaluate microbial quality of water
- Compare results with WHO and NSDWQ standards
- Assess suitability for domestic and agricultural use

2. Study Area and Geological Setting

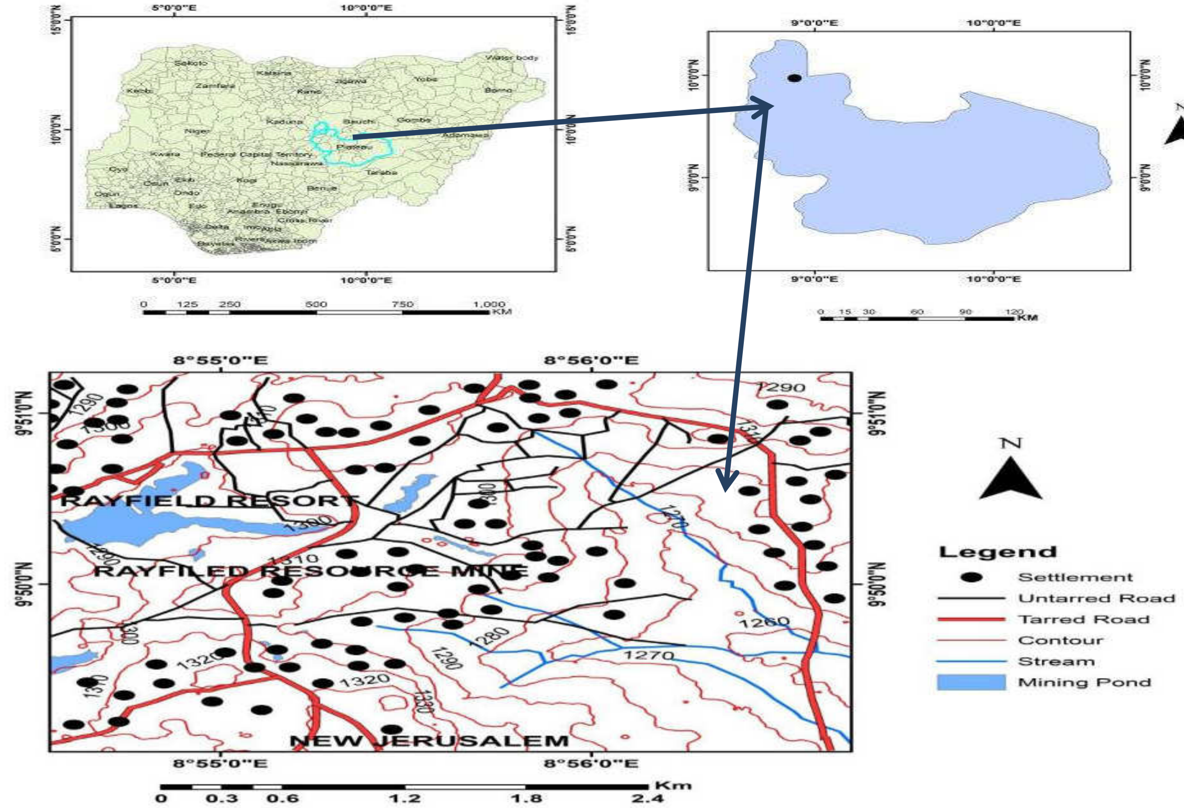

Figure 1. Map of Nigeria, Plateau State and Topographic Map of the Study Area.

The study was conducted in Jos South Local Government Area of Plateau State, North Central Nigeria. Geographically, the area lies within longitudes 08°54′32.40″E to 08°56′42.00″E, latitude 09°49′01.20″N to 09°51′14.40″N. The region is well-connected by a network of major, minor, and secondary roads, which provide access to both rural communities and mining zones.

Geologically, the study area falls within the Younger Granite Province of the Jos-Bukuru Ring Complex, a well-known petrographic province in West Africa. This province is characterized predominantly by acidic plutonic rocks rich in economically important minerals. Specifically, the Jos-Bukuru complex consists of biotite granite plutons which are globally recognized for hosting substantial deposits of cassiterite (tin ore) and columbite (niobium ore). According to Adiku-Brown (2001), this complex represents one of the richest zones of tin-columbite mineralization in Nigeria and has historically supported extensive mining activity, both mechanized and artisanal.

3. Materials and Method

The methodological framework adopted in this study was designed to ensure a comprehensive and scientifically rigorous assessment of water quality within a mining-impacted environment. A multi-stage approach integrating field sampling, laboratory analysis, and statistical evaluation was employed to capture both spatial and compositional variability in water quality. Eleven strategically selected sampling stations representing mine pits, boreholes, and hand-dug wells were investigated to reflect the diversity of water sources available to local communities. Sampling procedures strictly adhered to internationally recognized ISO standards to maintain consistency and minimize contamination.

Field investigations involved detailed reconnaissance surveys, during which geological characteristics such as lithology, structural features, and mineralization patterns were documented. These observations provided essential context for interpreting hydrogeochemical behaviour. Water samples were collected in sterilized containers, labelled systematically, and preserved under controlled conditions prior to laboratory analysis. This ensured that the integrity of both chemical and microbial constituents was maintained throughout the analytical process.

Laboratory analysis was conducted using advanced analytical instruments, including atomic absorption spectrophotometry for heavy metals and spectrophotometric techniques for anions and cations. Physical parameters such as pH, electrical conductivity, turbidity, and dissolved oxygen were measured using calibrated field and laboratory equipment. Microbial analysis focused on the detection of Escherichia coli and total coliforms using standard incubation techniques.

To enhance interpretation, quantitative indices such as Contamination Factor, Pollution Index, and Nemerow Pollution Index were applied. These indices provided a robust framework for evaluating pollution severity and spatial distribution. Additionally, irrigation suitability was assessed using the Sodium Adsorption Ratio, linking hydrochemical data to agricultural implications. Overall, the methodological approach ensured high data reliability and enabled a multidimensional understanding of mining-induced water quality changes.

4. Results and Discussion

4.1 Physical Parameters

Table 1: Physical Parameter Compliance Summary Table

Parameter	Observed Range	NSDWQ/WHO Limit	Compliance Status
pH	*6.27-7.43*	*6.5-8.5*	Compliant except WS5 (slightly low)
Temperature (Â°C)	24-28	No health limit	Within typical tropical range
EC (ÂµS/cm)	94.67-774.67	<1000 (operational)	All compliant
TDS (mg/L)	47-386	500	All compliant
Turbidity (NTU)	*5.11-23.54*	<5	All exceed; filtration required
TSS (mg/L)	73-302	No health limit	High at most sites; operational concern
DO (mg/L)	*3.60-6.11*	*6.5-8.0*	Contamination warning
BOD‚… (mg/L)	*1.17-4.23*	1-2	Elevated organics at some sites
COD (mg/L)	*4.14-16.98*	4-10	High at WS8; organic load spike
Total Hardness (mg/L CaCO)	as54-325	<500	Soft to very hard; scaling at WS1, WS9
Salinity (%)	*0.033-5.460*	<600-1000	Freshwater

Descriptive overview (means)

- pH: 6.27–7.43 (circum-neutral overall).
- Temperature: 24–28 °C (tropical ambient), modest spatial variation.
- EC: 94.7–774.7 µS/cm (fresh waters; WS1 and WS9 relatively mineralized).
- TDS: 47–386 mg/L (well below the NSDWQ/WHO 500 mg/L palatability ceiling).
- Turbidity: 5.11–23.54 NTU (elevated at many sites; worst at WS3).
- TSS: 73–302 mg/L (high at WS3, WS1, WS9, WS6, consistent with turbidity patterns).
- DO: 3.60–6.11 mg/L (moderate oxygenation).
- BOD_5: 1.17–4.23 mg/L (lowest at WS3; highest at WS7).
- COD: 4.14–16.98 mg/L (WS8 conspicuously high).
- Total hardness: 54–325 mg/L as $CaCO_3$ (soft at WS7; very hard at WS1; several in moderate–hard classes).
- “Salinity % is 0.0386 (TDS 386 mg/L ≈ 0.0386 %)

4.1.1 Discussion of Physical Parameters

The physical water quality profile for the eleven sampling stations (WS1–WS11) in the Rayfield Resort and its environs and environs was characterized using pH, temperature, electrical conductivity (EC), total dissolved solids (TDS), salinity, dissolved oxygen (DO), biochemical oxygen demand (BOD_5), chemical oxygen demand (COD), total hardness (as $CaCO_3$), turbidity, and total suspended solids (TSS). The results were compared with the Nigerian Standard for Drinking Water Quality (NSDWQ) and World Health Organization (WHO) guidelines to assess compliance and implications for suitability in drinking and agricultural uses.

pH:The measured pH values ranged from 6.27 to 7.43, with a mean of 6.73. Except for WS5 (6.27), all stations fell within the NSDWQ and WHO recommended range of 6.5–8.5 for potable water (WHO, 2017; SON, 2015). Near-neutral pH is favourable for water treatment and distribution, reducing corrosion risk in pipelines and optimizing chlorine disinfection efficiency (Edokpayi, 2018). The marginally acidic nature of WS5 may increase corrosivity towards metallic fittings but can be corrected through simple alkalinity adjustment during treatment.

Temperature: Water temperature varied between 24 °C and 28 °C, consistent with tropical ambient conditions. While temperature is not directly regulated, it influences aesthetic perception, taste, and residual chlorine stability (Sorlini, 2013). The range observed is within acceptable limits for drinking and agricultural uses, though slightly elevated values (>26 °C at WS2, WS5–WS7, WS11) may encourage microbial regrowth in distribution systems if residual disinfectant levels are not maintained.

Electrical Conductivity and Total Dissolved Solids: EC values ranged from 94.67 µS/cm (WS7) to 774.67 µS/cm (WS1), with corresponding TDS levels between 47 mg/L and 386 mg/L. All samples were well below the NSDWQ/WHO maximum permissible limit of 500 mg/L for TDS (SON, 2015; WHO, 2017), indicating low mineralization and a freshwater classification. Such low TDS values generally improve palatability and are associated with reduced scaling potential, though excessively low TDS (<100 mg/L) can result in flat taste and increased corrosivity (Gibbs, 2011). The strong correlation between EC and TDS in the dataset supports the use of EC as a rapid field indicator of ionic content.

Turbidity and Total Suspended Solids: Turbidity values ranged from 5.11 NTU (WS10) to 23.54 NTU (WS3), with all stations exceeding the NSDWQ/WHO limit of 5 NTU. TSS values were also high, between 73 mg/L (WS8) and 302 mg/L (WS3). Elevated turbidity and TSS can interfere with disinfection efficiency by shielding microorganisms and are often indicative of surface runoff, erosion, and particulate matter from mining activities (Ramakrishnaiah, 2009; Akabzaa, 2007). The highest turbidity/TSS at WS3 and WS1 suggests proximity to disturbed soil or tailings piles without adequate sediment control.

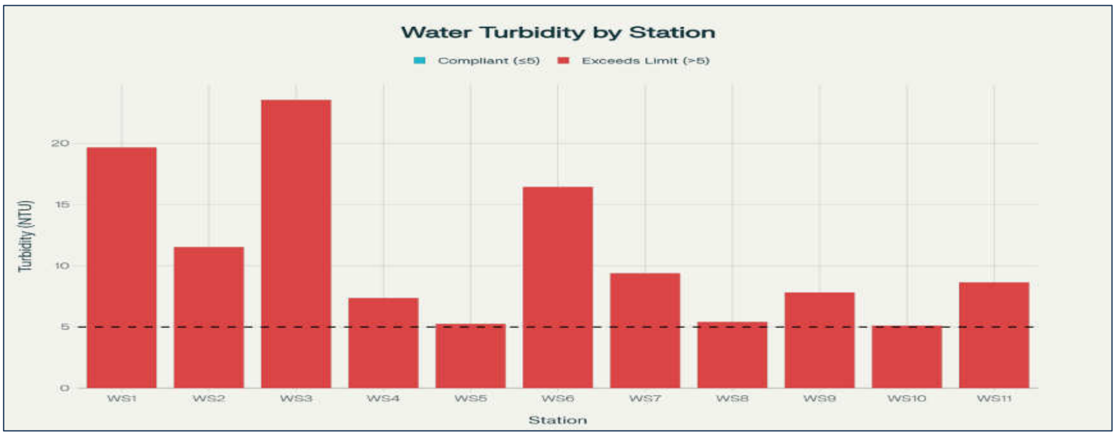

Figure 2. Water Turbidity by Station

Dissolved Oxygen, BOD_5, and COD: DO levels (3.60–6.11 mg/L) indicate moderate oxygenation, typical of surface and shallow groundwater in open systems. BOD_5 values ranged from 1.17 mg/L (WS3) to 4.23 mg/L (WS7), while COD values ranged from 4.14 mg/L (WS10) to 16.98 mg/L (WS8). Elevated COD at WS8 suggests significant oxidizable organic matter input, potentially from domestic wastewater infiltration, process water discharges, or decomposing biomass. While DO, BOD_5, and COD are not primary drinking water health indicators, they provide important information on organic load, potential taste/odour problems, and the likelihood of microbial regrowth in distribution systems (EPA, 2022).

Total Hardness: Total hardness ranged from 54 mg/L (WS7, classified as soft) to 325 mg/L (WS1, classified as very hard). WS1 and WS9 fall into the very hard category (>180 mg/L), WS3 and WS11 are hard (121–180 mg/L), and the remaining stations are moderately hard (61–120 mg/L). While hardness is not a health concern, very hard water can cause scaling in distribution systems and appliances, and moderately hard water may require more soap for washing (McNeill & Edwards, 2001). In agricultural contexts, hardness levels in this range pose no direct hazard to crops.

Salinity: This is measured as Total Dissolved Solids(TDS) with DTS values of 386 mg/L corresponds to a salinity of approximately 0.0386%. Regard to the EC and TDS data confirm that all samples fall within the low salinity hazard category for irrigation (Ayers & Westcot, 1985).The effects of salinity vary significantly depending on whether the water is being used for drinking, farming or industrial purposes. TDS less than 1000 is categorized as freshwater (Ayers and Westcot,1985) is good for drinking and agricultural purposes.

Generally, from a physical quality perspective, turbidity/TSS are the primary limiting factors. Even stations with near-ideal pH, TDS, and hardness require filtration or clarification to meet drinking water standards. High turbidity not only violates aesthetic and operational guidelines but also increases the risk of pathogen survival during disinfection. Conversely, the generally acceptable pH, TDS, and hardness suggest that, after clarification and disinfection, most sources could be made potable.

Low EC and TDS values indicate excellent suitability for irrigation from a salinity standpoint, with low sodium adsorption ratio (SAR) values previously computed for these samples. However, the high TSS could lead to emitter clogging in drip irrigation systems, necessitating filtration. Additionally, in fields where raw-eaten crops are cultivated, microbial safety (addressed elsewhere in this thesis) must be considered.

The physical quality profile aligns with typical surface mining-impacted waters, where physical disturbances and sediment mobilization dominate the degradation pattern rather than dissolved solids or salinity. The elevated turbidity and TSS, coupled with localized high COD, point to runoff carrying fine sediments and organic residues from exposed surfaces, overburden, and possibly unlined process water channels.

In summary, while the physical chemistry of the water in the Rayfield Resort and its environs area is largely compliant with drinking water guidelines for pH, TDS, and hardness, the universally elevated turbidity/TSS necessitates sediment control measures at source and effective filtration prior to disinfection. For irrigation, the waters are low in salinity hazard and acceptable for most crops, but sediment removal is recommended to prevent clogging of irrigation systems.

4.2 Chemical Parameters

Table 2: Results of Chemical Parameters (Anions)

Station	NO_3^- (mg/L)	PO_4^{3-} (mg/L)	SO_4^{2-} (mg/L)	Cl^- (mg/L)	F^- (mg/L)
WS1	48.56	17.68	34.72	156	*0.082*
WS2	32.15	*5.54*	46.46	45	*0.019*
WS3	26.46	*8.42*	53.47	78	*0.065*
WS4	11.39	*6.53*	37.75	32	BDL
WS5	16.34	*2.51*	45.55	29	BDL
WS6	14.47	*3.53*	56.40	21	*0.054*
WS7	37.52	11.52	28.53	17	BDL
WS8	28.25	*7.38*	13.59	25	BDL
WS9	51.56	18.45	11.48	123	*0.057*
WS10	32.38	*5.44*	14.70	21	BDL
WS11	46.63	*3.08*	52.58	46	*0.038*

BDL = Below Detection Limit

The chemical composition of the water reflects both geogenic and anthropogenic influences. Nitrate concentrations ranged from 11.39 mg/L to 51.56 mg/L, with WS9 exceeding the WHO limit of 50 mg/L and WS1 (48.56 mg/L) and WS11 (46.63 mg/L) approaching critical thresholds. This indicates significant nutrient contamination, likely from agricultural runoff and sewage infiltration. Phosphate concentrations varied from 2.51 mg/L to 18.45 mg/L, with particularly high values at WS1 and WS9, suggesting strong anthropogenic inputs.

Sulphate concentrations were relatively low, ranging from 11.48 mg/L to 56.40 mg/L, while chloride ranged from 17 mg/L to 156 mg/L, both within acceptable limits. Fluoride concentrations were minimal, between 0.019 mg/L and 0.082 mg/L, indicating no risk of fluorosis but also suggesting limited dental health benefits. Overall, nitrate and phosphate emerge as the primary chemical constraints affecting water quality in the study area.

4.3 Heavy Metal Contamination

Table 3: Summary of Heavy Metals Parameters

Parameter	Observed range (mg/L)	Limit (mg/L)	Stations exceeding (health-based)	Comment
Pb	*0.0000–0.0243*	*0.01*	WS8, WS9, WS10	Localized exceedance; ore/waste contact & workshops plausible sources
Cr	*0.0000–0.0856*	*0.05*	WS2, WS8	Two hotspots (WS2, WS8); others acceptable
Cd	*0.0000–0.0574*	*0.003*	WS1, WS3–WS6, WS8–WS11	Widespread and dominant exceedance driver
As	*0.0000–0.0278*	*0.01*	WS8, WS9, WS10	Moderate exceedance at three sites
Ni	*0.0029–0.0838*	*0.07*	WS9 only	Borderline to moderate at one site
Fe	*0.0112–0.0854*	*0.3*	None	All within aesthetic limit
Cu	*0.0063–0.0643*	*2.0*	None	All well below health limit
Zn	*1.2942–5.6834*	*3.0*	WS1, WS3, WS4, WS7, WS8, WS11 (aesthetic)	Taste/aesthetic exceedance; not health-limiting

Heavy metal concentrations reveal significant contamination, particularly in mining-influenced zones. Cadmium exceeded permissible limits in multiple stations, especially WS1, WS3–WS6, WS8, WS9, WS10, and WS11, making it the dominant toxic contaminant. Lead concentrations exceeded WHO limits in WS8, WS9, and WS10, while arsenic showed elevated levels in the same stations, indicating localized hotspots of contamination.

Nickel showed marginal exceedance at WS9, while iron and copper remained within acceptable limits across all stations. Zinc exceeded aesthetic limits in several locations, though not posing immediate health risks. The contamination factor (CF) values for cadmium were consistently greater than 1 in most stations, indicating significant contamination, while CF values for other metals varied spatially. The Nemerow Pollution Index identified WS11, WS8, WS10, WS1, and WS9 as heavily polluted zones, confirming that contamination is concentrated around active mining areas.

4.4 Microbial Analysis

Microbial analysis revealed severe contamination across all sampling stations. Escherichia coli was detected in every sample, while total coliform counts were consistently high, indicating widespread faecal contamination. This renders all water sources unsafe for direct consumption without treatment. The presence of microbial contaminants is likely linked to poor sanitation practices, open defecation, and infiltration of wastewater into groundwater systems.

The combination of high turbidity values (up to 23.54 NTU) and microbial presence further complicates treatment, as suspended particles can protect microorganisms from disinfection. These findings highlight a critical public health risk, particularly for communities relying on untreated water sources.

4.5 Pollution Indices and Water Quality Evaluation

The application of pollution indices provides a comprehensive assessment of water quality. Contamination Factor values for major cations were generally less than 1, indicating low salinity hazard, while heavy metal CF values, particularly for cadmium, exceeded 1 in most stations. Pollution Index values confirmed moderate to high contamination levels across the study area.

The Nemerow Pollution Index further classified stations into pollution categories, with WS11, WS8, WS10, WS1, and WS9 falling into the heavily polluted class. These stations correspond to areas with intense mining activities and high anthropogenic influence. The overall water quality is therefore compromised, with multiple parameters exceeding recommended limits, particularly turbidity, nitrate, heavy metals, and microbial indicators.

4.6 Suitability for Agricultural Use

The assessment of irrigation suitability indicates generally favourable conditions in terms of salinity and sodicity. Total dissolved solids ranged from 47 mg/L to 386 mg/L, corresponding to salinity levels of approximately 0.0047% to 0.0386%, which fall within the freshwater category suitable for irrigation. Sodium Adsorption Ratio values were predominantly below 3, indicating low sodium hazard and minimal risk of soil dispersion.

However, the high total suspended solids values (up to 302 mg/L) may lead to clogging of irrigation systems, particularly in drip irrigation setups. Additionally, the presence of microbial contaminants poses risks for crops consumed raw. Therefore, while the water is chemically suitable for irrigation, pre-treatment such as filtration and controlled application methods are necessary to ensure safe agricultural use.

5. Conclusion

The study demonstrates that water resources in the Rayfield mining area are significantly impacted by surface mining and associated human activities. While physicochemical parameters such as pH (6.27–7.43) and TDS (47–386 mg/L) indicate relatively stable conditions, critical issues arise from elevated turbidity (5.11–23.54 NTU) and TSS (73–302 mg/L), which exceed acceptable limits across all stations.

Chemical analysis identified nitrate contamination as a key concern, with values reaching 51.56 mg/L, exceeding WHO standards, while phosphate levels reached as high as 18.45 mg/L, indicating strong anthropogenic influence. Heavy metal contamination, particularly cadmium, lead, and arsenic, was prominent in several stations, with contamination factors exceeding unity and NPI classifying multiple sites as heavily polluted.

Microbial contamination was universal, with E. coli detected in all samples, rendering the water unsafe for direct consumption. Despite these challenges, irrigation suitability remains relatively favorable due to low salinity and SAR values. Overall, the study confirms that water quality degradation is driven by a combination of mining activities, runoff processes, and poor sanitation practices.

6. Recommendations

To address the identified water quality challenges, it is essential to implement targeted and evidence-based interventions. Given the consistently high turbidity values (5.11–23.54 NTU) and suspended solids (73–302 mg/L), the installation of effective filtration systems is necessary to improve water clarity and enhance disinfection efficiency.

Heavy metal contamination, particularly cadmium and lead, requires the adoption of advanced treatment technologies such as adsorption or membrane filtration in hotspot areas like WS8, WS9, WS10, and WS11, where pollution indices indicate severe contamination.

The widespread presence of E. coli necessitates the implementation of reliable disinfection systems, including chlorination or ultraviolet treatment, to ensure microbiological safety. In addition, improving sanitation infrastructure is critical to reducing faecal contamination at the source.

For agricultural use, although TDS values (47–386 mg/L) and SAR levels indicate suitability, high TSS levels necessitate pre-filtration to prevent irrigation system clogging. Farmers should also adopt safer irrigation practices to minimize health risks associated with contaminated water.

Finally, regulatory agencies must enforce environmental monitoring and require mining operators to implement runoff control measures and proper waste management practices. Continuous monitoring of key parameters such as nitrate (up to 51.56 mg/L) and heavy metals is essential to track improvements and ensure sustainable water resource management.

References

[1] Akcil, A., & Koldas, S. (2006). Acid mine drainage (AMD): Causes, treatment and case studies. *Journal of Cleaner Production*, 14(12–13), 1139–1145.

[2] American Public Health Association. (2012). *Standard methods for the examination of water and wastewater* (22nd ed.). Washington, DC: APHA.

[3] Appelo, C. A. J., & Postma, D. (2005). *Geochemistry, groundwater and pollution* (2nd ed.). Rotterdam, Netherlands: A.A. Balkema.

[4] Boateng, T. K., Opoku, F., Acquaah, S. O., & Akoto, O. (2015). Pollution evaluation, sources and risk assessment of heavy metals in hand-dug wells from Ejisu-Juaben Municipality, Ghana. *Environmental Systems Research*, 4(1), 18.

[5] Freeze, R. A., & Cherry, J. A. (1979). *Groundwater*. Englewood Cliffs, NJ: Prentice-Hall.

[6] Giri, S., Singh, A. K., Tewary, B. K., & Singh, T. N. (2012). Review of coal mine water quality and its management. *International Journal of Mining Science and Technology*, 22(6), 847–852.

[7] Hem, J. D. (1985). *Study and interpretation of the chemical characteristics of natural water* (3rd ed.). Washington, DC: U.S. Geological Survey.

[8] Jarvie, H. P., Neal, C., & Withers, P. J. A. (2006). Sewage-effluent phosphorus: A greater risk to river eutrophication than agricultural phosphorus? *Science of the Total Environment*, 360(1–3), 246–253.

[9] Khan, S., Shahnaz, M., Jehan, N., Rehman, S., Shah, M. T., & Din, I. (2013). Drinking water quality and human health risk in Charsadda district, Pakistan. *Journal of Cleaner Production*, 60, 93–101.

[10] Kumar, M., Ramanathan, A. L., Rao, M. S., & Kumar, B. (2006). Identification and evaluation of hydrogeochemical processes in the groundwater environment of Delhi, India. *Environmental Geology*, 50(7), 1025–1039.

[11] Mohan, S. V., Nithila, P., & Reddy, S. J. (1996). Estimation of heavy metals in drinking water and development of heavy metal pollution index. *Journal of Environmental Science and Health*, 31(2), 283–289.

[12] Simate, G. S., & Ndlovu, S. (2014). Acid mine drainage: Challenges and opportunities. *Journal of Environmental Chemical Engineering*, 2(3), 1785–1803.

[13] Subramani, T., Elango, L., & Damodarasamy, S. R. (2005). Groundwater quality and its suitability for drinking and agricultural use in Chithar River Basin, Tamil Nadu, India. *Environmental Geology*, 47(8), 1099–1110.

[14] United Nations Environment Programme. (2019). *Global environment outlook – GEO-6: Healthy planet, healthy people*. Nairobi, Kenya: UNEP.

[15] World Health Organization. (2017). *Guidelines for drinking-water quality* (4th ed.). Geneva, Switzerland: WHO.