Acid Mine Drainage and Climate Change: Evolving Risks and Responses in India

Aparna Dutta [1*] and Bratati Chowdhury [2]

[1]Department of Civil Engineering, Indian Institute of Technology Roorkee, Roorkee-247667, Uttarakhand

[2]Soil & Water Conservation Engineering, Faculty of Technology, Uttar Banga Krishi Viswavidayalaya, Coochbehar-736165, West Bengal

Corresponding Author: adutta@ce.iitr.ac.in

Acid Mine Drainage (AMD) is the acidic water draining out of mines situated in the geologically pyrite-enriched regions. The acid is formed by oxidation (bio-chemical) of pyrite and marcasite into sulfate with release of protons (H^+). Due to the low pH, AMD also dissolves minerals from the soil and rocks it contacts. Therefore, at the macroscopic level, the scale of mining primarily dictates the exposure of buried pyrites to atmospheric oxygen and water that are essential for the chemical reaction forming AMD. However, at the micro level, the further weathering of excavated rocks is influenced by the temperature variation and rainfall. Thus, the most important factors governing the kinetics of AMD formation are climatic parameters, i.e., temperature and rainfall. The global climate is undergoing an unprecedented change and even more pronounced effects are being observed in India in forms of extreme heat and precipitation events (Chowdhury, 2022; Rajulapati et al., 2020). Increased intensity of rainfalls and extreme events drive episodic flushing of mine wastes, producing strong pulses of acidic metal-rich runoff into streams and aquifers. Intense monsoon storms increase acute contamination events. Several researchers have observed the effects of seasonal variations on AMD characteristics in the eastern Himalayan sub-region (Equeenuddin et al., 2010; Kumar et al. 2024). Besides, further intensification of extreme rainfall is predicted for north-eastern India (Mishra et al., 2021; Rajulapati et al., 2021). Multi-day extreme precipitation events are linked to floods and slope failures across Indian monsoon belt where cloudburst and flash floods may breach mine dumps exposing new pyrite faces forming sustained AMD generation sources (Chupal et al., 2025). According to the IPCC 2023 report, South Asia projects further warming causing greater atmospheric moisture finally resulting in heavier rains. Moreover, such variable storm-pulse events may overwhelm the undersized neutralization treatment units at mines (Weinberg et al., 2022). Therefore, we can see a clear link between the changing climate and the AMD occurrences in geologically susceptible regions. Thus, emphasizing the need for better monitoring and management of AMD at the mines and develop a decision support system based on the extensive studies on extreme weather events in these areas.

The mineral industry forms the backbone of economic development of a country. In India, the mineral sector also employs a large proportion of the workforce. The mining leases occupy around 0.21 percent of the total land area of India. Of the 2729 mines operational in India, 21 percent are coal mines (CPCB, 2011). Commercial coal mining in India began in 1774 in the Raniganj coalfield. Globally, India ranks sixth in the coal reserves of Gondwana and tertiary formations. The general practice at mines is to collect the mine water in sumps, then pump to ground level for further settlement of solids, reuse in dust suppression, supply to coal washeries, and/or discharged into nearby creeks and streams (CPCB, 2011). Due to lesser occurrence of pyritic bands, the Indian coal mines are usually considered free of the AMD problems (Ray and Dey, 2020). Such a premise has led to limited studies on the water quality at the Indian coal mines unless faced with environmental regulatory concerns.

Nevertheless, the limited scientific investigations on the AMD afflicted mining regions of north-eastern, central, southern and western India set sufficient pretext to consider mining related water quality issues, an important concern under the changing climatic conditions. In Assam, the Oligocene coal has a high sulfur content of up to eight percent, with 10-25 % as pyrite or sulfate (Baruah and Khare, 2007). Besides, the ecologically fragile environment, the noxious coal characteristics of Makum coalfield makes the management of environmental impacts of coal mining in the region very challenging. Further, the high average annual rainfall, very low pH (<2) and high iron content makes passive treatment non-viable in the area (Choudhury et al., 2021). The cost-effectiveness, secondary contamination threats, and site-specific applicability were major constraints affecting the success of an AMD remediation technology in the region (Choudhury et al., 2021). Although the AMD situation in Assam has attracted attention from researchers, the studies are discontinuous in terms of their spatial and temporal differences with respect to climate. Similarly, the coal found in the Jaintia Hills of Meghalaya is mostly sub-bituminous with high sulfur content (three to five percent). (Sahoo et al., 2014) studied their minerology and acid generating potential. The precipitation of efflorescent salts under high evaporation during the dry season followed by their dissolution during rains contributed high flux of metals and sulfate into the water suggesting a strong climatic control on AMD (Sahoo et al., 2014). So far AMD treatment technologies based on chemical neutralisation with lime, limestone drains, wetland, vertical flow reactors, and diversion wells have been suggested in the region (Pyrbot et al., 2019; Singh and Chakraborty, 2020). A study by (Semy and Singh, 2021) on the water quality along the traditionally significant Tsurang river in Mokokchung, Nagaland indicated the river turned acidic (pH 3.3-4.9) with increased sulfate (231-308 mg/L) during the summer and autumn seasons due to coal mining and other anthropogenic activities mandating treatment before consumption by the local population.

In the Gorbi coal mines of Singrauli, Madhya Pradesh, three pit lakes indicated an acidic pH (2.5) besides elevated TDS (2270 ppm), EC (2990 µS/cm), sulfate (190 mg/L), and metals like iron, aluminum and manganese (Shirin et al., 2021). Further study on the water quality in the area revealed that although suitable for irrigation but water near the mines was unsuitable for domestic consumption due to contamination from mining waste dumps, AMD, and industrial discharges (Khan et al., 2013). (Kumar et al., 2022) observed acidification and elevated dissolved solids in the ground and river water near the three AMD afflicted coal mines: Bhatgaon and Mahamaya (UG) and Mahan (OC) mines in the Mahan River catchment of Chhattisgarh. In the Sattupalli coalfields of Telangana, sulfide mineralization of hydrothermal origin was observed along the faults, fractures, and cleats (Prachiti et al., 2011).

The coal deposits in the Gondwana formations of Jharkhand and West Bengal are not associated with pyrites and have low sulfur, hence these mines generally do not face AMD problem. However, the presence of heavy metals in toxic concentrations was also reported in the drainage from Rajrappa coal mine complex of Jharkhand where cat fishes (*Clarias batrachus)* at laboratory exposed to mine drainage experienced bioaccumulation of metal severely depleting their nutritional value rendering them unfit for human consumption (Lakra et al., 2021). The coal mines from Jharia, Jharkhand and Raniganj, West Bengal discharge water with a circumneutral to alkaline pH, slightly elevated sulfate concentration and high mineralisation (Ray and Dey, 2020). Similar observations were made by (Tiwary and Dhar, 1994) about the drainage from certain mines in the Damodar River basin, where the groundwater quality was significantly affected due to mining activities but the mine drainage water had circumneutral pH with enhanced sulfate concentration (206-401.2 mg/L). Additionally, (Neogi et al., 2017) observed mildly acidic to alkaline mine drainage with sulfate as the dominant anion in the North Karanpura coalfields, Jharkhand; which was attributed to oxidation of pyrite and/or coupled reactions involving carbonic acid weathering.

Mine water pollution is emerging as a significant water-quality challenge across India's mineral-rich states. The interaction of intense monsoon rainfall, prolonged dry spells, and increasingly frequent extreme weather events amplify AMD generation and transport. For instance, Jharkhand and Odisha face acute risk of ground water depletion and contamination of fresh water resources from extensive coal mining; Meghalaya and Assam due to their high sulfur coal, steep terrain and high rainfall are highly vulnerable to rapid erosion, flood borne contamination problems; Madhya Pradesh and Rajasthan interspersed with coal and mineral mines experience most localised contamination which can threaten irrigation and groundwater quality. The changing weather pattern further accelerates the weathering, erosion and transport processes at the mines. Therefore, addressing AMD under a changing climate requires state-specific action plans anchored in early-warning monitoring, climate resilient mine waste management, and strong community protection measures. Without proactive interventions, AMD will remain a climate-aggravated-barrier to safeguard the limited fresh water resources and sustainable development in these mining regions.

References

Baruah, B. P., and Khare, P. (2007). Desulfurization of oxidized Indian coals with solvent extraction and alkali treatment. Energy and Fuels, 21(4), 2156–2164. https://doi.org/10.1021/ef070087a

Choudhury, A., Lahkar, J., Saikia, B. K., Singh, A. K. A., Chikkaputtaiah, C., and Boruah, H. P. D. (2021). Strategies to address coal mine-created environmental issues and their feasibility study on northeastern coalfields of Assam, India: a review. Environment, Development and Sustainability, 23. Springer Netherlands. https://doi.org/10.1007/s10668-020-01091-4

Chuphal, D. S., I. Malik, R. Singh, Vangala, G., Niranjannaik, M., Vegad, U., Dilip, N.K., Mukhopadhyay, P., Selvan, J.P., Kapadia, V.,and Mishra, V. 2025. Multi-Day Extreme Precipitation Caused Major Floods in India During Summer Monsoon of 2024. Earth's Future, 13(5). https://doi.org/10.1029/2024EF005497.

Chowdhury, B. (2022). Trends, intensification, attribution and uncertainty of projected heatwaves in India. International Journal of Climatology, 42 (15), 7563-7582. https://doi.org/10.1002/joc.7665

CPCB, C. Z. O. (2011). Impact of Coal Mine Waste Water Discharge on Surroundings With Reference to Heavy Metals. Bhopal.

Equeenuddin S.K., Tripathy S., Sahoo P.K., Panigrahi M.K. (2010). Hydrogeochemical characteristics of acid mine drainage and water pollution at Makum Coalfield, India. Journal of Geochemical Exploration, 105(3), 75-82, ISSN 0375-6742, https://doi.org/10.1016/j.gexplo.2010.04.006.

IPCC (2023). Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change (Core Writing Team, Lee, H., & Romero, J., Eds.). Geneva, Switzerland: IPCC. https://doi.org/10.59327/IPCC/AR6-9789291691647

Khan, I., Javed, A., and Khurshid, S. (2013). Physico-chemical analysis of surface and groundwater around Singrauli Coal Field, District Singrauli, Madhya Pradesh, India. Environmental Earth Sciences, 68(7), 1849–1861. https://doi.org/10.1007/s12665-012-1873-y

Kumar, N., Tiwari, M. K., Singh, R., and Singh, A. K. (2022). Chemometrics in Ascertaining Hydrogeochemical Characteristics of Coal Mine Discharge vis-à-vis Behaviour of Surface and Groundwater Resources of the Mahan River Catchment Area, Central India. Mine Water and the Environment, 41(2), 518–532. https://doi.org/10.1007/s10230-022-00854-x

Kumar, V., Paul, D., and Kumar, S. (2024). Acid mine drainage from coal mines in the eastern Himalayan sub-region: Hydrogeochemical processes, seasonal variations and insights from hydrogen and oxygen stable isotopes. Environmental Research, 252(4), 119086. https://doi.org/10.1016/j.envres.2024.119086

Lakra, K. C., Banerjee, T. K., and Lal, B. (2021). Coal mine effluent-induced metal bioaccumulation, biochemical, oxidative stress, metallothionein, and histopathological alterations in vital tissues of the catfish, Clarias batrachus. Environmental Science and Pollution Research. https://doi.org/10.1007/s11356-021-12381-3

Mishra, V., Aadhar, S. and Mahto, S.S. (2021). Anthropogenic warming and intraseasonal summer monsoon variability amplify the risk of future flash droughts in India. npj Clim Atmos Sci 4. https://doi.org/10.1038/s41612-020-00158-3

Neogi, B., Singh, A. K., Pathak, D. D., and Chaturvedi, A. (2017). Hydrogeochemistry of coal mine water of North Karanpura coalfields, India: implication for solute acquisition processes, dissolved fluxes and water quality assessment. Environmental Earth Sciences, 76(14), 1–17. https://doi.org/10.1007/s12665-017-6813-4

Prachiti, P. K., Manikyamba, C., Singh, P. K., Balaram, V., Lakshminarayana, G., Raju, K., Singh, M.P., Kalpana M.S., and Arora, M. (2011). Geochemical systematics and precious metal content of the sedimentary horizons of Lower Gondwanas from the Sattupalli coal field, Godavari Valley, India. International Journal of Coal Geology, 88(2–3), 83–100. https://doi.org/10.1016/j.coal.2011.08.005

Pyrbot, W., Shabong, L., and Singh, O. P. (2019). Neutralization of Acid Mine Drainage Contaminated Water and Ecorestoration of Stream in a Coal Mining Area of East Jaintia Hills, Meghalaya. Mine Water and the Environment, 38(3), 551–555. https://doi.org/10.1007/s10230-019-00601-9

Rajulapati, C.R., Papalexiou, S.M., Clark, M.P., Razavi, S., Tang, G., and Pomeroy, J.W. (2020). Assessment of extremes in global precipitation products: How reliable are they? J Hydrometeorol, 21, 2855–2873. https://doi.org/10.1175/JHM-D-20-0040.1

Ray, S., and Dey, K. (2020). Coal Mine Water Drainage: The Current Status and Challenges. Journal of The Institution of Engineers (India): Series D, 101(2), 165–172. https://doi.org/10.1007/s40033-020-00222-5

Sahoo, P. K., Tripathy, S., Panigrahi, M. K., and Equeenuddin, S. M. (2014). Geochemical characterization of coal and waste rocks from a high sulfur bearing coalfield, India: Implication for acid and metal generation. Journal of Geochemical Exploration, 145, 135–147. https://doi.org/10.1016/j.gexplo.2014.05.024

Semy, K., and Singh, M. R. (2021). Quality assessment of Tsurang River water affected by coal mining along the Tsurangkong Range, Nagaland, India. Applied Water Science, 11(7), 1–11. https://doi.org/10.1007/s13201-021-01444-y

Shirin, S., Jamal, A., Emmanouil, C., and Yadav, A. K. (2021). Assessment of characteristics of acid mine drainage treated with fly ash. Applied Sciences (Switzerland), 11(9). https://doi.org/10.3390/app11093910

Singh, S., and Chakraborty, S. (2020). Performance of organic substrate amended constructed wetland treating acid mine drainage (AMD) of North-Eastern India. Journal of Hazardous Materials, 397(April), 122719. https://doi.org/10.1016/j.jhazmat.2020.122719

Tiwary, R. K., and Dhar, B. B. (1994). Environmental Pollution From Coal Mining Activities in Damodar River Basin, India. Mine Water and the Environment, 13, 10. Retrieved from www.IMWA.info

Weinberg, R., Coyte, R., Wang, Z., Das, D., and Vengosh, A. (2022). Water quality implications of the neutralization of acid mine drainage with coal fly ash from India and the United States. Fuel, 330, 125675. https://doi.org/10.1016/j.fuel.2022.125675

* * * * * * * * *