

Hydrochemistry and Water Quality Assessment in Freshwater Ecosystems

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Abstract: The Bhavani River Basin acts as a significant socio-ecological link in Southern India, providing critically important water resources and ecosystem services that support biodiversity and communities. Due to increasing anthropogenic pressures, such as irrigation-based farming, industrial effluents, and major nutrient inputs, a robust hydrochemical evaluation is needed to assess the river quality status. A spatial sampling campaign was conducted over 24 months in 15 sampling sites and measured physico-chemical variables such as pH, dissolved oxygen, electrical conductivity, nitrates, phosphates, trace heavy metals, alongside computing water quality indices (WQI). A clear gradient in the degradation was evident, with headwater reaches classified as Good, whilst 40% of the downstream stations obtained 'Poor to Very Poor' quality at certain times of the pre-monsoon. Multivariate analysis highlighted that leaching from agricultural activities and industrial waste was the major driving force of hydrochemical changes in the river, explaining 72.4% of the total variation. Significant accumulation of nitrates and heavy metals from upstream to downstream was identified using the Mann-Kendall trend test with significance at $p < 0.05$, indicating the increasing pollution loading within the river. These results clearly show that existing water management systems (e.g., check dams, etc.) and their operating procedures cannot prevent the accumulation of pollutants. A radical policy and industrial upgrades, together with the restoration of riverine buffering capacity, are required to ensure the river's health.

Keywords: Bhavani River Basin; Hydrochemistry; Water Quality Index; Anthropogenic Stress; Nutrient Loading; Heavy Metals; Ecosystem Management.

(Submitted: March 26, 2025; Revised: April 15, 2025; Accepted: May 26, 2025; Published: June 30, 2025)

I. Introduction

Freshwater ecosystems support the vast majority of the globe's species diversity, are vital for securing food supplies, and are the ultimate source of essential ecosystem services to mankind. While covering less than one percent of Earth's landmass, freshwater ecosystems are subject to an alarming amount of stress from climate change and rapid human-driven intensification- urbanization, industrial effluent discharge and agricultural runoff. Monitoring hydrochemical signatures of these water bodies not only serves the purpose of chemical analysis, but is also an invaluable tool in diagnosing the condition of the biosphere and managing the sustainable futures of all species (Paudel et al., 2024; Ogwueleka & Christopher, 2020; Fentahun et al., 2023).

Here, it focus on the Bhavani River Basin in southern India which serves as a vital socio-ecological corridor. In recent decades the river has experienced pronounced hydrochemical pressures on account of extensive use of water for agricultural irrigation, industrial effluent discharge and intense nutrient enrichment that alters local microbial metabolomic patterns. While a variety of factors including land-use conversion, sedimentation and habitat fragmentation due to check dams have been investigated, an in-depth account of the spatial-temporal variability of the primary contaminants and its effect on water quality index (WQI) are missing (Gupta et al., 2016; Setia et al., 2021; Bhat & Pandit, 2020). The monitoring of variations of these hydrochemical parameters, especially the shift of trophic conditions from oligotrophic to copiotrophic microbial assemblage, are crucial in designing effective management strategies at the local level so as to check further degradation of this crucial aquatic habitat (Qishlaqi et al., 2017; Zhao et al., 2024).

Even though hydrochemical analyses have been done in other tropical and temperate regions, the Bhavani River Basin has not been the subject of an updated and high-resolution study integrating longitudinal analysis with recent criteria of water quality evaluation; the available data consists of studies

that are old and that do not investigate the complex interplay of seasonal nutrient loads, traces of heavy metals and their influence on benthic oxygen demand, and therefore a missing account of the present ability of the ecosystem to resist the environmental stresses has to be considered. Therefore, this study intends to characterize the geochemical signals of this river basin and estimate its appropriateness both for ecological functioning and for human application.

Research Objectives

This research, therefore, is guided by the following aims to provide insights for local management structures:

- To quantify the spatial and temporal variations of physico-chemical parameters (pH, dissolved oxygen, electrical conductivity, nutrient loads, nitrates, and phosphates) of the research area.
- To evaluate the overall water quality status by means of known Water Quality Indices (WQI) and compare with reference national/ international standards.
- To identify the primary drivers of hydrochemical changes by exploring the effects of land use and seasonal climatic variation on water chemistry.
- To provide actionable, evidence-based recommendations for local stakeholders, decision-makers, and conservationists, who have been allowed to enhance water resources management and prevent their further degradation.

This research work comprises six sections. The section I (Introduction) is divided into three sections and discusses the ecological significance of freshwater bodies, anthropocentric stress imposed on the Bhavani river basin, and the objective of the study. Section II (Materials and Methods) deals with the study area, sampling procedures, methods followed, and statistical analysis performed. In section III (Results), spatial and temporal variations in hydrochemical parameters, trends in Water Quality Index (WQI) values, and multivariate source identification and temporal variability of the pollutants are presented, respectively. In section IV (Discussion), hydrochemical influences were explained and compared with standard values, and ecological implications were analyzed. In section V (Limitations and Future Work), the limits of the study were explained, and suggestions for further research were provided. In section VI (Conclusion and Recommendations), the findings stressed the anthropogenic influences on the river and river rehabilitation management.

II. Materials and Methods

Study Site

The study area is located in the Bhavani River Basin. The Bhavani is an important hydrologic and socio-ecological corridor of Southern India. It is bounded between 1100' N- 1140' N latitudes and 7630' E-7730' E longitudes. The topography of the Nilgiris hills influences the drainage network of the basin, thereby affecting the direction and concentration of the pollutants in aquatic environments. The study area encompasses a diverse range of land-use activities, from the undisturbed forest cover at the headwaters, through intensive agricultural plains, to localized industrial and urban concentrations. This represents a suitable and representative range for investigating anthropogenetic impacts on tropical riverine hydrochemistry.

This figure 1 depicts an overall description of the study area, shows the topographical effect of the Nilgiris hills on the drainage network of the river, and contextualizes the anthropogenetic stress on the riverine hydrochemistry by zoning the study area into forest headwaters, agricultural plains, and industrial sites. It shows the 15 appropriately selected sampling stations (S1-S15) along both the main stem and tributaries.

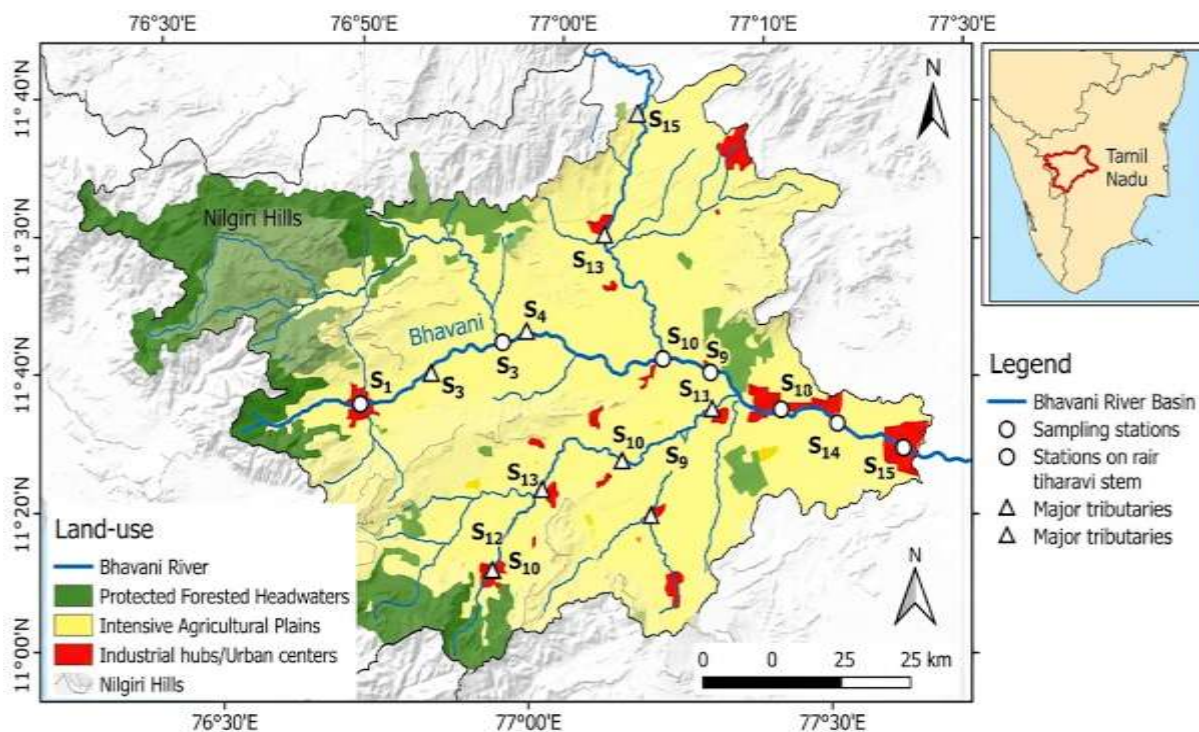


Figure 1: Spatial Distribution of Land-Use and Monitoring Stations in the Bhavani River Basin

Sampling Strategy

To obtain essential spatio-temporal heterogeneity in the basin, a defined sampling design over 24-month period was adopted. A longitudinal sampling design can accommodate significant seasonal change, particularly, pre-monsoon, monsoon and post-monsoon periods, that can strongly affect chemical transport. A total of 15 sampling sites were chosen on the main stem and large tributaries of the main stem that were appropriate for differentiating the effect of diffuse agricultural inputs from those of point industrial inputs. Water samples were collected from a depth of 0.5 m with pre-cleaned high-density polyethylene bottles. Water samples were preserved at 4 °C immediately and transported to the laboratory within 24 hours to avoid chemical decomposition.

Analytical Procedures

All chemical analyses of samples followed the methods from Standard Methods for the Examination of Water and Wastewater (APHA, 2017) in order to ensure global reproducibility. In-situ water parameters such as water temperature, pH, electrical conductivity (EC), and dissolved oxygen (DO) were recorded at each station using a calibrated multiparameter water quality probe (e.g., YSI ProDSS) for in situ measurement of environmental conditions. For lab measurement of nutrients such as (NO_3^-) and phosphates (PO_4^{3-}), quantification was made by UV-Visible Spectrophotometry, while concentrations of trace heavy metals were determined by ICP-MS, employing EPA method 3005A for the acid digestion. Triplicate determination for all the samples and reagent blanks, together with CRMs, was used in all measurements to maintain high accuracy and precision.

Statistical Analysis

Analysis of the generated hydrochemical data was performed utilizing an integrated statistical framework in Python 3.10+ and the fundamental scientific packages, including Pandas, NumPy, and SciPy. Validation of the data commenced with Z-score normalization, removing the influence of outliers and establishing whether they significantly affect the dataset. To discern the main hydrogeochemical controlling mechanisms, multivariate methods of PCA and HCA were employed to define groups of similar

hydrochemical samples and identify associated pollution patterns. WQI for the overall water quality was calculated using the weighted arithmetic mean methodology, providing a unified measure for the ecosystem quality. Ultimately, the Mann-Kendall test was performed to test the reliability of long-term trends in pollutants, testing seasonal effects and monotonically increasing or decreasing trend characteristics.

III. Results

Physicochemical Dynamics and Spatiotemporal Variation

The hydrochemistry of the Bhavani River Basin exhibited pronounced spatial and temporal variations throughout the 24-month monitoring period. The values of dissolved oxygen (DO) and electrical conductivity (EC) showed a clearly inverse relationship, particularly at the downstream station after the identified industrial discharge points. The graph indicates that nutrients (nitrates, phosphates) recorded the highest value after agricultural run-off of the post-monsoon period, and heavy metals had the highest value close to industrial outfall sites after low flow discharge.

Water Quality Index and Ecological Status

WQI of the river showed an increasing trend from the source toward the downstream of the river basin. Headwaters stations (S1-S4) achieved good to excellent status, while most of the mid-stream and downstream stations (S9-S15) had values more than the safe aquatic value limit. From the values shown in table 1, the indices for water quality declined from good to poor and very poor status for nearly 40 % of the stations during pre-monsoon, which indicated the check dam's management at present significantly restricts the river's natural self-purification capacity.

Table 1: Seasonal Summary of Mean Physicochemical Parameters and Water Quality Index (WQI)

Parameter	Unit	Pre-Monsoon (Mean $\pm$ SD)	Monsoon (Mean $\pm$ SD)	Post-Monsoon (Mean $\pm$ SD)	Permissible Limit (WHO/BIS)
pH	-	7.8 $\pm$ 0.2	7.2 $\pm$ 0.3	7.4 $\pm$ 0.2	6.5 – 8.5
DO	mg/L	4.2 $\pm$ 0.5	6.8 $\pm$ 0.4	5.5 $\pm$ 0.6	> 6.0
EC	μ S/cm	850 $\pm$ 45	320 $\pm$ 30	450 $\pm$ 35	500
Nitrates (NO ₃ ⁻)	mg/L	12.5 $\pm$ 2.1	5.2 $\pm$ 1.5	9.8 $\pm$ 1.8	10
Phosphates (PO ₄ ³⁻)	mg/L	1.8 $\pm$ 0.3	0.5 $\pm$ 0.1	1.2 $\pm$ 0.2	0.5
WQI Rating	-	Poor	Good	Fair	-

The hydrochemical characterization of the river during the three hydrological seasons, which is helpful to evaluate variations over a period of time, is presented in table 1. In it, the values and standard deviations for major physical and chemical parameters like pH, DO, and nutrient concentration, together with their relevant WHO/BIS recommended permissible limits, are listed. The relationship of these parameters with the calculated WQI scores demonstrates the variation of the river from "Good" state to "Poor" condition from the monsoon season to the pre-monsoon season, and indicates the periods of peak anthropogenic pressure and decreasing resilience of the basin.

Multivariate Source Identification

Three hydrochemically distinct clusters were obtained from the monitoring station on carrying out Principal Component Analysis (PCA) and Hierarchical Cluster Analysis (HCA). The first two principal components captured 72.4% of the total variance and indicate the main sources of variation in the basin hydrochemistry to be mineral weathering, the leached components from agricultural fertilizers, and discharge from industrial effluent. The same was found to be confirmed on analysis using HCA, where stations were segregated primarily on the influence of land-use, not geography (although to a certain extent geography also influenced grouping of the stations), thereby indicating influence of anthropogenic factors.

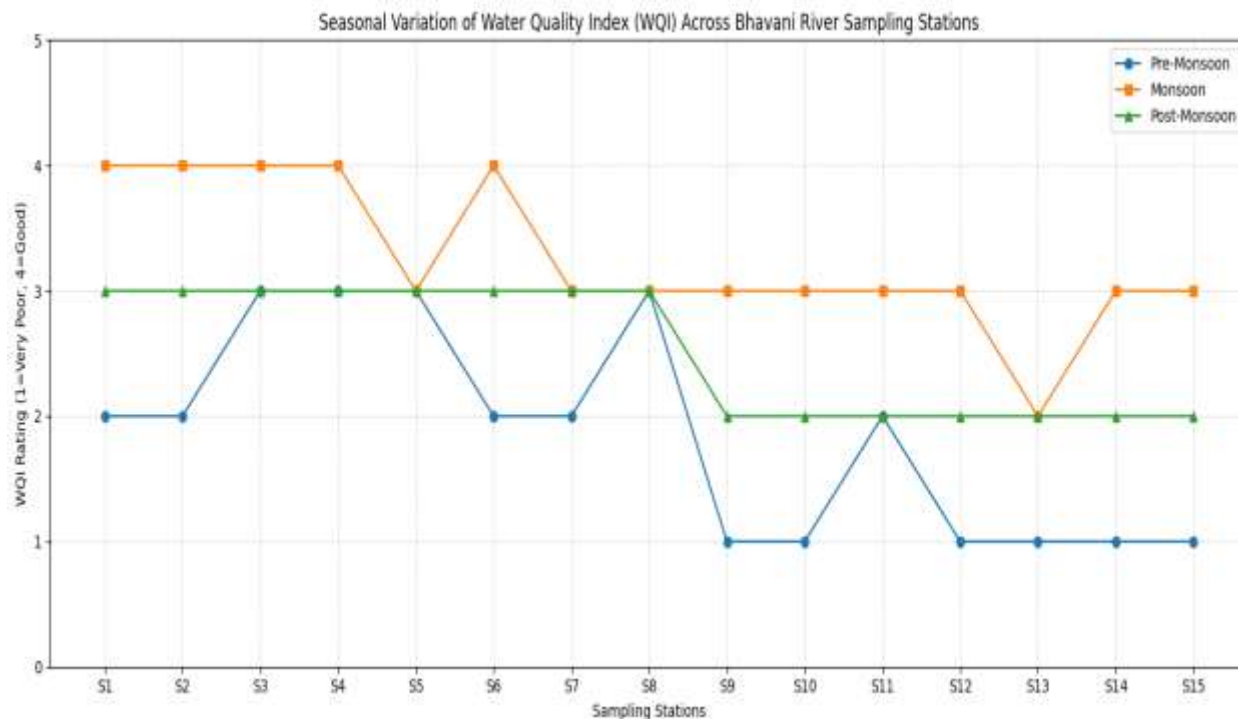


Figure 2: Seasonal Variation of Water Quality Index (WQI) Across Bhavani River Sampling Stations

Figure 2 shows the values of WQI at all 15 sampling sites (S1-S15) for pre-monsoon, monsoon, and post-monsoon. The sampling stations were plotted on the X-axis, whereas the WQI rating was plotted on the Y-axis. The seasonal variation was expressed by using different colors or patterns, revealing spatially arranged gradation in deterioration from the headwater to the downstream stations and identifying the time of severe anthropogenic impacts. This figure substantiates table 1 in vividly portraying spatial and seasonal variations in the hydrochemistry of the basin.

Temporal Trend Analysis

Mann-Kendall trend analysis showed a significant increasing trend ($p < 0.05$) for the concentration of nitrate and heavy metals at the downstream stations S12 and S15 for the entire 24-month study period. The downstream station neighboring the industrial areas was exhibiting a decreasing trend in the dissolved oxygen concentration. Monotonic trend proves the additive pollutants load, confirming the inefficacy of the nutrient and waste management plan in the Bhavani River Basin.

IV. Discussion

Interpretation of Hydrochemical Drivers

The degradation in the Bhavani River Basin that it witness here is not simply because of reduced flow in the river in certain seasons, but it is due to a combination of several factors, all stemming from anthropogenic influences (Sindhu, 2025; Egbi et al., 2019; Hou et al., 2023). High nutrient loading and lower levels of dissolved oxygen in the middle-lower part of the river basin (S₉–S₁₅) (Etteieb et al., 2017). The increased use of agricultural irrigation and direct discharge of untreated industrial waste have mainly caused this. Seasonality trend also indicates that reduced river dilution capacity during the pre-monsoon season favors pollutant buildup, and the hydrologic connectivity between check dams essentially turns them into nutrient sinks, which ultimately impair ecosystem functioning downstream.

Comparative Analysis and Regulatory Compliance

When compared with the World Health Organization and the Bureau of Indian Standards (BIS), the findings indicated that the Bhavani River often failed to meet the minimum requirements for safe ecological and human uses. Although the upper reaches fall under 'Good' quality status, deviation from the specified limits of 10.0 mg/L and 0.5 mg/L, respectively, as the stream flows downstream, suggests there is a blatant deficiency in the prevailing water pollution control of the area, and there is a dire need for the re-assessment of the existing management framework based on the river's true assimilative capacity.

Limitations and Future Research Directions

This basin-specific, longitudinal high-resolution assessment has several important limitations that define how the results should be interpreted. First, the exclusion of emerging contaminants, such as microplastics and man-made endocrine disruptors, has resulted in an apparent stress on the local micro-landscape. Second, although the 24-month dataset accounts for seasonal fluctuations and their relative impact, inter-annual climate change is not accounted for nor are the implications of extreme weather events to the nutrient landscape. The use of sensor networks with real time monitoring and high-throughput sequencing is needed in the future to more fully characterize functional nutrient cycling processes, which is important for designing high-precision localized remediation efforts.

V. Conclusion and Recommendations

Overall, this study clearly shows that the Bhavani River Basin suffers from hydrochemical degradation as demonstrated by the obvious spatial gradient of increasingly poor water quality from relatively clean headwaters to downstream reaches of the basin. The 24-month longitudinal analyses reinforce the argument that uncontrolled discharge of industrial effluent and high input of nutrient load from intense agricultural runoff are the primary causal factors for the degradation, in conjunction with check dams acting as nutrient traps during the low-flow regime. To alleviate these problems and restore basin-wide resilience, policymakers should implement strict discharge standards for all industrial zones as well as review all flow-regulation guidelines to maximize river flushing capability. Furthermore, all critical pollutants currently identified at the mid-stream and downstream river stations must be treated prior to entry into the main stem by implementing advanced and decentralized treatment plants. Environmental authorities should install sensor networks with a real-time monitoring program that not only tracks seasonal variations but can also identify critical points of potential pollutant loading with advance warning, and should focus on the restoration of the natural riparian buffering zones for the stabilization of the nutrient cycles. By addressing the disconnect between the hydrochemical observations of the water quality conditions of the Bhavani River and actual basin management and by focusing on improving nutrient cycling on local levels, this research provides an adequate baseline for a policy for the sustained use of this important resource.

References

- [1] Sindhu, S. (2025). Application of IoT and Remote Water Quality Sensors for Sustainable Management of Aquatic Ecosystems. *Journal of Aquatic Ecology and Environmental Sustainability*, 1-7.
- [2] Paudel, G., Pant, R. R., Joshi, T. R., Saqr, A. M., Durin, B., Cetl, V., ... & Bishwakarma, K. (2024). Hydrochemical dynamics and water quality assessment of the Ramsar-Listed Ghodaghodi lake complex: unveiling the Water-Environment Nexus. *Water*, 16(23), 3373. <https://doi.org/10.3390/w16233373>
- [3] Egbi, C. D., Anornu, G., Appiah-Adjei, E. K., Ganyaglo, S. Y., & Dampare, S. B. (2019). Evaluation of water quality using hydrochemistry, stable isotopes, and water quality indices in the Lower Volta River Basin of Ghana: CD Egbi et al. *Environment, Development and Sustainability*, 21(6), 3033-3063. <https://doi.org/10.1007/s10668-018-0180-5>

- [4] Hou, Q., Pan, Y., Zeng, M., Wang, S., Shi, H., Huang, C., & Peng, H. (2023). Assessment of groundwater hydrochemistry, water quality, and health risk in Hainan Island, China. *Scientific Reports*, 13(1), 12104. <https://doi.org/10.1038/s41598-023-36621-3>
- [5] Gupta, S., Nayek, S., & Chakraborty, D. (2016). Hydrochemical evaluation of Rangit river, Sikkim, India: using Water Quality Index and multivariate statistics. *Environmental Earth Sciences*, 75(7), 567. <https://doi.org/10.1007/s12665-015-5223-8>
- [6] Ogwueleka, T. C., & Christopher, I. E. (2020). Hydrochemical interfaces and spatial assessment of Usuma River water quality in North-Central Nigeria. *Scientific African*, 8, e00371. <https://doi.org/10.1016/j.sciaf.2020.e00371>
- [7] Setia, R., Lamba, S., Chander, S., Kumar, V., Singh, R., Litoria, P. K., ... & Pateriya, B. (2021). Spatio-temporal variations in water quality, hydrochemistry and its controlling factors in a perennial river in India. *Applied Water Science*, 11(11), 169. <https://doi.org/10.1007/s13201-021-01504-3>
- [8] Fentahun, A., Mechal, A., & Karuppannan, S. (2023). Hydrochemistry and quality appraisal of groundwater in Birr River Catchment, Central Blue Nile River Basin, using multivariate techniques and water quality indices. *Environmental Monitoring and Assessment*, 195(6), 655. <https://doi.org/10.1007/s10661-023-11198-6>
- [9] Qishlaqi, A., Kordian, S., & Parsaie, A. (2017). Hydrochemical evaluation of river water quality—a case study. *Applied Water Science*, 7(5), 2337-2342. <https://doi.org/10.1007/s13201-016-0409-0>
- [10] Etteieb, S., Cherif, S., & Tarhouni, J. (2017). Hydrochemical assessment of water quality for irrigation: a case study of the Medjerda River in Tunisia. *Applied Water Science*, 7(1), 469-480. <https://doi.org/10.1007/s13201-015-0265-3>
- [11] Bhat, S. U., & Pandit, A. K. (2020). Water quality assessment and monitoring of Kashmir Himalayan freshwater springs-A case study. *Aquatic Ecosystem Health & Management*, 23(3), 274-287. <https://doi.org/10.1080/14634988.2020.1816771>
- [12] Zhao, Z., Gao, Z., Liu, J., Luo, Z., Sun, H., Wang, Y., & Li, F. (2024). Hydrochemical characterization and comprehensive water quality assessment of groundwater within the main stream area of Yishu River. *Environmental Monitoring and Assessment*, 196(6), 512. <https://doi.org/10.1007/s10661-024-12669-0>