Groundwater evaluation for drinking and irrigation in Pakistan's mountainous terrain: hydro-chemical characteristics and health risks

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Renowned for its agriculture, livestock and mining, Zhob district, Pakistan faces the urgent problem of declining groundwater quality due to natural and human-induced factors. This deterioration poses significant challenges for residents who rely on groundwater for drinking, domestic, and irrigation purposes. Therefore, this novel study aimed to carry out a comprehensive assessment of groundwater quality in Zhob district, considering various aspects such as hydrochemical characteristics, human health risks, and suitability for drinking and irrigation purposes. While previous studies may have focused on one or a few of these aspects, this study integrates multiple analyses to provide a holistic understanding of the groundwater quality situation in the region. Additionally, the study applies a range of common hydro-chemical analysis methods (acid-base titration, flame atomic absorption spectrometry, and ion chromatography), drinking water quality index (WQI), irrigation indices, and health risk assessment models, using 19 water quality parameters. This multi-method approach enhances the robustness and accuracy of the assessment, providing valuable insights for decision-makers and stakeholders. The results revealed that means of the majority of water quality parameters, such as pH (7.64), electrical conductivity (830.13 μScm^{-1}), total dissolved solids (562.83 mgL^{-1}), as well as various anions ((mgL^{-1}) F^{-} = 0.55±0.42, Cl^{-} = 81.43±115, SO_4^{2-}=156.67±94.96, HCO_3^{-}=183.33±46.93, and NO_3^{-} = 2.61±2.24), and cations ((mgL^{-1}) Na^{+} = 61.87±38.79, Ca^{2+} = 65±39.06, Mg^{2+} = 34.89±25.2, and K^{+} = 3.57±2.14), were in line with drinking water norms. However, the water quality index (WQI) predominantly

indicated poor drinking water quality (range = 51–75) at 50% sites, followed by good quality (range = 26-50) at 37% of the sites, with 10% of the sites exhibiting very poor quality (range = 76-100). For irrigation purposes, indices such as sodium percent (mean = 31.37%), sodium adsorption ratio (mean = 0.98 $meqL^{-1}$), residual sodium carbonate (–3.15 $meqL^{-1}$), Kelley's index (mean = 0.49), and permeability (mean = 49.11%) indicated suitability without immediate treatment. However, the magnesium hazard (mean = 46.11%) and potential salinity (mean = 3.93) demonstrated that prolonged application of groundwater for irrigation needs soil management to avoid soil compaction and salinity. Water samples exhibit characteristics of medium salinity and low alkalinity (C2S1) as well as high salinity and low alkalinity (C3S1) categories. The Gibbs diagram results revealed that rock weathering, including silicate weathering and cation exchange, is the primary factor governing the hydrochemistry of groundwater. The hydro-chemical composition is dominated by mixed Ca–Mg–Cl, followed by Na–Cl and Mg–Cl types. Furthermore, the human health risk assessment highlighted that fluoride (F^-) posed a higher risk compared with nitrate (NO_3^-). Additionally, ingestion was found to pose a higher risk to health compared to dermal contact, with children being particularly vulnerable. The average hazard index (HI) for children was 1.24, surpassing the allowable limit of 1, indicating detrimental health effects on this subpopulation. Conversely, average HI values for adult females (0.59) and adult males (0.44) were within safe levels, suggesting minimal concerns for these demographic groups. Overall, the study's interdisciplinary approach and depth of analysis make a significant contribution to understanding groundwater quality dynamics and associated risks in Zhob district, potentially informing future management and mitigation strategies.