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Unraveling Natural and Anthropogenic Geochemical Processes Driving Groundwater Salinization and Its Health Implications in Cascade Irrigation Systems of Semi-Arid Agricultural Regions: An Integrated Geochemical Approach

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Cascade irrigation networks are an ancient rainwater harvesting method used to overcome water scarcity, provide irrigation water, and act as a source of groundwater recharge, particularly in South Asia. Highly salinized groundwater has been reported in many cascade irrigation systems in semi-arid agricultural regions and in many freshwater aquifers worldwide. However, the geochemical processes and salinity sources are not well understood yet. To investigate the issue, thirty-one water samples were collected from surface water, shallow groundwater, and deep groundwater within the Madderambawa cascade irrigation system, Sri Lanka, and analyzed for major cations, major anions, trace elements, and stable water isotopes of ^{18}O and ^{2}H. In the study region, 50% of groundwater is classified as highly saline (EC > 2250 µS/cm), located as isolated pockets in regolith aquifers. Except for alkalinity, major ions did not show a significant difference ($p>0.05$) between surface water and groundwater. Electrical conductivity (EC) showed a significant positive correlation with Na^+ ($r=+0.89$) and Cl^- ($r=+0.97$). Based on the results, groundwater chemistry in the region is primarily driven by natural geochemical processes such as water-rock interactions, ion exchange reactions, and evaporative concentration. However, high salinity in certain groundwater sources is mainly caused by anthropogenic factors, particularly the excessive application of KCl fertilizers and unregulated groundwater extraction. These processes have been further intensified by climate change. Almost all trace element concentrations were below permissible limits except for Mn, As, and Fe, which were elevated in a few wells. Additionally, 60% of wells exceeded the maximum allowable levels for Na^+ (200 mg/L) and Cl^- (250 mg/L), with mean concentrations of 461 mg/L and 879 mg/L, respectively. The consumption of high-salinity water has been linked to increased blood pressure among local communities. Furthermore, 72% of groundwater samples exceeded the maximum allowable hardness (250 mg/L), and 48% exceeded the fluoride limit (1.0 mg/L), both of which are associated with chronic kidney disease of unknown aetiology (CKDu) in semi-arid regions. The study highlights the urgent need to rehabilitate traditional tank cascade systems and regulate fertilizer use in semi-arid agricultural areas in tropical climates to mitigate groundwater salinization and its associated health risks.