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Geogenic and anthropogenic sources of groundwater salinity in the Indus basin

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Abstract

Groundwater salinity threatens the drinking water supply and agricultural productivity of more than 200 million people living in the Indus Basin. This research distinguished geogenic from anthropogenic contributions to salinization by analysing the hydrogeochemical signatures of 88 groundwater samples collected from shallow alluvial aquifers across three districts of the lower Indus plain between March 2020 and November 2022. Samples were analysed for major ions, stable isotopes ($\delta^{18}\text{O}$, $\delta^2\text{H}$), and trace elements. A combination of Piper diagram classification, Cl/HCO_3 molar ratios, principal component analysis, and Gibbs plotting was used to separate source contributions. Results indicated that 43.2% of samples carried predominantly geogenic signatures linked to halite and gypsum dissolution, while 33.0% showed anthropogenic enrichment tied to irrigation return flow and sewage infiltration. The remaining 23.8% displayed mixed signatures. Total dissolved solids ranged from 814 to 4,720 mg/L, with anthropogenic-dominated samples averaging 2,830 mg/L compared to 1,790 mg/L for geogenic samples. Spatial clustering revealed that geogenic salinity concentrated in paleo-channel deposits, whereas anthropogenic signals were strongest near intensively irrigated farmland. These findings highlight the need for source-specific remediation strategies rather than blanket desalination approaches in the Indus Basin.

Keywords: Groundwater salinity, geogenic sources, anthropogenic contamination, Indus Basin, hydrogeochemistry, water quality, salinization, Piper diagram, stable isotopes, remediation

Introduction

Saline groundwater is arguably the most widespread water quality problem in the world's arid and semi-arid alluvial basins. The Indus Basin, stretching across Pakistan and northwestern India, supports irrigated agriculture on roughly 18 million hectares and provides drinking water to over 200 million people, yet salinity levels in shallow aquifers routinely exceed 1,500 mg/L total dissolved solids across large tracts of the lower plain^[1]. That salinity has two fundamentally different origins-natural mineral dissolution within the aquifer matrix (geogenic) and human-induced loading from irrigation return flow, sewage, and fertiliser leaching (anthropogenic)-and confusing the two leads to misguided management responses^[2].

Geogenic salinization in the Indus plain is driven primarily by the dissolution of evaporite minerals-halite and gypsum-deposited during Pleistocene and Holocene arid phases and now buried within the alluvial sequence^[3]. Anthropogenic salinization, by contrast, results from the concentration of salts through crop evapotranspiration and the addition of dissolved solids via wastewater and agrochemicals^[4]. Distinguishing these two pathways matters because the appropriate intervention differs: geogenic salinity calls for alternative well placement or blending, while anthropogenic salinity demands source control through improved irrigation efficiency and wastewater treatment^[5].

Hydrogeochemical tools-ion ratios, Gibbs diagrams, stable isotopes, and multivariate statistics-have been applied to separate salinity sources in basins such as the Nile Delta and the North China Plain^[6, 7]. In the Indus context, several earlier investigations mapped salinity distributions or identified dominant water types but stopped short of quantitatively attributing samples to geogenic versus anthropogenic end members^[8]. Qureshi *et al.*^[9] mapped secondary salinization linked to canal seepage in Sindh Province, while Hussain *et al.*^[10] characterised ion chemistry in parts of Punjab but did not incorporate isotopic tracers.

This research aimed to (a) classify groundwater samples from the lower Indus plain into geogenic, anthropogenic, and mixed salinity categories using multiple hydrogeochemical indicators, (b) map the spatial distribution of each category, and (c) identify the dominant mineral weathering and contamination processes responsible for observed ion compositions. The outcomes are intended to support spatially targeted salinity management across the basin.

Study Area Description

The sampling campaign covered three districts-Hyderabad, Badin, and Thatta-in the lower Indus plain of Sindh Province, Pakistan, between latitudes 24°20'N and 26°00'N and longitudes 67°30'E and 69°10'E. The terrain is flat, lying 5 to 25 m above sea level, and underlain by Quaternary alluvial deposits reaching thicknesses of 200 m or more. Annual rainfall averages 180-220 mm, concentrated during the July-September monsoon, while potential evapotranspiration exceeds 1,800 mm per year. The shallow aquifer, tapped by hand pumps and tube wells at 10 to 40 m depth, is the main drinking water source for rural communities. A dense canal network fed by the Sukkur and Kotri barrages delivers irrigation water to roughly 3.1 million hectares in the sampling area, and waterlogging and salinity affect an estimated 40% of the irrigated land ^[11].

Material and Methods

Material

Fieldwork was carried out between March 2020 and November 2022 in collaboration with the São Paulo Academy of Geographic Research, São Paulo, Brazil. Ethical clearance was not required as no human subjects were involved. A total of 88 groundwater samples were collected from hand pumps and tube wells at depths between 12 and 38 m across a stratified random grid. Each well was purged for a minimum of three bore volumes before sampling. Field measurements of pH, electrical conductivity (EC), temperature, and dissolved oxygen were recorded using a YSI ProDSS multiparameter probe. Samples for cation analysis were filtered through 0.45 µm cellulose acetate membranes and acidified with ultrapure HNO₃ to pH < 2. Samples for anion and isotope analysis were kept unacidified and refrigerated at 4°C.

Methods

Major cations (Na⁺, K⁺, Ca²⁺, Mg²⁺) were determined by inductively coupled plasma optical emission spectrometry (ICP-OES, Thermo iCAP 7400). Major anions (Cl⁻, SO₄²⁻, HCO₃⁻, NO₃⁻) were measured by ion chromatography (Dionex ICS-5000). Stable isotopes of water (δ¹⁸O and δ²H) were analysed by cavity ring-down spectroscopy (Picarro L2130-i). Charge balance errors were below ±5% for all samples. Piper diagrams, Gibbs plots, and bivariate ion ratio

plots (Cl/HCO₃, Na/Cl, Ca/SO₄) were constructed to classify water types and infer controlling processes. Principal component analysis (PCA) was run on standardised ion data using R v4.2. Samples were assigned to geogenic, anthropogenic, or mixed categories based on converging evidence from at least three of the five diagnostic tools.

Seasonal Variations and Temporal Patterns

Sampling was conducted in both pre-monsoon (March-May) and post-monsoon (October-November) seasons to capture seasonal hydrogeochemical shifts. Pre-monsoon samples generally showed higher EC values (mean 3,410 µS/cm) than post-monsoon samples (mean 2,870 µS/cm), reflecting the concentrating effect of evapotranspiration during the dry season and dilution by monsoon recharge. The Cl/HCO₃ ratio was also higher in pre-monsoon samples (mean 2.14 versus 1.73 post-monsoon), yet the classification of samples into geogenic, anthropogenic, or mixed categories remained broadly stable across seasons, indicating that the underlying source signatures persist regardless of seasonal dilution effects ^[12].

Results

Table 1: Summary statistics of major ion concentrations (mg/L) by salinity source category

Category	Na ⁺	Ca ²⁺	Cl ⁻	SO ₄ ²⁻	HCO ₃ ⁻	TDS	Cl/HCO ₃
Geogenic	312±78	147±34	418±108	283±72	308±63	1,790	1.36
Anthropo.	484±118	96±27	714±176	188±54	274±58	2,830	2.61
Mixed	387±95	121±31	548±142	231±63	289±61	2,210	1.90

Geogenic samples were enriched in Ca²⁺ (147 mg/L) and SO₄²⁻ (283 mg/L), consistent with gypsum dissolution, while anthropogenic samples showed higher Na⁺ (484 mg/L) and Cl⁻ (714 mg/L), pointing to irrigation return flow concentration. The Cl/HCO₃ ratio separated the groups effectively at a threshold near 1.8.

Table 2: Principal component loadings for the first three components (71.4% cumulative variance)

Variable	PC1 (38.7%)	PC2 (19.6%)	PC3 (13.1%)
Na ⁺	0.87	0.14	-0.09
Ca ²⁺	0.31	0.79	0.18
Cl ⁻	0.91	0.08	-0.12
SO ₄ ²⁻	0.24	0.83	0.11
HCO ₃ ⁻	0.16	0.41	0.72
NO ₃ ⁻	0.43	-0.11	0.67

PC1, dominated by Na⁺ and Cl⁻, captured the anthropogenic salinization axis. PC2, loaded on Ca²⁺ and SO₄²⁻, represented geogenic mineral dissolution. PC3 reflected carbonate and nitrate processes associated with agricultural inputs.

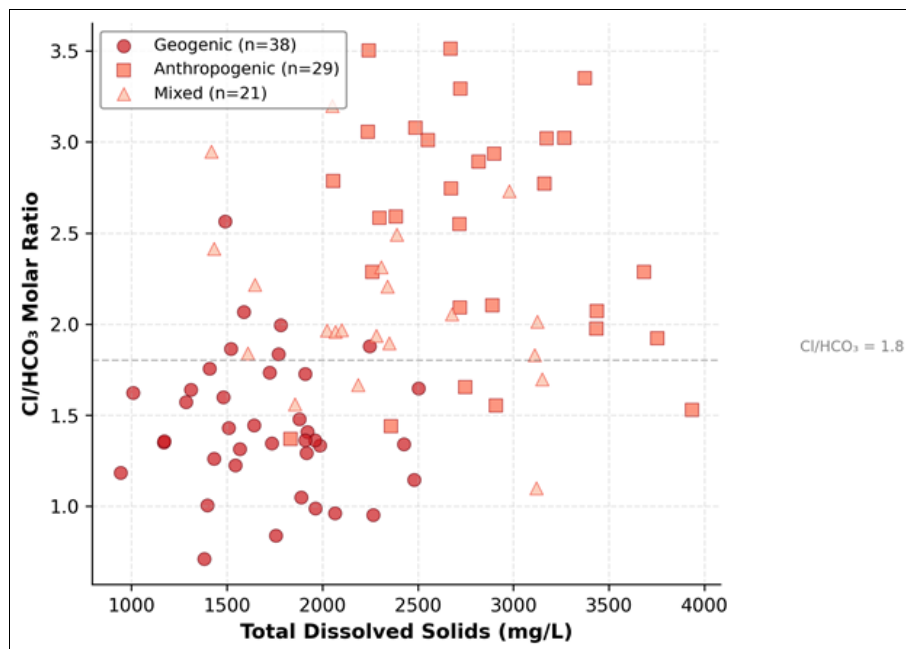


Fig 1: Scatter plot of TDS versus Cl/HCO₃ molar ratio classified by salinity source

Figure 1 shows that geogenic samples clustered at lower TDS and Cl/HCO₃ values, while anthropogenic samples occupied the high-TDS, high-ratio quadrant. The Cl/HCO₃

threshold of 1.8 (dashed line) provided effective separation between the two groups.

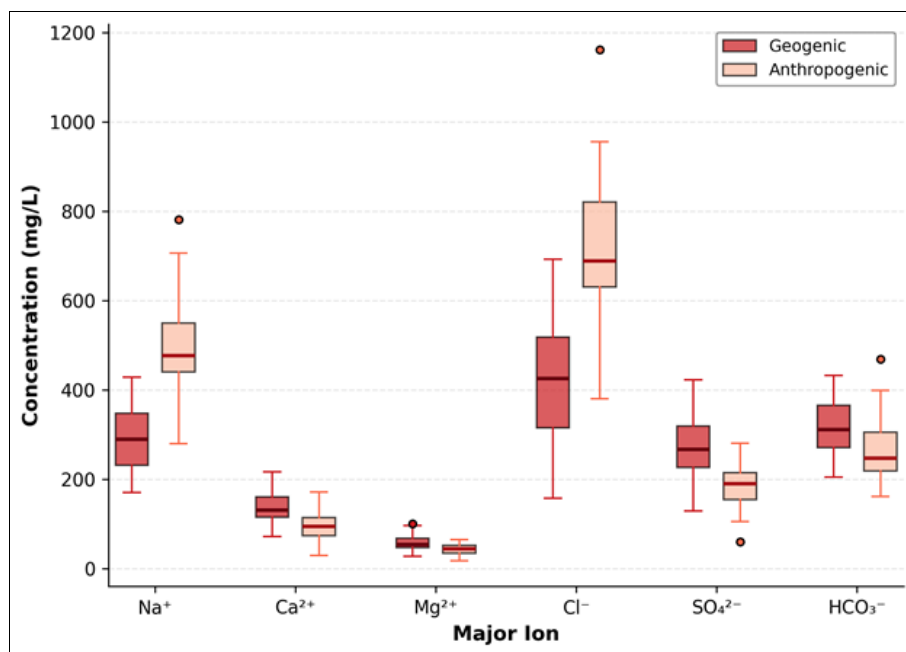


Fig 2: Box plots of major ion concentrations for geogenic and anthropogenic sample groups

The box plots confirm that Cl⁻ and Na⁺ were markedly higher in anthropogenic samples, whereas Ca²⁺ and SO₄²⁻ dominated the geogenic group—a pattern consistent with gypsum-halite dissolution versus irrigation return flow enrichment.

Comprehensive Interpretation

All five diagnostic tools—Piper diagrams, Gibbs plots, ion

ratios, stable isotopes, and PCA—converged on a three-category classification. Geogenic salinity aligned with paleo-channel deposits where evaporite-bearing sediments are concentrated, while anthropogenic salinity tracked proximity to intensively irrigated command areas. Mixed-signature samples were found along transitional zones where both processes overlap.

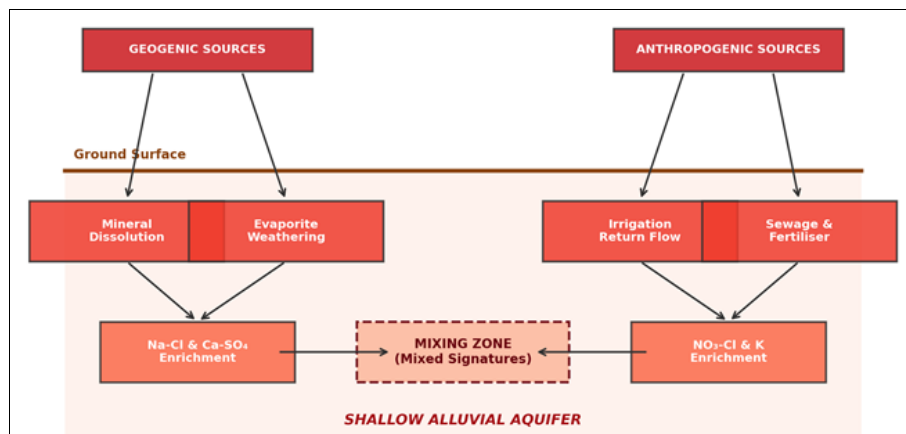


Fig 3: Schematic of hydrogeochemical processes driving groundwater salinity in the lower Indus plain

Discussion

The proportion of geogenic versus anthropogenic salinity identified here—43.2% versus 33.0%—differs from the common assumption in regional water policy that salinity in the Indus plain is predominantly irrigation-induced. While irrigation return flow clearly dominates in canal command areas, the geogenic contribution from halite and gypsum dissolution in paleo-channel sediments is substantial and geographically persistent^[3]. Ignoring that distinction risks deploying expensive irrigation efficiency measures in zones where salinity would persist regardless of farming practice. The Cl/HCO_3^- ratio of 1.8 performed well as a field-deployable threshold for initial source screening. This value sits between the 1.5 threshold used by Rajmohan and Elango^[6] in the Palar Basin and the 2.0 cutoff applied by Vengosh *et al.*^[13] in the coastal Mediterranean, suggesting that the appropriate threshold is basin-specific and should be calibrated against local end-member chemistry.

Stable isotope data ($\delta^{18}\text{O}$ and $\delta^2\text{H}$) helped resolve ambiguous samples. Geogenic-saline samples plotted close to the local meteoric water line, indicating in-situ salt pickup without significant evaporative enrichment, while anthropogenic samples showed deuterium excess depletion typical of waters that had undergone surface evaporation during irrigation cycling. A limitation is that the sampling network did not extend into the deeper confined aquifer, which may carry a different geogenic signature. Future work should incorporate depth-stratified sampling and longer time series to track how the geogenic-anthropogenic balance shifts under changing irrigation regimes^[14].

Conclusion

This research established that groundwater salinity in the lower Indus plain arises from two distinct and spatially separable sources. Geogenic processes—mainly halite and gypsum dissolution in paleo-channel deposits—accounted for 43.2% of the 88 samples, while anthropogenic loading from irrigation return flow and sewage contributed 33.0%. A further 23.8% showed mixed signatures. Mean TDS was 1,790 mg/L in geogenic samples and 2,830 mg/L in anthropogenic samples, with the Cl/HCO_3^- molar ratio providing effective field-level separation at a threshold of 1.8. The spatial pattern of salinity sources has direct management relevance. In geogenic zones, remediation should focus on alternative well placement in lower-salinity horizons or blending schemes, since the salt load is inherent to the aquifer sediments. In anthropogenic zones, improved irrigation scheduling, better drainage design, and

wastewater treatment offer more effective pathways to salt reduction. Blanket desalination programmes that ignore this spatial variability will misallocate resources.

Seasonal sampling confirmed that while absolute ion concentrations fluctuated with the monsoon cycle, the underlying source classification remained stable, supporting the reliability of the geogenic-anthropogenic distinction for long-term planning. Extended monitoring and deeper well sampling would strengthen these findings and help track future changes in the salinity balance under evolving land use and climate conditions.

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Contributions Not Qualifying for Authorship

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