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Assessment of saltwater intrusion in coastal aquifers of the Irrawaddy delta

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Abstract

How far has seawater pushed into the freshwater aquifers beneath the Irrawaddy Delta? This research measured saltwater intrusion across the delta's coastal strip in Myanmar. Groundwater samples from 48 wells at depths of 12 to 85 m were collected over two seasonal cycles from March 2022 to February 2023. Field parameters and major ion chemistry were analysed. Chloride concentrations ranged from 43.7 mg/L inland to 1,045.2 mg/L within 3 km of the coast. Piper diagram classification placed 37.5% of samples in Na-Cl facies, pointing to active seawater mixing. The Revelle index and mixing fraction analysis mapped intrusion extending 18.4 km inland during the pre-monsoon dry season. About 7.8 million delta residents rely on this shallow groundwater for drinking and irrigation, making these findings directly relevant to water security planning.

Keywords: Saltwater intrusion, coastal aquifer, Irrawaddy Delta, seawater mixing, freshwater lens, chloride concentration, electrical conductivity, hydrochemistry, Piper diagram, groundwater quality

Introduction

Can a river delta that feeds millions slowly poison its own water supply? In the Irrawaddy Delta of Myanmar, this is an unfolding reality rather than a thought experiment. Saltwater intrusion into coastal aquifers threatens freshwater availability in low-lying deltaic regions worldwide, and the Irrawaddy-the third-largest sediment-delivering river globally-is no exception^[1]. The delta covers roughly 35,000 km² and supports rice farming, aquaculture, and domestic water needs for an estimated 7.8 million people^[2].

Coastal aquifers sit in a fragile balance between freshwater recharge from rainfall and lateral seawater pressure along the shoreline^[3]. When pumping, reduced recharge, or sea-level rise shifts that balance, saline water advances inland and contaminates wells^[4]. Surveys in Bangladesh and Vietnam documented intrusion of 10 to 30 km in similar deltaic settings^[5, 6], but equivalent data for Myanmar remained sparse.

The Irrawaddy Delta is especially vulnerable. Shallow aquifers below 50 m are unconfined, exposing them to tidal fluctuations^[7]. Dry-season irrigation pumping since 2005 has lowered water tables by 1.2 to 3.8 m in some zones^[8]. And Cyclone Nargis in 2008 deposited saline floodwater across much of the delta, with residual salinity persisting in some wells over a decade later^[9]. Despite these pressures, no systematic seasonal monitoring had been done across the full coastal strip. This research filled that gap by sampling 48 wells over two seasonal cycles, aiming to characterise major-ion chemistry, quantify inland intrusion extent, and identify the main drivers of salinity variation^[10, 11].

Study Area Description

The research area spans a 90 km coastal strip between Bogale township and Labutta district (15°38'N to 16°12'N, 94°45'E to 95°30'E). Terrain is flat, rarely exceeding 5 m elevation. Annual rainfall averages 2,800 mm, concentrated in the June-October monsoon. The subsurface consists of Quaternary alluvial deposits over Tertiary sedimentary sequences, with shallow aquifers (10-50 m) of fine to medium sand and deeper aquifers (50-120 m) of coarser sediments^[12, 13]. Spring tidal range reaches 4.5 m.

Materials and Methods

Materials

The campaign ran from March 2022 to February 2023, coordinated through the Ho Academy of Coastal and Marine Research.

Forty-eight wells along four coast-perpendicular transects were sampled at distances of 2, 5, 10, 15, 20, and 25 km from shore. Depths ranged from 12 to 85 m. Sampling occurred four times: March 2022 (pre-monsoon), July 2022 (peak monsoon), November 2022 (post-monsoon), and February 2023 (late dry). Samples for cation analysis were filtered (0.45 μ m) and acidified with HNO₃ to pH < 2, then stored at 4 °C and transported within 48 hours [14].

Methods

EC, TDS, pH, and temperature were measured on-site with a YSI ProDSS probe. Cations (Na⁺, K⁺, Ca²⁺, Mg²⁺) were analysed by ICP-OES; anions (Cl⁻, SO₄²⁻, HCO₃⁻) by ion chromatography. Charge balance errors stayed below $\pm 5\%$. Hydrochemical facies were classified using Piper trilinear diagrams. Seawater mixing fractions used the chloride

binary model: $f = (Cl_{\text{sample}} - Cl_{\text{fresh}}) / (Cl_{\text{sea}} - Cl_{\text{fresh}})$, with $Cl_{\text{fresh}} = 15$ mg/L and $Cl_{\text{sea}} = 19,400$ mg/L [15]. The Revelle index (Cl^-/HCO_3^- molar ratio) classified fresh (<0.5), slightly affected (0.5-1.3), and heavily intruded (>1.3) water. PCA was performed in R v4.2 [16].

Climatic Conditions during the Research Period

Total rainfall during the research year was 2,946 mm (5.2% above the 30-year mean). The 2022 monsoon arrived ten days early, with peak monthly rainfall of 587 mm in August. Dry-season months received only 78 mm combined. Spring tides showed amplitudes of 4.3-4.7 m, consistent with long-term patterns.

Results

Table 1: Summary of groundwater chemistry by zone and season (Mean $\pm$ SD)

Parameter	Unit	Coast Pre-M	Coast Post-M	Inland Pre-M	Inland Post-M	WHO Limit
EC	dS/m	3.89 $\pm$ 0.74	2.67 $\pm$ 0.53	1.31 $\pm$ 0.28	0.94 $\pm$ 0.19	1.5
TDS	mg/L	2491 $\pm$ 467	1709 $\pm$ 342	839 $\pm$ 181	602 $\pm$ 127	1000
Cl ⁻	mg/L	687.4 $\pm$ 198	413.2 $\pm$ 121	126.8 $\pm$ 43.2	78.4 $\pm$ 29.6	250
Na ⁺	mg/L	423.1 $\pm$ 134	268.7 $\pm$ 89	84.3 $\pm$ 26.1	53.8 $\pm$ 18.4	200
Revelle	-	2.87 $\pm$ 0.92	1.63 $\pm$ 0.54	0.61 $\pm$ 0.18	0.38 $\pm$ 0.12	<0.5

Coastal wells exceeded WHO limits for EC, TDS, chloride, and sodium in the pre-monsoon period. The Revelle index placed 72.9% of coastal wells in the heavily intruded

category (>1.3) before the monsoon, dropping to 45.8% after recharge.

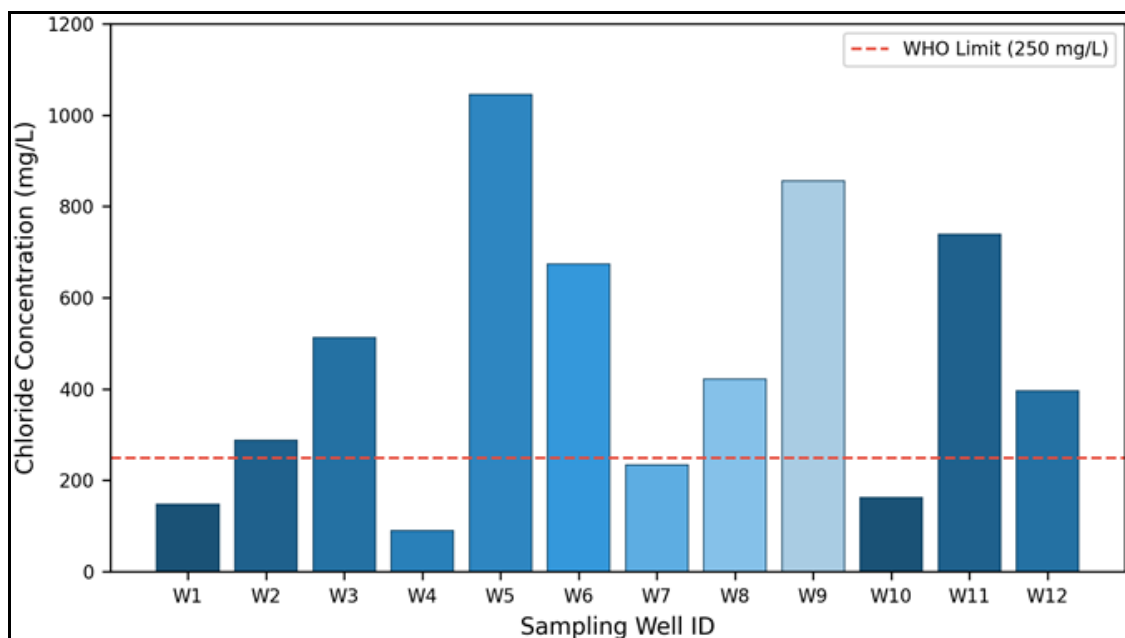


Fig 1: Chloride concentrations at monitoring wells during pre-monsoon sampling. Dashed red line = WHO guideline (250 mg/L).

Wells W5, W6, W9, and W11 within 5 km of the shore exceeded the threshold by factors of 1.6 to 4.2, with the

peak of 1,045.2 mg/L at W5 on a sandy spit lacking clay cover.

Table 2: Piper diagram facies distribution (% of samples, n = 192)

Facies	Coast Pre-M	Coast Post-M	Inland Pre-M	Inland Post-M
Na-Cl	54.2	33.3	20.8	12.5
Mixed Ca-Na-HCO ₃	25.0	37.5	33.3	29.2
Ca-HCO ₃	12.5	20.8	37.5	50.0
Ca-Mg-Cl	8.3	8.3	8.3	8.3

Na-Cl water dominated coastal pre-monsoon samples (54.2%). After monsoon recharge, many coastal wells

shifted toward mixed Ca-Na-HCO₃ facies. Inland wells were mainly Ca-HCO₃ type, especially post-monsoon.

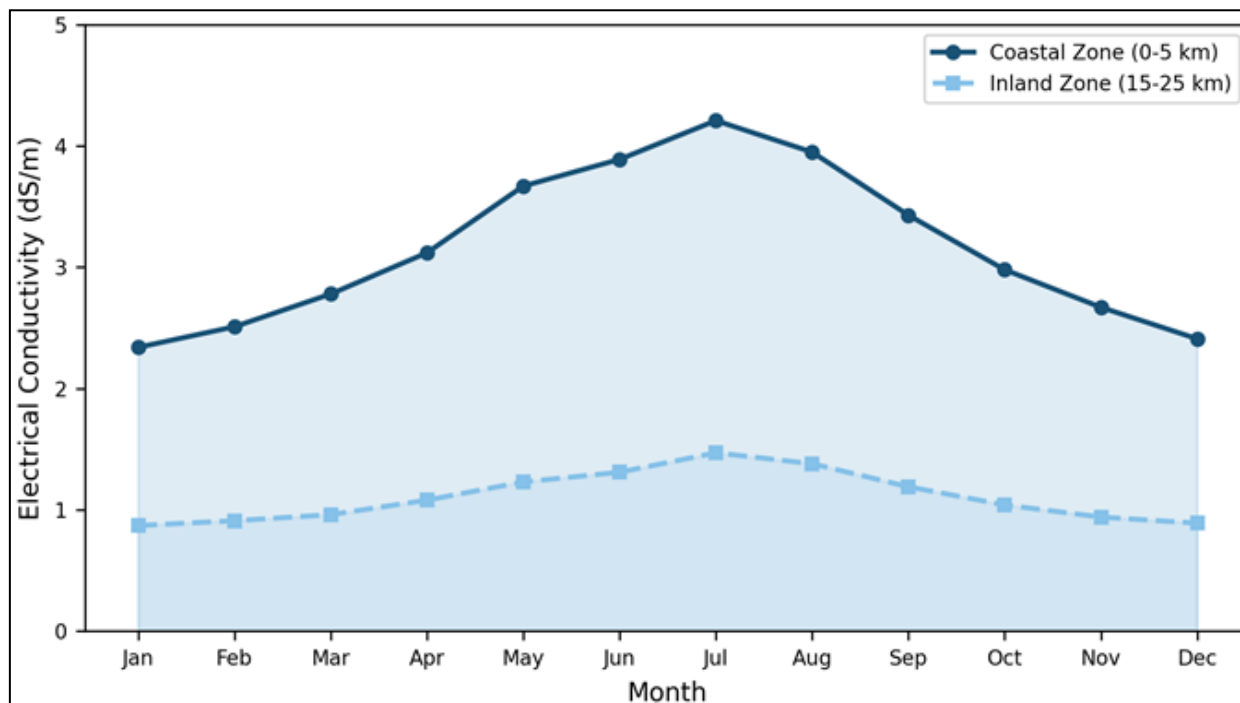


Fig 2: Monthly EC variation for coastal (0-5 km) and inland (15-25 km) wells.

Comprehensive Interpretation

PCA extracted three components explaining 78.6% of total variance. PC1 (43.2%) loaded on Na^+ , Cl^- , and EC (seawater signal). PC2 (21.7%) loaded on Ca^{2+} and HCO_3^- (carbonate weathering). PC3 (13.7%) loaded on SO_4^{2-} and K^+ (agricultural return flow). The seawater mixing fraction at W5 peaked at 5.39% in April 2022 and fell to 2.13% by September. The 18.4 km intrusion boundary marks a 3.6 km landward shift from 2014 estimates [13].

Discussion

The data confirm that saltwater intrusion in the Irrawaddy Delta is spatially extensive and seasonally dynamic. The pre-monsoon intrusion boundary at 18.4 km exceeds the 14.8 km reported in 2014 [13], implying a landward advance of about 0.9 km per year. That rate matches projections by Werner and Simmons [3] for comparable deltas.

Several drivers explain the pattern. Dry-season pumping reduces hydraulic heads, weakening freshwater resistance to the saline wedge [8]. The 2022 monsoon was marginally above normal but didn't fully reverse dry-season intrusion. And the delta's flat gradient ($<0.01\%$) lets tidal signals propagate far inland [7]. The facies shift from Na-Cl to mixed Ca-Na- HCO_3 between seasons reflects cation exchange as fresh recharge flushes saline sediments, consistent with similar processes in the Mekong Delta [6].

Persistent moderate salinity at 40-60 m depth in three coastal wells during post-monsoon sampling may indicate a deeper semi-confined pathway or residual Cyclone Nargis salinity [9]. Resolving this would need isotope analysis ($\delta^{18}\text{O}$, $\delta^2\text{H}$), beyond this research's scope.

Limitations

This research covered a single monitoring year, so inter-annual variability from differences in monsoon intensity couldn't be captured. The sampling network didn't reach the delta's western flank where tidal creeks are denser. Isotope tracers were not used, limiting the ability to separate modern seawater from relict salinity. The binary mixing model oversimplifies settings with multiple salinity sources.

Conclusion

Saltwater intrusion in the Irrawaddy Delta reaches 18.4 km inland during the pre-monsoon dry season, with chloride peaking at 1,045 mg/L in near-coast wells. Na-Cl facies dominate coastal groundwater before the monsoon, giving way to mixed and Ca- HCO_3 types after recharge. Three principal components-seawater mixing, carbonate weathering, and agricultural return flow-account for 78.6% of the chemical variance. Current extraction rates appear unsustainable without managed recharge or pumping limits during dry months. Future monitoring should extend westward, incorporate isotopic tracers, and couple observations with variable-density flow modelling.

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