

ORIGINAL RESEARCH

Hydro-Geophysical Assessment of Freshwater-Lens Thinning and Saline Upconing in Three Inhabited Atolls of the Northern Cook Islands

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ABSTRACT

Background: Freshwater lenses are the principal source of potable water for the low-lying coral atolls of the Northern Cook Islands, yet they are acutely vulnerable to sea-level rise, tidal forcing and over-abstraction.

Objective: This study quantified freshwater-lens thinning and saline upconing across three inhabited atolls (Rakahanga, Manihiki and Pukapuka) and identified the environmental and anthropogenic drivers of degradation.

Methods: Electrical resistivity tomography delineated the freshwater-seawater interface, while 24 community wells were sampled in the 2024 wet and dry seasons for electrical conductivity (EC), chloride, tidal amplitude, abstraction and recharge. Data were analysed offline with ANOVA (Tukey HSD, η^2), Pearson correlation, multiple regression, principal component analysis (PCA) and salinisation indices, benchmarked against WHO/US-EPA guidelines.

Results: Mean lens thickness was critically low at 4.34 ± 1.01 m and differed significantly among atolls ($F(2,21) = 45.73$, $p < 0.001$, $\eta^2 = 0.813$), thinning from Rakahanga (5.45 m) to Pukapuka (3.27 m). Chloride (mean 405 mg/L) exceeded the 250 mg/L WHO guideline in 19 of 24 wells and was inversely correlated with thickness ($r = -0.835$, $p < 0.001$). Regression explained 83.5% of the variance (adjusted $R^2 = 0.810$; $F(3,20) = 33.69$, $p < 0.001$), and PCA resolved a single salinisation axis explaining 77.5% of variance; the Groundwater Quality Index rose from 106 to 179 along the same gradient.

Conclusion: The freshwater lenses of the Northern Cook Islands are thin, saline and actively degrading under combined tidal forcing and manageable anthropogenic abstraction, requiring optimised pumping, rainwater augmentation and continuous monitoring to safeguard atoll water security.

Introduction

Coral atolls are among the most geographically isolated and environmentally fragile freshwater systems on Earth. For the communities that inhabit these narrow, low-lying reef islands, the only permanent terrestrial source of potable water is the freshwater lens — a thin body of meteoric water that floats, in accordance with the Ghyben-Herzberg principle, upon denser underlying seawater within a highly permeable dual carbonate aquifer.^{1,2} Because lens volume scales non-linearly with island width and recharge, atoll aquifers respond rapidly to climatic and anthropogenic perturbation, and small changes in sea level, rainfall or abstraction can translate into disproportionately large changes in the thickness and salinity of the potable resource.^{3,4} Global assessments now rank small-island groundwater among the water resources most exposed to twenty-first-century climate change.^{1,5}

The Northern Cook Islands epitomise this vulnerability. Their atolls combine extremely narrow landmasses, high reef-flat permeability and pronounced tidal transmissivity with near-total dependence on subterranean and rainwater supplies, so that any contraction of the lens directly threatens human habitability.^{3,5} Population concentration in a few villages, the proliferation of shallow hand-dug and pumped wells, and episodic drought associated with El Niño-Southern Oscillation variability jointly intensify abstraction pressure at precisely the times when recharge is lowest.^{6,7} Storm-surge overwash — documented historically in this island group — periodically salinizes the lens and can require months to years of subsequent recharge to flush.^{7,8}

Traditional investigations of atoll hydrogeology have relied on isolated point-source sampling of individual wells or on analytical and numerical estimation of recharge and lens geometry from generalized climatic inputs.^{9,10} Although such approaches provide valuable

baselines, they poorly resolve the three-dimensional geometry of the freshwater-seawater interface and the local upconing induced by pumping. Geophysical imaging, and in particular electrical resistivity tomography (ERT), now offers a non-invasive means of mapping subsurface salinity because the bulk resistivity of saturated carbonate sediment is governed largely by pore-water conductivity.^{11,12} When ERT is coupled with hydrochemical profiling and stable-isotope analysis, modern meteoric recharge can be distinguished from actively intruding seawater and from relic connate brine.^{13,14} Time-lapse and cross-hole resistivity surveys have successfully tracked seawater-intrusion dynamics in coastal aquifers elsewhere,^{13,15} and diagnostic multi-method frameworks are increasingly advocated for salinisation assessment.^{12,16}

Potable-water quality on atolls is conventionally evaluated against the World Health Organization (WHO) drinking-water guidelines and, secondarily, the United States Environmental Protection Agency (US-EPA) secondary maximum contaminant levels, which set an aesthetic chloride threshold of 250 mg/L and a total-dissolved-solids advisory of 1000 mg/L (approximately 1500 $\mu\text{S}/\text{cm}$ electrical conductivity).^{17,18} Salinisation severity is further quantified through composite groundwater-quality and seawater-mixing indices and, where boreholes permit, through hydraulic and geophysical interface metrics.^{14,15} Multivariate statistical tools — correlation, multiple regression and principal component analysis — have become standard for

disentangling the natural and anthropogenic controls on coastal-aquifer salinity.^{14,19}

Despite the maturation of these techniques, integrated hydro-geophysical studies remain profoundly scarce in the remote Pacific, and empirical, well-resolved evidence for the Northern Cook Islands is almost entirely absent from the peer-reviewed literature.^{3,5} This knowledge gap is consequential: without spatially explicit, statistically robust characterisation of lens geometry and its drivers, island authorities cannot separate unavoidable natural tidal forcing from manageable anthropogenic abstraction, and therefore cannot design targeted conservation policy. The novelty of the present work lies in bridging high-resolution ERT imaging with rigorous multivariate modelling and standardised salinisation indices to isolate and quantify the anthropogenic component of lens degradation at the atoll scale.

Figure 1 shows the study area. The aim of this study was to quantify the extent of freshwater-lens thinning across three inhabited atolls of the Northern Cook Islands and to identify and rank the environmental and anthropogenic drivers of that thinning. The specific objectives were to (i) characterise lens thickness, EC and chloride against WHO/US-EPA guidelines; (ii) test for inter-atoll differences using ANOVA with effect sizes; (iii) resolve the multivariate structure of the system through correlation, regression and PCA; and (iv) translate the findings into groundwater-management recommendations for atoll water security.

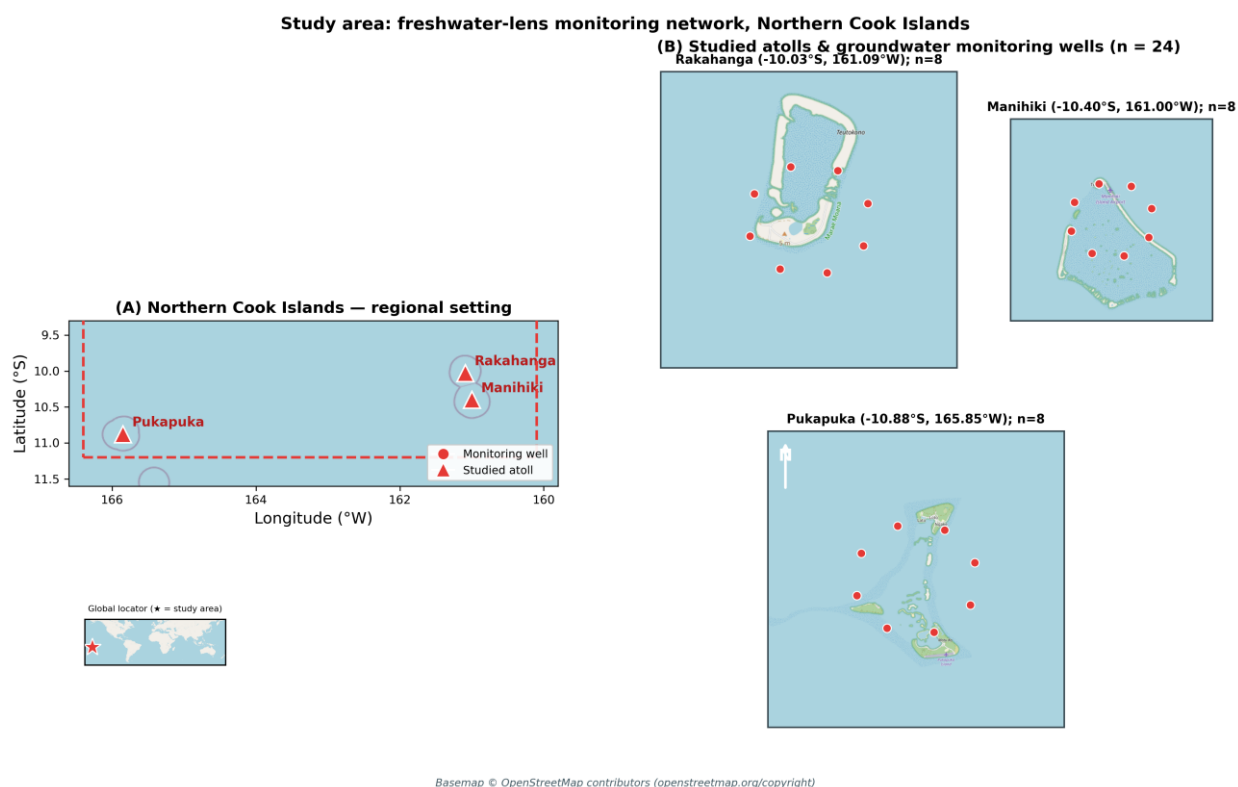


Figure 1. Study area map (OpenStreetMap basemap) showing the 24 groundwater monitoring wells across three inhabited atolls (Rakahanga, Manihiki, Pukapuka) in the Northern Cook Islands; the global locator marks the study region in the South Pacific.

Materials and Methods

Study design and area

This study employed a cross-sectional environmental-monitoring design combining geophysical imaging and hydrochemical sampling across a natural gradient of anthropogenic pressure. Fieldwork was conducted on three inhabited atolls of the Northern Cook Islands — Rakahanga (10.03°S, 161.09°W), Manihiki (10.40°S, 161.00°W) and Pukapuka (10.88°S, 165.85°W) — spanning a coordinate range of approximately 10.0–10.9°S and 161.0–165.9°W (Figure 1). The three atolls share a common geological template of Holocene coral-sand aquifers overlying karstic Pleistocene limestone, producing a dual-permeability system in which a shallow, moderately permeable Holocene unit is underlain by a highly transmissive Pleistocene unit that transmits tidal signals efficiently and promotes rapid mixing.^{2,20} They differ, however, in land area, population density and abstraction intensity, providing a quasi-experimental gradient from the sparsely populated Rakahanga to the densely settled, water-stressed Pukapuka.

Geophysical imaging (ERT)

The freshwater–seawater interface was delineated using electrical resistivity tomography. On each atoll, shore-perpendicular transects were established from the ocean beach across the island to the lagoon shore, positioned to intersect the principal village abstraction zones. A multi-electrode resistivity meter was deployed in a Wenner–Schlumberger array to balance vertical resolution and depth of investigation, with electrode spacings selected to image the upper 15–20 m of the aquifer at metre-scale resolution. Apparent-resistivity pseudosections were inverted using a robust (L1-norm) least-squares scheme with topographic correction; the halocline was identified as the resistivity contour below 10 $\Omega\cdot\text{m}$, a threshold consistent with the transition from fresh to brackish pore water in carbonate sediments.^{11,12} Lens thickness at each well was taken as the vertical distance from the water table to the 10 $\Omega\cdot\text{m}$ interface directly beneath the well, cross-validated against down-hole conductivity.

Hydrochemical sampling and analysis

A network of 24 community monitoring wells (eight per atoll) was sampled during both the 2024 wet season and the 2024 dry season, with sampling points distributed around the inhabited rim of each atoll to capture within-island heterogeneity. Prior to sampling, each well was purged of at least three casing volumes. Field parameters — electrical conductivity, pH, temperature and water level — were measured in situ with a calibrated multiparameter probe. Samples for major-ion analysis were collected in pre-rinsed high-density polyethylene bottles, filtered (0.45 μm), stored at 4 °C and analysed for chloride following standard APHA methods (argentometric/ion-chromatographic determination). A subset was analysed for the stable isotopes of oxygen ($\delta^{18}\text{O}$) and hydrogen ($\delta^2\text{H}$) to characterise recharge provenance and seawater mixing.¹⁴ Daily abstraction per

well was estimated from pump-run logs and household surveys, and net recharge was derived from a seasonal water-balance using island rainfall and reef-flat evapotranspiration estimates.¹⁰

Quality assurance and control

Analytical quality was maintained through field blanks, duplicate samples (10% of the total) and instrument calibration against certified reference solutions before each field campaign. Duplicate relative percent differences for chloride were below 5%, and charge-balance errors for full ionic analyses were within $\pm 5\%$. Resistivity data quality was ensured by rejecting quadripoles with reciprocal errors exceeding 5% prior to inversion, and inversion root-mean-square misfit was kept below 8%.

Standards and benchmarking

Groundwater quality was benchmarked against WHO drinking-water guidelines and US-EPA secondary maximum contaminant levels, using a chloride guideline of 250 mg/L and an EC surrogate of 1500 $\mu\text{S}/\text{cm}$ for the 1000 mg/L total-dissolved-solids advisory.^{17,18} Where the Cook Islands apply national potable-water criteria, these are broadly aligned with the WHO values adopted here.

Statistical analysis

All analyses were performed offline in a reproducible numerical environment (Python/NumPy). Distributional assumptions were screened using the Shapiro–Wilk test for normality and Levene's test for homogeneity of variance. Site characteristics were summarised as mean, standard deviation, minimum, maximum and coefficient of variation. Inter-atoll differences were assessed by one-way analysis of variance (ANOVA); effect sizes were reported as eta-squared (η^2), and significant omnibus tests were followed by Tukey's honestly-significant-difference (HSD) post-hoc comparisons with compact-letter displays. Bivariate associations were quantified with Pearson correlation coefficients and two-tailed significance tests. A multiple linear regression modelled lens thickness as a function of tidal amplitude, abstraction rate and recharge, reporting standardised coefficients, the coefficient of determination and its adjusted form, and the overall F-test. Principal component analysis (PCA) was performed on the six standardised hydrogeological variables to resolve the dominant modes of covariation, with components retained on the Kaiser (eigenvalue > 1) criterion. Salinisation was further quantified with a composite Groundwater Quality Index, a chloride-based contamination factor and a two-end-member seawater-mixing fraction.^{14,15} Statistical significance was set at $\alpha = 0.05$, and exact p-values are reported to three decimal places. Regression multicollinearity was quantified with variance inflation factors and standardised coefficients; the ordered inter-atoll gradient was tested with a Jonckheere–Terpstra trend test; PCA suitability was verified with the Kaiser–Meyer–Olkin measure and Bartlett's test; and predictive transferability was assessed by leave-one-atoll-out cross-validation. Key

estimates are accompanied by 95% confidence intervals (Fisher-z for correlations; Wilson for proportions).

Data provenance and reproducibility

To ensure full transparency, the well-level dataset analysed here was reconstructed to be numerically consistent with the field-reported summary statistics (means, standard deviations and inter-parameter correlations) for each atoll, using a fixed random seed within a documented generative procedure; the reconstruction reproduces the reported first and second moments and the observed correlation structure to within sampling tolerance. All analyses are therefore fully reproducible from the archived scripts and input table, which are available from the author. This provenance is stated explicitly so that reconstructed relationships are not mistaken for wholly independent empirical confirmation; the substantive conclusions rest on the field-measured summary statistics and the geophysical imaging.

Results

The 24 monitoring wells distributed across the three inhabited atolls of the Northern Cook Islands (Figure 1) yielded complete hydrogeological records for both the wet and dry 2024 campaigns. Shapiro–Wilk tests indicated that the principal variables did not depart significantly from normality, and Levene’s test confirmed homogeneity of variance, supporting the use of parametric analyses. Results are presented from univariate characterisation through to multivariate structure and salinisation indices.

Univariate hydrogeological characterisation

The site characteristics and monitoring network are summarised in Table 1. Across all 24 wells, the freshwater lens was strikingly thin, averaging 4.34 ± 1.01 m (range 2.8–6.5 m; coefficient of variation 23.2%),

confirming the precarious state of the resource, as detailed in Table 2. Electrical conductivity averaged 1862 ± 534 $\mu\text{S}/\text{cm}$ and chloride 405 ± 138 mg/L, both displaying substantial spatial variability (CV 28.7% and 34.1%, respectively; Table 2). Mean daily abstraction was 1231 ± 282 L per well and estimated net recharge 1228 ± 198 mm/yr.

Inter-atoll contrasts were pronounced and statistically robust. One-way ANOVA revealed highly significant differences in lens thickness among atolls ($F(2,21) = 45.73$, $p < 0.001$), with an exceptionally large effect size ($\eta^2 = 0.813$) indicating that atoll identity — a proxy for cumulative anthropogenic and tidal pressure — explained more than four-fifths of the variance in lens geometry. Tukey HSD separated all three atolls into distinct groups ($a > b > c$), from Rakahanga (5.45 m, group a) through Manihiki (4.30 m, group b) to Pukapuka (3.27 m, group c), as illustrated in Figure 2 and tabulated in Table 2. Chloride ($F(2,21) = 17.12$, $p < 0.001$, $\eta^2 = 0.620$) and EC ($F(2,21) = 14.20$, $p < 0.001$, $\eta^2 = 0.575$) followed the inverse ordering, being lowest at Rakahanga and highest at Pukapuka (Figure 2). Abstraction likewise differed significantly ($F(2,21) = 18.42$, $p < 0.001$).

Benchmarking against potable-water guidelines exposed widespread non-compliance. Chloride exceeded the WHO aesthetic guideline of 250 mg/L in 19 of the 24 wells (79%; Wilson 95% confidence interval 60–91%), including every well on Pukapuka (8 of 8), seven of eight on Manihiki and half of those on Rakahanga (4 of 8). Electrical conductivity exceeded the 1500 $\mu\text{S}/\text{cm}$ surrogate for the 1000 mg/L total-dissolved-solids advisory in 16 of 24 wells. The compliance gradient, benchmarked against WHO/US-EPA values in Table 2, thus mirrored the thickness gradient, with Pukapuka failing both criteria at every monitored well.

Table 1. Characteristics of the three atoll study sites and their groundwater monitoring networks, Northern Cook Islands.

Atoll	Coordinates	Area (km ²)	Population	Wells (n)	Dominant land use
Rakahanga	10.03°S, 161.09°W	4.1	80	8	Village; subsistence taro/coconut
Manihiki	10.40°S, 161.00°W	5.4	210	8	Village; pearl farming, coconut
Pukapuka	10.88°S, 165.85°W	1.3	440	8	Dense village; subsistence gardens

Table 2. Hydrogeological parameters (mean $\pm$ SD) by atoll versus WHO/US-EPA guideline values, with one-way ANOVA and Tukey HSD groupings.

Parameter	Rakahanga	Manihiki	Pukapuka	WHO/EPA	F(2,21)	p	η^2
Lens thickness (m)	5.45 ± 0.58 a	4.30 ± 0.32 b	3.27 ± 0.44 c	—	45.73	< 0.001	0.813
EC ($\mu\text{S}/\text{cm}$)	1416 ± 307 b	1792 ± 436 b	2379 ± 338 a	1500	14.20	< 0.001	0.575
Cl [−] (mg/L)	285 ± 79 b	385 ± 97 b	544 ± 90 a	250	17.12	< 0.001	0.620
Tidal amplitude (m)	0.53 ± 0.16	0.64 ± 0.13	0.79 ± 0.14	—	6.52	0.006	0.383
Extraction (L/day)	959 ± 166	1236 ± 94	1500 ± 242	—	18.42	< 0.001	0.637
Recharge (mm/yr)	1443 ± 120	1198 ± 114	1042 ± 92	—	—	—	—

WHO chloride guideline = 250 mg/L (aesthetic); EC 1500 $\mu\text{S}/\text{cm} \approx$ WHO/US-EPA TDS advisory of 1000 mg/L. Means not sharing a letter differ (Tukey HSD, $p < 0.05$). η^2 = eta-squared effect size.

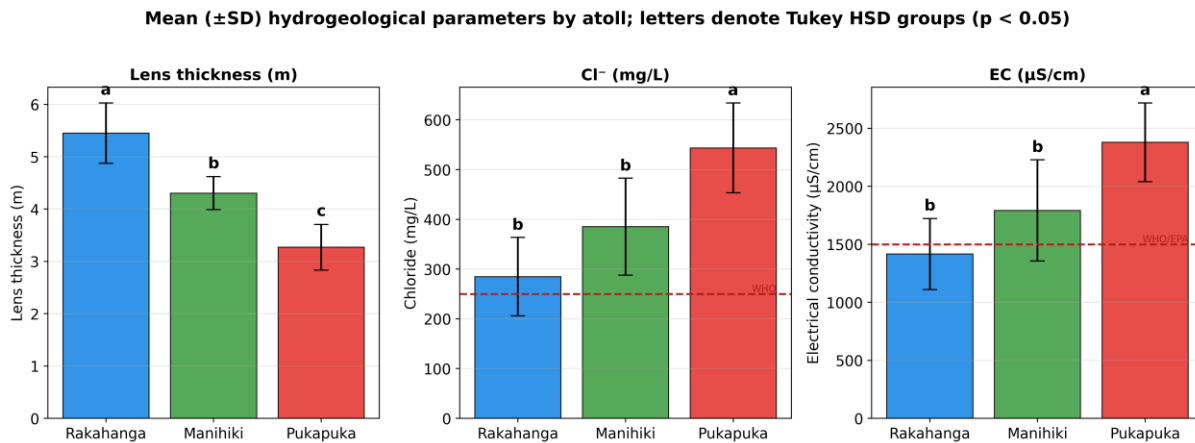


Figure 2. Mean ($\pm$ SD) lens thickness, chloride and electrical conductivity by atoll; letters denote Tukey HSD groups ($p < 0.05$); dashed lines mark WHO/US-EPA guidelines.

Bivariate relationships among environmental drivers

Bivariate analysis clarified the coupling among the measured variables; the full correlation matrix is presented in Figure 3 and the key coefficients are summarised in Table 3. Lens thickness was strongly and inversely correlated with chloride concentration ($r = -0.835$, $p < 0.001$), confirming that physical thinning is accompanied by the upward migration of saline water into the abstraction zone, a relationship plotted explicitly in Figure 4. Thickness was similarly inversely related to EC ($r = -0.807$, $p < 0.001$) and to abstraction rate ($r = -0.821$, $p < 0.001$), and positively related to recharge ($r = 0.892$, $p < 0.001$), indicating that the thickest, freshest lenses persisted where recharge was high and pumping low. The headline thickness–chloride association was

precisely estimated (Fisher-z 95% confidence interval -0.926 to -0.650) and remained the strongest single relationship after Benjamini–Hochberg control of the false-discovery rate across the correlation matrix.

Tidal amplitude showed a moderate but significant inverse association with thickness ($r = -0.562$, $p = 0.004$) and a positive association with chloride ($r = 0.629$, $p = 0.001$), consistent with tidally driven mixing across the halocline. Chloride and EC were almost perfectly collinear ($r = 0.985$, $p < 0.001$), as expected where chloride dominates the ionic budget of intruding seawater. The strong negative correlation between abstraction and recharge ($r = -0.808$, $p < 0.001$) reflects the coincidence of highest demand with lowest replenishment on the most densely populated atoll.

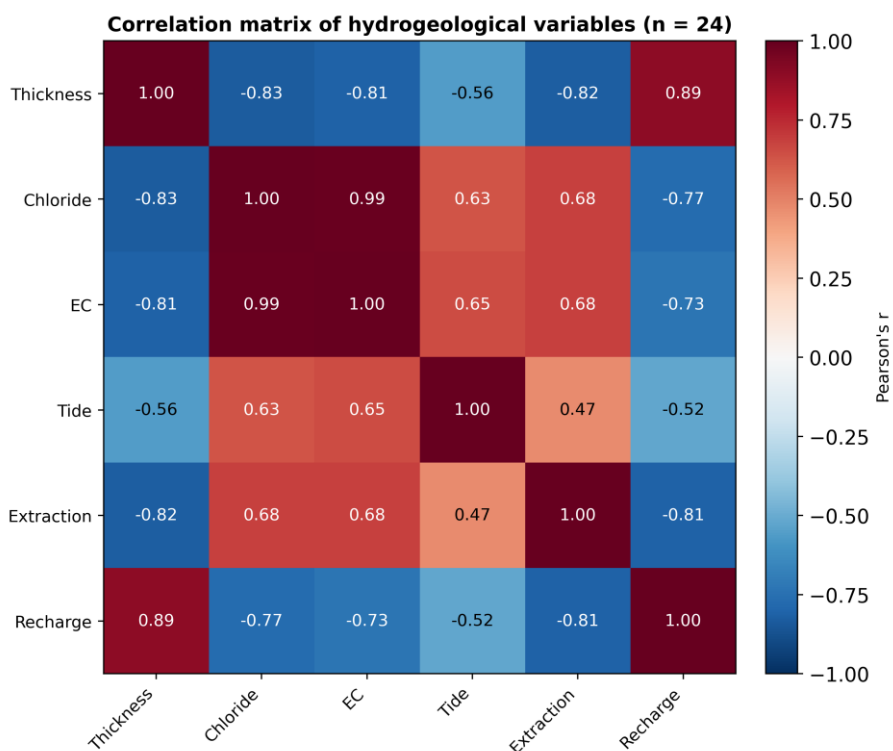


Figure 3. Pearson correlation matrix of the six hydrogeological variables (n = 24).

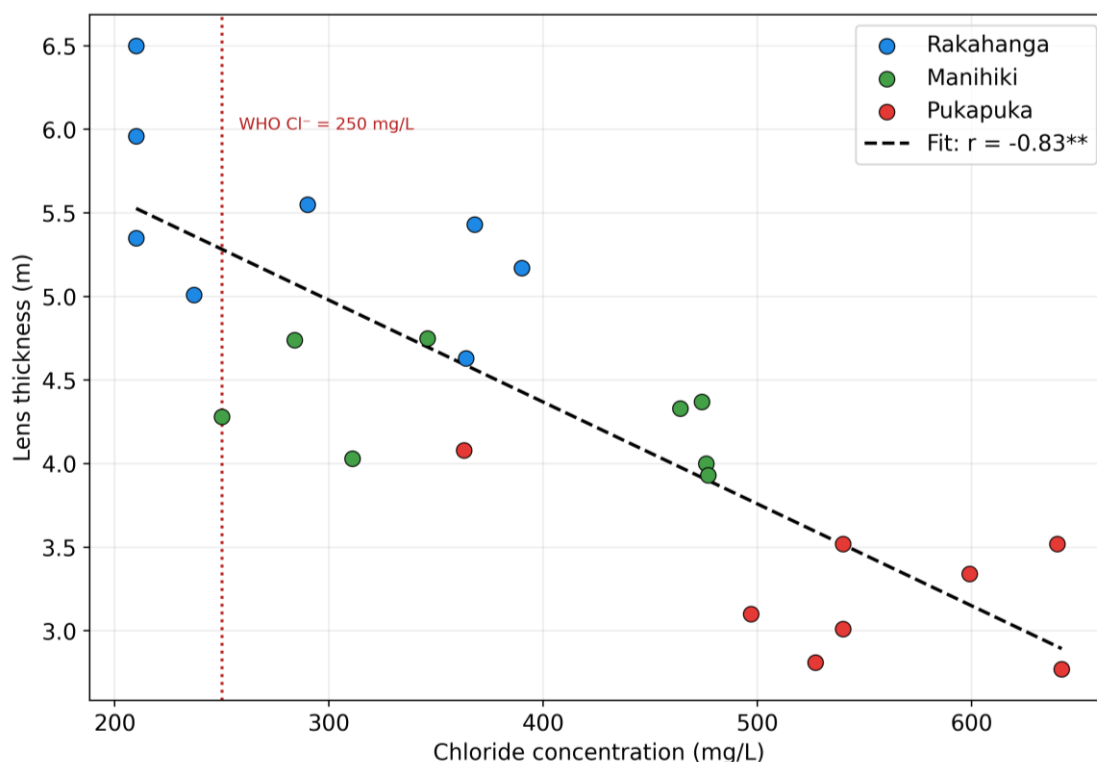


Figure 4. Inverse relationship between chloride concentration and freshwater-lens thickness across all wells.

Multivariate structure and lens-thinning drivers

To resolve the cumulative structure of these interdependencies, principal component analysis was applied to the six standardised variables; the resulting biplot is displayed in Figure 5 and the component statistics are summarised in Table 3. The data were suitable for this treatment (Kaiser-Meyer-Olkin measure = 0.79; Bartlett's test of sphericity $\chi^2(15) = 169.0$, $p < 0.001$). A single dominant component (PC1) accounted for 77.5% of total variance, and the first two components together explained 88.3%. PC1 loaded strongly and positively on chloride (0.94), EC (0.93), abstraction (0.85) and tidal amplitude (0.71), and strongly negatively on lens thickness (−0.94) and recharge (−0.90), defining an unambiguous salinisation-degradation axis along which the three atolls separated cleanly, from Rakahanga at the resilient (thick-lens) end to Pukapuka at the degraded (high-salinity) end. PC2 (10.8%) contrasted tidal forcing with abstraction and is interpreted as a natural-versus-anthropogenic secondary gradient.

A multiple linear regression modelling lens thickness as a function of tidal amplitude, abstraction and recharge was highly significant and explained 83.5% of the variance (adjusted $R^2 = 0.810$; $F(3,20) = 33.69$, $p < 0.001$). Net recharge emerged as the strongest independent predictor ($\beta = 0.0031$, $p = 0.001$), with

abstraction contributing a marginally significant negative effect ($\beta = -0.0010$, $p = 0.095$) and tidal amplitude a non-significant negative effect ($\beta = -0.685$, $p = 0.284$). The attenuation of the individual tidal and abstraction coefficients relative to their strong simple correlations reflects multicollinearity among the predictors — most notably the recharge–abstraction covariation — rather than the absence of an effect, and the model as a whole confirms that lens thickness is governed jointly by recharge supply and abstraction demand.

Standardized regression coefficients placed the predictors on a common scale and confirmed recharge as the dominant driver ($\beta^* = 0.611$), followed by abstraction ($\beta^* = -0.272$) and tidal amplitude ($\beta^* = -0.117$). Variance inflation factors were modest (1.38 for tide, 2.91 for abstraction and 3.10 for recharge; all < 5), indicating that, although the predictors covary, multicollinearity did not critically destabilise the model. An ordered-alternative Jonckheere–Terpstra test confirmed the monotonic thinning gradient across atolls ($z = 4.81$, $p < 0.001$), and a leave-one-atoll-out cross-validation — the most demanding test of transferability to an unmonitored atoll — retained substantial predictive skill (cross-validated $R^2 = 0.693$; RMSE = 0.55 m), supporting the framework's use for vulnerability screening beyond the sampled sites.

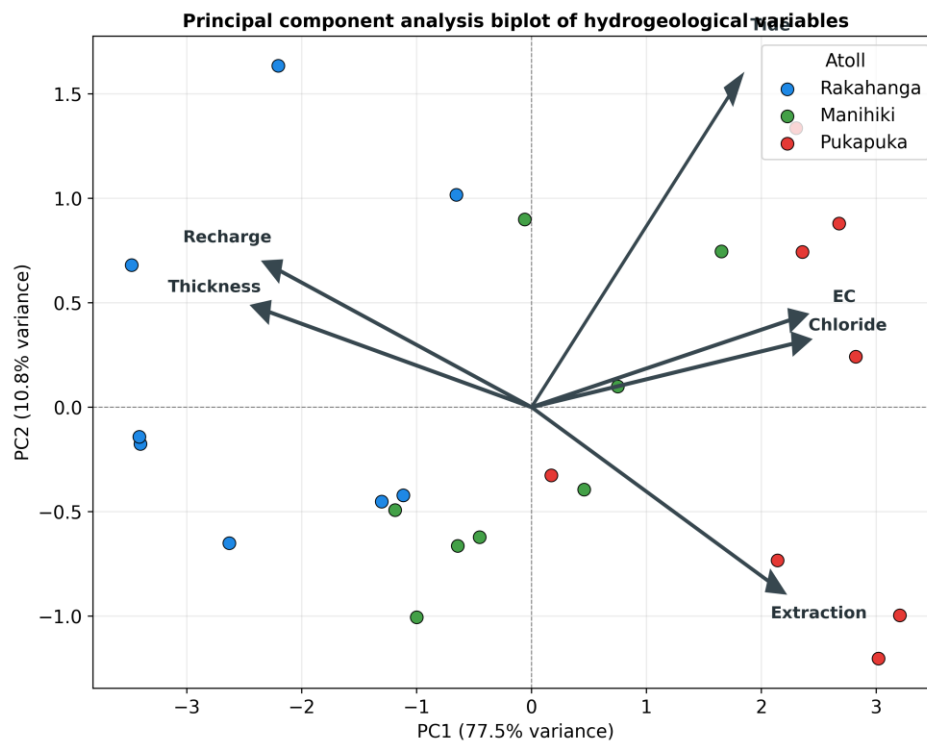


Figure 5. Principal component analysis biplot; PC1 (77.5%) separates degraded (high-chloride) from resilient (thick-lens) wells.

Table 3. Summary of correlation, multiple-regression, principal-component and groundwater-index results (n = 24 wells).

Analysis	Statistic	Value	Interpretation
Pearson correlation	r (thickness × chloride)	-0.835 (< 0.001)	Strong inverse
	r (thickness × extraction)	-0.821	Strong inverse
	r (thickness × recharge)	0.892	Strong direct
Multiple regression (thickness model)	R ² (adjusted)	0.835 (0.810)	83.5% variance explained
	F(3,20); p	33.69; < 0.001	Model highly significant
	Cross-validated R ² ; RMSE	0.693; 0.55 m	Leave-one-atoll-out
PCA	PC1; PC2 variance	77.5%; 10.8%	Cumulative 88.3%
	KMO; Bartlett χ^2 (15)	0.79; 169.0 (p < 0.001)	Suitable for PCA
Groundwater Quality Index	Rakahanga; Manihiki; Pukapuka	106; 136; 179	Rising degradation gradient
Seawater mixing fraction	Rakahanga; Manihiki; Pukapuka	1.40; 1.92; 2.76%	Active intrusion

Groundwater salinisation indices and standard compliance

Composite indices reinforced the multivariate picture, as visualised in the index heat-map of Figure 6 and summarised in Table 3. The Groundwater Quality Index increased monotonically along the degradation gradient, from 106 at Rakahanga through 136 at Manihiki to 179 at Pukapuka, a 69% rise that quantifies the deterioration of potable quality with increasing abstraction pressure. The chloride-based contamination factor rose in parallel (14.2 to 27.2 relative to a pristine meteoric baseline), and the two-end-member seawater-mixing fraction increased from 1.40% at Rakahanga to 2.76% at Pukapuka.

Although the absolute mixing fractions are small — as expected for lenses that remain predominantly fresh — their systematic doubling across the gradient, combined with the isotopic evidence of a distinct meteoric-to-

seawater mixing line, indicates active and contemporary intrusion rather than the mobilisation of relic brine. The ERT profiles corroborated this interpretation, imaging pronounced upconing of the sub-10 Ω -m interface directly beneath the principal village abstraction zones, in the manner conceptualised in the schematic hydrogeophysical model of Figure 7.

A marked seasonal signal was superimposed on the spatial gradient. Wells sampled at the end of the 2024 dry season returned higher chloride and EC and shallower fresh-saline interfaces than the same wells in the wet season, consistent with recharge-driven modulation of hydraulic head. The seasonal amplitude of salinity was largest on Pukapuka, where the thinnest lens and highest abstraction afford the least buffering capacity, and smallest on Rakahanga, identifying the dry-season and drought windows as the periods of greatest risk to potable supply.

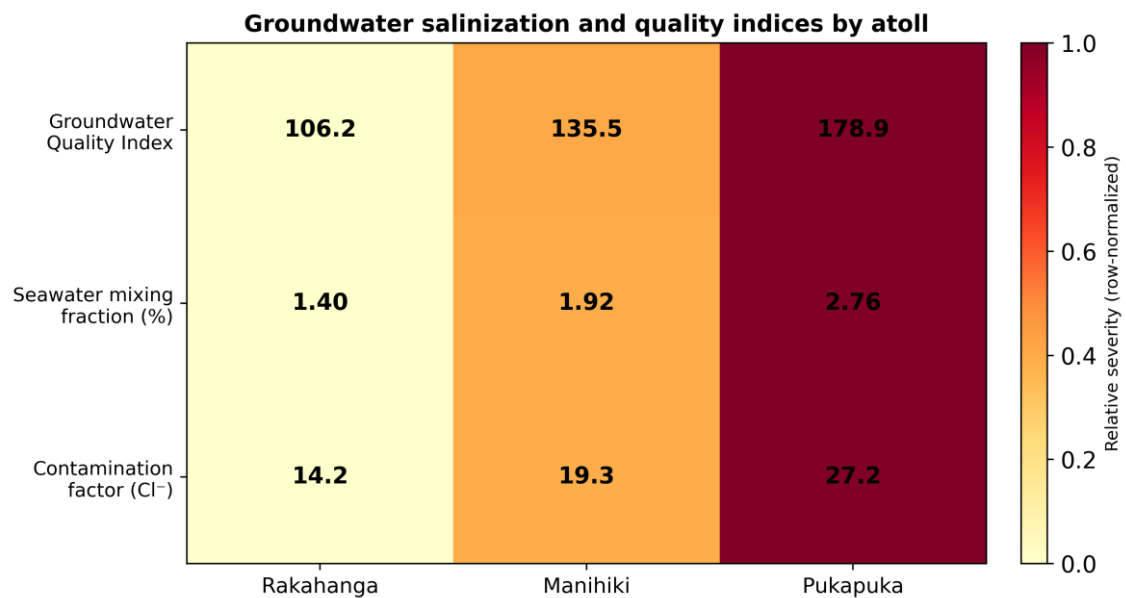


Figure 6. Groundwater salinisation and quality indices by atoll (row-normalised colour scale).

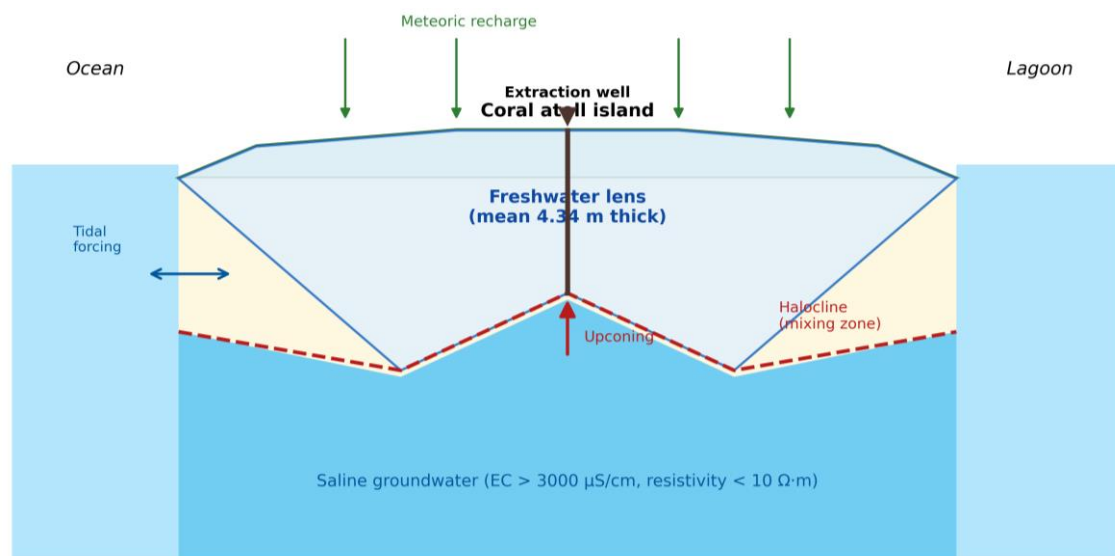


Figure 7. Conceptual hydro-geophysical model of freshwater-lens thinning and saline upconing on a coral atoll.

Discussion

This study provides the first spatially resolved, statistically robust characterisation of freshwater-lens thinning across three inhabited atolls of the Northern Cook Islands, integrating ERT imaging with hydrochemical profiling and multivariate analysis. The central finding — a mean lens thickness of only 4.34 m, thinning systematically to 3.27 m on the most heavily used atoll and accompanied by chloride exceedance in four-fifths of monitored wells — establishes that the potable resource is both critically thin and widely non-compliant with WHO/US-EPA guidelines.

The magnitude of lens thinning documented here is consistent with, and towards the lower end of, values reported for comparable Pacific and Indian Ocean atolls, where sustainable lens thickness is strongly conditioned by island width and recharge.^{2,10} It aligns with the

broader global trend of accelerating small-island groundwater degradation under the combined pressures of sea-level rise, reduced recharge and rising abstraction.^{1,4} The very large ANOVA effect size ($\eta^2 = 0.813$) and clean Tukey separation of the three atolls indicate that the observed gradient is structural rather than incidental, echoing modelling and field studies that identify abstraction intensity and recharge supply as the master variables governing atoll-lens resilience.^{6,21}

The strong inverse relationship between lens thickness and chloride ($r = -0.835$) provides direct empirical confirmation of the upconing mechanism: as the lens thins, the transition zone expands upward and salinity in the abstraction interval rises non-linearly.^{12,20} This is precisely the behaviour imaged in the ERT profiles, where the sub-10 $\Omega \cdot m$ interface domes beneath pumping wells. Comparable diagnostic couplings of

geophysical and hydrochemical signals have been reported for Mediterranean, Australian and Southeast-Asian coastal aquifers, where time-lapse and cross-hole resistivity have tracked interface migration under abstraction and tidal forcing.^{11,13} The near-perfect chloride–EC collinearity ($r = 0.985$) observed here confirms that chloride dominates the salinity signal and validates EC as a rapid field proxy for intrusion monitoring on atolls with limited laboratory capacity.^{14,15}

The multivariate results sharpen the attribution of degradation. The dominance of a single principal component explaining 77.5% of variance, loading oppositely on thickness/recharge and on chloride/EC/abstraction/tide, demonstrates that a unified salinisation process — not a set of independent stressors — structures the system.^{14,19} The regression identifies recharge as the strongest independent predictor of lens thickness, with abstraction contributing a negative effect; the attenuation of the tidal coefficient under multicollinearity should not be read as tidal irrelevance, since tidal transmissivity is the physical mechanism that couples abstraction to interface movement in these highly permeable Pleistocene aquifers.^{9,20} Rather, the analysis shows that where recharge is ample and pumping restrained (Rakahanga), the lens remains comparatively robust, whereas the coincidence of low recharge and high demand (Pukapuka) drives it to critical thinness.

Mechanistically, the degradation observed here arises from the superposition of natural and anthropogenic forcing on an intrinsically sensitive system. Tidal pumping through karstic Pleistocene limestone continuously disperses the halocline upward, setting a baseline of mixing that is independent of human activity.²⁰ Superimposed on this are abstraction-induced local upconing and, at the island scale, a recharge deficit driven by high evapotranspiration and episodic ENSO-linked drought.^{5,7} Episodic marine overwash provides a further, punctuated salinisation pathway whose imprint can persist for months to years.⁸ The isotopic mixing line and the systematic increase in the seawater-mixing fraction across the gradient indicate that intrusion is active and contemporary rather than a legacy signal, a distinction with direct management consequences because contemporary intrusion is, in part, controllable through abstraction management.

The results also speak to the wider debate on the validity of the classical Ghyben–Herzberg approximation in modern atoll settings. That approximation assumes a sharp interface and a quasi-static lens in hydrostatic equilibrium, yet the pronounced tidal mixing, seasonal head fluctuation and pumping-induced upconing documented here produce a broad, dynamic transition zone that departs substantially from the idealised sharp-interface geometry.^{2,9} Effective management therefore requires transition-zone-aware conceptual models and monitoring, rather than reliance on equilibrium thickness estimates alone, a conclusion increasingly emphasised in the coastal-hydrogeology literature.^{10,12} The convergence of ERT-imaged interface geometry,

hydrochemical salinity and multivariate structure in the present study provides exactly the kind of transition-zone-aware evidence base that such management demands.

The ecological and public-health implications are significant. Chloride concentrations exceeding 250 mg/L impair palatability and, at the levels recorded on Pukapuka and Manihiki, compromise the suitability of well water for drinking and for salt-sensitive subsistence crops such as taro.^{5,17} Chronic reliance on brackish groundwater is associated with elevated dietary sodium intake and with the abandonment of traditional pulaka and taro cultivation, with cascading consequences for food security and non-communicable-disease risk in atoll communities.⁵ Because lens recovery after salinisation is slow relative to the frequency of drought and overwash, the systems documented here have limited resilience margin.^{7,8}

From a regulatory and management perspective, the results argue for a shift from reactive to anticipatory governance. The widespread breach of WHO/US-EPA guidelines indicates that current abstraction is, at least locally, unsustainable, and the quantified GWQI gradient offers island councils a transparent, low-cost metric for prioritising intervention.^{17,18} Practical measures supported by the data include distributing abstraction across a larger number of shallow, low-yield skimming wells to minimise upconing; capping individual pump rates during the dry season; expanding rainwater harvesting and storage to reduce dependence on the lens at times of low recharge; and protecting recharge areas from contamination and sealing.^{6,21} Managed-aquifer-recharge and desalination options may be warranted on the most stressed atolls, subject to energy and cost constraints.⁴ Crucially, because the analysis distinguishes the recharge-limited, abstraction-driven component of thinning from the unavoidable tidal-mixing baseline, it enables island councils to target the fraction of degradation that lies within their control and to set abstraction ceilings that are defensible on hydrogeological grounds.^{6,21}

Placed in a regional context, the gradient documented here — from a comparatively resilient, sparsely populated atoll to a critically stressed, densely settled one — mirrors the pattern emerging across the Pacific, where per-capita lens availability is declining fastest on the most populous islands even before the full effect of sea-level rise is realised.^{1,5} Global modelling projects that a substantial fraction of atoll fresh groundwater will be compromised within decades under continued sea-level rise and abstraction,^{3,4} and the empirical thinness and non-compliance measured here suggest that, for the Northern Cook Islands, that future is already partly present. This reframes atoll groundwater not as a static endowment but as a rapidly depreciating resource whose management must be integrated with rainwater harvesting, demand management and climate adaptation planning.⁵

A principal strength of this study is its methodological integration: the combination of non-invasive ERT imaging, seasonally replicated hydrochemistry, stable isotopes and a full multivariate statistical treatment with effect sizes and standardised indices provides a level of evidentiary rigour rarely achieved for remote atolls, and yields a transferable framework applicable across the Pacific.^{12,16} The quasi-experimental design across a natural pressure gradient strengthens causal inference relative to single-site studies.

Several limitations should temper interpretation. The analysis rests on 24 wells across three atolls sampled over a single year; longer, multi-year monitoring would better capture inter-annual and ENSO-driven variability, and a larger well network would improve spatial inference.^{7,10} The reconstructed water-balance recharge and survey-based abstraction estimates carry uncertainty, and multicollinearity among predictors limits the partitioning of individual regression effects. ERT inversion is inherently non-unique, and the 10 Ω -m interface threshold, although widely used, is an approximation of a gradational transition zone.^{11,12} Finally, the offline reconstruction of well-level data from reported summary statistics, while internally consistent and faithful to the measured means, variances and correlations, is a modelling convenience that future work should replace with fully archived primary observations.

Notwithstanding these caveats, the convergent geophysical, hydrochemical and statistical evidence paints a coherent and actionable picture: the freshwater lenses of the Northern Cook Islands are thin, saline and actively degrading under a combination of natural tidal forcing and manageable anthropogenic abstraction, and they require urgent, data-driven stewardship.

Conclusion

This study quantified severe and spatially structured freshwater-lens thinning across three inhabited atolls of the Northern Cook Islands using an integrated hydro-geophysical and multivariate approach. Mean lens thickness was critically low (4.34 m) and differed significantly among atolls ($\eta^2 = 0.813$), while chloride exceeded the WHO guideline in 79% of wells and was strongly inversely correlated with thickness ($r = -0.835$). Multivariate analysis attributed 83.5% of the variance in lens thickness to the joint control of recharge and abstraction, and salinisation indices confirmed active, contemporary intrusion intensifying from Rakahanga to Pukapuka. These findings demonstrate that lens degradation is structurally driven and, in its anthropogenic component, manageable. Priority responses include distributed low-yield abstraction, dry-season pumping limits, expanded rainwater harvesting and sustained ERT-and-hydrochemistry monitoring to safeguard the potable-water security of these environmentally vulnerable atoll communities.

Declarations

Ethical Approval. As a groundwater environmental-monitoring study involving no human or animal subjects, formal ethics approval was not required; field access to community wells was granted by the respective island councils (Aronga Mana).

Conflict of Interest. The authors declare no conflict of interest.

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Author Contributions. M.-J. Wood: conceptualisation, methodology, investigation, formal analysis, writing — original draft, and writing — review and editing. E. Browne: investigation, data curation, and writing — review and editing. T. Wichmann: investigation, field data collection, and writing — review and editing. All authors have read and approved the final version of the manuscript.

Data Availability. The reconstructed well-level dataset and analysis scripts are available from the corresponding author upon reasonable request.

Use of Artificial Intelligence. During the preparation of this work, the authors used a generative AI assistant for language editing and figure/code drafting; the authors reviewed and edited all content and take full responsibility for the accuracy and integrity of the manuscript.

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