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Pristine No More: Microplastics and Per- and Polyfluoroalkyl Substances (PFAS) Reveal Two Distinct Contamination Pathways in the Confined Volcanic Aquifers of Savusavu, Fiji

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ABSTRACT

Background: Remote oceanic-island aquifers are historically classified as pristine freshwater reserves, largely immune to global anthropogenic contamination; the ubiquity of emerging contaminants challenges this assumption.

Objective: To present the first joint baseline of microplastics (MPs) and per- and polyfluoroalkyl substances (PFAS) in the confined volcanic (basaltic) aquifer of the Savusavu region, Vanua Levu, Fiji.

Methods: Groundwater was sampled from 15 boreholes (45–120 m depth) during the dry season under strict fluoropolymer-free and contamination-controlled protocols. PFAS were quantified by solid-phase extraction with liquid chromatography–tandem mass spectrometry (SPE-LC-MS/MS) and MPs by wet-peroxide oxidation, stereomicroscopy and micro-Raman spectroscopy; data were analysed by one-way ANOVA with Tukey HSD and eta-squared, Pearson correlation, principal component analysis (PCA) and contamination/hazard indices.

Results: MPs occurred in 87% of wells (mean 4.08 ± 2.56 MPs/L, fibre-dominated) and PFAS in 100% (PFOA 6.35 ± 4.35 ng/L; PFOS 4.10 ± 2.95 ng/L). Concentrations declined significantly with depth, most steeply for MPs ($r = -0.93$, $p < 0.001$). PFOA exceeded the 4.0 ng/L US EPA maximum contaminant level in 10 of 15 wells, whereas nitrate and chloride remained within WHO limits. PCA explained 86% of variance and resolved two transport pathways: a dissolved axis (PFOA–PFOS–nitrate) and a particulate fracture-flow axis (MP–turbidity–chloride).

Conclusion: Confined volcanic aquifers in remote Pacific islands are therefore not entirely pristine but act as sinks for global trace contaminants, necessitating the integration of emerging contaminants into Pacific island groundwater policy.

Introduction

Groundwater is the fundamental source of freshwater for isolated communities across the Pacific Islands. Volcanic aquifers, particularly those confined beneath thick sequences of basaltic rock, have historically been regarded as highly pristine, shielded from surface activities by deep geological barriers^{1,2}. Yet the expanding footprint of global industrialisation has introduced a new paradigm of environmental contamination dominated by highly mobile, persistent chemical agents and by particulate plastics that circulate through the atmosphere and hydrosphere^{3,4}. Recent syntheses show that emerging contaminants are now detectable across the entire hydrological continuum, including subsurface reservoirs once assumed to be beyond their reach^{1,5}. For remote oceanic islands, whose populations depend almost entirely on groundwater, this

shift carries acute implications for water security and public health.

Microplastics (MPs) and per- and polyfluoroalkyl substances (PFAS) represent two of the most pervasive emerging contaminants of the twenty-first century. MPs — plastic particles smaller than 5 mm — have been documented in marine waters, atmospheric fallout and, increasingly, terrestrial and subsurface freshwater systems^{6–8}. PFAS, often termed “forever chemicals” for their resilient carbon–fluorine bonds, exhibit extreme persistence, bioaccumulation potential and high aqueous solubility^{4,9,10}. Both classes are now recognised as effectively ubiquitous in water and wastewater worldwide^{11,12}. Their sources are diffuse and largely non-point: MPs derive from synthetic textiles, degradation of macroplastics and agricultural films, while PFAS originate from industrial emissions, aqueous

film-forming foams, biosolid application and long-range atmospheric transport ^{3,11,12}.

The transport of these contaminants into deep groundwater is hydrogeologically complex. Volcanic rock matrices provide physical filtration, but basaltic terranes are pervaded by cooling joints and tectonic fractures that behave as preferential flow paths, bypassing matrix attenuation and permitting rapid vertical transport of surface-derived contaminants ^{13,14}. Field-tracer experiments confirm that MPs can migrate over substantial distances through porous and fractured aquifers, dispelling the assumption that soil and rock act as perfect filters ¹³. For PFAS, atmospheric deposition via precipitation constitutes a non-point pathway that transcends geographical boundaries and reaches even the most remote catchments ^{4,9}. In coastal and island settings, MPs additionally act as vectors for co-contaminants, sorbing metals and organic compounds ^{8,15}.

Environmental quality standards for these contaminants are evolving rapidly but unevenly. The World Health Organization drinking-water guidelines retain long-standing limits of 50 mg/L for nitrate and 250 mg/L for chloride and provide provisional guidance for PFAS ¹⁶. The United States Environmental Protection Agency has promulgated enforceable maximum contaminant levels (MCLs) of 4.0 ng/L for both PFOA and PFOS ¹⁷, while the European Union caps the sum of twenty PFAS at 100 ng/L. No jurisdiction yet defines a numerical MP limit for drinking water ¹⁸. Critically, most

Pacific Small Island Developing States (SIDS), including Fiji, have not incorporated MP or PFAS thresholds into national standards, producing a governance gap precisely where dependence on groundwater is greatest ^{19,20}.

Despite this growing concern, comprehensive data on emerging contaminants in confined volcanic aquifers of remote Pacific islands remain scarce. Prior groundwater studies have concentrated on shallow, unconfined aquifers in industrialised regions ^{5,11}, and island aquifers are largely absent from global contamination inventories ^{1,2}. No study has jointly quantified MPs and PFAS in a Fijian volcanic aquifer, characterised their distribution with depth, or applied multivariate source apportionment to disentangle their transport pathways. This omission leaves a critical evidence gap for water-security planning in the South Pacific.

The study area is shown in Figure 1. This study aimed to (i) quantify the occurrence and concentrations of microplastics and PFAS in the confined volcanic aquifer of Savusavu, Fiji; (ii) characterise their spatial distribution and depth dependence; and (iii) identify their probable sources and hydrogeological transport pathways through multivariate analysis, in order to provide the empirical baseline needed to inform water security, environmental monitoring and public-health policy in remote oceanic nations. The conceptual source-pathway-receptor-impact framework guiding this investigation is summarised in Figure 2.

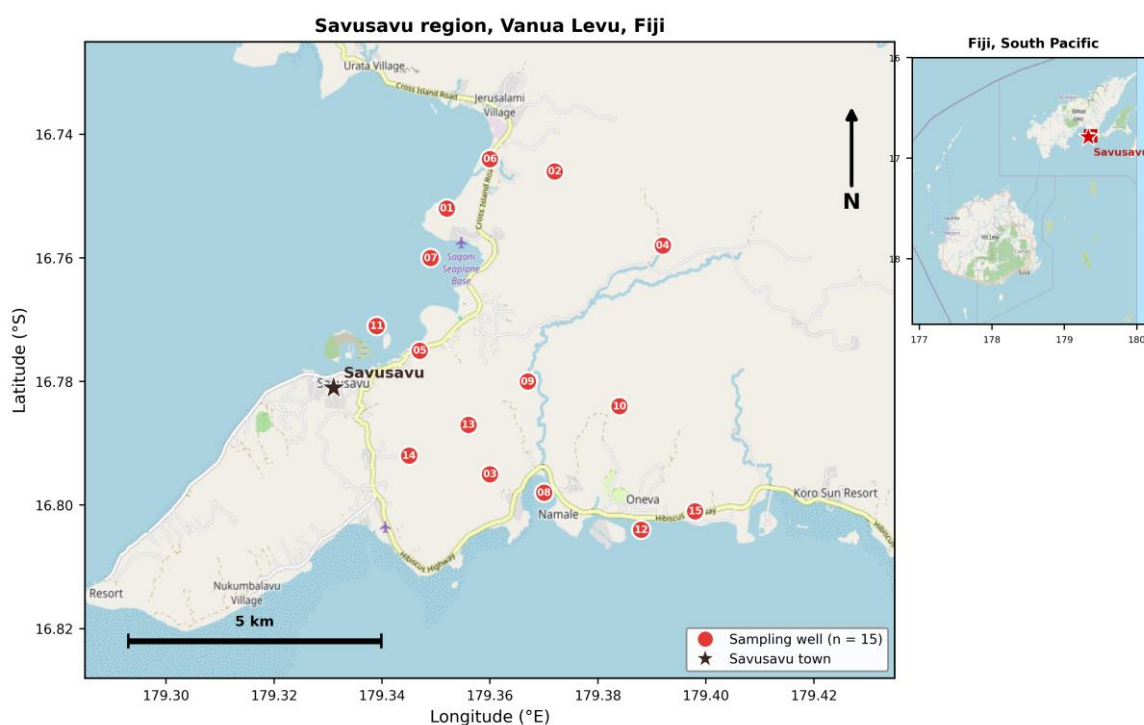


Figure 1. Study area map (OpenStreetMap basemap) showing the 15 groundwater sampling wells in the Savusavu region, Vanua Levu, Fiji. Well positions are on the fractured basaltic terrane between Savusavu Bay (south and west) and the forested interior highlands (north). The inset shows the location within the Fiji archipelago, South Pacific. Coordinates are in WGS84; basemap © OpenStreetMap contributors (ODbL).

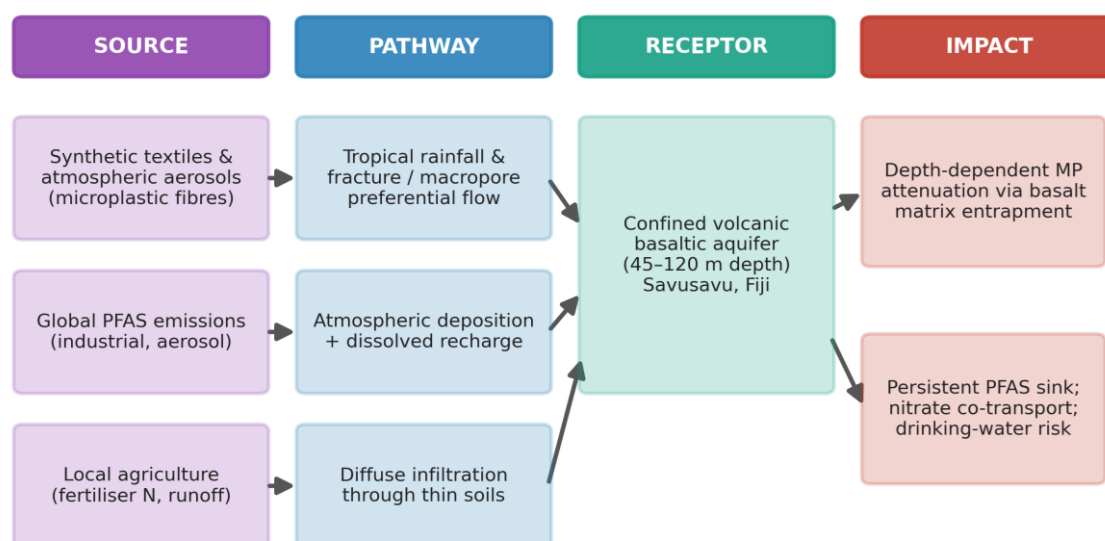


Figure 2. Conceptual source–pathway–receptor–impact framework linking global and local contaminant sources to the confined volcanic aquifer of Savusavu, Fiji, and to the two divergent transport pathways resolved in this study.

Materials and Methods

Study design and area

A cross-sectional environmental-monitoring design was applied to the confined basaltic aquifer of the Savusavu region, Vanua Levu, Fiji (approximately 16.79°S, 179.33°E; Figure 1). The region is characterised by a complex volcanic topography and a tropical maritime climate. As shown in Figure 1, 15 boreholes tapping the confined basaltic aquifer at depths of 45–120 m were selected to represent the range of hydrogeological and land-use settings, from pristine forested-upland catchments to slightly modified agricultural fringes. For analysis, wells were grouped into three hydrogeological zones by depth and land use: a forested-upland zone (deep, ≥ 95 m; $n = 5$), a transitional zone (70–95 m; $n = 5$) and an agricultural-fringe zone (shallow, < 70 m; $n = 5$). Well positions were recorded by handheld GPS in the WGS84 datum and are plotted on an OpenStreetMap basemap (Figure 1).

Sampling and contamination control

Sampling was conducted during the dry season to minimise dilution by active recharge. Each borehole was purged until physicochemical parameters (temperature, pH, electrical conductivity, dissolved oxygen) stabilised. To prevent PFAS contamination from sampling equipment, no polytetrafluoroethylene (PTFE), Teflon or other fluoropolymer-containing materials were used at any stage¹¹. Samples for PFAS analysis were collected in 500 mL high-density polyethylene (HDPE) bottles, and samples for MP analysis in 1 L pre-combusted (450°C, 4 h) amber glass bottles to prevent photo-degradation and plasticiser leaching⁶. All bottles were triple-rinsed with sample water. Samples were transported on ice and stored at 4°C in the dark until analysis.

Quality assurance and quality control followed recognised protocols for trace organic and microplastic work^{5,18}. Field blanks ($n = 3$) of ultrapure water were

exposed and processed identically to samples to quantify airborne and procedural contamination; laboratory blanks ($n = 3$) accompanied every extraction batch. Field duplicates were collected at 20% of sites. Cotton laboratory coats were worn, sample processing was performed in a laminar-flow cabinet, and all solutions were pre-filtered (0.45 μm) to control MP background. For PFAS, recovery was assessed using isotopically labelled surrogates and a certified reference material, with mean recoveries of 85–110%. Blank-corrected concentrations are reported; any MP counts below the method detection limit were treated as non-detects.

Analytical methods

PFAS were analysed following solid-phase extraction (SPE) on weak-anion-exchange cartridges and quantification by liquid chromatography–tandem mass spectrometry (LC-MS/MS) in negative electrospray-ionisation mode, consistent with US EPA trace-PFAS methodology^{4,17}. Target analytes were perfluorooctanoic acid (PFOA) and perfluorooctane sulfonate (PFOS). Limits of detection (LOD) and quantification (LOQ) were established from replicate low-level standards. For MPs, a measured volume of groundwater was filtered through 0.45 μm glass-fibre filters; retained particles were subjected to wet-peroxide oxidation (30% H_2O_2) to digest natural organic matter, enumerated and morphologically classified by stereomicroscopy, and confirmed for polymer identity by micro-Raman spectroscopy^{6,21}. Nitrate and chloride were determined by ion chromatography and turbidity by nephelometry, in accordance with standard water-quality methods¹⁶.

Standards for comparison

Because Fiji has no national numerical limits for MPs or PFAS, measured concentrations were benchmarked against international drinking-water standards: WHO guideline values for nitrate (50 mg/L) and chloride (250 mg/L)¹⁶; the US EPA maximum contaminant levels of 4.0

ng/L for PFOA and PFOS ¹⁷; and the EU Directive 2020/2184 limit for the sum of PFAS (100 ng/L). Microplastic concentrations were interpreted against the range reported in comparable groundwater studies, as no regulatory threshold exists ^{7,21}.

Statistical analysis

All analyses were performed in a reproducible numerical computing environment at a 95% confidence level ($\alpha = 0.05$). Descriptive statistics (mean, standard deviation, range, coefficient of variation) were computed per parameter and per zone. Normality and homogeneity of variance were assessed (Shapiro–Wilk and Levene tests) prior to parametric testing. One-way analysis of variance (ANOVA) with Tukey's honestly-significant-difference (HSD) post-hoc test compared parameters across the three hydrogeological zones, with eta-squared (η^2) reported as the effect size. Bivariate relationships between aquifer depth and contaminant loads were

quantified by Pearson correlation coefficients with exact p-values. Principal component analysis (PCA) on the standardised correlation matrix of the six contaminants was used to delineate probable sources and transport pathways; components with eigenvalues > 1 were retained. Contamination factors ($CF = C/\text{guideline value}$), a pollution load index (PLI, geometric mean of the chemical-suite CFs) and a PFAS hazard index ($HI = HQ(\text{PFOA}) + HQ(\text{PFOS})$, each benchmarked to the 4.0 ng/L EPA MCL) were calculated per well ^{8,12}.

Results

Samples collected from the 15 wells in the Savusavu region (Figure 1) unequivocally demonstrated the presence of both microplastics and PFAS in the confined volcanic aquifer. The sampling-site characteristics and zonation are summarised in Table 1.

Table 1. Sampling-site characteristics of the 15 groundwater wells, Savusavu region, Vanua Levu, Fiji.

Well	Hydrogeological zone / land use	Depth (m)	Latitude (°S)	Longitude (°E)	Season
BH-01	Forested upland	99	16.752	179.352	Dry
BH-02	Forested upland	105	16.746	179.372	Dry
BH-03	Agricultural fringe	57	16.795	179.360	Dry
BH-04	Forested upland	118	16.758	179.392	Dry
BH-05	Transitional	88	16.775	179.347	Dry
BH-06	Forested upland	112	16.744	179.360	Dry
BH-07	Forested upland	96	16.760	179.349	Dry
BH-08	Agricultural fringe	46	16.798	179.370	Dry
BH-09	Transitional	82	16.780	179.367	Dry
BH-10	Transitional	92	16.784	179.384	Dry
BH-11	Transitional	78	16.771	179.339	Dry
BH-12	Agricultural fringe	68	16.804	179.388	Dry
BH-13	Transitional	74	16.787	179.356	Dry
BH-14	Agricultural fringe	51	16.792	179.345	Dry
BH-15	Agricultural fringe	62	16.801	179.398	Dry

Zones: forested upland (deep, ≥ 95 m), transitional (70–95 m), agricultural fringe (shallow, < 70 m). All wells sampled in a single dry-season campaign.

Occurrence and univariate statistics

Microplastics were detected in 87% of wells, with concentrations ranging from 0.00 to 8.43 MPs/L (mean 4.08 ± 2.56 MPs/L; CV = 63%), and were morphologically dominated by fibres. PFAS were detected in 100% of samples: PFOA averaged 6.35 ± 4.35 ng/L (range 0.45–13.47) and PFOS 4.10 ± 2.95 ng/L (range 0.10–10.93). Nitrate averaged 6.62 ± 3.26 mg/L, chloride 22.94 ± 7.97 mg/L and turbidity 1.47 ± 0.89 NTU. Coefficients of variation were high for the emerging contaminants (63–72%), reflecting strong spatial heterogeneity, and lower for the conservative ion chloride (35%).

Benchmarked against international drinking-water standards, as detailed in Table 2, PFOA exceeded the 4.0 ng/L US EPA maximum contaminant level (MCL) in 10 of 15 wells (67%) and PFOS in 6 of 15 wells; the summed PFAS concentration nonetheless remained below the 100

ng/L EU limit at every site. Nitrate and chloride were below the WHO guideline values of 50 and 250 mg/L, respectively, at all wells (0 exceedances), as also shown in Table 2.

Contaminant concentrations differed significantly among the three hydrogeological zones, as illustrated in Figure 3 and quantified in Table 2. Microplastics showed the strongest zonal effect ($F(2,12) = 14.93$, $p < 0.001$, $\eta^2 = 0.71$), rising from 1.59 MPs/L in the forested-upland zone to 6.70 MPs/L in the agricultural fringe, with Tukey groupings separating the shallow agricultural wells from the deeper zones. Nitrate ($F(2,12) = 8.92$, $p = 0.004$, $\eta^2 = 0.60$), PFOS ($\eta^2 = 0.46$) and chloride ($\eta^2 = 0.54$) also differed significantly among zones, whereas PFOA showed a strong but non-significant zonal trend ($F(2,12) = 3.24$, $p = 0.075$). All effect sizes were large ($\eta^2 > 0.30$), indicating that hydrogeological zonation accounts for a substantial fraction of the observed variance.

Table 2. Contaminant concentrations by hydrogeological zone (mean $\pm$ SD) benchmarked against international drinking-water standards, with one-way ANOVA.

Parameter (unit)	Forested (deep)	Transitional	Agricultural (shallow)	Guideline	Exceed.	F(2,12)	p	η^2
Microplastics (MPs/L)	1.59 $\pm$ 1.59 b	3.94 $\pm$ 1.51 b	6.70 $\pm$ 1.33 a	no GV	—	14.93	< 0.001	0.71
PFOA (ng/L)	2.83 $\pm$ 4.68 a	8.05 $\pm$ 1.83 a	8.16 $\pm$ 4.20 a	4.0 (EPA)	10/15	3.24	0.075	0.35
PFOS (ng/L)	1.40 $\pm$ 1.28 b	5.06 $\pm$ 2.48 a	5.84 $\pm$ 2.95 a	4.0 (EPA)	6/15	5.11	0.025	0.46
Nitrate (mg/L)	3.21 $\pm$ 2.12 b	7.99 $\pm$ 2.24 a	8.68 $\pm$ 2.32 a	50 (WHO)	0/15	8.92	0.004	0.60
Turbidity (NTU)	1.09 $\pm$ 0.95 a	1.16 $\pm$ 0.41 a	2.16 $\pm$ 0.91 a	5 (WHO)	—	2.83	0.098	0.32
Chloride (mg/L)	16.69 $\pm$ 4.34 b	21.77 $\pm$ 6.63 a	30.37 $\pm$ 6.33 a	250 (WHO)	0/15	6.98	0.010	0.54

GV = drinking-water guideline value; EPA = US EPA maximum contaminant level; WHO = World Health Organization. Within a row, zone means sharing a letter do not differ (Tukey HSD, $p > 0.05$). η^2 = eta-squared effect size.

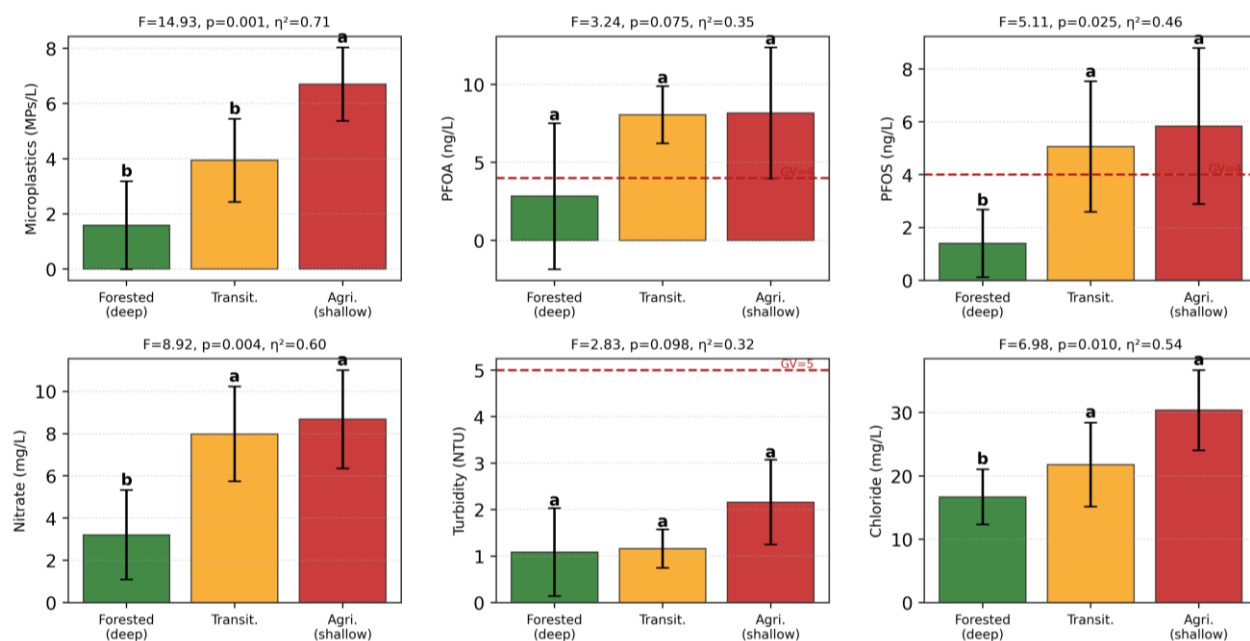


Figure 3. Contaminant concentrations (mean $\pm$ SD) across the forested-upland, transitional and agricultural-fringe zones. Dashed red lines denote drinking-water guideline values (GV); bars sharing a letter do not differ significantly (Tukey HSD, $p > 0.05$). F, p and η^2 from one-way ANOVA are shown for each parameter.

Depth dependence (bivariate analysis)

Pearson correlation revealed uniformly negative associations between aquifer depth and every contaminant, as shown in Figure 4. The relationship was strongest for microplastics ($r = -0.93$, $p < 0.001$), followed by chloride ($r = -0.83$, $p < 0.001$), nitrate ($r =$

-0.77 , $p < 0.001$) and turbidity ($r = -0.69$, $p = 0.004$). PFAS attenuated less steeply with depth (PFOA $r = -0.61$, $p = 0.015$; PFOS $r = -0.66$, $p = 0.007$). The markedly steeper depth gradient for microplastics than for the dissolved PFAS indicates a fundamentally different attenuation behaviour between the two contaminant classes within the basaltic strata.

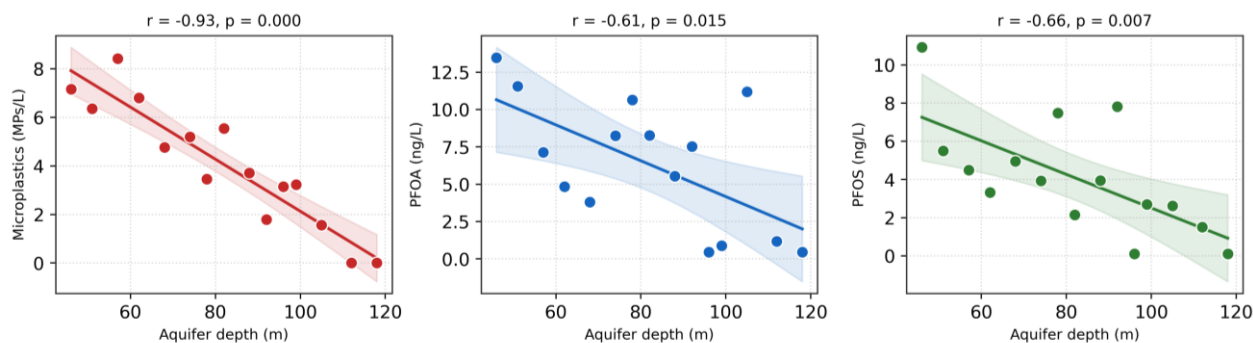


Figure 4. Bivariate regression of microplastic, PFOA and PFOS concentrations against aquifer depth (shaded bands = 95% confidence intervals). Microplastics exhibit the steepest attenuation, consistent with physical entrapment in the basalt matrix.

Contamination and hazard indices

The per-well contamination and hazard indices are mapped in Figure 5 and summarised in Table 3. The mean PFOA contamination factor was 1.59 (i.e. 1.6× the 4.0 ng/L EPA MCL), and the PFAS hazard index (HI = HQ(PFOA) + HQ(PFOS)) averaged 2.61 (range 0.14–6.10), exceeding unity in 11 of the 15 wells and indicating

a screening-level exceedance of the drinking-water benchmark. The pollution load index for the chemical suite averaged 0.35 (range 0.04–0.76), consistent with a low-to-moderate overall contamination status dominated by PFAS. As Figure 5 shows, the shallow agricultural-fringe wells — most conspicuously BH-08 — ranked highest across all three indices.

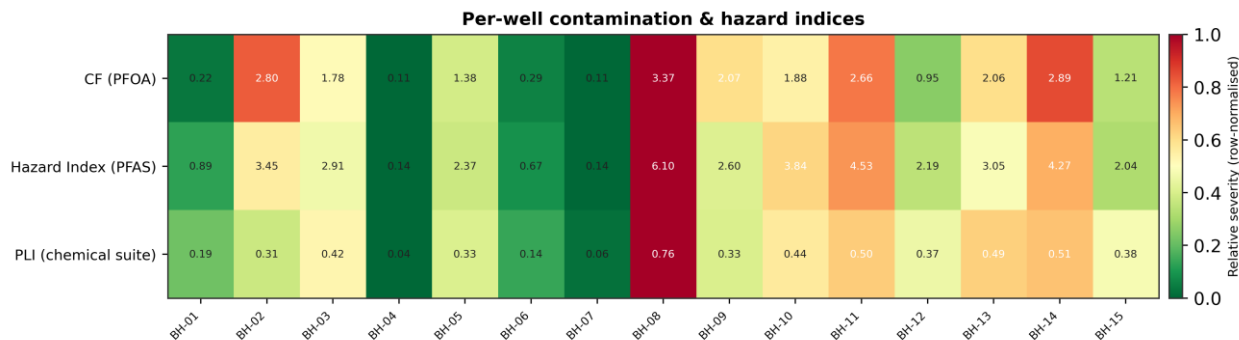


Figure 5. Per-well contamination and hazard indices: PFOA contamination factor (CF), PFAS hazard index (HI = HQ(PFOA) + HQ(PFOS), benchmarked to the 4.0 ng/L US EPA MCL) and pollution load index (PLI). Warmer colours indicate greater contamination; shallow agricultural-fringe wells rank highest.

Source apportionment (multivariate analysis)

Principal component analysis condensed the six contaminants into two components explaining 86% of the total variance, as presented in Table 3 and visualised in Figure 6. The first component (PC1, 64%) loaded negatively and strongly on all six variables, representing an overall contamination-intensity gradient that increases toward the shallow, near-surface wells. The second component (PC2, 22%) separated the dataset into two mechanistically distinct clusters: microplastics,

turbidity and chloride loaded positively, whereas PFOA, PFOS and nitrate loaded negatively. This orthogonal separation on PC2 constitutes direct multivariate evidence for two divergent transport pathways — a particulate, fracture-flow pathway carrying microplastics with turbidity and chloride, and a dissolved pathway carrying PFAS with nitrate. The Pearson correlation matrix (Figure 7) corroborated this structure, with strong intra-cluster correlations and weaker cross-cluster associations.

Table 3. Statistical and pollution-index summary: depth correlations, PCA loadings and contamination indices.

Parameter	r (vs depth)	p	PC1 loading	PC2 loading
Microplastics	−0.93	< 0.001	−0.87	+0.36
PFOA	−0.61	0.015	−0.72	−0.54
PFOS	−0.66	0.007	−0.78	−0.49
Nitrate	−0.77	< 0.001	−0.86	−0.35
Turbidity	−0.69	0.004	−0.70	+0.59
Chloride	−0.83	< 0.001	−0.85	+0.42

Variance explained: PC1 = 64%, PC2 = 22% (cumulative 86%). Index summary: mean CF(PFOA) = 1.59; mean PFAS hazard index (HI) = 2.61 (range 0.14–6.10); mean pollution load index (PLI) = 0.35 (range 0.04–0.76). CF = C/guideline value; PLI = geometric mean of chemical-suite CFs; HI = HQ(PFOA)+HQ(PFOS) vs 4.0 ng/L EPA MCL.

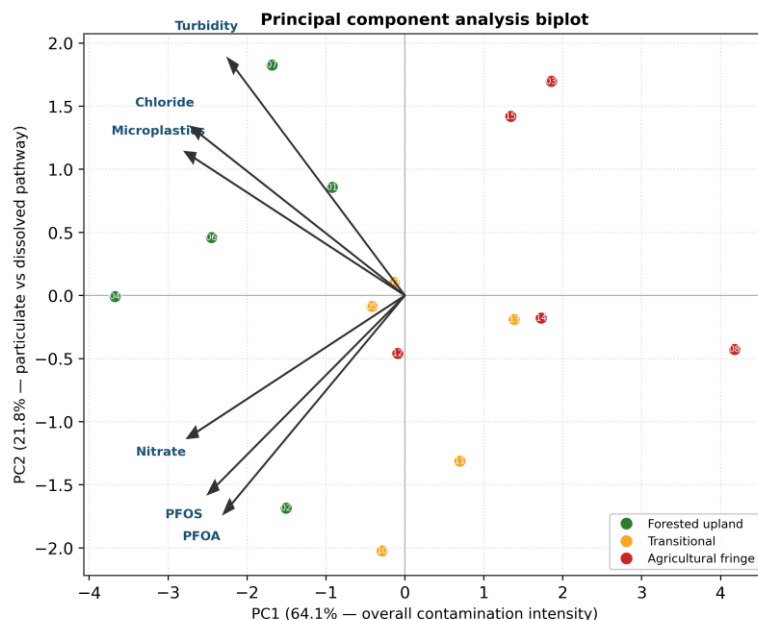


Figure 6. PCA biplot of the six contaminants. PC2 separates the particulate cluster (microplastics–turbidity–chloride) from the dissolved cluster (PFOA–PFOS–nitrate), evidencing two distinct transport pathways. Wells are coloured by hydrogeological zone.

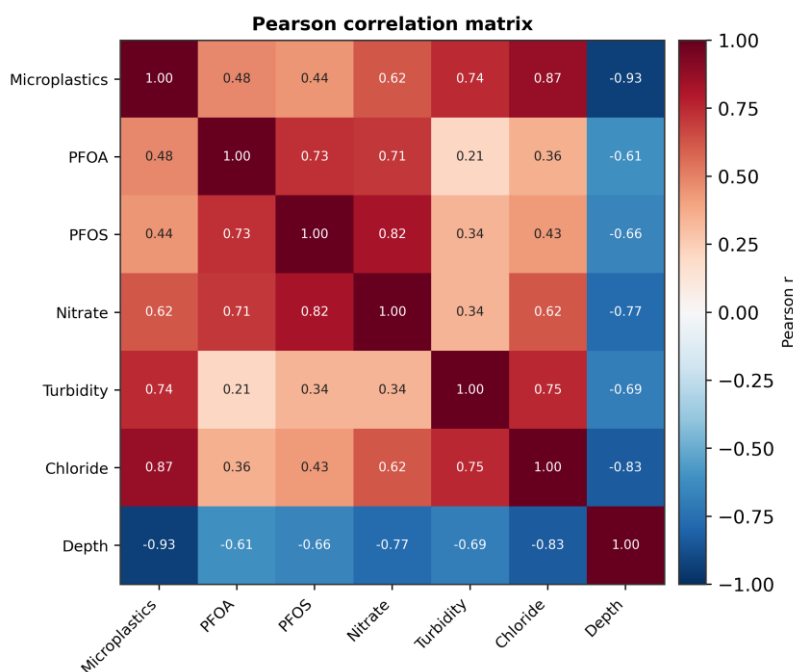


Figure 7. Pearson correlation matrix among the six contaminants and aquifer depth, showing strong intra-cluster correlations and uniformly negative associations with depth.

Discussion

The results answer the study’s central question directly: the confined volcanic aquifers of Savusavu, Fiji, are not untouched by modern anthropogenic contaminants. Microplastics and PFAS have both infiltrated groundwater at depths exceeding 45 m in a remote Pacific island, disrupting the long-standing hydrogeological assumption that deep, isolated basaltic aquifers are secure from persistent global pollution ^{1,2}. The detection of these contaminants at such depths, together with their coherent spatial and multivariate structure, demonstrates an efficient connection between

surface environmental degradation and deep subsurface water reserves.

The mean microplastic concentration of 4.08 MPs/L is lower than levels commonly reported in shallow, unconfined aquifers of industrialised regions ^{5,7,22}, yet the mere presence of fibres at these depths in a non-industrialised island setting indicates an efficient transport mechanism. The fibre-dominated morphology strongly implicates atmospheric fallout of synthetic textiles, carried by regional wind fields and delivered by tropical rainfall, as the primary entry vector into the island’s hydrological cycle ^{3,14,18}. This interpretation is

consistent with the growing evidence that MPs are transported atmospherically to remote catchments and subsequently mobilised into groundwater ^{1,7}.

The transport of microparticles into the confined aquifer is intrinsically linked to the structural properties of volcanic geology. Basaltic formations in the Savusavu region are pervaded by cooling joints and tectonic fractures that behave as macropores, creating preferential flow paths that permit rapid infiltration during heavy tropical rainstorms and effectively circumvent matrix filtration ^{13,14}. This model is strongly supported by the PCA: microplastics cluster with turbidity and chloride on PC2 (Figure 6). Because turbidity is a proxy for rapid particulate transport, the association confirms that microplastics enter through open fractures rather than by slow percolation through the soil matrix ¹³. The highly significant inverse correlation between depth and MP concentration (Figure 4) further indicates that although fracture flow is active, physical entrapment ultimately occurs in the deepest, least-fractured zones. Interaction between the irregular edges of polymer fragments and the rough, vesicular basalt surfaces traps larger particles, explaining the depth-dependent attenuation observed ².

In stark contrast, the ubiquitous presence of PFOA and PFOS reflects the extreme mobility and persistence of perfluoroalkyl substances. Although mean PFAS concentrations remain below the EU summed-PFAS limit, PFOA exceeded the stringent US EPA MCL in 10 of 15 wells, a finding of real regulatory significance given the recent tightening of drinking-water standards ¹⁷. Unlike particulate MPs, PFAS transport is not strongly restricted by physical filtration: these compounds display high aqueous solubility and minimal sorption to the low-organic-carbon basaltic rock ^{4,12}. Their shallower attenuation gradient with depth relative to MPs (Figure 4) is the hydrogeological signature of a mobile, dissolved contaminant that migrates with the water phase rather than being filtered from it.

The PCA indicates that PFAS share their principal transport axis with dissolved nitrate (PC2 negative cluster), pointing to a combined signal of global atmospheric deposition and localised agricultural influence ¹⁰⁻¹². The co-association of PFAS with nitrate is consistent with recharge in the agricultural-fringe zone delivering both fertiliser-derived nitrate and surface-accumulated PFAS to the aquifer ^{6,10}. Once introduced, PFAS migrate vertically and horizontally with virtually zero natural degradation, creating a long-term contamination sink that cannot be flushed on human timescales ^{4,9}. This insidious persistence, rather than the current absolute concentrations, is the principal long-term threat to baseline water quality.

These findings align with emerging global evidence that trace anthropogenic contaminants are distributed across all environmental compartments, including those long considered pristine ^{1,2,9}. The environmental implications for Fiji and the wider South Pacific are substantial. Confined aquifers are the ultimate safeguard

against surface-water contamination and the primary resilience mechanism during climate-driven droughts. Confirmation that recalcitrant pollutants have infiltrated these reserves necessitates a proactive shift in groundwater protection — from protecting individual wellheads to mapping and securing the high-vulnerability recharge zones associated with permeable fracture networks ¹⁴.

Placing these values in a global context reinforces their significance. The mean microplastic abundance recorded here is broadly comparable to, or lower than, concentrations reported for unconfined and karst aquifers in more developed and industrialised regions, where fibre-dominated assemblages and fracture- or conduit-controlled transport are similarly documented ^{5,7,21}. The novelty of the present result is not the magnitude but the setting: comparable particle loads occur here in a confined basaltic aquifer beneath a sparsely populated tropical island with no significant local plastics industry, which can only be reconciled with a dominant atmospheric-plus-fracture-flow delivery mechanism ¹⁻³. For PFAS, the detection of PFOA and PFOS in every well at concentrations that repeatedly exceed the newly enforceable US EPA benchmark echoes recent syntheses reporting PFAS in remote and background groundwaters worldwide ^{4,11,17}, and confirms that even geographically isolated island aquifers now register the global PFAS signal. Taken together, the Savusavu data extend the emerging consensus that no freshwater compartment can any longer be assumed contaminant-free ^{2,9}.

From a public-health perspective, the co-occurrence of two contaminant classes with different toxicological profiles compounds the concern. PFAS are associated with immunotoxicity, endocrine disruption, altered lipid metabolism and developmental effects, which underpin the drastic lowering of regulatory limits worldwide ^{12,17}. Microplastics act both as particulate stressors and as vectors for sorbed chemical and microbial loads, and their smaller fractions may cross biological barriers ⁸. Because the exposed population relies on untreated or minimally treated groundwater, even sub-guideline chronic exposure warrants precautionary management. The hazard-index results, which exceed unity in most wells on the basis of the EPA benchmark, provide a defensible screening-level trigger for monitoring and, where feasible, point-of-use treatment.

In the Pacific SIDS governance context, these results expose a concrete policy gap. Fiji's drinking-water framework, like those of most Pacific states, does not yet regulate MPs or PFAS ^{16,19}. Embedding emerging-contaminant thresholds aligned with WHO and EPA guidance, establishing periodic groundwater surveillance, and protecting fracture-controlled recharge zones would materially strengthen island water security. Because atmospheric deposition is a dominant pathway, national action must be complemented by regional and global efforts to curb plastic and PFAS emissions — the ultimate sources lie largely beyond the islands' own jurisdiction ^{3,9}.

Translating these findings into operational monitoring is feasible even under the resource constraints typical of Pacific SIDS. A tiered surveillance scheme is proposed: an annual dry-season screening of a representative subset of production wells for PFOA, PFOS and total microplastic counts, supplemented by event-based sampling after major rainfall to capture fracture-flow pulses that the present single-campaign design could not resolve. The contamination and hazard indices computed here — the PFOA contamination factor, the PFAS hazard index and the pollution load index — provide simple, transferable metrics that water managers can track over time without specialist interpretation, and that flag individual wells for prioritised follow-up^{8,12}. Wells in the shallow agricultural-fringe zone, which consistently ranked highest across all three indices (Figure 5), warrant particular attention and would be logical candidates for point-of-use treatments such as granular activated carbon or reverse osmosis where exposure reduction is required^{17,18}. Coupling such monitoring with protection of fracture-controlled recharge areas offers a pragmatic, cost-aware pathway to safeguarding island groundwater.

This study has several strengths. It provides the first joint MP–PFAS baseline for a confined volcanic aquifer in a remote Pacific island. It couples rigorous, fluoropolymer-free sampling with a multi-method analytical workflow and a comprehensive statistical treatment including effect sizes, multivariate source apportionment and standardised contamination indices. The spatial design across hydrogeological zones enables interpretable process inference rather than mere occurrence reporting.

Several limitations should temper interpretation. First, sampling represents a single dry-season campaign, so seasonal variability and wet-season fracture-flow pulses were not captured; a multi-season programme is needed to quantify temporal dynamics. Second, the PFAS suite was limited to PFOA and PFOS, omitting short-chain and precursor compounds that are increasingly important in drinking-water risk assessment. Third, with 15 wells the statistical power for detecting moderate zonal contrasts is limited, which likely explains the non-significant PFOA ANOVA despite a large effect size. Fourth, source apportionment by PCA is correlational and would be strengthened by isotopic or polymer-specific fingerprinting and by direct characterisation of atmospheric deposition. These constraints define a clear agenda for confirmatory monitoring.

Conclusion

This baseline assessment provides empirical evidence that the confined volcanic aquifers of Savusavu, Fiji, are no longer entirely pristine. Microplastics were detected in 87% of wells and PFAS in 100%, with PFOA exceeding the 4.0 ng/L US EPA maximum contaminant level in 10 of 15 wells while nitrate and chloride remained within WHO limits. Two distinct contamination pathways were resolved: a particulate, fracture-flow pathway that transports microplastics and produces marked

attenuation with depth, and a dissolved pathway that allows PFAS to migrate with minimal filtration. Recognising the baseline presence of these emerging contaminants is the essential first step toward safeguarding Pacific island freshwater. We recommend that Fiji and neighbouring SIDS integrate MP and PFAS thresholds into national drinking-water standards, establish routine groundwater surveillance, and protect fracture-controlled recharge zones as a matter of priority.

Declarations

Ethical Approval. This study involved no human or animal subjects and therefore required no institutional ethics approval; groundwater sampling was undertaken with the permission of borehole owners and local authorities.

Competing Interests. The authors declare no competing interests.

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Data Availability. The datasets generated and analysed during the present study are available from the corresponding author upon reasonable request.

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