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From salinity to nanoplastics: redefining safe yield in strip-island aquifers under emerging contaminant threats

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Abstract: Nanoplastic contamination is emerging as a significant threat to groundwater security on small islands, where freshwater lenses serve as primary water supplies. Existing groundwater management frameworks are largely based on salinity intrusion and do not account for the distinct transport behavior of nanoplastics. This study formulates a multi-physics numerical model incorporating variable-density groundwater flow, salt transport, and nanoplastic migration processes to investigate nanoplastic transport in idealized strip-island aquifers under pumping conditions. The model is calibrated using laboratory-scale data and evaluated at the field scale. Results show that nanoplastic migration is controlled not only by advection – dispersion processes but also by particle-specific interactions, leading to transport dynamics fundamentally different from those of dissolved salts. In particular, the higher effective dispersivity of nanoplastics causes earlier breakthrough at extraction wells and the formation of broader contaminant transition zones. Pronounced scale effects are observed: while laboratory simulations exhibit rapid upward coning and contamination, field-scale simulations indicate attenuated coning and stabilization over substantially longer timeframes. Sensitivity analysis identifies nanoplastic dispersivity as the dominant parameter influencing well contamination risk. These findings demonstrate that safe extraction strategies based solely on salinity thresholds may underestimate contamination risks and that well placement and pumping design must account for nanoplastic transition zones. The study provides a process-based framework for adapting groundwater management to emerging nanoplastic pollution in vulnerable island environments.

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Keywords: Groundwater lens; Seawater intrusion; Groundwater contamination; Pumping optimization

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1. Introduction

Islands, more than 340,000 worldwide, cover approximately 6.7% of the Earth's terrestrial surface and support nearly 10% of the global population (Sayre et al., 2019). On many small islands, limited surface water availability makes groundwater a critical resource for local communities (Dose et al., 2014). Notably, numerous Pacific islands rely on shallow freshwater lenses—buoyant bodies of freshwater overlying saltwater in highly permeable aquifers—as their primary water supply (Sharan et al., 2021; White and Falkland, 2010). The formation, stability, and morphology of these lenses result from the interplay between density contrasts and multiple external factors, including climate, geological structures, and anthropogenic activities such as groundwater pumping and subsurface barrier installation (Alsumaiei and Bailey, 2018; Ketabchi et al., 2014; Tang et al., 2021, 2022; Yan et al., 2021; Yang et al., 2025; Gao et al., 2025; Zheng et al., 2025). A persistent challenge is the sustainable extraction of freshwater, as excessive pumping can induce upward saline coning, degrade water quality, and threaten long-term water security (Abdoulhalik and Ahmed, 2018; Dagan and Bear, 1968; Houben and Post, 2017; Werner et al., 2009).

The maximum safe extraction rate for freshwater lenses is typically estimated using analytical solutions that assume a sharp interface between freshwater and seawater (Muskat, 1937). Such approaches are widely used in two-dimensional strip-island models to determine the pumping threshold at which the saline interface reaches the well screen (Tang et al., 2020, 2021, 2024). While computationally efficient, these models neglect hydrodynamic dispersion and the development of a brackish transition zone, which can be extensive in highly permeable island aquifers (Coulon et al., 2022; Babu et al., 2020). Consequently, current safe-yield assessments often overlook realistic mixing processes and contaminant transport within the transition zone, potentially underestimating water-quality risks.

Beyond salinity intrusion, microplastic contamination has emerged as an additional and largely unaddressed threat to island groundwater systems. Microplastics are pervasive environmental pollutants detected in marine environments,

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soils, and groundwater worldwide (Koelmans et al., 2022; Koutnik et al., 2021; Li et al., 2018; Ren et al., 2021; Thompson et al., 2024). Oceanic concentrations continue to rise due to plastic persistence and ongoing inputs (Isobe et al., 2019). The concentrations of nanoplastics—which are formed as a result of their breakdown—are even higher, with coastal waters often exhibiting higher levels than open-ocean regions (ten Hietbrink et al., 2025). Emerging evidence indicates that seawater intrusion facilitates the transport of microplastics into coastal aquifer systems (Chen et al., 2024). Because island aquifers are completely surrounded by seawater, freshwater lenses are particularly vulnerable to marine-sourced nanoplastic contamination (Fig. 1).

Transport processes of microplastics in porous media differ fundamentally from those of dissolved solutes. Early modeling efforts adapted classical advection-dispersion equations with simple adsorption terms (Babakhani et al., 2017), but subsequent studies have demonstrated that the migration of microplastics and nanoplastics involves additional mechanisms such as adsorption-desorption, clogging, interception, and aggregation (Liu et al., 2024; Yuan et al., 2024). Importantly, microplastic dispersion coefficients depend on particle size and flow velocity (Wang and Sedighi, 2023). Under pumping conditions that induce upward coning flow fields, these properties suggest that nanoplastics may migrate toward extraction wells more rapidly than salinity and form a broader or earlier contaminant transition zone. Traditional sharp-interface and salinity-based intrusion models fail to capture this behavior, which has remained largely unexplored in island freshwater lens studies.

Taken together, there are two critical gaps. First, existing safe-yield models oversimplify the freshwater-seawater transition zone by neglecting dispersion-driven mixing. Second, the distinct migration behavior of nanoplastics under pumping-induced coning remains poorly understood. Current modeling frameworks, largely derived from solute transport theory, do not adequately capture transient nanoplastic breakthrough or particle-specific transport dynamics.

To address these gaps, this study develops a coupled numerical model that

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integrates variable-density groundwater flow, salt transport, and nanoplastic migration in island aquifers. This study aims to: (1) quantify marine-derived nanoplastic accumulation in freshwater extraction wells under pumping conditions; (2) assess how nanoplastic transport, especially enhanced dispersivity, alters the maximum safe extraction rate compared to traditional salinity-based thresholds; and (3) evaluate the sensitivity of nanoplastic migration and associated risks to key hydrogeological parameters and operational factors. By incorporating nanoplastic transport parameters derived from laboratory column experiments and conducting simulations at both laboratory and field scales, this work provides critical insights for adjusting groundwater management strategies to safeguard island freshwater resouces in the face of emerging nanoplastic pollution.

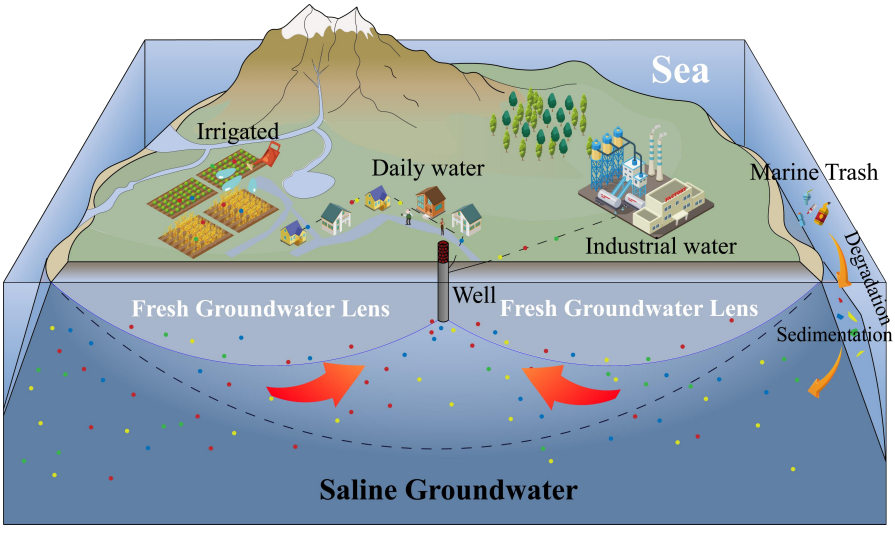

Fig. 1. Schematic diagram of freshwater lenses and nanoplastic contaminant distribution in an idealized strip-island aquifer under groundwater extraction.

2. Methods

2.1 Mathematical model

To simplify the problem and enhance computational tractability, the following key assumptions are adopted based on established modeling practices in coastal aquifer studies (Stoeckl and Houben, 2012; Yao et al., 2019): (i) the aquifer is

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homogeneous and isotropic; (ii) fluid density is solely dependent on groundwater salinity, with thermal effects considered negligible; (iii) the nanoplastic particle density is assumed to be approximately equal to the water density (e.g., some aged nanoplastics); (iv) the saturated zone is initially saturated with seawater, and rainfall infiltration is spatially uniform and temporally constant; and (v) groundwater flow is simulated within a two-dimensional vertical profile of the strip island, leveraging the geometric symmetry of the idealized domain.

This study presents an integrated numerical framework that extends a variable-density groundwater flow model for the unsaturated-saturated zone by incorporating salinity and nanoparticle transport modules. The nanoparticle transport model uniquely combines advective-diffusive transport with nanoplastic adsorption mechanisms. The resulting framework simultaneously simulates variable-density groundwater flow, solute salt transport, and nanoparticle migration via coupled advection-dispersion and adsorption processes. Governing equations for the variable-density flow and salinity transport components are available in Text S1.

Research suggests that nanoplastic transport is primarily influenced by particle movement and physical/physicochemical interactions with porous media surfaces (Al Harraq and Bharti, 2022; Ranjan et al., 2023; Ren et al., 2022; Waldschläger and Schüttrumpf, 2020). Particle movement is described in the equations as convection, diffusion and dispersion effects, while physicochemical interactions with porous media are characterized by mechanisms such as adhesion and detachment, mechanical strain on aggregates and individual particles, blockage, and maturation. The subsurface transport of nanoplastic particles is governed by an advection-diffusion equation, a framework established for nanoparticle migration that captures advection, dispersion, and adsorption processes (Yuan et al., 2024):

$$\frac{\partial}{\partial t}\left(S_{\mathrm{W}}\theta C_{\mathrm{np}}\right)+\frac{\partial}{\partial t}\left(\rho_{\mathrm{b}}s\right)+\nabla C_{\mathrm{np}}\,\frac{k_{\mathrm{r}}\mathbf{k}}{\mu}\nabla P+\nabla\cdot\left[-\theta S_{\mathrm{W}}D_{\mathrm{np}}\nabla C_{\mathrm{np}}\right]=f \qquad (1)$$

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$$\frac{\rho_b \partial s}{\partial t} = \theta K_{att} \psi_b C_{np} e^{-\frac{s}{\lambda}} - \rho_b K_{det} s + \theta \rho_b K_{rip} s C_{np} \quad (2)$$

where C_{np} represents the concentration of nanoplastics in groundwater [ML^{-3}], ρ_b denotes the density of the aquifer medium [ML^{-3}], s is the mass of nanoplastics attached per unit mass of solid [MM^{-1}], D_{np} is the hydrodynamic dispersion coefficient of nanoplastics [L^2T^{-1}], and f is the source-sink term [$ML^{-3}T^{-1}$]. K_{att} is the first-order colloidal attachment coefficient [T^{-1}], parameter λ represents the strain capacity of porous media [MM^{-1}], K_{det} is the first-order colloidal detachment coefficient [T^{-1}], and K_{rip} is the aging kinetic coefficient [$M^{-1}L^3T^{-1}$].

The adhesion of nanoplastics in porous media is described by the following governing equation:

$$\psi_b = (1 - \frac{s}{s_{max}}) \quad (3)$$

where ψ_b denotes the adhesion state of nanoplastics in porous media [-], and s_{max} represents the maximum mass of nanoplastics that can be retained per unit mass of porous medium [MM^{-1}].

The variation in hydraulic conductivity as a function of porosity is characterized by the following relationship (Zheng, 2014):

$$\frac{K}{K_0} = (\frac{\theta}{\theta_0})^3 (\frac{1-\theta_0}{1-\theta})^3 \quad (4)$$

where K is the hydraulic conductivity of the porous medium [LT^{-1}], K_0 is the hydraulic conductivity of the initial porous medium [LT^{-1}], and θ_0 is the porosity of the initial water-bearing medium [-].

The approximate analytical solution derived by Tang et al. (2021) describes the

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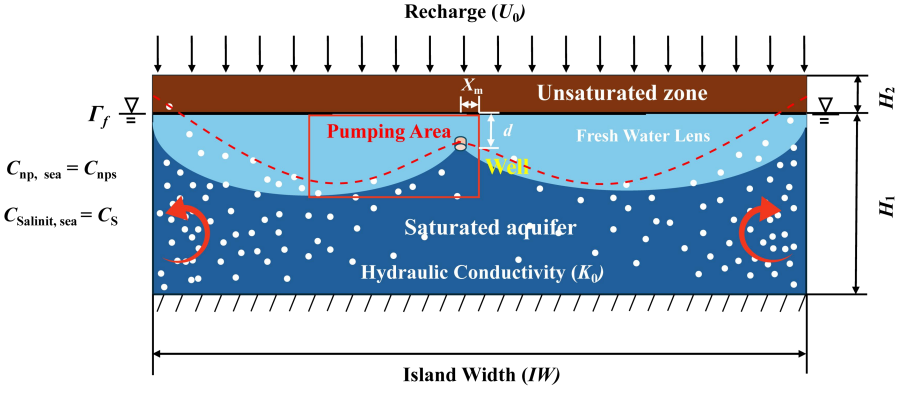
160 critical pumping rate preventing brine intrusion when pumping wells are located in
161 the idealized strip island's central region. The theoretical maximum safe extraction
162 rate is expressed as:

$$Q_{\mathrm{Tmax}} = \omega\left(W - x_{\mathrm{m}}\right) - \frac{\delta(1+\delta)Kd^2}{\left(W - x_{\mathrm{m}}\right)} \tag{5}$$

$$\delta = \frac{\left(\rho_{\mathrm{s}} - \rho_{\mathrm{f}}\right)}{\rho_{\mathrm{f}}} \tag{6}$$

163 where ω is the infiltration rate at the upper surface of the unsaturated zone [LT^{-1}],
164 ρ_s is the sea water density [ML^{-3}], ρ_f is the fresh water density [ML^{-3}], d is the
165 distance from the well to the lower boundary of the unsaturated zone [L], W is the half
166 width of the idealized strip island[L], x_m is the distance from the well to the centre
167 of the idealized strip island[L].



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169 Fig. 2. Conceptual model of nanoplastic pollution in an idealized strip-island aquifer
170 with central pumping. The model depicts an unsaturated zone (height H_2) over a
171 saturated zone (height H_1). Freshwater lenses are shown in light blue and saline
172 groundwater in dark blue. Key parameters include island width (IW), continuous
173 precipitation (U_0), seawater salinity (C_s), and seawater nanoplastic concentration
174 (C_{nps}).

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2.2 Numerical Simulation

The numerical simulation investigates the migration behavior of nanoplastics under pumping conditions in an idealized strip-island aquifer. The laboratory-scale model domain (60 cm×17 cm) was constructed following the configuration established by Tang et al. (2021) (Fig. S4), while a field-scale model (600 m×50 m) was developed to assess site-level transport phenomena. Key simulation parameters are provided in Table 1. Model parameters calibrated from laboratory-scale experiments were extrapolated to the field scale assumed for the modeling study to evaluate the consistency of nanoplastic migration patterns across scales. At the ocean boundary, a constant head (Dirichlet) condition was imposed with a specified hydraulic head (H_1) and a salt concentration of 34.7 g/L; tidal influences were neglected. A constant flux (Neumann) condition was applied to the upper boundary, representing recharge at a rate U_0. Fig. 2 shows a vertical cross-section of a typical freshwater groundwater lens in an idealized island under single-well pumping conditions. Additional aquifer properties are summarized in Table 1.

Table 1. Numerical Simulation Parameters for Variable-Density Flow and Nanoplastic Transport (Laboratory and Field Scales)

Parameter	Sympol	Unit	Value
Variable density parameter			
Density of sea water	ρ_0	kg/m^3	1025
Density of freshwater	ρ_f	kg/m^3	1000
brine concentration	C_s	mol/L	0.5989
Nanoplastics properties PS-Pd-1			
Constant a, b	λ	mg/g	1.6
Particle deposition rate coefficient a, b	K_{att}	1/s	0.0025
Euler number a	e	—	2.7183
The maximum solid phase particle con centration a, b	S_{max}	m^3/kg	10

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Particle release rate coefficient a, b	K_{det}	1/s	0.001
Maturity rate of nanoplastics a, b	K_{rip}	m^3 /(s·mol)	0.009
Longitudinal dispersivity b	$\alpha_{LPS-Pd-1}$	cm	1.06
The average relative molecular weight of nanoplastics c	N_m	g/mol	70000
Nanoplastics properties PS-Pd-2			
Constant a, b	λ	mg/g	1.7
Particle deposition rate coefficient a, b	K_{att}	1/s	0.0002
The maximum solid phase particle concentration a, b	S_{max}	m^3/kg	10
Particle release rate coefficient a, b	K_{det}	1/s	0.005
Maturity rate of nanoplastics a, b	K_{rip}	m^3 /(s·mol)	0.007
Longitudinal dispersivity b	$\alpha_{LPS-Pd-2}$	cm	0.91
The average relative molecular weight of nanoplastics c	N_m	g/mol	70000
Laboratory Porous medium properties			
Island width d	IW	cm	60
Saturated zone thickness d	H_1	cm	15
Unsaturated zone thickness d	H_2	cm	2
Rainfall infiltration d	U_0	cm/min	0.80
Porosity d	θ_0	—	0.38
Longitudinal dispersivity	α_L	cm	0.2
Hydraulic conductivity d	K_0	cm/min	200
Field-scale Porous medium properties			
Island width	IW	m	600
Saturated zone thickness	H_1	m	45
Unsaturated zone thickness	H_2	m	5
Rainfall infiltration	U_0	m/s	2×10^{-8}

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Porosity	θ_0	—	0.38
Longitudinal dispersivity	α_L	m	0.5
Hydraulic conductivity	K_0	m/s	0.0001

a. Data from Liu et al. (2024)

b. Data inversion was performed based on the experimental.

c. Data from Singh et al. (2025)

d. Experimental water pumping scenario from Tang et al. (2021)

The coupled governing equations for variable-density saturated groundwater flow and solute transport were solved numerically via COMSOL Multiphysics, with boundary conditions prescribed accordingly. The system of equations was solved iteratively using a preconditioned conjugate gradient (PCG) method with a relative tolerance of 1×10^{-4}. Initial time steps of 0.001 s and 0.001 d were adopted for the transient analyses.

The computational domain for the laboratory-scale model was discretized into 63,928 triangular elements and 32,350 nodes, with a maximum element diameter of 2 mm. For the field-scale model, the domain was discretized into 30,000 quadrilateral elements and 30,651 nodes, with a maximum element diameter of 1 m. The selected mesh sizes, in conjunction with the hydrodynamic dispersion parameters, conformed to the Péclet number criterion to minimize numerical dispersion and ensure solution stability (Voss and Provost, 2002):

$$Pe_1 = \frac{v_1 \Delta L_1}{D_1 + \alpha_{L1} v_1} \approx \frac{\Delta L_1}{\alpha_{L1}} = 1 \le 4 \tag{7}$$

$$Pe_2 = \frac{v_2 \Delta L_2}{D_2 + \alpha_{L2} v_2} \approx \frac{\Delta L_2}{\alpha_{L2}} = 2 \le 4 \tag{8}$$

where Pe_1 is the Péclet number in laboratory-scale [-], Pe_2 is the Péclet number in site-scale [-], ΔL_1 is the grid length in laboratory-scale [L], ΔL_2 is the grid length in site-scale [L], v_1 is flow velocity in laboratory-scale [LT^{-1}], v_2 is flow velocity in

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site-scale [LT^{-1}], D_1 is diffusion coefficient in laboratory-scale [L^2T^{-1}], D_2 is diffusion coefficient in site-scale [L^2T^{-1}], α_{L1} is the Longitudinal dispersivity in laboratory-scale [L], α_{L2} is the Longitudinal dispersivity in site-scale [L].

A continuous rainfall-driven model was developed to simulate freshwater lens dynamics and well extraction in an idealized island aquifer. The simulation comprises two distinct hydraulic phases: Phase I involves the formation of a stable freshwater lens under continuous rainfall infiltration and seawater intrusion; Phase II initiates groundwater extraction via a single pumping well, leading to the development of a stable saline upconing zone. In the laboratory-scale setup, the horizontal distance x_m from the standard well to the island center was set to 0, 2.5, 5, 7.5, 10, 12.5, 15, 17.5, and 20 cm. The vertical distance d from the well screen to the base of the saturation zone was defined as 0, 5, 10, 12, 15, 18, 20, and 25 mm. Hydraulic conductivity K_0 values were assigned as 150, 175, 200, 225, and 250 cm/min, with corresponding recharge rates U_0 of 0.6, 0.7, 0.8, 0.9, and 1.0 cm/min. For the field-scale scenario, the pumping well was positioned at a horizontal distance x_m=5 m from the island center, corresponding to a central well location. The hydraulic conductivity K_0 was set to 1×10^{-4} m/s, with a recharge rate $U_0 = 2\times10^{-8}$ m/s (Tang et al., 2021).

2.3 Evaluation Indicators

Nanoplastic concentrations at the wellhead were monitored to evaluate the impacts of nanoplastics on island freshwater lens development projects. The seawater-freshwater interface of the freshwater lens was designated as 0.347 g/L, corresponding to 1% seawater salinity. Contemporary laboratory investigations typically utilize nanoplastic concentrations ranging from 10 μg/L to 100 mg/L. Owing to constraints associated with nanoplastic preparation protocols and detection capabilities, the migration parameters of nanoplastics in this study were derived under an initial concentration of 10 mg/L. To date, the highest measured nanoplastic concentrations in natural environments have reached 3.02 mg/L in the North Pacific, while a maximum concentration of 162 mg/L has been documented in relevant studies

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(Moore et al., 2001; Reddy et al., 2006). Sussarellu et al. (2016) reported that a nanoplastic concentration of 22 μg/L induced alterations in feeding behavior and reproductive disruption in oysters. Adopting the 1% seawater salinity threshold as a reference for nanoplastic concentrations facilitates comparisons of migration patterns between nanoplastics and dissolved salts under freshwater extraction scenarios in idealized strip-shaped islands, while incorporating the biological toxicity of nanoplastics as a critical constraint.

Concurrently, the distribution of nanoplastics within freshwater lenses is characterized by comparing the volume reduction rate (*VR*) of freshwater lenses over a given time period:

$$VR = \frac{V_0}{V_w} \tag{9}$$

where V_0 represents the volume of freshwater lenses not yet pumped [L^3], V_w represents represents the volume of freshwater lenses after pumped [L^3],

Accounting for the implications of the transition zone theory for groundwater pumping practices, the following indicator is defined: the ratio of the actual maximum safe extraction capacity to the theoretical maximum safe extraction capacity (*ASYR*):

$$ASYR = \frac{Q_{Amax}}{Q_{Tmax}} \tag{10}$$

where Q_{Amax} represents the actual maximum safe extraction volume [L^3T^{-1}], Q_{Tmax} represents the theoretical maximum safe extraction volume [L^3T^{-1}]

Taking into account the potential reduction in groundwater extraction capacity induced by nanoplastic contamination, the following indicator is defined: the ratio of the maximum safe extraction capacity reduction caused by nanoplastic retention to the maximum safe extraction capacity (*RRSY*):

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$$RRSY = \frac{Q_{Amax} - Q_{Smax}}{Q_{Amax}} \quad (11)$$

where Q_{Smax} represents the maximum safe extraction volume without nanoplastic influence [L^3T^{-1}].

2.4 Model Calibration

This study examined the migration patterns of two synthetic nanoplastics (PS-Pd-1 and PS-Pd-2) that exhibit contrasting hydrophobicity. The detailed synthesis protocols are available in Supplementary Materials (Text S2). To ensure model accuracy, migration parameters for nanoplastics in quartz sand (Table 1) were validated using column experiment data from Liu et al. (2024). The experimental setup and methodology are detailed in Text S3 and Fig. S1, with calibration processes and results illustrated in Fig. S2 and S3. The primary objective was to quantify how differential nanoplastic-solid phase interactions influence contamination levels in freshwater lenses (Amirmoshiri et al., 2020; Wang et al., 2021). As summarized in Table 1, PS-Pd-1 exhibits strong solid-phase adsorption capacity, whereas PS-Pd-2 demonstrates weaker adsorption. Given potential scale-dependence in nanoplastic transport parameters, current research remains largely focused on laboratory-scale investigations (Johnson, 2020; Li et al., 2021; Liu et al., 2024).

A single-well extraction scheme was implemented in the central region of an idealized strip island aquifer. The maximum safe extraction rate, calculated based on sharp-interface theory, served as the baseline scenario. However, the applicability of this theoretical maximum for island freshwater lenses requires critical re-evaluation, as previous sharp-interface analytical and numerical studies have largely neglected the transition zone formed by salinity dispersion and diffusion—a factor addressed in only limited corrections (Coulon et al., 2022). To determine a more accurate maximum safe extraction rate, a series of numerical simulations with predefined pumping rates were conducted to calibrate both laboratory-scale and site-scale conceptual models.

Although Tang et al. (2021) provided preliminary numerical validation via Fig.

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S4(a)(b), their simulations omitted the effects of the unsaturated zone and the salinity transition zone. In contrast, our validation-based simulations (Fig. S4(c)(d)), which incorporate the unsaturated zone and employ dispersion parameters consistent with Chen et al. (2024), indicate that the 1% salinity contour exceeds the well bottom elevation by 2.03 m. This signifies that pumping-induced salinity surpasses regulatory thresholds, necessitating a reduction in extraction volume.

The relationship between well salinity and the extraction volume ratio (actual to theoretical) is illustrated in Fig. 3. Results confirm that the presence of the unsaturated and transition zones reduces the extraction capacity to 50%–60% of the theoretical maximum (Q_{Tmax}). Specifically, under laboratory conditions, the maximum safe extraction capacity decreased to 61% and 53% of Q_{Tmax} for shallow (d=0 cm) and deep (d=1.5 cm) extraction scenarios, respectively (Fig. 3(a)). Corresponding field-scale simulations showed reductions to 57% and 51% of Q_{Tmax} for shallow (d=0 m) and deep (d=15 m) extraction. The temporal evolution of well salinity during freshwater lens re-stabilization (Fig. 3(b)) further demonstrates that salinity stabilization occurs within 12 minutes at the laboratory scale but requires approximately 4.5 years at the field scale, highlighting significant temporal disparities influenced by scale effects.

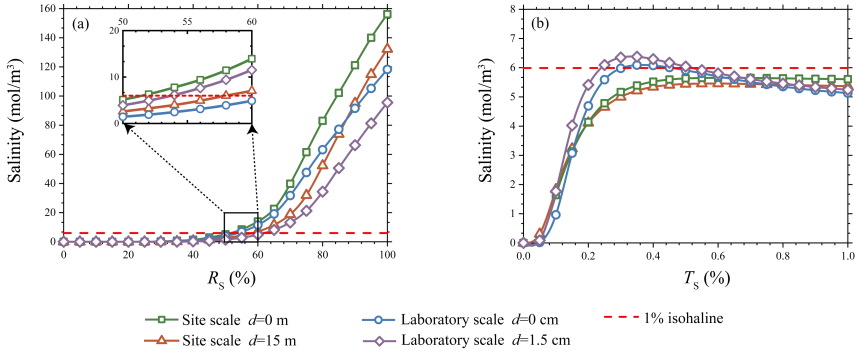

Fig. 3. Variations in well salinity as a function of the ratio of extraction volume to theoretical maximum (R_S) and the ratio of time to theoretical equilibrium time (T_S) during pumping at different depths, measured at both field and laboratory scales: (a)

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Well salinity versus extraction volume, with the magnified region indicating the extraction volume range where well concentration approaches the 1% isohaline; (b) Temporal concentration variations for wells with salinity near the 1% isohaline in panel (a).

3. Results and Discussion

3.1 Distribution Patterns of Nanoplastics Under Pumping Conditions

Hydrophobic microplastics (NPs) were selected as the primary research focus of this study. Text S4 and Fig. S5 demonstrate that hydrophobic molecules exhibit higher mobility and pose more significant hazards than hydrophilic counterparts under simulated single-well pumping conditions.

Fig. 4(a_1-a_4) illustrates an "upper cone" phenomenon in nanoplastic concentrations during pumping, analogous to that of salinity. Fig. 4(a_1) reveals that highly dispersive nanoplastics may form anomalous distributions in the central banded region of the island—a zone previously referred to as the "stagnation zone" (Wang et al., 2023). Nearshore aquifers on both sides of the island undergo intense convection, driven by groundwater discharge to the sea and seawater intrusion induced by density currents. At the laboratory scale, this convective zone spans approximately 10 cm; at the field scale, it extends to around 100 meters, where groundwater Darcy velocities exceed 1×10^{-3} m/s. In contrast, velocities within the central "stagnation zone" remain below 1×10^{-8} m/s. This zone is dominated by weak convection, with material transport in groundwater primarily governed by dispersion and interactions with the solid phase.

Fig. 4(b) presents dynamic nanoplastic isoconcentration lines at the wellhead, where concentrations first increase and then decrease—indicating that wellhead nanoplastics are influenced by the "stagnation zone". The discrepancy in migration behavior between nanoplastics and dissolved solutes stems primarily from their distinct physicochemical properties: as colloidal particles, nanoplastic migration is regulated not only by advection-dispersion but also by particle-medium interactions

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(e.g., adsorption-desorption, clogging, and filtration). Fig. 4(c_1-c_3) depicts variations in nanoplastic concentrations. Nanoplastics extracted from the well resulted in an additional 37.48% reduction in the initial freshwater lens area, while the maximum depth of freshwater bodies surrounded by nanoplastics increased by 0.030 m.

Fig. 4(d_1-d_4) compares the distribution patterns of salinity and nanoplastics, revealing that nanoplastics exceeding 1% of the critical nanoplastic concentration (C_{nps}) are concentrated within freshwater lens layers. With the disappearance of the original "stagnation zone", a new flow field transition zone is formed, triggering the emergence of a new "stagnation zone". The proportion of the freshwater lens occupied by the nanoplastic transition zone (dark blue areas in Fig. 4(d_1-d_4)) increased from 30.27% to 41.24%. Compared to dissolved solutes, nanoplastics possess larger hydrodynamic diameters and unique surface properties, leading to distinctive migration patterns in porous media.

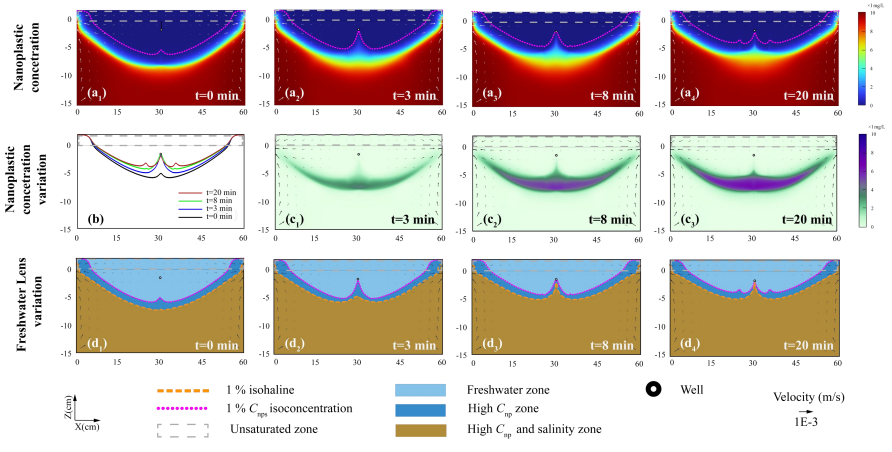

Fig. 4. Distribution and concentration dynamics of PS-Pd-2 hydrophobic nanoplastics and corresponding freshwater lens alterations at the laboratory scale (60 cm×17 cm) during pumping (R_S = 53%): (a_1-a_4) freshwater lenses demarcated by the 1% isoconcentration line of PS-Pd-2 hydrophobic nanoplastics at 0, 3, 8 and 20 minutes post-pumping, (b) temporal variation of the 1% C_{nps} isoconcentration line, (c_1-c_3) net concentration variations relative to the baseline (0 min) at 3, 8 and 20 minutes

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post-pumping, (d_1-d_4) spatial offset between the 1% isohaline and 1% C_{nps} isoconcentration line around the freshwater lens.

Fig. 5(a) presents the vertical concentration profile of nanoplastics at the wellhead, further validating the aforementioned mechanism. Prior to pumping initiation, the nanoplastic transition zone was situated 0.07 - 0.10 m below the well bottom. Following pumping initiation, the transition zone underwent a rapid upward migration and expansion to 0.02 m below the well bottom. Thirty minutes post-pumping, although the transition zone exhibited a slight recession, a stable transition zone was maintained at 0.06 m below the well bottom, while a new steep transition zone formed at 0.03 m. nanoplastic concentrations at the wellhead increased markedly within the first 4 minutes, started to decline after 8 minutes, stabilized at 30 minutes post-pumping, and ultimately converged with the concentration trends of chloride (Cl^-), indicating that solute and colloidal transport are governed primarily by convection. The observed transport behavior can be interpreted through the lens of effective dispersion parameters. In porous media transport modeling, the macroscopic dispersion coefficient in advection-dispersion equations serves as an effective parameter that implicitly captures the integrated effects of various pore-scale processes, including particle-pore interactions, flow path tortuosity, and temporary retention at pore throats. While these microscopic processes are not explicitly resolved in the current continuum-scale model, their integrated effects are reflected in the calibrated dispersion parameters.

Fig. 5(b) illustrates the dynamic concentration dynamics of hydrophilic and hydrophobic nanoplastics, both of which exhibit an initial increase followed by a subsequent decrease. During the initial pumping phase (0 - 6 min), high-concentration nanoplastics in the immediate vicinity of the well were the primary fraction extracted by pumping, leading to a sharp concentration increase to a peak of 2.489% C_{nps}. With prolonged pumping (6 - 32 min), relatively low-nanoplastic peripheral groundwater gradually infiltrated the pumping-affected zone. The original stagnation zone was reconfigured under the influence of pumping, with new stagnation zones emerging on

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both sides of the well. The system eventually attained a state of dynamic equilibrium after 32 min of pumping, with nanoplastic concentrations stabilizing at a steady level. Notably, salinity variations under distinct contamination scenarios involving hydrophilic and hydrophobic nanoplastics also exerted a notable regulatory influence on this process. This phenomenon is hypothesized to originate from an approximate 40% reduction in hydraulic conductivity, which is induced by the solid-phase enrichment of hydrophilic nanoplastics in specific central regions of the study domain.

With respect to the distinct distribution characteristics of wellborne hydrophobic nanoplastics presented in Fig. 5(b), which diverge from those of salinity, the application of a 1% concentration threshold to nanoplastics (consistent with the salinity threshold) results in wellhead nanoplastic concentrations exceeding this criterion for more than 80% of the duration prior to the attainment of a stable system state. To mitigate the adverse impacts of the extensive dispersion of hydrophobic nanoplastics on the quality of pumped groundwater, Fig. 5(c) presents the correlations between hydrophilic and hydrophobic nanoplastic concentrations at the wellhead and the cumulative pumped water volume. Under the theoretical maximum safe pumping rate, hydrophobic nanoplastics accumulate at the wellhead to a concentration of 1.939 mg/L during the initial pumping phase. To reduce the initial wellhead nanoplastic concentrations to below the 1% C_{nps} threshold, the actual maximum safe pumping rate must be further reduced to 37% of the theoretical maximum safe pumping rate. Fig. 5(d) verifies that this identical phenomenon is observable in wellhead nanoplastic concentrations at the field scale, where nanoplastics at such concentrations are still rapidly entrained into the pumping well—indicating that the enrichment mechanism driven by high nanoplastic dispersibility remains valid at the field scale. High-concentration nanoplastic influxes at the wellhead persisted over a 5 - 28 year timeframe at the field scale. Conversely, nanoplastic concentrations in the upper cone region are comparatively lower, with those in the island’s pumping wells reaching only 1.329 % C_{nps}. A detailed elucidation of the underlying mechanisms for this

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phenomenon is presented in Section 3.2.

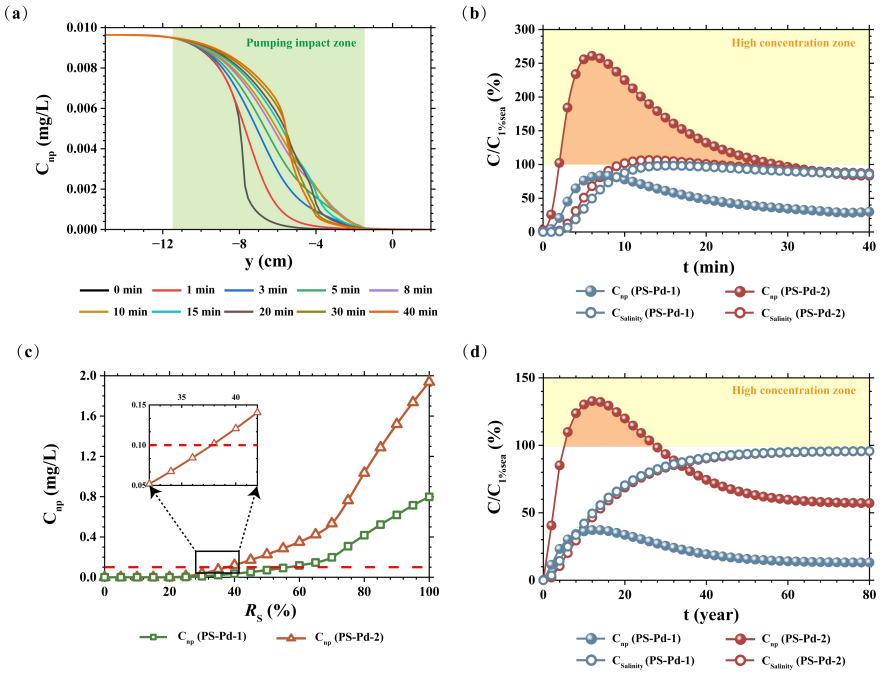

Fig. 5. Concentration dynamics at laboratory and field scales and their responses to pumping rate adjustments: (a) 1% C_{nps} isoconcentration line variation along the central axis (x=30 cm) at laboratory scale; (b) Temporal variations in salinity and nanoplastic concentrations for hydrophilic and hydrophobic nanoplastics at laboratory scale; (c) Well nanoplastic concentration as a function of pumped volume-to-theoretical maximum ratio (Rs) for groundwater nanoplastics of distinct hydrophilic-hydrophobic properties; (d) Temporal variations in well salinity and nanoplastic concentrations for hydrophilic and hydrophobic nanoplastics at field scale.

3.2 Scale Effects on Nanoplastic Transport

In field-scale simulations, the background concentration of hydrophobic nanoplastics was set to 1 μg/L (C_{nps}). Dispersion parameters were adjusted based on scaling-up experience (Gelhar et al., 1992), with the corresponding simulation results presented in Fig. 6. Fig. 6(a_1) shows that following stabilization of the freshwater lens, the 90%–10% C_{nps} transition zone in the central island region thickened to more than

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10 m, yet no prominent dispersion-driven upward cone formed in the island's core area. Scale effects exert their influence primarily in two aspects: with increasing scale, the heterogeneity of the aquifer medium becomes more complex, which may mask the unique migration behavior of nanoplastics. Additionally, streamline curvature is reduced and flow velocity distributions are more homogeneous at larger scales, thereby attenuating inertial effects.

Upon pumping initiation at the field scale, the depth of the freshwater lens decreased from 20.168 m to 13.785 m, while the maximum depth of the freshwater lens encircled by nanoplastics decreased from 17.943 m to 14.610 m. Fig. 6(c_1-c_3) depicts variations in nanoplastic concentration within the lens: the volumetric fraction of nanoplastics occupying the freshwater lens decreased from 31.48% to 23.40%, a trend that deviates from the increasing pattern observed at the laboratory scale. Fig. 6(d_1-d_4) reveals the existence of a ~3 m-thick residual dissolved nanoplastic layer within the freshwater lens, with concentrations at 1-5% of the nanoplastic concentration in seawater. Upon stabilization of pumping, the transition zone migrated upward toward the bilateral jet zones but no new upward cone was generated. At the field scale, the enhancement of nanoplastic dispersion relative to solute dispersion was no longer pronounced, a phenomenon likely due to improved flow stability and inherent scale effects. In addition, the residence time of colloidal filtration and entrainment processes is extended at this scale, which may consequently modify the final spatial distribution of nanoplastics.

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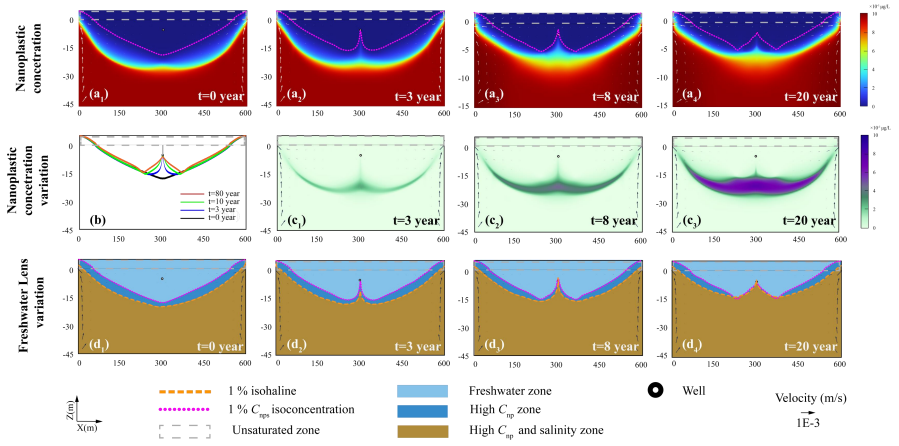

Fig. 6. Hydrophobic nanoplastic concentration dynamics and corresponding freshwater lens alterations at field scale (600 m×50 m) during pumping (R_S = 51%): (a_1-a_4) Freshwater lenses demarcated by the 1% PS-Pd-2 nanoplastic isoconcentration line at 0, 3, 8 and 20 years post-pumping; (b) 1% C_{nps} isoconcentration line variation; (c_1-c_3) Net nanoplastic concentration variations relative to the initial time point (0 year) at 3, 8 and 20 years post-pumping; (d_1-d_4) Spatial offset between the 1% isohaline and 1% C_{nps} isoconcentration line around the freshwater lens.

3.3 Sensitivity Analysis

Four factors were selected for analysis, with the *VR*, *ASYR*, and *RRSY* metrics employed to evaluate nanoplastic contamination in freshwater and freshwater lenses, as well as its implications for pumping operations.

Fig. 7(a_1, b_1) demonstrates that dispersion exhibits a significant correlation with *VR*, and nanoplastic dispersivity exerts a notable influence on pumping efficiency. When nanoplastic dispersivity is lower than that of solutes, the distribution range of nanoplastics closely approximates that of solutes, resulting in a narrow transition zone, while Q_{Amax} is exclusively governed by salinity. When nanoplastic dispersivity equals that of solutes, the freshwater lens zone formed by nanoplastics nearly perfectly overlaps with the seawater-enclosed area. As dispersivity increases to 10 times that of solutes, the volume of freshwater lenses decreases by approximately 30%. When the

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dispersivity of residual nanoplastics exceeds 17 times that of salinity, the expanded dispersion range causes the 1% C_{nps} isoconcentration line to cover the wellhead area. The high sensitivity of nanoplastic behavior to dispersivity stems from their particulate nature: nanoplastics migrate not only via hydraulic dispersion but also through mechanisms such as Brownian motion, gravitational settling, and media interception. High dispersivity reflects the selective migration capacity of nanoplastics within complex pore structures, which is closely associated with their surface properties and hydrodynamic characteristics.

Fig. 7(a_2,b_2) reveals that *VR* gradually increases with rising hydraulic conductivity. At a hydraulic conductivity of 250 cm/min, 46.68% of the freshwater lens area is occupied by high-concentration nanoplastics. Under pumping conditions, both high hydraulic conductivity and high-permeability media result in a significant reduction in the usable portion of freshwater lens layers surrounded by nanoplastics. Aquifer hydraulic conductivity is another critical parameter regulating solute migration and retention. Previous studies have demonstrated that higher hydraulic conductivities result in reduced freshwater lens volumes and correspondingly decreased groundwater availability (Bailey and Jenson, 2014; Cui et al., 2021; Gao et al., 2025). The spatial distribution and magnitude of freshwater lenses surrounded by nanoplastics are consistent with these findings. High hydraulic conductivity accelerates freshwater discharge on both sides of the island, reducing the area where freshwater lenses can maintain equilibrium. For nanoplastics, increased hydraulic conductivity enhances flow velocity and convective transport capacity, thereby facilitating their intrusion into freshwater lenses.

Recharge rates were used to simulate precipitation intensity on the island. Fig. 7(a_3) shows that precipitation significantly reduces the spatial distribution density of nanoplastics within freshwater lenses, with this effect being pronounced both before and after pumping. Increased recharge leads to a decrease in *VR*; when recharge rises to 1.0 cm/min, *VR* declines to 33%. Conversely, when recharge drops below 0.65 cm/min, the final variation in *VR* also weakens, suggesting that nanoplastic

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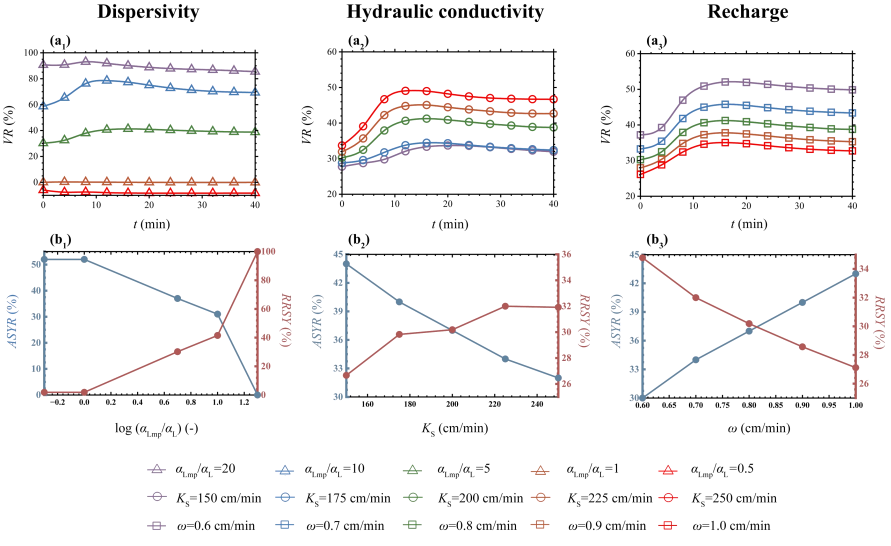
504 concentrations are more difficult to mitigate with increased pumping intensity. Fig.
505 7(b_3) illustrates that enhanced recharge reduces the volume occupied by
506 high-concentration nanoplastics in freshwater lenses, significantly increasing
507 exploitable freshwater volume and alleviating the impact of nanoplastics on maximum
508 safe pumping rates. Previous studies indicate that the volume and thickness of island
509 freshwater lenses are positively correlated with precipitation (Zheng et al., 2025). The
510 "flushing effect" of precipitation on nanoplastic distribution likely operates through
511 two mechanisms: first, precipitation acts as the main source of freshwater storage in
512 lenses. As the freshwater lens area expands, the thick transition zone formed by
513 hydrophobic nanoplastics remains unaffected by convection and maintains a constant
514 thickness, leading to a reduced proportion of nanoplastics despite unchanged total
515 volume. Second, increased recharge may expand the strong convection zones on both
516 sides of the seawater boundary, shrinking the central "stagnation zone" and thereby
517 relatively weakening dispersion effects.

518 Among the analyzed media and environmental conditions, dispersivity emerges
519 as the key parameter governing nanoplastic retention behavior in freshwater lenses,
520 with high dispersivity exerting the most pronounced inhibitory effect on Q_{Amax}.



522 Fig. 7. The volume reduction rate of freshwater lenses (*VR*), the ratio of actual

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maximum safe extraction capacity to theoretical maximum safe extraction capacity (*ASYR*), and the ratio of maximum safe extraction capacity reduction due to nanoplastic retention to maximum safe extraction capacity (*RRSY*) versus (a_1-a_3) dispersivity, (b_1-b_3) hydraulic conductivity, and (c_1-c_3) recharge rate.

Fig. 8(a) and (b) present the theoretically derived maximum safe pumping rate near the freshwater lens center (Tang et al., 2021) and the actual maximum safe pumping rate, respectively. Under standard pumping conditions, the presence of a transition zone reduces the effective area of the freshwater lens by 16.12% and its thickness by 7.77 m. The position of pumping wells directly influences pumping rates: as the distance from the central region increases, pumping rates decrease linearly, as expressed in Equation (10). Simulation results demonstrate that the maximum safe pumping rate of freshwater lenses does not exhibit a perfect linear correlation with the distance from the surface central axis. During shallow pumping, higher rates may even be achieved near the coastal sides due to the low-velocity zone in the center. The actual maximum safe pumped volume occurs at x=10 cm, corresponding to two-thirds of the island's width from the central axis, with a pumping rate of 2.667×10^{-5} kg/s (200% of the theoretical value). At the center, the rate decreases to 2.480×10^{-5} kg/s, equivalent to 62% of the theoretical value. Under idealized strip-shaped island hydrodynamic conditions, seawater infiltrates from both bottom sides, forming an outflow zone at the top of the coastline, with a "stagnation zone" emerging in the island center—a phenomenon confirmed in previous studies. Owing to the slow, predominantly vertical flow in the central region, residual brackish water persists and disperses upward primarily via vertical dispersion. Thus, for single-well pumping projects on small idealized strip-shaped islands, central pumping may not be optimal, whereas lateral single-well operations can yield higher freshwater outputs. For deep pumping, given that freshwater lenses on such islands are approximately semicircular, deeper pumping is feasible near the center.

Fig. 8(c) illustrates that nanoplastic concentration constraints reduce freshwater lens volume by 13-28%, with more significant reductions in areas farther from the

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island's surface central axis, attributed to the uneven distribution of the nanoplastic transition zone. With respect to the reduction in maximum safe pumping rates, Fig. 8(d) demonstrates the decline in pumped volumes at the island center when nanoplastic concentration limits are considered. Centered at the pumping point (x=20 cm, y=0 cm), the maximum safe pumped volume gradually decreases with increasing distance from this center due to nanoplastic concentration restrictions. Near the seawater boundary, the transition zone completely covers the area within 10 cm of the shoreline. Under the 1% C_{nps} concentration limit, regions deeper than 25 mm are designated as non-exploitable zones. This phenomenon arises because the nanoplastic transition zone is relatively extended in the island's central region. Certain central regions exhibit pathway advantages, facilitating faster nanoplastic accumulation into wells. Near the seawater boundary, exploitable volumes decrease due to the influence of seawater nanoplastic source concentrations. Consequently, the combined effect of these two factors results in the highest exploitable volumes occurring in the upper regions near the central axis.

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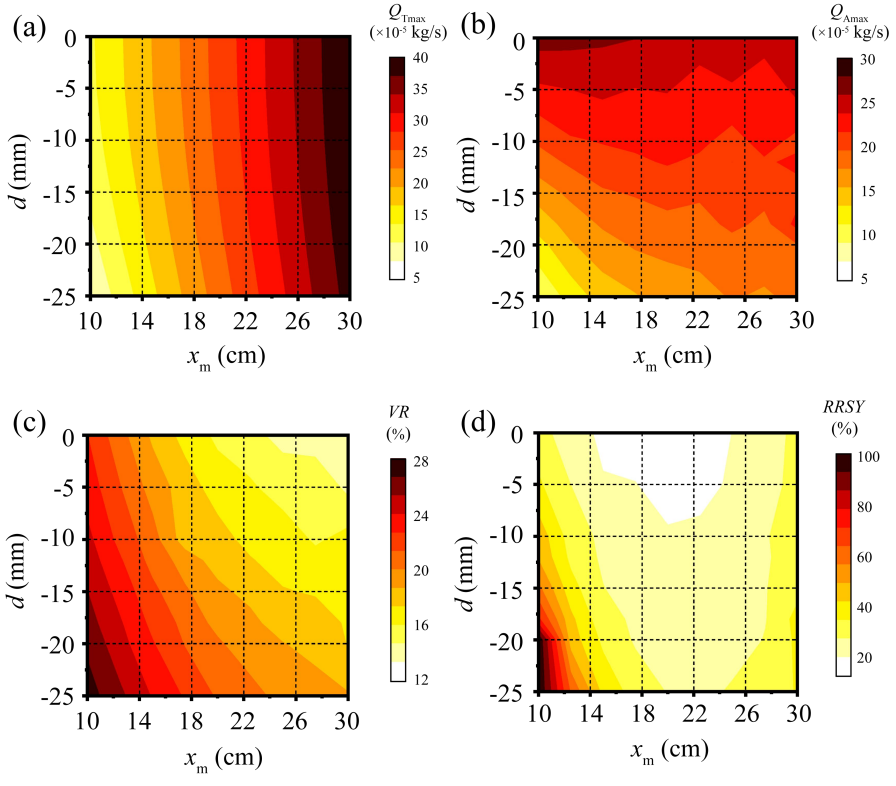

Fig. 8. Combined effects of pumping depth (d) and shore distance (x_m) on (a) theoretical maximum safe extraction capacity (Q_{Tmax}), (b) actual maximum safe extraction capacity (Q_{Amax}), (c) freshwater lens volume reduction rate (VR), and (d) the ratio of maximum safe extraction capacity reduction due to nanoplastic retention to maximum safe extraction capacity ($RRSY$).

4. Conclusion

This study established a coupled variable-density groundwater flow and transport model to explore nanoplastic migration in the freshwater lenses of idealized strip islands under pumping scenarios. By integrating laboratory-calibrated parameters with field-scale simulations, we identify fundamental differences between nanoplastic and traditional solute transport processes and evaluate their implications for groundwater management in island aquifers. Key conclusions are summarized as

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follows:

(1) Nanoplastic transport differs fundamentally from dissolved salt transport. In contrast to dissolved salts, whose behavior is mainly regulated by advection and dispersion, nanoplastics are further affected by particle-specific processes, such as adsorption-desorption, clogging, and filtration. The higher effective dispersivity leads to earlier breakthrough at extraction wells and the development of broader contaminant transition zones compared to salinity alone.

(2) Transport behavior exhibits strong scale dependence. Laboratory-scale simulations showed rapid contamination and prominent "upper cone" formation within minutes, whereas field-scale simulations demonstrated attenuated upward coning and much longer stabilization times on the order of years. This contrast highlights the importance of multi-scale modeling when extrapolating experimental results to real-world island aquifers.

(3) Dispersivity is the dominant control on nanoplastic risk. Among the evaluated parameters, nanoplastic dispersivity exerts the strongest influence on contaminant accumulation in extraction wells, with hydraulic conductivity and recharge rates playing secondary but important roles. When nanoplastic dispersivity exceeds approximately 17 times that of dissolved solutes, the contaminant plume can fully envelop the well screen, reducing the maximum safe extraction rate by 37-50% compared to salinity-based thresholds.

(4) Well placement strategies must account for nanoplastic transition zones. Traditional guidelines based solely on salinity intrusion may not minimize contamination risks. Simulations suggest that central pumping locations are not always optimal; lateral well placement (approximately two-thirds of the distance from the island centerline) can increase freshwater yield while reducing nanoplastic contamination potential.

Several simplifying assumptions were adopted in this study, including homogeneous aquifer properties, idealized boundary conditions, and limited

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representation of nanoplastic diversity. In practice, aquifer heterogeneity, tidal fluctuations, storm events, and the wide range of environmental nanoplastic properties, including particle size distribution, aging state, and surface chemistry, may further influence transport behavior. Moreover, only two synthetic nanoplastic types of synthetic nanoplastics were considered here, whereas natural systems contain a broader and more complex spectrum of particles. Despite these limitations, the present study establishes a mechanistic framework for evaluating nanoplastic transport in coastal freshwater lenses. By coupling variable-density flow with particle-specific transport processes and quantifying impacts on safe extraction thresholds, this study provides a process-based basis for revising groundwater management strategies in island settings. Future research should incorporate heterogeneous aquifer structures, dynamic hydrological forcing, and broader nanoplastic characteristics to enhance predictive capability and support water security in increasingly plastic-polluted coastal environments.

Data availability

The data of this study can be found in Zheng (2026, https://zenodo.org/records/19150343).

Author contributions

TYZ: Conceptualization, Writing-Original Draft, Methodology, Resources, Writing-Review and Editing, Funding acquisition, Supervision.

CXM: Investigation, Software, Writing-Original Draft, Writing-Review and Editing, Visualization, Data Curation, Conceptualization.

SBG: Methodology, Formal Analysis, Investigation, Visualization, Writing-Review and Editing.

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JL: Writing-Review and Editing, Methodology, Supervision, Conceptualization.

Competing interests

The contact author has declared that none of the authors has any competing interests.

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https://doi.org/10.5194/egusphere-2026-1601
Preprint. Discussion started: 31 March 2026

Reference

Abdoulhalik, A., & Ahmed, A. A. (2018), Transient investigation of saltwater upconing in laboratory-scale coastal aquifer, Estuarine, Coastal and Shelf Science, 214, 149-160. https://doi.org/10.1016/j.ecss.2018.09.024.

Al Harraq, A., & Bharti, B. (2022), Microplastics through the Lens of Colloid Science, ACS Environmental Au, 2(1), 3-10. https://doi.org/10.1021/acsenvironau.1c00016.

Alsumaiei, A. A., & Bailey, R. T. (2018), Quantifying threats to groundwater resources in the Republic of Maldives Part I: Future rainfall patterns and sea-level rise, Hydrological Processes, 32(9), 1137-1153. https://doi.org/10.1002/hyp.11480.

Amirmoshiri, M., Zhang, L., Puerto, M. C., Tewari, R. D., Bahrim, R. Z. B. K., Farajzadeh, R., Hirasaki, G. J., & Biswal, S. L. (2020), Role of Wettability on the Adsorption of an Anionic Surfactant on Sandstone Cores, Langmuir, 36(36), 10725-10738. https://doi.org/10.1021/acs.langmuir.0c01521.

Babakhani, P., Bridge, J., Doong, R. A., & Phenrat, T. (2017), Continuum-based models and concepts for the transport of nanoparticles in saturated porous media: A state-of-the-science review, Advances in colloid and interface science, 246, 75-104. https://doi.org/10.1016/j.cis.2017.06.002.

Babu, R., Park, N., & Nam, B. (2020), Regional and well-scale indicators for assessing the sustainability of small island fresh groundwater lenses under future climate conditions, Environmental Earth Sciences, 79(1), 47. https://doi.org/10.1007/s12665-019-8773-3.

Bailey, R. T., & Jenson, J. W. (2014), Effects of Marine Overwash for Atoll Aquifers: Environmental and Human Factors, Groundwater, 52(5), 694-704. https://doi.org/10.1111/gwat.12117.

Chen, G., Zou, Y., Xiong, G., Wang, Y., Zhao, W., Xu, X., Zhu, X., Wu, J., Song, F., & Yu, H. (2024), Microplastic transport and ecological risk in coastal intruded aquifers based on a coupled seawater intrusion and microplastic risk assessment model, Journal of hazardous materials, 135996. https://doi.org/10.1016/j.jhazmat.2024.135996.

Chen, Q., Zhang, L., Shen, C., & Lu, C.(2024), Effects of groundwater pumping on pore water flow and salt transport in tide-controlled unconfined coastal aquifers, Hydrological Processes, 38(8), e15261. https://doi.org/10.1002/hyp.15261.

Coulon, C., Lemieux, J. M., Pryet, A., Bayer,P., Young, N. L., & Molson, J. (2022), Pumping Optimization Under Uncertainty in an Island Freshwater Lens Using a Sharp-Interface Seawater Intrusion Model, Water Resources Research, 58(8). https://doi.org/10.1029/2021WR031793.

Cui, X., Zhu, C., Hu, M., Wang, R., & Liu, H. (2021), Permeability of porous media in coral reefs, Bulletin of Engineering Geology and the Environment, 80(6), 5111-5126. https://doi.org/10.1007/s10064-020-02082-5.

Dagan, G., & Bear, J. (1968), Solving The Problem Of Local Interface Upconing In A Coastal Aquifer By The Method Of Small Perturbations, Journal of Hydraulic Research, 6(1), 15-44. https://doi.org/10.1080/00221686809500218.

Dose, E. J., Stoeckl, L., Houben, G. J., Vacher, H. L., Vassolo, S., Dietrich, J., & Himmelsbach, T. J. J. o. H.(2014), Experiments and Modeling of Freshwater Lenses in Layered Aquifers: Steady State Interface Geometry, 509, 621-630.

https://doi.org/10.5194/egusphere-2026-1601
Preprint. Discussion started: 31 March 2026

http://dx.doi.org/10.1016/j.jhydrol.2013.10.010.

Gao, C., Zheng, T., Chang, Q., Zheng, X., Song, X., & Luo, J. (2025), Dynamics of Irregular Freshwater Lenses Evolution in Thin Aquifers of Reclaimed Circular Islands, Water Resources Research, 61(7), e2024WR038880. https://doi.org/10.1029/2024WR038880.

Gelhar, L. W., Welty, C., & Rehfeldt, K. R. (1992), A critical review of data on field-scale dispersion in aquifers, Water Resources Research, 28(7), 1955-1974. https://doi.org/10.1029/92WR00607.

Houben, G., & Post, V. E. A. (2017), The first field-based descriptions of pumping-induced saltwater intrusion and upconing, Hydrogeology Journal, 25(1), 243-247. https://doi.org/10.1007/s10040-016-1476-x.

Isobe, A., Iwasaki, S., Uchida, K., & Tokai, T. (2019), Abundance of non-conservative microplastics in the upper ocean from 1957 to 2066, Nature Communications, 10(1), 417. https://doi.org/10.1038/s41467-019-08316-9.

Johnson, W. P. (2020), Quantitative Linking of Nanoscale Interactions to Continuum-Scale Nanoparticle and Microplastic Transport in Environmental Granular Media, Environmental Science & Technology, 54(13), 8032-8042. https://doi.org/10.1021/acs.est.0c01172.

Ketabchi, H., Mahmoodzadeh, D., Ataie-Ashtiani, B., Werner, A. D., & Simmons, C. T. (2014), Sea-level rise impact on fresh groundwater lenses in two-layer small islands, Hydrological Processes, 28(24), 5938-5953. https://doi.org/10.1002/hyp.10059.

Koelmans, A. A., Redondo-Hasselerharm, P. E., Nor, N. H. M., de Ruijter, V. N., Mintenig, S. M. , & Kooi, M. (2022), Risk assessment of microplastic particles, Nature Reviews Materials, 7(2), 138-152. https://doi.org/10.1038/s41578-021-00411-y.

Koutnik, V. S., Leonard, J., Alkidim, S., DePrima, F. J., Ravi, S., Hoek, E. M. V., & Mohanty, S. K. (2021), Distribution of microplastics in soil and freshwater environments: Global analysis and framework for transport modeling, Environmental pollution (Barking, Essex : 1987), 274, 116552. https://doi.org/10.1016/j.envpol.2021.116552.

Li, J., Liu, H., & Paul Chen, J. (2018), Microplastics in freshwater systems: A review on occurrence, environmental effects, and methods for microplastics detection, Water Research, 137, 362-374. https://doi.org/10.1016/j.watres.2017.12.056.

Li, M., Zhang, M., Rong, H., Zhang, X., He, L., Han, P., & Tong, M. (2021), Transport and deposition of plastic particles in porous media during seawater intrusion and groundwater-seawater displacement processes, Science of The Total Environment, 781, 146752. https://doi.org/10.1016/j.scitotenv.2021.146752.

Liu, Y., Zheng, T., Guo, B., Jiang, S., Cao, M., & Zheng X. (2024), Adsorption Characteristics of Dissolved Organic Nitrogen on Aquifer Porous Media: The Role of Media Particle Size, ACS ES&T Water, 4(5), 2170-2180. https://doi.org/10.1021/acsestwater.3c00815.

Moore, C. J., Moore, S. L., Leecaster, M. K., & Weisberg, S. B. (2001), A Comparison of Plastic and Plankton in the North Pacific Central Gyre, Marine Pollution Bulletin, 42(12), 1297-1300. https://doi.org/10.1016/S0025-326X(01)00114-X.

Muskat, M. (1937), The Flow of Fluids Through Porous Media, Journal of Applied Physics, 8(4), 274-282. https://doi.org/10.1063/1.1710292.

Ranjan, V. P., Joseph, A., Sharma, H. B., & Goel, S. (2023), Preliminary investigation on effects of size, polymer type, and surface behaviour on the vertical mobility of microplastics in a porous media, Science of The Total Environment, 864, 161148.

https://doi.org/10.5194/egusphere-2026-1601
Preprint. Discussion started: 31 March 2026

https://doi.org/10.1016/j.scitotenv.2022.161148.

Reddy, M. S., Shaik, B., Adimurthy, S., & Ramachandraiah, G. (2006), Description of the small plastics fragments in marine sediments along the Alang-Sosiya ship-breaking yard, India, Estuarine, Coastal and Shelf Science, 68(3), 656-660. https://doi.org/10.1016/j.ecss.2006.03.018.

Ren, Z., Gui, X., Xu, X., Zhao, L., Qiu, H., & Cao, X. (2021), Microplastics in the soil-groundwater environment: Aging, migration, and co-transport of contaminants - A critical review, Journal of hazardous materials, 419, 126455. https://doi.org/10.1016/j.jhazmat.2021.126455.

Ren, Z., Gui, X., Xu, X., Zhao, L., Qiu, H., Wang, X., & Cao, X. (2022), Weathering of microplastics and their enhancement on the retention of cadmium in coastal soil saturated with seawater, Journal of hazardous materials, 440, 129850. https://doi.org/10.1016/j.jhazmat.2022.129850.

Sayre, R., Noble, S., Hamann, S., Smith, R., Wright, D., Breyer, S., Butler, K., Van Graafeiland, K., Frye, C., Karagulle, D., Hopkins, D., Stephens, D., Kelly, K., Basher, Z., Burton, D., Cress, J., Atkins, K., Van Sistine, D. P., Friesen, B., Allee, R., Allen, T., Aniello, P., Asaad, I., Costello, M. J., Goodin, K., Harris, P., Kavanaugh, M., Lillis, H., Manca, E., Muller-Karger, F., Nyberg, B., Parsons, R., Saarinen, J., Steiner, J., & Reed, A (2019), A new 30 meter resolution global shoreline vector and associated global islands database for the development of standardized ecological coastal units, Journal of Operational Oceanography, 12(sup2), S47-S56. https://doi.org/10.1080/1755876X.2018.1529714.

Sharan, A., Lal, A., & Datta, B. (2021), A review of groundwater sustainability crisis in the Pacific Island countries: Challenges and solutions, Journal of Hydrology, 603, 127165. https://doi.org/10.1016/j.jhydrol.2021.127165.

Singh, A., Chauhan, A., & Gaur, R. (2025), A comprehensive review on the synthesis, properties, environmental impacts, and chemiluminescence applications of polystyrene (PS), Discover Chemistry, 2(1), 47. https://doi.org/10.1007/s44371-025-00125-y.

Stoeckl, L., & Houben, G. (2012), Flow dynamics and age stratification of freshwater lenses: Experiments and modeling, Journal of Hydrology, 458-459, 9-15. https://doi.org/10.1016/j.jhydrol.2012.05.070.

Sussarellu, R., Suquet, M., Thomas, Y., Lambert, C., Fabioux, C., Pernet, M. E. J., Le Goïc, N. Quillien, V., Mingant, C., Epelboin, Y.,Corporeau, C., Guyomarch, J., Robbens, J., Paul-Pont, I., Soudant, & P., Huvet, A. (2016), Oyster reproduction is affected by exposure to polystyrene microplastics, Proceedings of the National Academy of Sciences, 113(9), 2430-2435. https://doi.org/10.1073/pnas.1519019113.

Tang, Y., Lu, C., & Luo, J. (2022), An Analytical solution for groundwater lens pumping in a three-dimensional rectangular island, Journal of Hydrology, 617, 128928. https://doi.org/10.1016/j.jhydrol.2022.128928.

Tang, Y., Lu, C., & Luo J. (2024), Optimizing groundwater pumping in small island groundwater lenses: An analytical approach, Journal of Hydrology, 629, 130579. https://doi.org/10.1016/j.jhydrol.2023.130579.

Tang, Y., Rathore, S., Lu, C., & Luo, J. (2020), Development of Groundwater Lens for Transient Recharge in Strip Islands, Journal of Hydrology, 590, 125209. https://doi.org/10.1016/j.jhydrol.2020.125209.

https://doi.org/10.5194/egusphere-2026-1601
Preprint. Discussion started: 31 March 2026

Tang, Y., Yan, M. , Wang, X., Lu, C., & Luo, J. (2021), Experimental and modeling investigation of pumping from a fresh groundwater lens in an idealized strip island, Journal of Hydrology, 602, 126734. https://doi.org/10.1016/j.jhydrol.2021.126734.

ten Hietbrink, S., Materić, D., Holzinger, R., Groeskamp, S., & Niemann, H. (2025), Nanoplastic concentrations across the North Atlantic, Nature, 643(8071), 412-416. https://doi.org/10.1038/s41586-025-09218-1.

Thompson, R. C., Courtene-Jones, W., Boucher, J., Pahl, S., Raubenheimer, K., & Koelmans, A. A. (2024), Twenty years of microplastic pollution research—what have we learned?, Science, 386(6720), eadl2746. https://doi.org/10.1126/science.adl2746.

van Genuchten, M.T. (1980), A Closed-form Equation for Predicting the Hydraulic Conductivity of Unsaturated Soils. Soil Science Society of America Journal, 44: 892-898. https://doi.org/10.2136/sssaj1980.03615995004400050002x.

Voss, C., & Provost, A. M. (2002), SUTRA: A model for 2D or 3D saturated-unsaturated, variable-density ground-water flow with solute or energy transport, Report Rep. 2002-4231. https://doi.org/10.3133/wri024231.

Waldschläger, K., & Schüttrumpf, H. (2020), Infiltration Behavior of Microplastic Particles with Different Densities, Sizes, and Shapes—From Glass Spheres to Natural Sediments, Environmental Science & Technology, 54(15), 9366-9373. https://doi.org/10.1021/acs.est.0c01722.

Wang, R., Shu, L., Zhang, R., & Ling, Z. (2023), Determination of Exploitable Coefficient of Coral Island Freshwater Lens Considering the Integrated Effects of Lens Growth and Contraction, Water, 15(5), 890, doi: 10.3390/w15050890. https://doi.org/10.3390/w15050890.

Wang, X., Bolan, N., Tsang, D. C. W., Sarkar, B., Bradney, L., & Li, Y. (2021), A review of microplastics aggregation in aquatic environment: Influence factors, analytical methods, and environmental implications, Journal of hazardous materials, 402, 123496. https://doi.org/10.1016/j.jhazmat.2020.123496.

Wang, Z., & Sedighi, M. (2023), Dispersion properties of nanoplastic spheres in granular media at low Reynolds numbers, Journal of Contaminant Hydrology, 259, 104244. https://doi.org/10.1016/j.jconhyd.2023.104244.

Werner, A. D., Jakovovic, D., & Simmons, C. T. (2009), Experimental observations of saltwater up-coning, Journal of Hydrology, 373(1), 230-241. https://doi.org/10.1016/j.jhydrol.2009.05.004.

White, I., & Falkland, T. (2010), Management of freshwater lenses on small Pacific islands, Hydrogeology Journal, 18(1), 227-246. https://doi.org/10.1007/s10040-009-0525-0.

Yan, M., Lu, C., Werner, A. D., & Luo, J. (2021), Analytical, Experimental, and Numerical Investigation of Partially Penetrating Barriers for Expanding Island Freshwater Lenses, Water Resources Research, 57(3), e2020WR028386. https://doi.org/10.1029/2020WR028386.

Yang, J., Wang, Q., Heidbüchel, I., Xu, T., & Lu, C. (2025), Cut-off walls alter nitrogen loads and fluxes in small islands, Journal of Hydrology, 647, 132266. https://doi.org/10.1016/j.jhydrol.2024.132266.

Yao, Y., Andrews, C., Zheng, Y., He, X., Babovic, V., & Zheng, C. (2019), Development of Fresh Groundwater Lens in Coastal Reclaimed Islands, Journal of Hydrology, 573, 365-375. https://doi.org/10.1016/j.jhydrol.2019.03.062.

https://doi.org/10.5194/egusphere-2026-1601
Preprint. Discussion started: 31 March 2026

Yuan, C., Hu, L., Ren, Z., Xu, X., Gui, X., Gong, X., Wu, R., Sima, J., & Cao, X. (2024), Marine Microplastics Enhance Release of Arsenic in Coastal Aquifer during Seawater Intrusion Process, Journal of Hazardous Materials, 475, 134804. https://doi.org/10.1016/j.jhazmat.2024.134804.

Zheng, T. (2014), Numerical Analysis of Modeling Concepts for Salt Precipitation and Porosity - Permeability Evolution during Brine Evaporation.

Zheng, T., Meng, Y., Meng, X., Gao, S., Zhang, L., Zhang, B., Liu, T., & Luo, J. (2025), Influence of time-space variability of rainfall infiltration recharge on fresh groundwater lens, Physics of Fluids, 37(3), 036623. https://doi.org/10.1063/5.0253940.