Responses to the comments on the manuscript "From salinity to nanoplastics: redefining safe yield in strip-island aquifers under emerging contaminant threats" by Zheng et al. submitted to *Hydrology and Earth System Sciences*

Dear editor,

Thank you for providing us with the opportunity to revise our manuscript, ID [egusphere-2026-1601], titled "From salinity to nanoplastics: redefining safe yield in strip-island aquifers under emerging contaminant threats" and for forwarding the insightful comments and suggestions made by the reviewers. We appreciate the time and effort the reviewers have put into assessing our manuscript, and we believe that their feedback has greatly contributed to enhancing the quality of our work.

Below, we have carefully addressed each point raised by the reviewers. Our response will be marked in blue and the modification will be marked in red:

Dear Anonymous Referee #1,

We sincerely appreciate your thorough review, insightful comments, and constructive suggestions on our manuscript. Your professional evaluation has greatly helped us identify areas for improvement and significantly enhance the logic, clarity, and academic rigor of this work. We have carefully addressed every comment you raised, with detailed revisions and explanations provided below. For detailed information, please refer to the Supplement.

General Comments:

This study addresses the issue that existing groundwater management frameworks are largely based on salinity intrusion and do not account for the distinct transport behavior of nanoplastics. A multi-physics numerical model was developed, incorporating variable-density groundwater flow, salt transport, and nanoplastic migration processes, to investigate the transport characteristics of nanoplastics in idealized strip-island aquifers under pumping conditions. The model was validated using laboratory experiments, and its scale effects were evaluated while sensitivity analyses were conducted. The application of this model provides a process-based scientific framework for adapting groundwater management strategies to emerging nanoplastic pollution in vulnerable island environments. Although this is a very comprehensive study, the following issues still need to be addressed:

Response:

Thank you for your positive feedback and constructive suggestions provided. We have addressed all points as detailed below:

Comment (1): *The nanoplastics is the primary keywords in the manuscript title, but the deep introduction of nanoplastics comes too late in the introduction section, so it is suggested to* *simplify or even rephrase the statements from the beginning to Line 79.*

Response:

Line 1-79:

Thank you for your constructive suggestion. We fully agree with your comment that the introduction of nanoplastics appears relatively late in the original Introduction section, which is not consistent with its status as the core keyword of the manuscript.

To address this issue, we have simplified and streamlined the sentences from the beginning up to Line 79, and rearranged the paragraph order by moving the original third paragraph (focused on nanoplastics) ahead of the original second paragraph. This adjustment ensures that nanoplastics are introduced much earlier and more prominently, highlighting the core research object at the start of the Introduction and improving the logical flow and readability of the manuscript.

The revised content is presented as follows: "

1.Introduction

Islands host nearly 10% of the global population and cover approximately 6.7% of the Earth's terrestrial surface (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). Excessive pumping readily induces saline upconing, degrades water quality, and threatens long-term water security (Abdoulhalik and Ahmed, 2018; Dagan and Bear, 1968; Houben and Post, 2017; Werner et al., 2009).

Beyond salinity intrusion, nanoplastic contamination has emerged as an additional and largely unaddressed threat to island groundwater systems. Microplastics are pervasive environmental pollutants detected in marine environments, 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). Nanoplastics, which are generated through the fragmentation of larger plastic debris and microplastics, may occur at even higher particle-number concentrations, 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., 2024a). Because island aquifers are completely surrounded by seawater, freshwater lenses are particularly vulnerable to marine-sourced nanoplastic contamination (Fig. 1).

The maximum safe extraction rate for freshwater lenses is typically estimated using analytical solutions that assume a sharp interface between freshwater and seawater (Muskat, 1938). 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."

Comment (2): *Lines 86-90: Some relevant citations are encouraged to be added here.*

Response:

Line 86-90:

Thank you for your valuable suggestion. We have supplemented the relevant citations at Lines 86–90 to strengthen the academic support and logical rigor of this section.

Specifically, we have added the studies of Wang and Sedighi (2023), Alkindi et al. (2011), and Lee et al. (2017) to elaborate the fundamental differences between nanoplastic transport and dissolved solute transport:

- Wang and Sedighi (2023) confirmed that nanoplastics exhibit higher effective dispersivity than common dissolved solutes.
- Alkindi et al. (2011) pointed out that, as particulate phases, nanoplastics migration is accompanied by interface disturbance, velocity contrast, and pressure gradient fluctuations in porous media.
- Lee et al. (2017) indicated that nanoplastics behave as a discrete phase with much stronger equivalent drag effects than dissolved solutes.

Together, these studies clearly demonstrate that, especially at pumping wells where pressure changes sharply, nanoplastics with higher dispersivity present distinctly different transport behaviors from solutes, which can lead to unexpected groundwater contamination risks during extraction.

Reference

Alkindi, A., Al-Wahaibi, Y., Bijeljic, B. and Muggeridge, A. (2011), Investigation of longitudinal and transverse dispersion in stable displacements with a high viscosity and density contrast between the fluids. Journal of Contaminant Hydrology, 120-121, 170-183. https://doi.org/10.1016/j.jconhyd.2010.06.006.

Lee, J., Rolle, M. and Kitanidis, P. (2017), Longitudinal dispersion coefficients for numerical

modeling of groundwater solute transport in heterogeneous formations. Journal of Contaminant Hydrology, 212, 41-54. https://doi.org/10.1016/j.jconhyd.2017.09.004.

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.

Comment (3): *Lines 91-94: It is recommended to add one or two sentences to highlight the correlation between these two gaps, so that readers can understand the systematic nature of this study.*

Response:

Line 91-94:

We appreciate this insightful comment. To better emphasize the systematic logic of the research gaps and their internal connections, we have revised Lines 91–94 by adding explanatory sentences that link the two key gaps together.

This revision makes it clearer that the shortcomings of traditional safe- yield models and the lack of nanoplastic transport knowledge are interrelated rather than independent, which strengthens the overall motivation and coherence of the study. Specifically, neglecting the transition zone (Gap 1) creates an oversimplified flow and mixing field, which in turn invalidates the direct application of solute-based models to predict nanoplastic transport (Gap 2).

The modified content is shown below:“

Taken together, there are two critical gaps that are interdependent and collectively undermine reliable groundwater management. First, existing safe-yield models oversimplify the freshwater-seawater transition zone by neglecting dispersion-driven mixing. This oversimplification is further exacerbated when combined with the poorly characterized transport of nanoplastics, which exhibit unique migration dynamics that cannot be captured by traditional solute models. 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."

Comment (4): *1 and 2: There is no information about nanoplastics in this figurem.*

Response:

Fig. 1 and 2:

We greatly appreciate your careful check on the figures. We have noticed the lack of nanoplastic - related labels in Fig. 1 and 2, and have added clear nanoplastic identifiers and annotations to both figures accordingly.

These revisions make the core research object more visible in the conceptual model diagrams, improving the clarity and completeness of the figure presentation.

The updated figures are shown below and included in the revised manuscript.

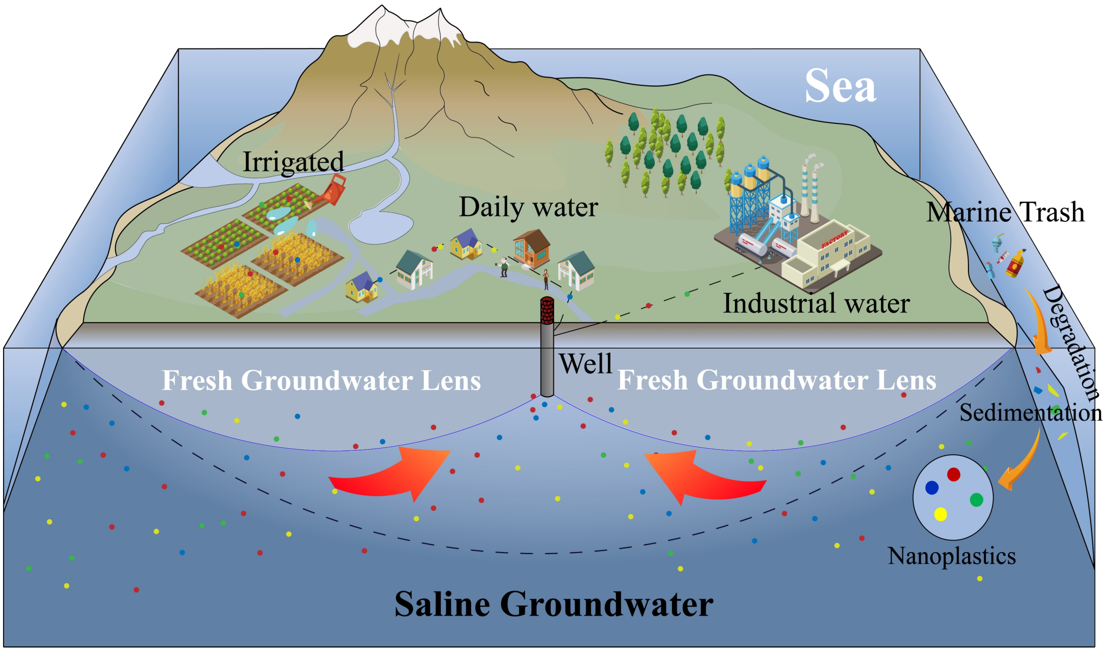

Fig. 1. Schematic diagram of freshwater lenses and nanoplastic contaminant distribution in an idealized strip-island aquifer under groundwater extraction.

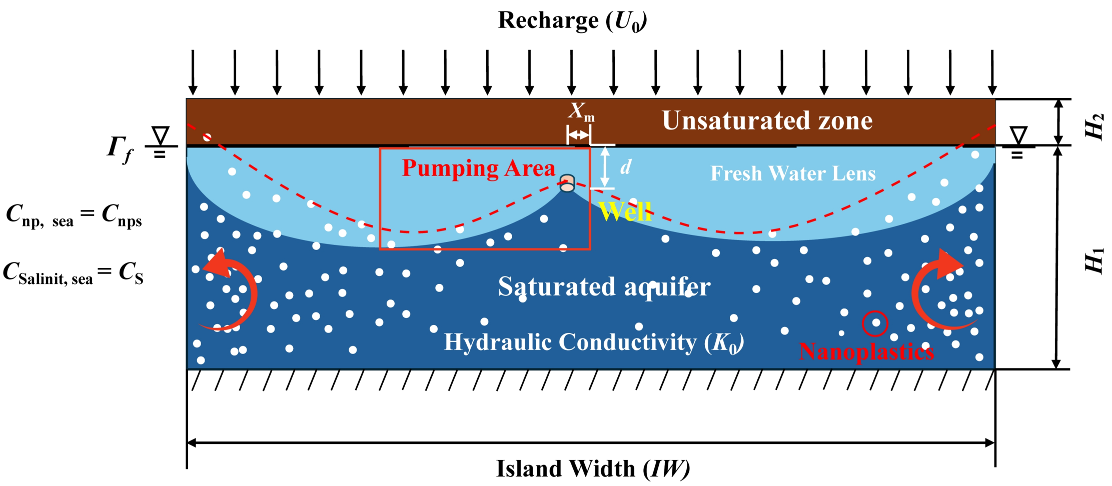

Fig. 2. Conceptual model of nanoplastic pollution in an idealized strip-island aquifer with central pumping. The model depicts an unsaturated zone (height H_2) over a saturated zone (height H_1). Freshwater lenses are shown in light blue and saline groundwater in dark blue. Key parameters include island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

Comment (5): *Lines 142-143: More specifically, it should be called bulk density.*

Response:

Lines 142-143:

Thank you for this precise correction. We have revised the relevant term to bulk density at Lines 142–143 to ensure accuracy and standardization in the description of aquifer medium properties.

Comment (6): *The title of chapter 2.2 is suggested to be revised into numerical soluton, since "numerical simulation"includes the establishment of mathematical model in chapter 2.1.*

Response:

Section 2.2:

Thank you for your professional suggestion on optimizing the section structure. We have revised the title of Section 2.2 from "Numerical Simulation" to "Numerical Solution" in accordance with your comment.

This adjustment better distinguishes the mathematical model establishment (Section 2.1) from the subsequent numerical solving process, making the logical hierarchy of the methodology clearer and more rigorous.

Comment (7): *Line251: double "represents".*

Response:

Line251:

Thank you for catching this typographical error. We have removed the redundant represents at Line 251 to ensure grammatical accuracy and fluency of the manuscript.

Comment (8): *About the evaluation indicators: It is recommended to present the functions or roles of these indicators mentioned here in a concise list format at the end of the section, which can help readers easily understand what they are used to indicate.*

Response:

Line251:

We appreciate this valuable suggestion for improving readability. To help readers quickly grasp the purpose and implications of the evaluation indicators, we have added a concise table at the end of the evaluation indicators section.

This table clearly summarizes the application role of each indicator, making the framework more intuitive and systematic.

The revised section with the new table is shown below and provided in the revised manuscript:

Table 2 provides a systematic description of the representative roles of the three evaluation metrics used in this paper:

Table 2. Summary of Evaluation Indicators and Their Functions

Symbol	**Full name**	**Description**
VR	Volume reduction rate	Quantifies the shrinkage degree of usable freshwater lens volume under pumping and

		nanoplastic contamination.
ASYR	Ratio of the actual maximum safe extraction capacity to the theoretical maximum safe extraction capacity	Evaluates the reduction degree of practical safe extraction capacity relative to the theoretical threshold.
RRSY	Ratio of the maximum safe extraction capacity reduction caused by nanoplastic retention to the maximum safe extraction capacity	Assesses the additional loss of safe extraction capacity specifically caused by nanoplastic retention and contamination.

Comment (9): Fig. 3: *It is necessary to clarify whether the results presented in Figure 3 and the accompanying explanations are obtained from numerical simulations or laboratory experiments. Other similar figures should also be handled following this suggestion.*

Response:

Thank you for this important comment on improving clarity. We have carefully checked Figure 3 and all other relevant figures in the manuscript. We have added clear annotations in the text to explicitly state whether each result is from numerical simulations or laboratory experiments, ensuring full transparency and consistency throughout the text.

These revisions make the data source of each figure unambiguous and greatly enhance the readability and reliability of the results:"

The relationship between well salinity and the extraction volume ratio (actual to theoretical) in numerical simulations 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})."

Comment (10): *8: It is recommended that the figure caption not be directly named "combined effects"; instead, it should directly describe the indicators presented in the figure.*

Response:

Thank you for your constructive suggestion to improve the accuracy and informativeness of figure captions. We have revised the caption of Fig. 8 by replacing the general phrase "combined effects" with a direct, detailed description of the indicators and variables shown in the figure.

This revision makes the figure caption more specific, standardized, and consistent with academic publishing norms, allowing readers to immediately understand the content of the figure.

The revised figure caption is as follows:"

Effects of pumping depth (d) and horizontal distance from the island center (x_m) on (a) theoretical maximum safe extraction rate (Q_{Tmax}), (b) actual maximum safe extraction rate (Q_{Amax}), (c) freshwater lens volume reduction rate (VR), and (d) reduction ratio of safe yield caused by nanoplastic retention ($RRSY$) in the idealized strip-island aquifer"

Comment (11): *Conclusions1 to 3 do not seem to specify the environmental context in which this finding was made. Therefore, I am curious whether this conclusion applies universally to any scenario, or only in the context of pumping in coastal zones?*

Response:

We appreciate this critical and constructive comment. To enhance the precision and applicability of our conclusions, we have added clear contextual qualifiers to Conclusions 1−3, explicitly stating that these findings are derived under the scenario of groundwater pumping in coastal strip-island aquifers.

This revision clarifies the specific environmental setting of the study and avoids overgeneralization, making the conclusions more rigorous and scientifically sound.

The revised conclusions are presented as follows: "

(1) Nanoplastic transport differs fundamentally from dissolved salt transport within the freshwater lenses of idealized strip-island aquifers during groundwater pumping. 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 under pumping-induced upconing conditions in coastal island aquifers.

(2) Transport behavior exhibits strong scale dependence in strip-island freshwater lens systems under pumping stress. 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 subject to freshwater extraction and seawater intrusion.

(3) Dispersivity is the dominant control on nanoplastic risk for pumping wells tapping freshwater lenses in strip-island coastal aquifers. 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 to 37-50% of the salinity-based thresholds under island pumping scenarios."

Dear Anonymous Referee #2,

We are deeply grateful for your careful assessment and valuable feedback on our manuscript. Your positive recognition of the research topic and structure, together with your targeted revision advice, have been crucial for us to refine the novelty, model transparency, terminology consistency, and practical implications of the study. We have fully responded to all your comments with specific revisions as detailed in the following sections.

General Comments:

This manuscript develops a coupled numerical model to investigate microplastic migration in idealized strip-island aquifers under pumping conditions, aiming to redefine safe yield by integrating microplastic contamination with traditional salinity intrusion. The research topic aligns well with the scope of HESS, addressing an emerging groundwater pollution issue with practical implications for island freshwater resource management. The manuscript is generally well-structured with clear research objectives, systematic numerical simulations, and multi-scale comparative analysis. However, minor revisions are recommended, with key improvements including:

Response:

Thank you for your positive feedback and the constructive suggestions provided. We will address the issues as follows:

Comment (1): *The introduction adequately identifies research gaps but lacks in-depth discussion on limitations of previous studies (especially on microplastic transport in island freshwater lenses and safe-yield models), weakening the novelty statement.*

Response:

We highly appreciate this insightful comment that helps strengthen the novelty and rationale of our study. We agree that the original introduction lacked sufficient discussion on the limitations of previous research related to nanoplastic transport and safe-yield models in island freshwater lenses.

In response, we have thoroughly revised the relevant paragraph to deeply analyze the deficiencies of existing studies, clarify the interdependence of the two key research gaps, and highlight the unique value of this work. By emphasizing the failure of traditional models to capture nanoplastic - specific transport behaviors and the oversimplification of transition zones, we have significantly improved the expression of novelty and research necessity.

The revised content is shown below: "

Taken together, there are two critical gaps that are interdependent and collectively undermine reliable groundwater management. First, existing safe-yield models oversimplify the freshwater-seawater transition zone by neglecting dispersion-driven mixing. This oversimplification is further exacerbated when combined with the poorly characterized transport of nanoplastics, which exhibit unique migration dynamics that cannot be captured by traditional solute models. 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. "

Comment (2): *Clarify model assumptions explicitly: State that the aquifer is homogeneous and isotropic, lateral groundwater flow is ignored, and tidal influences are neglected; explain how these simplifications may affect simulation results (e.g., failing to account for tidal effects may result in an overestimation of the maximum safe extraction rate of freshwater lenses on islands.).*

Response:

We highly appreciate this insightful comment that helps strengthen the novelty and rationale of our study. We agree that the original introduction lacked sufficient discussion on the limitations of previous research related to nanoplastic transport and safe-yield models in island freshwater lenses.

In response, we have thoroughly revised the relevant paragraph to deeply analyze the deficiencies of existing studies, clarify the interdependence of the two key research gaps, and highlight the unique value of this work. With the exception of lines 116−123, we provide a detailed description of the potential impact of these assumptions in line 606. By emphasizing the failure of traditional models to capture nanoplastic - specific transport behaviors and the oversimplification of transition zones, we have significantly improved the expression of novelty and research necessity.

The revised content is shown below:“

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 homogeneous and isotropic; (ii) fluid density depends solely on groundwater salinity, with thermal effects considered negligible; (iii) the density of nanoplastic particles is assumed to be approximately equal to that of water, which is representative of neutrally buoyant or aged nanoplastic particles; (iv) the saturated zone is initially saturated with seawater, and rainfall infiltration is spatially uniform and temporally constant; (v) groundwater flow is simulated within a two-dimensional vertical profile of the strip island, leveraging the geometric symmetry of the idealized domain; and (vi) tidal influences are neglected, and constant head boundary conditions are imposed at the seawater interface.”

“Several simplifying assumptions were adopted in this study, including homogeneous aquifer properties, idealized boundary conditions, and limited representation of nanoplastic diversity. In practice, aquifer heterogeneity, tidal fluctuations and storm events may further influence the groundwater flow field and, consequently, the transport of substances. Furthermore, the diverse properties of environmental nanoplastics such as particle size distribution, aging state and surface chemistry will also bring additional impacts on their migration. In addition, only two types of synthetic nanoplastics were considered in this study, 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."

Comment (3): *Some sentences use microplastics and nanoplastics interchangeably; unify to nanoplastics where appropriate.*

Response:

Thank you for this important suggestion on terminology consistency. We have carefully reviewed the entire manuscript and uniformly standardized inconsistent uses of microplastics / nanoplastics to nanoplastics where appropriate, ensuring clarity and precision throughout the text.

Revisions were made at the following positions:

Line 66, 79, 85, 316

Comment (4): *Table 1: Typo Sympol - Symbol; based on the experimental - complete as based on the experimental data.*

Response:

Thank you for your careful correction. We have fixed the typographical errors in Table 1 as suggested:

Sympol has been revised to Symbol

based on the experimental has been completed to based on the experimental data

All corrections have been implemented in the revised manuscript to ensure accuracy and standardization.

Comment (5): *Clarify the derivation of key time nodes (e.g., stabilization time at laboratory/field scale) and how they are determined via simulation calculation.*

Response:

Thank you for this rigorous suggestion. We have supplemented a clear explanation in Section 2.2 to explicitly clarify the derivation and determination criteria of key stabilization times at both laboratory and field scales.

We have added a formal convergence criterion to define when the system reaches a steady state, making the simulation setup more transparent and reproducible.

The revised content is shown below:“

Stabilization times for laboratory and field simulations were determined using a convergence criterion: the system was considered stable when the relative change in wellhead salinity and nanoplastic concentration was less than 1% over three consecutive time steps.”

Comment (6): *Ensure consistent use of site scale rather than mixing site scale and field scale.*

Response:

Thank you for your valuable comment on terminology consistency. We have carefully reviewed the entire manuscript and uniformly adopted “field scale” throughout the text, replacing all inconsistent uses of “site scale” to ensure standardization and coherence.

All relevant expressions have been revised accordingly, enhancing the formal rigor of the manuscript.

Comment (7): *Further highlight the practical application value: Clarify implications for well design, pumping rate optimization, and groundwater management planning in small island aquifers.*

Response:

We appreciate this insightful suggestion that enhances the practical significance of our work. We have revised the manuscript to further highlight the real-world application value of our findings, with explicit clarification of the implications for well design, pumping rate optimization, and groundwater management planning in small island aquifers.

This revision strengthens the translational relevance of the research and better connects scientific findings to practical coastal groundwater governance.

The revised content in line 615 is shown below:“

In addition, only two types of synthetic nanoplastics were considered in this study, 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 clear practical implications for well design, pumping optimization, and groundwater management on small islands."

Comment (8): *Further highlight the practical application value: Clarify implications for well design, pumping rate optimization, and groundwater management planning in small island aquifers.*

Response:

We highly appreciate your constructive suggestion to strengthen the practical implications of our study. We have revised the manuscript to more clearly emphasize the practical application value of our findings, explicitly elaborating their guiding significance for well design, pumping rate optimization, and groundwater management planning in small- island aquifers.

We have supplemented and refined the relevant content in the conclusion sections, highlighting the guidance of this study for actual island groundwater resource development and protection.

The revised content is presented as follows:

Line 606:"

Several simplifying assumptions were adopted in this study, including homogeneous aquifer properties, idealized boundary conditions, and limited representation of nanoplastic diversity. In practice, aquifer heterogeneity, tidal fluctuations and storm events may further influence the groundwater flow field and, consequently, the transport of substances. Furthermore, the diverse properties of environmental nanoplastics such as particle size distribution, aging state and surface chemistry will also bring additional impacts on their migration. In addition, only two types of synthetic nanoplastics were considered in this study, 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. "

Line618“

Future research should perform heterogeneous aquifer simulations, consider dynamic tidal and sea-level rise scenarios, and adopt more realistic natural micro/nanoplastic properties to further improve prediction accuracy and practical applicability for water security in plastic-polluted coastal environments.”