

Beyond the transect: Longshore Heterogeneity of Subterranean Estuaries Across Contrasting Coastal Settings

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Research Article

Keywords: subterranean estuary, spatial heterogeneity, beach aquifer, sampling design, submarine groundwater discharge

Posted Date: September 21st, 2026

DOI: <https://doi.org/10.21203/rs.3.rs-10841842/v1>

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Abstract

Submarine groundwater discharge (SGD) and associated biogeochemical processes are governed by mixing of fresh groundwater and seawater within subterranean estuaries (STEs). We investigated two contrasting STEs: a tropical beach along the Odisha coast, India, and the temperate barrier island of Spiekeroog, Germany; using a metre-scale, grid-based porewater salinity surveys at a depth of 50 cm across the intertidal zones. Both sites showed strong spatial heterogeneity, with localized freshening zones, patchy mixing structures, and strong salinity variations over short alongshore distances. The observed lateral variability reflects combined controls of morphology, sediment permeability and density driven flow. At the tropical site, seasonal differences further indicated shifts in the position and intensity of freshening zones within the STE associated with monsoonal recharge. Despite contrasting hydrogeological and hydrodynamic settings, both beaches exhibited laterally discontinuous mixing patterns in meter scale. Our results show that the single shore-perpendicular transects commonly used for STE investigations may not capture the spatial complexity of these systems and can introduce uncertainty in SGD interpretation when lateral variability is not considered. We therefore recommend lateral pre-screening of the STEs by evaluating porewater salinity in order to assess its spatial heterogeneity and guide the selection of representative transects which consequently will improve the investigations of STEs and SGD at beach scale.

1. Introduction

Subterranean estuaries (STEs) are dynamic mixing zones in the land-sea continuum, for example beneath the beach face, where fresh groundwater from the coastal aquifers interacts with saline seawater (Moore, 1999). These transition zones host complex hydrological and biogeochemical processes that regulate the fluxes of nutrient, trace element, and carbon to the coastal ocean (Moore, 2010; Santos et al., 2021). Their role in controlling submarine groundwater discharge (SGD) has made STEs as the important zones for coastal hydrogeology and biogeochemistry research (Moosdorf et al., 2021; Wilson et al., 2024).

Classic STE features such as freshwater discharge tubes (FDTs), upper saline plumes (USPs), and up-coning of freshwater; although traditionally described from vertical transects (Robinson et al., 2006; Robinson et al., 2007) have been observed to migrate spatially and vary in intensity (Evans & Wilson, 2016; Waska et al., 2019). These features reflect the interplay of sedimentary structure, density driven flow, hydraulic conductivity, permeability contrasts, and transient flow patterns that disrupt any presumption of laterally continuous mixing. Anthropogenic pressures e.g., abstraction (Michael et al., 2017) and nutrient inputs (Santos et al., 2021) further complicates the STE dynamics and create complex, small-scale variations in their physical and chemical conditions (Robinson et al., 2018; Santos et al., 2012). As a result, even visually homogeneous beaches can exhibit strong spatial variability in their geochemical setup.

Recent field-based investigations employing geophysical imaging (Erkul et al., 2025; Grünenbaum et al., 2023) and high-resolution chemical profiling (Waska et al., 2019) have revealed significant spatial variability driven by tide and wave-induced infiltration, micro-topography, and permeability contrasts. Likewise, 2D numerical models (Greskowiak & Massmann, 2021) and 3D groundwater-seawater interface visualization (Paepen et al., 2020) also emphasize that beach morphology and storm or tidal forcing can produce transient, spatially irregular patchy salinity fields over short time spans. These studies collectively highlight that STEs are inherently heterogeneous systems across multiple spatial scales.

Despite the well-known spatio-temporal variability of STEs (Michael et al., 2005; Robinson et al., 2006; Robinson et al., 2007) and widely recognised importance of temporal variability in SGD (McKenzie et al., 2021; Michael et al., 2005; Taniguchi et al., 2008), much less attention has been paid to the spatial dimension i.e., heterogeneity alongshore (Reckhardt et al., 2024; Stieglitz et al., 2008). Many SGD-related studies continue to rely on single shore perpendicular transects to map porewater salinity, mixing patterns and solute gradients across the intertidal zone. These transects are operationally efficient and frequently serve as the basis for modeling groundwater flow (Greskowiak et al., 2025) and solute transport (Evans & Wilson, 2017; Spiteri et al., 2008). Their usage, however, often without explicit mention implies an assumption of alongshore uniformity or representativeness of the surrounding beach section. While it may have raised from operational constraints or methodological legacy, it influences the way researchers interpret and conceptualize the STE system. As a result, single-transect sampling often misses the lateral heterogeneity, may capture the non-representative section of STEs and bias the reliability of SGD and solute load estimates.

To address this spatial complexity, the present study employs closely spaced shore-perpendicular sampling grids to investigate beach-scale variability in porewater salinity within the STEs. The study was conducted across two contrasting coastal environments: a tropical beach along the Odisha coast of India and a temperate barrier-island beach in Spiekeroog, Germany. Using high-resolution sampling grids spaced only a few metres apart, the study captures fine-scale variability in fresh-saline mixing patterns and discusses the hydrogeological and hydrodynamic controls governing the observed heterogeneity. This analysis provides insights into the spatial complexity of STE mixing processes across contrasting beach systems and contributes to improve the conceptual understanding of beach-scale subsurface dynamics.

2. Methods

2.1 Study Sites

Marine Drive beach in Odisha, India:

Marine Drive beach in Puri is located on the central coast of Odisha, eastern India, along the Bay of Bengal (Fig. 1). The site experiences a tropical monsoon climate with an average annual rainfall of 1550

mm, driving significant seasonal recharge to the coastal aquifers (Mohanti & Swain, 2005). The beach has a dissipative morphology with a gentle slope and well-developed intertidal and backshore zones. Sediments consist predominantly of fine-medium sands, with moderate-good sorting and interbedded finer layers (Mishra et al., 2024). The beach borders the protected Balukhand-Konark-Sanctuary, where limited groundwater extraction maintains a shallow groundwater level (Nayak & Nandimandalam, 2024). The permeable sandy sediments and relatively high hydraulic gradients facilitate fresh groundwater-seawater mixing at the beach (Nayak & Nandimandalam, 2025). The site experiences mesotidal semidiurnal conditions, with spring and neap tidal ranges of 2.39 and 0.85 m, respectively and a mean tidal range of ~ 1.62 m (Kumar et al., 2010). Wave energy is seasonal, with mean significant wave height (SWH) of ~ 1.34 m, peaks to 2.5–3.5 m during the southwest monsoon (June–September), while extreme tropical cyclones occasionally generate waves exceeding 5 m and storm surges up to 6.7 m (Dube et al., 2009). The beach represents an upper moderate energy system (Massmann et al., 2025).

Spiekeroog beach, Germany:

Spiekeroog beach is located on the northern part of Spiekeroog island, a barrier island in the southern North Sea along the northwestern coast of Germany (Fig. 1). The site experiences a temperate oceanic climate with mean annual precipitation of 808 mm, of which 300–400 mm recharges the freshwater lens in the permeable dune aquifer system (Röper et al., 2012). The beach is highly dynamic and wave-dominated, with a steep foreshore slope and well-sorted, fine to medium high permeable quartz sands (Beck et al., 2017). The beach face shows ridge-runnel topography and frequently reshaped by energetic wave action and tidal currents (Grünenbaum et al., 2020). The site is exposed to meso- to macro-semidiurnal tides, with a mean tidal range of ~ 2.7 m (spring: ~ 3.6 – 4.2 m; neap: ~ 1.2 – 1.8 m). The mean SWH is ~ 1.4 m, driven by persistent North Sea swell and storm events with offshore waves reaching up to 11 m (Herrling & Winter, 2015; Massmann et al., 2023). These hydrodynamic forces induce groundwater-seawater exchange and salinity gradients in the subterranean estuary. The beach represents a high-energy system (Massmann et al., 2025) with a well-established monitoring infrastructure to investigate groundwater-seawater interactions (Massmann et al., 2023).

2.2 Sampling Design and Procedure

Porewater salinity measurements were conducted across the intertidal zone during low tide periods at both beaches. A locally fabricated push-point sampler (material: steel, length 1m, diameter: 5mm), following (Berg & McGlathery, 2001), was used for porewater extraction, and salinity was measured in-situ using a portable multiparameter probe (WTW; Xylem Analytics Germany).

At Marine Drive beach, sampling was conducted during the post-monsoon (October-2024) and pre-monsoon (March-2026) seasons over a ~ 200 m $\times$ 50 m beach section, with 5–10 m grid interval across the intertidal zone. A total of 104 and 116 porewater samples were collected during the post- and pre-monsoon seasons, respectively, from a depth of 50cm. A similar approach was followed at Spiekeroog

beach over a $\sim 100 \text{ m} \times 50 \text{ m}$ beach section using a grid interval of $\sim 10 \text{ m}$ and 32 porewater samples were collected from an 8x4 grid at 50 cm depth.

Sampling locations were mapped using QField for QGIS connected via Bluetooth to a Trimble DA2 GNSS receiver with an active Catalyst subscription. The setup provided positioning accuracy of up to 0.01 m and recorded GPS coordinates alongside field measurements.

3. Results

Distribution of porewater salinity

At Marine Drive beach, porewater salinity showed a strong variability across the intertidal zone and between the seasons (Fig. 2A & B). Salinity ranged from 1 to 26 PSU in post-monsoon (Fig. 2A) and from 12 to 32 PSU in pre-monsoon (Fig. 2B). Patchy zones of relatively low salinity were observed at multiple locations, particularly between the mid and low-tide lines. These zones formed irregular salinity plumes extending laterally and seaward across the transects. The low-salinity areas were approximately 10–30 m wide, with sharp salinity gradients occurring over distances of only 5–10 m. In both seasons, the low-salinity zones were broadly aligned; however, during the post-monsoon they occurred towards inland, whereas during the pre-monsoon they shifted closer to the shoreline. Overall, the porewater salinities were consistently higher during the pre-monsoon than post-monsoon.

At Spiekeroog beach, a salinity heterogeneity was also observed in the porewater across the surveyed beach. Salinity ranged from 19 to 34 PSU, with isolated low-salinity plumes occurring in narrow bands approximately 8–15 m wide near to the shoreline (Fig. 2C). These anomalies were irregularly distributed and showed no consistent pattern either along or across the transects. Compared to the Marine Drive beach, the salinity differences were less prominent but were evident across the metre-scale survey grid (Fig. 2C).

4. Discussion

4.1 Longshore variability in STE

The strong spatial variation of salinity along the shoreline at the study sites demonstrates the spatial complexity and heterogeneous fresh-saline mixing within the STE, with variable porewater salinity over short lateral distances (Fig. 3). The porewater salinity distribution at Marine Drive beach during the post-monsoon (Fig. 3A) shows a non-linear cross-shore pattern characterised by alternating salinity zones within the intertidal zone. Salinity was higher in the upper lines (L5 and L6, representing alongshore sections: Fig. 2), lower in the mid lines (L3 and L4), and higher again in the lower lines (L1 and L2). We interpret the high-salinity upper lines as the upper saline plume (USP) and mid-salinity depressions as freshwater discharge tubes (FDTs). However, the FDTs showed substantial lateral variability within the same lines, with L3 varying from 2 to 23 PSU and L4 from 4 to 26 PSU (Fig. 3A). This suggests that STE features are not laterally continuous but occur as discrete, patchy structures even within a homogeneous-

looking beach over short spatial distance. Similarly, during the pre-monsoon (Fig. 3B), salinity was high in the upper lines (L4, L5 and L6), followed by a dip in the mid lines (L2 and L3), and increasing again in L1, the lowest line we could physically sample into the sea. Lines L4-L6 are interpreted as USP and L2-L3 as the FDT. Within the FDT, lateral variability was noticeable, with L2 varying from 14 to 28 PSU and L3 from 12 to 28 PSU, showing their patchy nature (Fig. 3B).

At Spiekeroog beach (Fig. 3C), a similar pattern was observed, with relatively high saline upper lines (L3 and L4) followed by lower salinity in L2 and L1, which we interpret as FDTs. In Spiekeroog, it is known that structures like USP are larger than the scale we have observed (Massmann et al., 2023), still the small scale features show variability within the individual lines with L1 ranging from 20 to 32 PSU and L2 from 19 to 32 PSU, which should still fall within the USP according to previous studies (Greskowiak & Massmann, 2021; Greskowiak et al., 2025). This speaks towards internal variability within larger STE structures.

Treating the survey grids as individual shore-perpendicular transects (Fig. 2) and comparing between them shows that salinity distributions vary substantially in both intensity and position over only a few metres. While some transects capture strong freshening signatures, others show weaker or laterally displaced signatures within the same beach body. This highlights the uncertainties that a single-transect may carry. The observed heterogenous behaviour within a seemingly homogenous STE indicates that single transects provide only a partial representation of the underlying mixing structure, with the uncertainty to either overemphasize or underrepresent localized discharge features. Such small-scale lateral variability introduces an observational uncertainty in STE interpretation and highlights the importance of first resolving spatial variability to identify representative transect locations for detailed hydrogeological and geochemical investigation.

4.2 Drivers of porewater salinity structure

The heterogenous salinity patterns observed at both beaches reflect the surface expressions of subsurface complex circulation structures (Fig. 4). The observed patterns are consistent with conceptual and numerical models of macro-scale groundwater-seawater circulation structures of beach aquifers, including USPs, saline recirculation (SR) cells, salt fingering and focused FDTs, which develop under the influence of hydraulic gradients, tidal forcing, beach morphology, aquifer properties and also shifts dynamically with change in boundary conditions (Evans & Wilson, 2016; Greskowiak, 2014; Meyer et al., 2025; Robinson et al., 2007). Although the present shallow observations cannot resolve the complete three-dimensional geometry of these structures, the alternating freshened and saline zones observed at both sites are consistent with localized expressions of these broader circulation patterns (Fig. 4).

Our results show that those macro-scale structures are not laterally uniform but vary substantially over short distances and are modified at the local scale within the same section of the beach. The sharp lateral variability observed at both beaches indicates that sediment heterogeneity plays an important

role in controlling flow pathways (Evans & Wilson, 2017). Variations in grain size, patchy sedimentary layering, and permeability contrasts likely altering the hydraulic conductivity, redirecting the porewater flow into preferential pathways, or fragmenting continuous flow systems into discrete discharge patches through localized flow barriers such as clay layers and tightly packed fine sediments (Fig. 4).

Hydrodynamic forcing, including wave-driven infiltration and tidal pumping (Robinson et al., 2007; Santos et al., 2012) continuously modifying the pressure gradients across the beach face and redistributing the mixing zones and subsurface circulation patterns. At Spiekeroog, short-term morphodynamical adjustments caused by wave action, storm events, and aeolian sediment redistribution further restructuring local permeability architecture and altering exchange pathways (Greskowiak & Massmann, 2021).

Seasonal recharge provides an additional control (Michael et al., 2005), particularly at Marine Drive beach, where monsoonal recharge likely strengthens freshwater discharge through high hydraulic gradient and expands mixing zones during post-monsoon period (Nayak & Nandimandalam, 2025). The low-salinity zones observed at Marine Drive beach (Fig. 2) occupied broadly similar positions during both seasons, suggesting relatively stable preferential discharge pathways. However, the freshening zones occurred further landward during the post-monsoon than during the pre-monsoon survey, indicating seasonal changes in hydraulic gradients associated with monsoonal recharge. Higher groundwater heads following the monsoon have promoted stronger freshwater discharge and a more landward expression of the freshening zones, whereas reduced recharge during the pre-monsoon have weakened the freshwater influence, resulting in comparatively higher porewater salinities and a seaward migration of the discharge zones. These patterns highlight the strong influence monsoon has on the shape of STEs in tropical monsoonal climates. In contrast, the relatively distributed and lower-intensity recharge at Spiekeroog may result on weaker freshening signatures.

These interacting controls collectively generate the observed salinity variability, whereby regional hydrogeological forcing defines the broader mixing framework while local sedimentary and hydrodynamic processes generate the fine-scale heterogeneity at the beach scale (Fig. 4).

4.3 Comparative behaviour between the sites

Odisha and Spiekeroog represent two contrasting coastal settings with different hydrogeological, climatic and hydrodynamic conditions, providing an opportunity to examine whether the observed spatial heterogeneity is site-specific or a more general characteristic of STEs. Odisha experiences a tropical monsoonal climate, where seasonal recharge during the monsoon increases groundwater levels, strengthens hydraulic gradients and promotes freshwater discharge across the beach plain (Nandimandalam et al., 2023; Nayak & Nandimandalam, 2025). In contrast, Spiekeroog is a temperate high-energy meso-tidal system where recharge is less prominent, while dynamic runnel-ridge morphology continuously modifies local pressure gradients and drives seawater infiltration and recirculation (Waska et al., 2019). Sediment properties also differ; Marine Drive consists of fine- to

medium-grained sands with occasional low-permeability layers that create preferential flow paths, whereas Spiekeroog contains well-sorted permeable sands where storm deposits and aeolian activity generate transient sedimentary layering and local permeability contrasts (Massmann et al., 2023). The beach slope is more at Marine Drive beach than Spiekeroog. Furthermore, although direct tidal measurements are limited for Marine Drive beach, the coastal flat-ridge system suggests rapid groundwater-seawater exchange driven by tidal head fluctuations, whereas at Spiekeroog strong tidal oscillations and morphodynamic changes continuously redistribute the mixing zones (Greskowiak & Massmann, 2021).

Despite these contrasting boundary conditions, both sites exhibit similar spatial behaviour i.e., groundwater-seawater mixing occurring as localized, laterally discontinuous zones rather than as a continuous salinity gradient. Observed freshening zones are spatially patchy, vary over short distances, and differ in their intensity and lateral extent, indicating that groundwater discharge is inherently heterogeneous at the beach scale. Thus, although the dominant controls differ between the two sites, they primarily influence the position, extent and intensity of the mixing structures rather than their heterogeneous nature. This suggests that the small-scale spatial heterogeneity is a common feature of STEs across contrasting environments and should be considered when interpreting groundwater-seawater exchange and designing field investigations.

4.4 Implications for subterranean estuary investigations and sampling design

Many beach-scale STE investigations rely on a single shore-perpendicular transect because detailed porewater sampling is time consuming, labour intensive and constrained by field logistics. Although transect-based approaches remain practical for characterizing vertical salinity profiles and groundwater-seawater mixing, the present results show that porewater salinity can vary sharply over short alongshore distances. Under such conditions, the position of transects if not appropriately selected, can strongly influence STE interpretation and may under- or overrepresent localized discharge features.

Our results therefore highlight the importance of selecting the best representative transects with prior knowledge of alongshore variability. A practical approach is to first conduct a rapid grid-based survey at a fixed shallow sediment depth (e.g., 50 cm) using push-point samplers or similar methods across the intertidal zone (Kreuzburg et al., 2023; Szymczycha et al., 2012). Such surveys can efficiently identify areas of freshwater influence, saline recirculation, or sharp mixing transitions, guiding the placement of representative transects for detailed depth profiling. Wherever feasible, geophysical methods may further improve subsurface characterization (Erkul et al., 2025). Accurate positioning of transect during this stage is important for reliable spatial mapping and repeatability. We therefore recommend a two-step field strategy: first assess beach-scale heterogeneity through rapid lateral screening, then conduct targeted transect investigations for vertical characterization. This approach retains the practicality of transect-based sampling while improving the representativeness of STE observations and reducing uncertainty in their interpretation.

5. Conclusions

This study demonstrates that fresh-saline mixing within subterranean estuaries is highly heterogeneous even in visually homogenous beaches, with strong alongshore variability in porewater salinity and localized discharge features occurring over short spatial distances. The results indicate that longshore variability is an important component of beach-scale STE structure irrespective of contrasting climatic, sedimentary, morphological, and hydrodynamic settings. The study highlights that the representativeness of shore-perpendicular transects strongly depends on their position within such spatially variable system. Therefore, conscious selection of transect locations based on prior knowledge of longshore variability is an important step in STE investigations. Rapid lateral screening of shallow porewater salinity provides a practical first step to identify spatial heterogeneity and guide the selection of representative transects for detailed investigation. Incorporating this spatial perspective can improve the characterization of STE structure and reduce uncertainty in interpretations of groundwater-seawater exchange and associated SGD.

Declarations

Declarations

The authors declare there are no conflicts of interest for this manuscript.

Acknowledgements:

This study was supported through project INPA (Grant No. 1051559 - IND - IP), funded by Alexander von Humboldt (AvH) foundation through the AvH research group linkage program. Additional support was provided through RETAKE-H-II (Grant No. 03F0965H) funded by German Ministry for Education and Research (BMBF) within the framework of DAM-CDRmare mission. SKN thanks the NAM Fellowship Programme 2025 (Award No. NAM – 05/69/2025) for supporting his research stay at ZMT (June to August 2025), while the manuscript was initiated. The DFG funded DynaDeep project for the facilities in the field site in Spiekeroog. Nele Grünenbaum (University of Oldenburg) is acknowledged for helping with the logistics for the fieldwork at Spiekeroog and Naveen Gupta (JNU) is acknowledged for supporting the fieldwork at Odisha.

Data availability:

All data used for this study are available at PANGAEA repository (Nayak et al., 2026) and can be accessed via <https://doi.org/10.1594/PANGAEA.995958>. As the data is under moratorium, the reviewers can access the data with the temporary access code (valid for 180 days) via <https://www.pangaea.de/tok/6ca5683184fae3bafd367189a953bdfb61c1b82c>

Author Contribution Statement:

SKN: Writing-original draft, conceptualization, methodology, investigation, formal analysis, data curation, visualization, writing-review and editing; **CVA, MR:** Methodology, investigation, writing-review and editing; **AN:** Investigation, visualization, writing-review and editing, **JRN:** Methodology, investigation, writing-review and editing, project administration; **NM:** Conceptualization, methodology, investigation, writing-review and editing, project administration.

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Figures

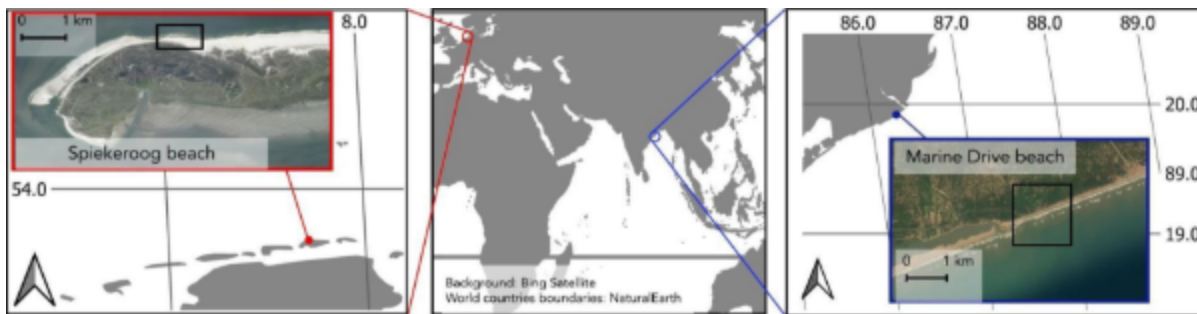


Figure 1

Map showing the study sites. The left panel shows Spiekeroog beach, Germany (temperate), and the right panel shows the Marine Drive beach in Puri, Odisha, India (tropical).

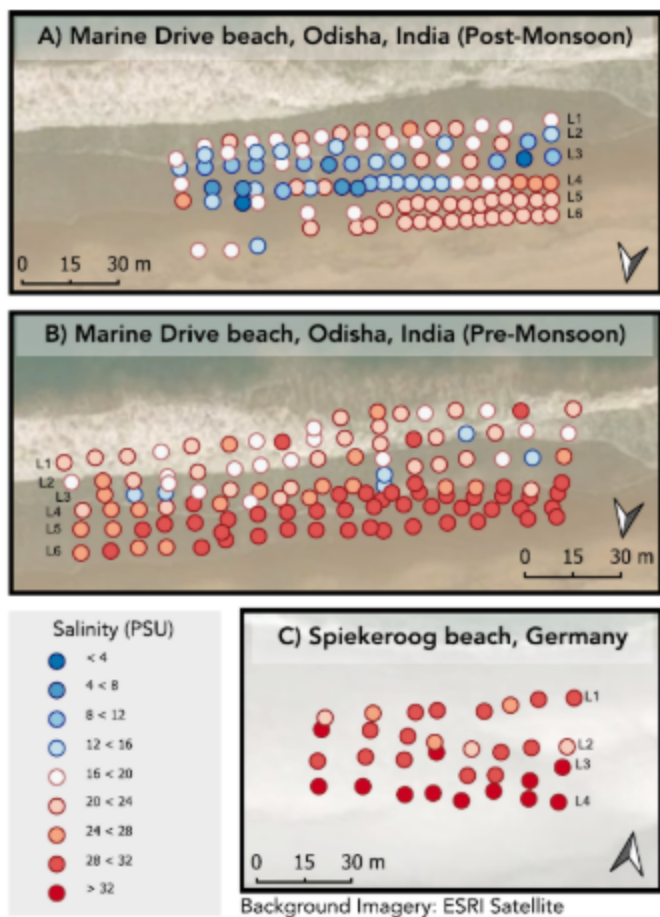


Figure 2

Porewater salinity (50 cm depth) across the intertidal zone at (A) Marine Drive beach during post-monsoon (B) Marine Drive beach during pre-monsoon and (C) Spiekeroog beach. L_x indicates the 'shore-parallel lines' referred to in **Fig. 3** and the Discussion.

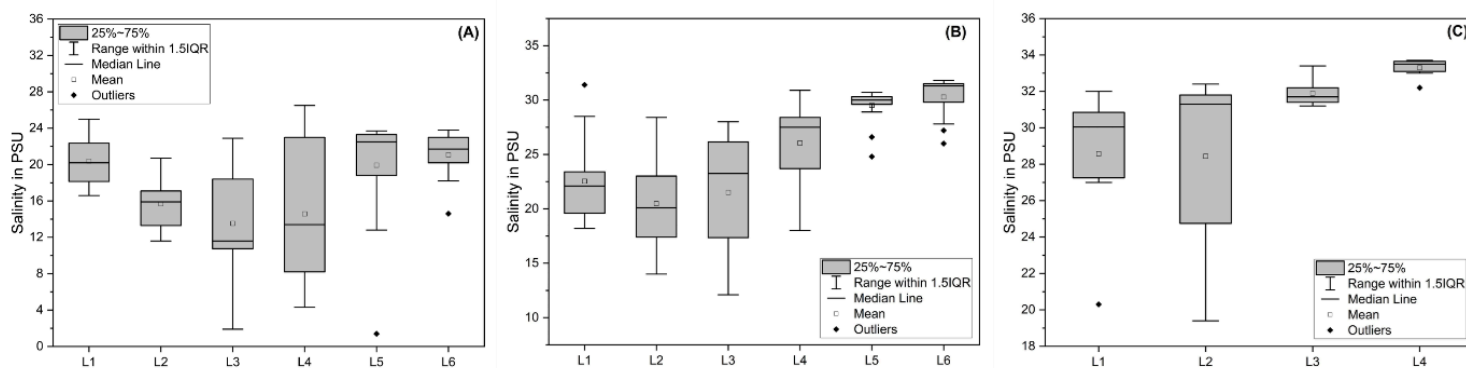


Figure 3

Box plots showing sharp lateral variability in porewater salinity along the shore line at (A) Marine Drive beach (post-monsoon) (B) Marine Drive beach (pre-monsoon), and (C) Spiekeroog beach. L1-L6 represents shore parallel lines shown in **Fig 2**.

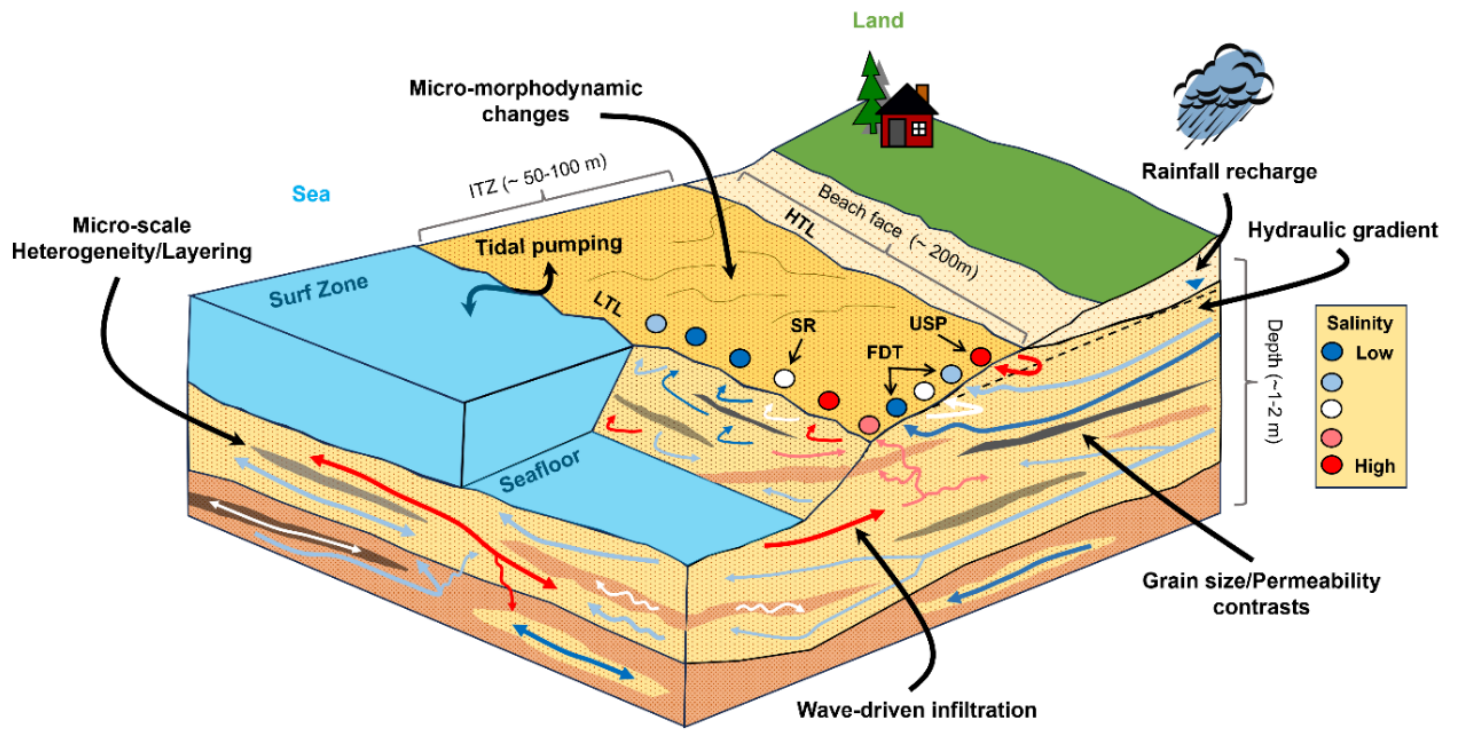


Figure 4

Proposed conceptual 3D model showing the observed porewater salinity heterogeneity may have attributed from the combined influence of hydrological, sedimentological, and morphological drivers operating at varying scale within the STE. (ITZ: inter tidal zone, HTL: high tide line, LTL: low tide line, USP: upper saline plume, FDT: freshwater discharge tube, and SR: saline recirculation. Black arrows indicate drivers, coloured arrows represent porewater flow paths with variable salinity, and undulating arrows represent transient flow paths. Model not to scale.)