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Editorial: Subterranean estuaries

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Editorial on the Research Topic
Subterranean Estuaries

Advancing subterranean estuary characterization

Groundwater flows in STEs are complex and driven by dynamic marine and continental forces acting on the land-ocean interface. The convergence of these forces in the subsurface translates into the variable morphology of STEs, regulates the timing of sub-estuarine circulation and physically constrains the residence time of water, regulating STE biogeochemistry, like their surface analogues. To characterize STEs in a way that is useful for fully integrated coastal monitoring and management, we need to untangle the different ways in which the multiple forces acting on STEs interact, driving morphodynamics, mixing regimes, and biogeochemical and microbiological zonation. In parallel, research must extend to probe the influence of STE dynamics on both oceanic and freshwater compartments so that the full aquatic continuum is covered. Achieving this objective requires improving our ability to characterize STEs and monitor net water flows into and out of STEs, from local to global scales, as well as to explore and document life within these subsurface environments.

Modelling has been useful to conceptualize groundwater flow and transport in STEs under different physical constraints, guiding research in real-world systems. Here, Yu et al. show that the salinity distributions in STEs exposed to a multi-constituent tidal signal depends on antecedent tidal oscillations, as well as on the inland extent of the freshwater aquifer. This finding implies that groundwater resource management landward of the littoral zone will affect the biogeochemical dynamics of STEs, changing net mass fluxes seaward, and impact coastal ecotones that may be distant from the decision in time and in space, thus stressing the importance of joined-up thinking in ICZM (Rocha et al., 2021).

It is well established that Submarine Groundwater Discharge (SGD) rates are highly variable in time and space. However, accurate estimates of both infiltration and exfiltration rates are key to determine net mass outflow from STEs and gauge the contribution of SGD to the biogeochemical budgets of coastal surface and subsurface water bodies. Grünenbaum et al. combine an array of methods to assess infiltration and exfiltration across the land-ocean interface in a high energy beach. Their results can be generalized to show that at the littoral zone, STE exchange rates are linked to beach topography, which in turn is affected by weather and by coastal management decisions including erosion control. This information is important to evaluate the impact of coastal management choices on ecosystem function and plan monitoring programmes. Due to the high spatial and temporal variability, monitoring SGD rates effectively for coastal management requires flexible and accurate methodologies that overcome the large human resource requirement. To this end Schlüter and Maier develop and test a scalable, inexpensive automated seepage meter, based on the dilution of tracer (saline water) injections. They use the mean residence time concept to determine SGD rates by modelling tracer breakthrough curves. This system may yet provide a means to develop efficient, networked monitoring of land-ocean transfer of materials in coastal environments *via* SGD.

The capacity for routine, continuous (and affordable) monitoring would contribute to holistic coastal management incorporating the complete water continuum, filling large knowledge gaps in our understanding of the coast, since SGD has an impact on the ecology of coastal systems. Because STE exfiltration zones may extend beyond the intertidal and proximal subtidal zone, far into the continental shelf area, it is critical to develop a physical understanding of STE circulation even when advection of continental groundwater becomes relatively less important. By examining the mixed-convective processes that occur when freshwater rises into a saline groundwater body of water, Solorzano-Rivas et al. set the basis for better understanding of fresh groundwater circulation in regions of sandy seafloor sediments where convection is more important than Darcian flow. Von Ahn et al. show in their Baltic Sea study that where it is necessary to cover both the littoral zone and the contiguous shelf area to monitor the ecosystem-level impact of STEs, combining environmental tracers and geophysical methods is promising. While logistic limitations still constrain regular, sustained, and high frequency sampling and monitoring of STE outflows across field, basin, and regional scales, Moorsdorf et al. show how the combination of different environmental tracer methodologies, geophysical approaches, remote sensing, and hydrogeological modelling could unravel the measurable signatures of STE processes to resolve their regional-scale impact on solute fluxes to the coastal ocean.

Origin and turnover of organic matter in subterranean estuaries

Knowledge of the origin, transfer, turnover, and fate of organic matter in STEs is essential to assign ecosystem-level function to these subsurface units. This information is needed to quantify mass transport across the land-ocean interface and understand the impacts of climate and environmental change on one of the most anthropogenically pressured portions of the Earth system. As with (surface) estuarine science in the past, achieving this aim requires we accept the unique functional identity of STEs and integrate research efforts traditionally conducted by different disciplines under this new praxis. To refocus the scientific community on this point, Moore and Joye emphasise how local changes to land and water use have expanded STEs over the last century, changing the environment in which continental carbon had been stored for millennia. They predict climate-driven sea level rise will accelerate fluid turnover within STEs, conceivably catalysed by higher net groundwater recharge. This acceleration triggers higher chemical mobility near the land-ocean interface and enhances elemental fluxes from aquifers to the coastal oceans. These changes disrupt the balance between soil organic matter burial and mobilization achieved before the growth of groundwater mining in the last century and foretell profound alterations to aquatic and terrestrial biomes that will affect how coastal ecosystems support humanity's needs for food, transport, and recreation.

This emerging higher-order understanding is consistent with findings in a wide variety of STEs in different settings. Waska et al. find evidence of enhanced mineralization of organic matter at STEs in barrier islands of the southern North Sea accompanying high dissolved organic matter (DOM) diversity in the local freshwater lens. Paffrath et al. show how net SGD fluxes of both fresh groundwater and recirculated seawater are a source of rare Earth elements (REEs) to the ocean because of enhanced mineralization rates in the STE. Further South, Ibanhez et al. present evidence of how nitrate enrichment enhances the metabolic turnover of sedimentary organic matter (SOM) in the STE, implying that DIN (dissolved inorganic nitrogen) pollution of coastal aquifers may reduce the residence time of aged organic C within the STE, driving carbon from continental storage into the coastal ocean.

In Sanggou Bay, Jiang et al. combine flow reactor experiments with 16S rDNA probing and stable isotopes to show how nitrate processing in STEs relies on a highly flexible bacterial community that adapts more readily to terminal electron acceptor than DOM availability. The results reveal a specialized microbial community endemic to STEs, rather than a transient one comprising a mix of continental or marine populations arriving onsite with STE mixing endmembers–thus supporting the thesis that STEs are unique habitats. In complementary fashion, Calvo-Martin et al. show

how sedimentary structure of STEs controls biogeochemical zonation by directing water flow, which regulates availability of terminal electron acceptors for OM oxidation. Hence the function of STEs as sources or sinks of N may change depending on structural aspects of the coastal subsurface. Similarly, O'Connor et al. show how the speciation and mobility of redox-sensitive metals depends on oxidation-reduction dynamics within the STE, which in turn drive microbial activity, OM composition and heterogeneous reactions.

The mounting evidence indicates that STEs are efficient, permeable, biogeochemical reactors with internal process dynamics and reaction kinetics set by the prevalent flow regimes. Substrate availability along circulation pathways depends on the biogeochemical legacy of the mixture. This depends on how internal circulation navigates an internal structure shaped by sedimentary morphodynamics that supports a highly adaptable, endemic ecology.

Life in subterranean estuaries

Surface (open water) and subsurface estuaries (STEs) belong in the marine biome. Whilst the biogeochemistry of STEs is driven by the coastal and beach aquifer microbiome, very little is still known about the microbes that populate these systems. Archana et al. critically review the narrow literature available on the subject to reveal that the beach aquifer microbiome is dominated by Proteobacteria, followed by Chloroflexi and Bacteroidetes. Insights from their critical synthesis reveal important blind spots on research conducted so far. For example, understanding how STEs outflows might contribute to eutrophication of the coastal ocean has justified most research on the subject to date, but it would also be important to figure out what impact eutrophication has on microbial communities and genetic composition. Yet, we have poor understanding of the impacts of pollution on STE microbiomes. Still, the full arsenal of the microbiologist has yet to be trained on the problem, since the beach microbiome has mostly been studied with 16S ribosomal DNA sequencing. Metagenomics and metatrasncriptomics would help understand both metabolism and ecology of microorganisms in STEs, necessary to comprehend biogeochemical dynamics.

Even if microbiology and microbial ecology are the poor relatives of Research Topic on STEs, Degenhardt et al. point out that Archean and meiofaunal diversity have been even more neglected. They find archaea contribute ~1%–4% to the 16S rRNA gene sequence bank of prokaryotes, while nematodes made most of the eukaryotes in a southern North Sea STE. Importantly, the study supports insights derived from studies of organic matter turnover by providing direct evidence of the existence of a core prokaryotic community in STEs. This community adapts quickly to SGD compositional dynamics, triggering biogeochemical feedback loops that in turn structure the spatial distribution and composition of eukaryotic communities. Brankovits et al. adds that soil organic matter distribution and deposition dynamics also impact meiofauna composition in karst STEs (previously classified as anchialine systems, Bishop et al., 2015). The evidence so far indicates that prokaryotic community composition and patchiness help shape the local eukaryotic community and biomass distribution within STEs, irrespective of type. The same picture is reconstructed over time by Cresswell and Hengstun. In a breakthrough study conducted in Bermuda, they show that spatiotemporal heterogeneity in POM source, quantity, and mode of delivery drives the co-existence of benthic foraminifera species in karst STE's. The emerging global picture is that POM deposition dynamics and patchiness is the main structural driver of marine benthic community composition and distribution in STEs.

Conclusion

To further our understanding of the function of subterranean estuaries in global biogeochemical cycling, future research must focus on:

1) Physically and mathematically describing internal structures of STEs, classifying their manifestation at diverse sites in terms of hydraulics, the physico-chemical drivers of mixing, as well as the spatiotemporal scales at which they operate.
2) Describing real-life STEs in time and space and moving beyond a focus on either the seepage face or the landward edge. We need better integration of forcing functions and more effective monitoring techniques. Future studies require a better amalgamation of functional drivers, rather than describing features. This focus on function rather than form would be an essential step toward an STE typology across different spatial scales.
3) Exploring what controls the distribution and function of microbial populations in STEs and consequently their biogeochemistry. For instance, it has been valuable to study the factors affecting availability and exchange of carbon in STEs. A focus on carbon will uncover the role of STEs in the atmosphere, land and ocean carbon cycles and their interactions.
4) Increased study of the biology and ecology of STEs, including the description of structure and function of microbial food webs as well as the meiofauna. Ecosystem engineers such as nematodes are likely to link STE food webs and coastal system ecology. We should aim to understand intrinsic and specific characteristics of STEs and how they might be considered biomes on their own right.

Overall, this e-book sheds light on an invisible, subsurface coastal ecotone that has received increasing attention since the term was coined in 1999 (Moore, 1999). Coasts are, more than any ecosystem on Earth, the showcase of the increasing connectivity between human activity and ecosystem function defining the Anthropocene. Almost all the known issues affecting the unadulterated function of socio-ecological coastal systems converge on STEs, making them critical components of the coast. To further advance subterranean estuary science, we need a refined, integrated understanding of how feedbacks between the physics, chemistry, and biology of STEs will affect coastal system function. This understanding will provide more options to adapt and manage the increasing impact of climate and environmental change on natural services on which we all depend.

Summary

Subterranean estuaries (STEs) are an important driver of coastal and marine ecosystem function. Understanding their hydraulics, biogeochemistry, and ecology is critical for the success of integrated coastal zone management (ICZM). Yet, STEs remained largely unexplored as unique, functioning components of the land-ocean continuum until recently. This lack of recognition is in part because STEs are generally invisible, structurally complex, and difficult to sample or even detect, in some cases—in contrast to their better understood surface counterparts. Nevertheless, research into groundwater-seawater interactions resulted in thousands of studies published with the keyword "subterranean estuary" since the term was introduced by Willard Moore in 1999. The field is maturing, following the steps taken in the historical development of estuarine science. A community of dedicated researchers has come into focus, addressing common problems from a toolbox of proven methods. They have now produced undeniable evidence demonstrating the importance of STE and the need to include them as essential components of coastal ecosystem function research, monitoring, policy, and management.

This Research Topic provides a synthesis of knowledge on STEs, including the interplay between physics, chemistry and biology that determines their biogeochemical function at the coast. It provides evidence that STEs constitute distinct habitats, puts forward new methodologies and identifies important aspects of carbon and nitrogen cycling within. Following the early impetus provided by Willard Moore, this Research Topic builds on decades of research by the SGD community to highlight knowledge gaps in our understanding of STEs and draw attention to emerging research opportunities.

Author contributions

All authors listed have made a substantial, direct, and intellectual contribution to the work and approved it for publication.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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