



OPEN ACCESS

EDITED BY
Xiaoyi Gloria Guo,
Ocean University of China, China

REVIEWED BY
Henry Bokuniewicz,
The State University of New York (SUNY),
United States
Yehuda Levy,
Geological Survey of Israel, Israel

*CORRESPONDENCE
Xiaolong Geng
✉ gengxiaolong@gmail.com

RECEIVED 25 November 2025
REVISED 22 January 2026
ACCEPTED 27 January 2026
PUBLISHED 16 February 2026

CITATION

Geng X, Haroon A, Zhang X, Zhang H
and Kanoa H (2026) From pores to
coastlines: multiscale perspectives on
submarine groundwater discharge and
coastal ecosystems.
Front. Mar. Sci. 13:1753663.
doi: 10.3389/fmars.2026.1753663

COPYRIGHT

© 2026 Geng, Haroon, Zhang, Zhang and
Kanoa. This is an open-access article
distributed under the terms of the
[Creative Commons Attribution License
\(CC BY\)](https://creativecommons.org/licenses/by/4.0/). The use, distribution or
reproduction in other forums is
permitted, provided the original
author(s) and the copyright owner(s) are
credited and that the original publication
in this journal is cited, in accordance
with accepted academic practice. No
use, distribution or reproduction is
permitted which does not comply with
these terms.

From pores to coastlines: multiscale perspectives on submarine groundwater discharge and coastal ecosystems

Xiaolong Geng^{1,2*}, Amir Haroon³, Xiaolang Zhang⁴,
Hong Zhang¹ and Hope Kanoa¹

¹Department of Earth Sciences, University of Hawai'i at Mānoa, Honolulu, HI, United States, ²Water Resources Research Center, University of Hawai'i at Mānoa, Honolulu, HI, United States, ³The Hawai'i Institute of Geophysics and Planetology, University of Hawai'i at Mānoa, Honolulu, HI, United States, ⁴Department of Geosciences, Florida Atlantic University, Boca Raton, FL, United States

Submarine groundwater discharge (SGD) is a major pathway linking terrestrial aquifers to the coastal ocean, influencing nutrient delivery, biogeochemical cycling, and ecosystem resilience. Yet a key challenge persists: connecting the fine-scale structural and reactive processes that govern flow and transport within sediments to the hydrodynamic drivers and coastal-scale discharge patterns observed in the field. This perspective highlights the need for an integrated multiscale framework that links pore-scale flow dynamics, microbial and geochemical reactions, and sediment heterogeneity to the larger-scale architecture of coastal aquifers and to hydrodynamic forcing that operates from seconds to centuries. We synthesize recent advances showing how pore geometry, facies transitions, permeability contrasts, and volcanic or sedimentary heterogeneity regulate mixing, residence times, and solute transformation. We further outline how wave swash, tidal pumping, hydroclimatic variability, and long-term coastal boundary evolution interact across temporal scales to reorganize SGD magnitude, timing, and spatial distribution. Emerging tools, including high-resolution imaging, geophysics, tracer methods, numerical modeling, and machine-learning-enabled data integration, offer new opportunities to bridge these scales. We argue that progress will require robust upscaling approaches, long-term multiscale monitoring, and coupled groundwater-nearshore models capable of representing cross-scale hydrodynamic and biogeochemical feedbacks. Such advances are essential for predicting SGD's role in nutrient fluxes, contaminant transport, carbon cycling, and coastal ecosystem response under climate and land-use change.

KEYWORDS

hydrodynamic forcing, multiscale transport processes, submarine groundwater discharge (SGD), subsurface heterogeneity, upscaling modeling

1 Introduction

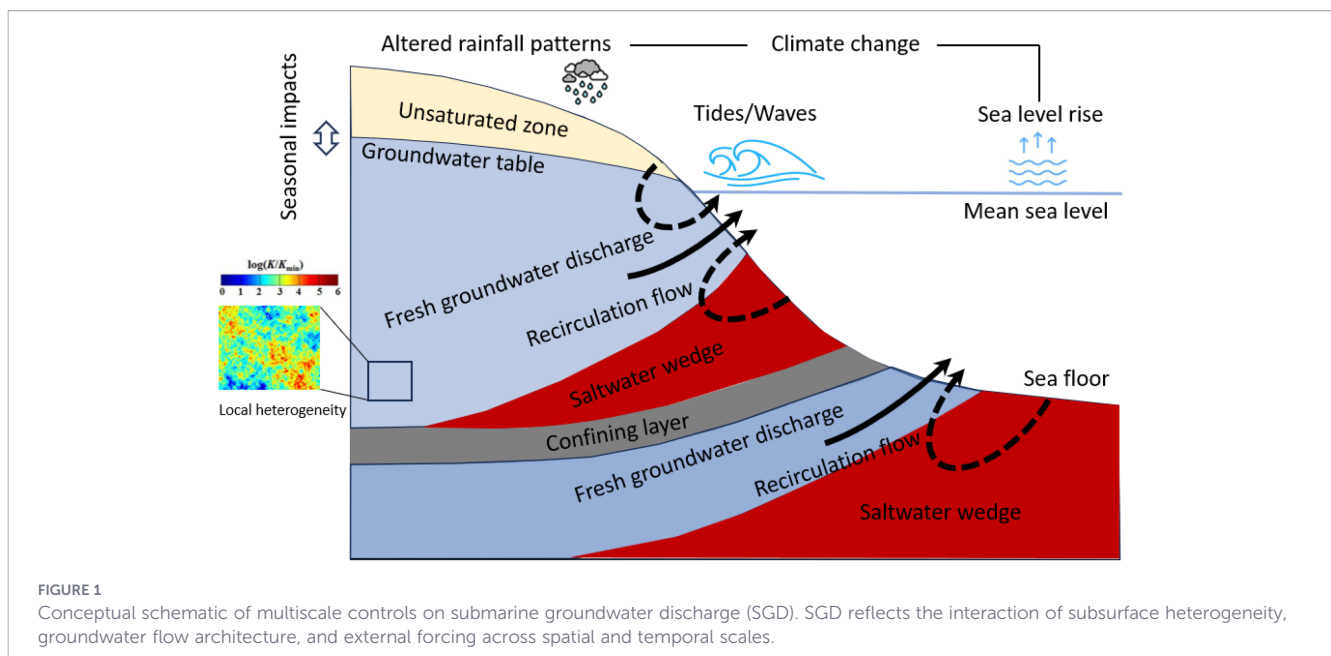
Submarine groundwater discharge (SGD) is widely recognized as a key pathway of groundwater-seawater exchange, linking terrestrial aquifers to coastal ecosystems and influencing nutrient dynamics, water quality, and biogeochemistry cycling (Mee, 2012; Amato et al., 2016; Bone et al., 2006; Geng and Michael, 2021; Moore et al., 2002; Guild et al., 2025). Despite major advances over the past decades, a fundamental challenge remains insufficiently addressed: how processes operating across multiple spatial and temporal scales collectively control the magnitude, timing, and ecological impacts of SGD (Figure 1). Although individual drivers, such as tides, waves, sea-level anomalies, density gradients, and aquifer geologic heterogeneity, have been studied extensively, most investigations isolate a subset of processes due to methodological or computational constraints. These reductionist approaches leave important gaps limit the applicability of current SGD models and conceptual frameworks to real coastlines, where multiple drivers co-occur and interact nonlinearly. For example, large-scale density-driven flow models often neglect wave- and tide-driven circulation, even though wave setup and tidal oscillations can generate dynamic pressure gradients that restructure the freshwater-saltwater interface across event to seasonal timescales and substantially enhance SGD (De Sienes et al., 2011; Michael et al., 2016; Yu et al., 2017; Taniguchi et al., 2019; Jiang et al., 2021; Beebe et al., 2022). Likewise, studies that focus solely on wave pumping or tidal oscillations may overlook longer-term sea-level anomalies and seasonal recharge variability because of limited spatial and temporal domains, even though these processes modulate the background hydraulic gradients governing SGD (Tur-Piedra et al., 2024; Keshariya et al., 2025). Growing evidence indicates that omitting key multiscale drivers can lead to substantial predictive errors (Xin et al., 2010; Kretschmer et al., 2023). Models that neglect wave-pumping- or tide-driven flows have been shown to underestimate nearshore circulation cells and SGD fluxes by an

order of magnitude, while studies that ignore seasonal variability often misattribute observed water-quality trends because the timing of SGD pulses is mismatched with ecological responses (Sawyer et al., 2013; Jiang et al., 2021; Lin et al., 2024). Similarly, field observations from heterogenous coastlines have revealed that small-scale sediment variability can generate highly localized discharge hotspots that are not captured by coarse-resolution regional models (e.g., Stieglitz et al., 2008). These examples illustrate a broader issue: current understanding of SGD is limited not by a lack of knowledge of individual processes, but by a lack of integration across scales.

This perspective argues that resolving this multiscale disconnect is essential for improving predictive understanding of SGD, especially as climate and anthropogenic pressures reshape coastal zones. By conceptualizing SGD as a nested system governed by processes spanning spatial scales, from pore-scale flow pathways and sediment heterogeneity to coastline-scale hydrodynamics, and temporal scales, from wave and tidal fluctuations to seasonal and long-term climatic drivers, we can more accurately determine how SGD shapes coastal ecosystem structure, function, and resilience. This Perspective does not aim to provide a comprehensive solution to the long-standing challenges of SGD characterization, nor to propose a single unifying methodology. Instead, it seeks to synthesize existing knowledge across spatial and temporal scales, identify structural disconnects in current approaches, and articulate realistic pathways for incremental progress under persistent data limitations and uncertainty.

2 Multiscale subsurface architecture and coastal heterogeneity

Submarine groundwater discharge (SGD) originates at the smallest spatial scales, where the sediment and rock at microscales govern how water, solutes, and microorganisms



migrate through the subsurface (Evans and Lizarralde, 2003; Viso et al., 2010). At this fundamental scale, pore geometry, characterized by grain size distribution, porosity, and pore connectivity and tortuosity, governs the hydraulic conductivity and capillarity that determine the medium's effective transport properties (Berg, 2014; Ghanbarian et al., 2013). Subtle variations in grain packing and the presence of micro-fractures or micropores can significantly influence how density-driven flow evolves, particularly when freshwater and seawater interact. Density contrasts generate gravitational instabilities that produce fingering patterns, localized convective cells, and sharp mixing interfaces where biogeochemical reactions are amplified (Li et al., 2019; Meng et al., 2020; Pu et al., 2020). Microbial communities also exert a strong influence on the effective transport properties of porous media. Through biofilm growth, extracellular polymeric substance (EPS) production, and microbially mediated mineral precipitation and dissolution, microorganisms actively modify pore geometry and connectivity. These alterations can reduce or enhance permeability, redistribute porosity, and change the reactive surface area available for sorption and redox reactions, thereby reshaping flow and solute transport pathways over time (Taylor and Jaffé, 1990; Thullner et al., 2002). Grain-surface reactions, including sorption-desorption, carbonate dissolution, metal redox cycling, and organic matter degradation, further regulate the mobility and transformation of nutrients, carbon species, and contaminants within sediment pores (Goldberg et al., 2007; Huang and Weber, 1997; McMahan et al., 2011). Although the importance of these microscale processes has long been acknowledged, only recently have advanced techniques such as microfluidics and X-ray imaging, provided direct, quantitative observations of pore-scale flow and reaction dynamics under controlled conditions. Yet a persistent challenge remains: translating these fine-resolution observations into scalable parameters that can reliably inform mesoscale and field-scale modeling.

As pore-scale processes integrate over larger spatial domains, sediment heterogeneity and subsurface architecture exert dominant control over the magnitude, pathways, and spatial distribution of SGD (Michael and Voss, 2008; Michael et al., 2016; Geng et al., 2020; Kreyns et al., 2020; Heiss et al., 2020; Yu and Michael, 2022). Coastal aquifers are rarely homogeneous; instead, they comprise stratified, discontinuous, and anisotropic sedimentary and volcanic units shaped by complex depositional histories and subsequent diagenetic, weathering, and structural modifications (Todd and Mays, 2005; Cantelon et al., 2022; Semeniuk, 1981). Variations in grain size, facies transitions, and abrupt permeability contrasts create preferential flow paths as well as diffusion-limited zones where solutes may experience prolonged residence and enhanced reaction (Long et al., 1982). Localized lenses of high- or low-porosity material interbedded fine layers, and permeability anisotropy further modulate hydraulic gradients and determine where exchange fluxes become enhanced and diminished (Gelhar et al., 1992; Sudicky, 1986; Zhang et al., 2024). In volcanic island settings, heterogeneity is amplified by the inherent complexity of basaltic architectures. Highly permeable lava flows, clinker zones,

and interflow rubble layers are often interlayered with low-permeability ash beds, weathered saprolite, and paleosols (Kiernan et al., 2003; Kreyns et al., 2020). Secondary porosity formed by fractures, cooling joints, voids, and lava tubes creates a network of conduits and barriers that can either move groundwater quickly over long distances or isolate it within separate compartments (Berkowitz, 2002). These structure elements strongly influence whether SGD emerges as focused point-source discharge, manifested as submarine springs, seepage faces, or as diffusive discharge distributed across broad shelf areas with long and variable residence times (Michael and Voss, 2008). In sedimentary coastal systems, additional heterogeneity arises from buried estuarine deposits, deltaic deposits, tidal flat sequences, and cross-bedded units that impart directional anisotropy to groundwater flow (Russoniello et al., 2013; Semeniuk, 1981). Biogenic modifications, including burrow networks, root channels, and bioturbated layers, further generate fine-scale preferential pathways that enhance mixing while also creating micro-zones of reduced permeability (Hose and Stumpp, 2019). Over geologic timescales, aquifer architecture is further reshaped by shoreline migration, sediment compaction, sea-level change, and tectonic deformation, all of which modify hydraulic connectivity and reorganize the spatial configuration of SGD pathways (Minderhoud et al., 2025; Church and Slaymaker, 1989).

Advances in characterization techniques are greatly enhancing our capacity to resolve and interpret this structural complexity. Marine geophysics including controlled source electromagnetics, multi-channel seismic reflection and acoustic imaging, electrical resistivity imaging, distributed temperature sensing, fiber-optic techniques, tracer tests, and Bayesian or machine-learning-enhanced inverse modeling are allowing researchers to identify SGD across larger spatial scales and map seafloor heterogeneity and pore fluid salinity with greater accuracy and depth (Andrés and MacGregor, 2008; Tur-Piedra et al., 2024; Taniguchi et al., 2019). Yet despite these advances, the functional implications of structural and offshore aquifer heterogeneity remain underexplored, largely because structural geophysical data lack resolution to allow integration with process-based measurements, and because small-scale heterogeneity often produces hydrologic and biogeochemical effects that only become apparent at much larger scales. This disconnect limits our ability to understand how heterogeneity reshapes groundwater-seawater exchange. Heterogeneity not only redistributes groundwater flow but also modulates biogeochemical transformations by influencing residence time distributions, redox zonation, and mixing intensity (Santos et al., 2021). These changes regulate nutrient retention, contaminant attenuation, and ecological connectivity between terrestrial and marine environments (Cai et al., 2011). Recognizing SGD as a multiscale, evolving subsurface system, linking pore-scale processes with the stratigraphic, geomorphological, and structural frameworks of coastal aquifers, is therefore essential for improving predictive capabilities. Only by explicitly embracing this spatial multiscaling can we capture the emergent patterns of SGD and their ecological and geochemical consequences.

3 Multiscale hydrodynamic drivers of SGD

SGD is continuously reshaped by hydrodynamic forcing that operates across a wide spectrum of temporal and spatial scales, producing exchange patterns that cannot be understood using a single-scale perspective. At the shortest timescales, seconds to minutes, wave swash motions and wave setup impose rapidly fluctuating cross-shore hydraulic gradients that force high-frequency seawater-groundwater exchange across the beach face, reorganizing pore-scale flow paths and creating alternating phases of infiltration and exfiltration (Geng et al., 2017; Geng et al., 2020a; Delisle et al., 2025; Geng et al., 2025); these high-frequency oscillations modulate mixing within the shallow aquifers, enhance dispersive exchange across the sediment-water interface (Olorunsaye and Heiss, 2024; Zheng et al., 2024), and generate transient SGD pulses that respond directly to wave energy (Yu et al., 2022). At hourly timescales, tidal oscillations impose longer-period pressure gradients that propagate landward and seaward (Geng and Boufadel, 2017; Huang et al., 2025), driving oscillatory flow, establishing tidally driven circulation cells within the subterranean estuary (Wang et al., 2025), and pumping solutes through beach aquifers (Geng et al., 2020b). These tidal pressure variations generate flushing cycles that extend beyond the wave-affected zone and modulate both the magnitude and timing of SGD (McKenzie et al., 2021; Hingst et al., 2024). At seasonal to interannual scales, variability in precipitation, aquifer recharge, regional groundwater levels, and coastal water levels modifies the land-sea hydraulic gradients that control the magnitude and alongshore distribution of SGD (Tur-Piedra et al., 2024; Dang et al., 2025; Lopez et al., 2025). These intermediate-scale processes can amplify or dampen the effects of shorter-term tidal and wave-driven forcing, generating multifrequency interactions and nonlinear responses that challenge steady-state or single-scale conceptualizations of coastal groundwater flow. Over decadal to centennial timescales, sea-level rise, land subsidence, and other geomorphic adjustments shift freshwater-saltwater interfaces, alter aquifer geometry and storage, and reorganize the spatial configuration of SGD pathways (Geng and Michael, 2021; Nicholls et al., 2021; Minderhoud et al., 2025). These long-term boundary changes establish the broader hydrogeologic framework within which higher-frequency processes operate, generating hierarchical cross-scale interactions that propagate from pore-scale mixing zones to kilometer-scale coastal discharge patterns.

Progress in resolving these multiscale hydrodynamic controls increasingly depends on integrated observational and modeling methodologies (Wang et al., 2022; Jin et al., 2024). Numerical approaches now span from pore-scale reactive transport simulations to coastal-scale density-dependent flow models, each capturing different dimensions of the hydrodynamic spectrum (Geng et al., 2020c; Geng et al., 2021; Wang et al., 2024). Complementary geophysical, geochemical, tracer-based, and fiber-optic methods provide spatial and temporal constraints needed to validate, refine, and upscale these models (Folch et al., 2020; Furlanetto et al., 2024; Zhao et al., 2022). Machine-learning and data-assimilation frameworks offer new opportunities to extract hydrodynamic patterns from large datasets and to translate small-

scale process understanding into actionable parameterizations for larger-scale modeling (McKenzie et al., 2023; Cao et al., 2024; Dai et al., 2025). Long-term monitoring networks equipped with autonomous sensors, coupled with time-series and spectral analyses in the frequency domain, have been used to reveal temporal dynamics, including rapid responses to storms, spring-neap tidal cycles, and climate extremes (Geng and Boufadel, 2017; Nordio et al., 2023; Williams et al., 2024). Such multiscale methodological integration is critical for resolving how interactions across different timescales give rise to emergent SGD behavior.

4 Future directions: toward predictive, multiscale frameworks for SGD

The multiscale controls described in Sections 2 and 3 reveal a central challenge for SGD research: integrating fine-scale subsurface architecture with hydrodynamic drivers acting across broad temporal and spatial scales. Future progress will require theoretical and computational frameworks that explicitly couple pore-scale processes with field-scale transport while acknowledging persistent data limitations. Although pore-scale imaging and characterization have advanced rapidly, a key unresolved challenge is identifying which fine-scale structural and biogeochemical features exert first-order control on effective field-scale transport parameters, and how these controls depend on hydrodynamic conditions. Addressing this challenge requires distinguishing between measurable fine-scale attributes and those that are transferable and predictive under realistic wave-, tide-, and recharge-driven forcing, rather than assuming that increased resolution alone will yield improved field-scale understanding. Data-driven approaches are most effective when applied to specific tasks, such as inferring effective transport parameters or quantifying uncertainty, rather than attempting full predictive replacement of physics-based models. Operative strategies include machine-learning-assisted upscaling that uses a limited set of pore-scale structural descriptors (e.g., connectivity metrics or characteristic length scales) in combination with high-resolution process-based simulations to estimate effective transport parameters; physics-informed data-driven models that constrain learning using mass and momentum conservation while allowing parameters to vary with subsurface heterogeneity and dynamic hydrodynamic forcing; and Bayesian data-assimilation frameworks that integrate geophysical imaging and hydrogeologic observations to iteratively update spatially distributed parameters, explicitly quantify uncertainty, and resolve scale-dependent spatial variability that cannot be captured by deterministic upscaling alone. A second priority is improving representation of multiscale temporal forcing in SGD studies. Future work should focus on identifying dominant modes of interaction among wave-driven swash, tidal oscillations, seasonal recharge, and long-term sea-level trends. Addressing these challenges will require robust upscaling approaches that connect high-frequency coastal forcing with intermediate-scale hydroclimate variability and long-term evolution of coastal boundary conditions. Example studies include phase-averaged and net-inflow approaches,

which respectively upscale wave effects into an effective mean head gradient (i.e., wave setup) or represent wave-induced seawater infiltration as a net flux boundary condition (Robinson et al., 2014; Geng and Boufadel, 2015). Finally, deep and confined aquifers represent a critical but underexplored component of the SGD spectrum. While deep SGD may contribute substantial nutrient and contaminant fluxes, its quantification is limited by sparse data and detection challenges. Progress in this area will likely depend on targeted integration of geophysical imaging, geochemical tracers, and autonomous offshore observations, rather than comprehensive mapping, to identify preferential pathways and bound their potential contribution.

Advances will also depend on improved mapping and interpretation of terrestrial aquifer structure, as subsurface architecture fundamentally constrains where and how SGD emerges. While inadequate subsurface information remains a pervasive limitation in most coastal settings, this constraint underscores, rather than diminishes, the need for integrated, multiscale approaches. Because no single observational technique can resolve the full complexity of subsurface pathways, progress will depend on selectively combining complementary methods, including hydrogeologic characterization, thermal and acoustic imaging, tracer-based surveys, offshore geophysics, and emerging fiber-optic approaches, to delineate dominant discharge zones and bound flux estimates under uncertainty. Long-term, high-resolution monitoring at a limited number of strategically chosen sites, combined with targeted tracer injections and coordinated field experiments, provides a realistic pathway for resolving temporal variability and system responses that episodic sampling cannot capture. Analytical tools, including spectral, statistical, and machine-learning approaches, should be viewed not as substitute for data scarcity, but as means to extract process-relevant information from sparse, noisy, and multiscale observations. Predicting how SGD will respond to climate change further amplifies these challenges. Sea-level rise, altered precipitation patterns, intensified storms, and changes in groundwater withdrawal will modify aquifer structure and hydrodynamic gradients. Progress will therefore require downscaling large-scale climatic and oceanographic drivers to the spatial and temporal scales at which SGD operates, supported by coupled, density-dependent groundwater-nearshore hydrodynamic models capable of representing for anticipating changes in nutrient and contaminant delivery, carbon cycling, ecosystem thresholds, and coastal resilience. Together, these directions emphasize that predictive capability in SGD will emerge not from data volume, but from integrative frameworks designed to operate under persistent data limitations.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material. Further inquiries can be directed to the corresponding author.

Author contributions

XG: Funding acquisition, Visualization, Project administration, Formal analysis, Validation, Resources, Conceptualization, Data curation, Writing – review & editing, Methodology, Supervision, Software, Writing – original draft, Investigation. AH: Investigation, Writing – review & editing, Writing – original draft. XZ: Investigation, Writing – original draft, Writing – review & editing. HZ: Writing – original draft, Writing – review & editing, Investigation. HK: Writing – original draft, Investigation, Writing – review & editing.

Funding

The author(s) declared that financial support was received for this work and/or its publication. This work was funded by the US NSF (EAR 2429852). However, it does not necessarily reflect the views of the funding agency, and no official endorsement should be inferred.

Conflict of interest

The author(s) declared that this work was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

The author XG declared that they were an editorial board member of *Frontiers*, at the time of submission. This had no impact on the peer review process and the final decision.

Generative AI statement

The author(s) declared that generative AI was not used in the creation of this manuscript.

Any alternative text (alt text) provided alongside figures in this article has been generated by *Frontiers* with the support of artificial intelligence and reasonable efforts have been made to ensure accuracy, including review by the authors wherever possible. If you identify any issues, please contact us.

Publisher's note

All claims expressed in this article are solely those of the authors and do not necessarily represent those of their affiliated organizations, or those of the publisher, the editors and the reviewers. Any product that may be evaluated in this article, or claim that may be made by its manufacturer, is not guaranteed or endorsed by the publisher.

References

- Amato, D. W., Bishop, J. M., Glenn, C. R., Dulai, H., Smith, C. M., and Whittier, R. B. (2016). Impact of submarine groundwater discharge on marine water quality and reef biota of Maui. *PLoS One* 11, e0165825. doi: 10.1371/journal.pone.0165825
- Andrés, D., and MacGregor, L. (2008). Controlled-source electromagnetic sounding in shallow water: Principles and applications. *Geophysics* 73, F21–F32. doi: 10.1190/1.2815721
- Beebe, D. A., Huettemann, M. B., Webb, B. M., and Jackson, W. T. Jr. (2022). Atmospheric groundwater forcing of a subterranean estuary: A seasonal seawater recirculation process. *Geophys. Res. Lett.* 49, e2021GL096154. doi: 10.1029/2021GL096154
- Berg, C. F. (2014). Permeability description by characteristic length, tortuosity, constriction and porosity. *Transport Porous Media* 103, 381–400. doi: 10.1007/s11242-014-0307-6
- Berkowitz, B. (2002). Characterizing flow and transport in fractured geological media. *J. Contam. Hydrol.* 64, 143–160. doi: 10.1016/S0309-1708(02)00042-8
- Bone, S. E., Gonnee, M. E., and Charette, M. A. (2006). Geochemical cycling of arsenic in a coastal aquifer. *Environ. Sci. Technol.* 40, 3273–3278. doi: 10.1021/es052472x
- Cai, W. J., Hu, X., Huang, W. J., Murrell, M. C., Lehrter, J. C., Lohrenz, S. E., et al. (2011). Acidification of subsurface coastal waters enhanced by eutrophication. *Nat. Geosci.* 4, 766–770. doi: 10.1038/ngeo1297
- Cantelon, J. A., Guimond, J. A., Robinson, C. E., Michael, H. A., and Kurylyk, B. L. (2022). Vertical saltwater intrusion in coastal aquifers driven by episodic flooding: A review. *Water Resour. Res.* 58, e2022WR032614. doi: 10.1029/2022WR032614
- Cao, C., Zhang, J., Gan, W., Nan, T., and Lu, C. (2024). A deep learning-based data assimilation approach to characterizing coastal aquifers amid non-linearity and non-gaussianity challenges. *Water Resour. Res.* 60, e2023WR036899. doi: 10.1029/2023WR036899
- Church, M., and Slaymaker, O. (1989). Disequilibrium of Holocene sediment yield in glaciated British Columbia. *Nature* 337, 452–454. doi: 10.1038/337452a0
- Dai, Z., Zhan, C., Yin, H., Chen, J., Xu, L., Xia, Y., et al. (2025). Incorporating deep learning into hydrogeological modeling: Advancements, challenges, and future directions. *J. Geophys. Res.: Mach. Learn. Comput.* 2, e2025JH000703. doi: 10.1029/2025JH000703
- Dang, M.-Q., Hsu, F.-H., Su, C.-C., Wang, S.-J., Fu, C.-C., and Lin, I.-T. (2025). Investigation of seasonal variations in submarine groundwater discharge using radium isotopes under drought conditions in northwestern coastal Taiwan. *J. Hydrol.* 649, 132450. doi: 10.1016/j.jhydrol.2024.132450
- Delisle, M.-P. C., Kim, Y., and Gallien, T. W. (2025). Modeling beach groundwater impacts on wave runup: Mechanisms and implications. *J. Waterway Port Coastal Ocean Eng.* 151, 4025032. doi: 10.1061/JWPED5.WWENG-2265
- De Sieres, N. R., Yamahara, K. M., Paytan, A., and Boehm, A. B. (2011). Submarine groundwater discharge to a high-energy surf zone at Stinson Beach, California, estimated using radium isotopes. *Estuar. Coasts* 34, 256–268. doi: 10.1007/s12237-010-9305-2
- Evans, R. L., and Lizarralde, D. (2003). Geophysical evidence for karst formation associated with offshore groundwater transport: An example from North Carolina. *Geochem. Geophys. Geosyst.* 4, 1069–1077. doi: 10.1029/2003GC000510
- Folch, A., Del Val, L., Luquot, L., Martínez-Pérez, L., Bellmunt, F., Le Lay, H., et al. (2020). Combining fiber optic DTS, cross-hole ERT and time-lapse induction logging to characterize and monitor a coastal aquifer. *J. Hydrol.* 588, 125050. doi: 10.1016/j.jhydrol.2020.125050
- Furlanetto, D., Camporese, M., Schenato, L., Costa, L., and Salandin, P. (2024). Fiber optics passive monitoring of groundwater temperature reveals three-dimensional structures in heterogeneous aquifers. *Sci. Rep.* 14, 8430. doi: 10.1038/s41598-024-58954-3
- Gelhar, L. W., Welty, C., and Rehfeldt, K. R. (1992). A critical review of data on field-scale dispersion in aquifers. *Water Resour. Res.* 28, 1955–1974. doi: 10.1029/92WR00607
- Geng, X., and Boufadel, M. C. (2015). Numerical study of solute transport in shallow beach aquifers subjected to waves and tides. *J. Geophys. Res. Oceans* 120 (2), 1409–1428.
- Geng, X., and Boufadel, M. C. (2017). Spectral responses of gravel beaches to tidal signals. *Sci. Rep.* 7, 40770. doi: 10.1038/srep40770
- Geng, X., Boufadel, M. C., Rajaram, H., Cui, F., Lee, K., and An, C. (2020a). Numerical study of solute transport in heterogeneous beach aquifers subjected to tides. *Water Resour. Res.* 56, e2019WR026430. doi: 10.1029/2019WR026430
- Geng, X., Heiss, J. W., Michael, H. A., and Boufadel, M. C. (2017). Subsurface flow and moisture dynamics in response to swash motions: Effects of beach hydraulic conductivity and capillarity. *Water Resour. Res.* 53, 10317–10335. doi: 10.1002/2017WR021248
- Geng, X., Heiss, J. W., Michael, H. A., Boufadel, M. C., and Lee, K. (2020b). Groundwater flow and moisture dynamics in the swash zone: Effects of heterogeneous hydraulic conductivity and capillarity. *Water Resour. Res.* 56, e2020WR028401. doi: 10.1029/2020WR028401
- Geng, X., Heiss, J. W., Michael, H. A., Li, H., Raubenheimer, B., and Boufadel, M. C. (2021). Geochemical fluxes in sandy beach aquifers: Modulation due to major physical stressors, geologic heterogeneity, and nearshore morphology. *Earth Sci. Rev.* 221, 103800. doi: 10.1016/j.earscirev.2021.103800
- Geng, X., and Michael, H. A. (2021). Along-shore movement of groundwater and its effects on seawater-groundwater interactions in heterogeneous coastal aquifers. *Water Resour. Res.* 57, e2021WR031056. doi: 10.1029/2021WR031056
- Geng, X., Michael, H. A., Boufadel, M. C., Molz, F. J., Gerges, F., and Lee, K. (2020c). Heterogeneity affects intertidal flow topology in coastal beach aquifers. *Geophys. Res. Lett.* 47, e2020GL089612. doi: 10.1029/2020GL089612
- Geng, X., Michael, H. A., Heiss, J. W., Boufadel, M. C., Li, H., and Zhang, Y. (2025). Groundwater flow and salinity dynamics in swash zones: Combined effects of evaporation, waves, and geologic heterogeneity. *J. Hydrol.* 646, 132322. doi: 10.1016/j.jhydrol.2024.132322
- Ghanbarian, B., Hunt, A. G., Ewing, R. P., and Sahimi, M. (2013). Tortuosity in porous media: a critical review. *Soil Sci. Soc. America J.* 77, 1461–1477. doi: 10.2136/sssaj2012.0435
- Goldberg, S., Criscenti, L. J., Turner, D. R., Davis, J. A., and Cantrell, K. J. (2007). Adsorption-desorption processes in subsurface reactive transport modeling. *Vadose Zone J.* 6, 407–435. doi: 10.2136/vzj2006.0085
- Guild, R., Wang, X., and Quijón, P. A. (2025). Climate change impacts on coastal ecosystems. *Environ. Res.: Climate* 3, 042006. doi: 10.1088/2752-5295/ad7d45
- Heiss, J. W., Michael, H. A., and Koneshloo, M. (2020). Denitrification hotspots in intertidal mixing zones linked to geologic heterogeneity. *Environ. Res. Lett.* 15, 084015. doi: 10.1088/1748-9326/ab90a6
- Hingst, M. C., Housego, R. M., He, C., Minsley, B. J., Ball, L. B., and Michael, H. A. (2024). Beyond the wedge: Impact of tidal streams on salinization of groundwater in a coastal aquifer stressed by pumping and sea-level rise. *Water Resour. Res.* 60, e2023WR035840. doi: 10.1029/2023WR035840
- Hose, G. C., and Stumpp, C. (2019). Architects of the underworld: Bioturbation by groundwater invertebrates influences aquifer hydraulic properties. *Aquat. Sci.* 81, 20. doi: 10.1007/s00027-018-0613-0
- Huang, F.-K., Lin, Y.-F., Wang, G. S., and Kurylyk, B. L. (2025). Tidal signal propagation in coastal aquifers considering semi-permeable boundaries and partial penetration effects. *J. Hydrol.* 652, 132657. doi: 10.1016/j.jhydrol.2024.132657
- Huang, W., and Weber, W. J. (1997). A distributed reactivity model for sorption by soils and sediments. 10. Relationships between desorption, hysteresis, and the chemical characteristics of organic domains. *Environ. Sci. Technol.* 31, 2562–2569. doi: 10.1021/es960995e
- Jiang, Z. P., Lv, J., Li, Q., Dai, M., Kao, S. J., Zheng, N., et al. (2021). Tidal-driven submarine groundwater discharge and its influences on the carbonate system of a coastal coral reef in the Northern South China Sea. *J. Geophys. Res.: Oceans* 126, e2021JC017203. doi: 10.1029/2021JC017203
- Jin, J., Espino, M., Fernández, D., and Folch, A. (2024). Coupling of numerical groundwater-ocean models to improve understanding of the coastal zone. *Numerical Models/Coastal Near-Shore Processes*. 21, 1407–1410. doi: 10.5194/egusphere-2024-3384
- Keshariya, A., Verma, A., and Yadav, B. K. (2025). Seasonal dynamics of submarine groundwater discharge zones along the Southeastern Arabian Sea coastline. *Environ. Monit. Assess.* 197, 787. doi: 10.1007/s10661-025-14193-1
- Kiernan, K., Wood, C., and Middleton, G. (2003). Aquifer structure and contamination risk in lava flows: Insights from Iceland and Australia. *Environ. Geol.* 43, 852–865. doi: 10.1007/s00254-002-0707-8
- Kretschmer, D., Michael, H. A., Moosdorf, N., Oude Essink, G., Bierkens, M. F., Wagener, T., et al. (2023). Submarine Groundwater Discharge and Seawater Intrusion: Two sides of the same coin that are rarely studied simultaneously. *Authorea Preprints*. 2–4. doi: 10.22541/essoar.168652289.91346805/v1
- Kreyns, P., Geng, X., and Michael, H. A. (2020). The influence of connected heterogeneity on groundwater flow and salinity distributions in coastal volcanic aquifers. *J. Hydrol.* 586, 124863. doi: 10.1016/j.jhydrol.2020.124863
- Li, Q., Cai, W., Li, F.-C., Li, B., and Chen, C.-Y. (2019). Miscible density-driven flows in heterogeneous porous media: Influences of correlation length and distribution of permeability. *Phys. Rev. Fluids* 4, 1–3. doi: 10.1103/physrevfluids.4.014502
- Lin, X., Chen, X., Chen, F., Jin, G., Wang, C., Mayakrishnan, M., et al. (2024). Seasonal dynamics of submarine groundwater discharge in Zhanjiang Bay: an investigative study utilizing ²²²Rn as a tracer. *Front. Mar. Sci.* 11, 1451533. doi: 10.3389/fmars.2024.1451533
- Long, J. C. S., Remer, J. S., Wilson, C. R., and Witherspoon, P. A. (1982). Porous media equivalents for networks of discontinuous fractures. *Water Resour. Res.* 18, 645–658. doi: 10.1029/WR018i003p00645
- Lopez, E., Geng, X., Haroon, A., Zhang, H., Zou, Y., Yan, T., et al. (2025). Seasonal coastal groundwater dynamics in lahaina beaches, Hawai'i: Implications for

- contaminant transport in a post-wildfire setting. *Mar. pollut. Bull.* 220, 118424. doi: 10.1016/j.marpolbul.2025.118424
- McKenzie, T., Dulai, H., and Fuleky, P. (2021). Traditional and novel time-series approaches reveal submarine groundwater discharge dynamics under baseline and extreme event conditions. *Sci. Rep.* 11, 22570. doi: 10.1038/s41598-021-01920-0
- McKenzie, T., Dulai, H., Lee, J., Dimova, N. T., Santos, I. R., Zhang, B., et al. (2023). Using deep learning to model the groundwater tracer radon in coastal waters. *Water Resour. Res.* 59, e2022WR033870. doi: 10.1029/2022WR033870
- McMahon, P. B., Chapelle, F. H., and Bradley, P. M. (2011). "Evolution of redox processes in groundwater," in *Aquatic redox chemistry* (Washington, DC, USA: American Chemical Society), 581–597.
- Mee, L. (2012). Between the devil and the deep blue sea: The coastal zone in an era of globalisation. *Estuar. Coast. Shelf Sci.* 96, 1–8. doi: 10.1016/j.ecss.2011.07.007
- Meng, X., Sun, H., Guo, Z., and Yang, X. (2020). A multiscale study of density-driven flow with dissolution in porous media. *Adv. Water Resour.* 142, 103640–103640. doi: 10.1016/j.advwatres.2020.103640
- Michael, H. A., Scott, K. C., Koneshloo, M., Yu, X., Khan, M. R., and Li, K. (2016). Geologic influence on groundwater salinity drives large seawater circulation through the continental shelf. *Geophys. Res. Lett.* 43, 10–782. doi: 10.1002/2016GL070863
- Michael, H. A., and Voss, C. I. (2008). Evaluation of the sustainability of deep groundwater as an arsenic-safe resource in the bengal basin. *Proc. Natl. Acad. Sci.* 105, 8531–8536. doi: 10.1073/pnas.0710477105
- Minderhoud, P. S. J., Shirzaei, M., and Teatini, P. (2025). From InSAR-derived subsidence to relative sea-level rise—A call for rigor. *Earth's Future* 13, e2024EF005539. doi: 10.1029/2024EF005539
- Moore, W. S., Krest, J., Taylor, G., Roggenstein, E., Joye, S., and Brandes, J. (2002). Thermal evidence of water exchange through a coastal aquifer: Implications for nutrient fluxes. *Geophys. Res. Lett.* 29, 49-1–49-4. doi: 10.1029/2002GL014923
- Nicholls, R. J., Lincke, D., Hinkel, J., Brown, S., Vafeidis, A. T., Meyssignac, B., et al. (2021). A global analysis of subsidence, relative sea-level change and coastal flood exposure. *Nat. Climate Change* 11, 338–342. doi: 10.1038/s41558-021-00993-z
- Nordio, G., Frederiks, R., Hingst, M., Carr, J., Kirwan, M., Gedan, K., et al. (2023). Frequent storm surges affect the groundwater of coastal ecosystems. *Geophys. Res. Lett.* 50, e2022GL100191. doi: 10.1029/2022GL100191
- Olorunsaye, O., and Heiss, J. W. (2024). Stability of saltwater-freshwater mixing zones in beach aquifers with geologic heterogeneity. *Water Resour. Res.* 60, e2023WR036056. doi: 10.1029/2023WR036056
- Pu, L., Xin, P., Nguyen, T. T. M., Yu, X., Li, L., and Barry, D. A. (2020). Thermal effects on flow and salinity distributions in coastal confined aquifers. *Water Resour. Res.* 56, 3–6. doi: 10.1029/2020wr027582
- Robinson, C., Xin, P., Li, L., and Barry, D. A. (2014). Groundwater flow and salt transport in a subterranean estuary driven by intensified wave conditions. *Water Resour. Res.* 50, 165–181. doi: 10.1002/2013WR013813
- Russoniello, C. J., Fernandez, C., Bratton, J. F., Banaszak, J. F., Krantz, D. E., Andres, A. S., et al. (2013). Geologic effects on groundwater salinity and discharge into an estuary. *J. Hydrol.* 498, 1–12. doi: 10.1016/j.jhydrol.2013.05.049
- Santos, I. R., Burnett, W. C., Chanton, J., Moosdorf, N., Hoareau, G., and Workman, R. (2021). Submarine groundwater discharge impacts on coastal nutrient biogeochemistry. *Nat. Rev. Earth Environ.* 2, 307–323. doi: 10.1038/s43017-021-00152-0
- Sawyer, A. H., Shi, F., Kirby, J. T., and Michael, H. A. (2013). Dynamic response of surface water-groundwater exchange to currents, tides, and waves in a shallow estuary. *J. Geophys. Res.: Oceans* 118, 1749–1758. doi: 10.1002/jgrc.20154
- Semeniuk, V. (1981). Sedimentology and the stratigraphic sequence of a tropical tidal flat, north-western Australia. *Sediment. Geol.* 29, 195–221. doi: 10.1016/0037-0738(81)90007-5
- Stieglitz, T., Taniguchi, M., and Neylon, S. (2008). Spatial variability of submarine groundwater discharge, Ubatuba, Brazil. *Estuar. Coast. Shelf Sci.* 76, 493–500. doi: 10.1016/j.ecss.2007.07.038
- Sudicky, E. A. (1986). A natural gradient experiment on solute transport in a sand aquifer: Spatial variability of hydraulic conductivity and its role in the dispersion process. *Water Resour. Res.* 22, 2069–2082. doi: 10.1029/WR022i013p02069
- Taniguchi, M., Dulai, H., Burnett, K. M., Santos, I. R., Sugimoto, R., Stieglitz, T., et al. (2019). Submarine groundwater discharge: Updates on its measurement techniques, geophysical drivers, magnitudes, and effects. *Front. Environ. Sci.* 7. doi: 10.3389/fenvs.2019.00141
- Taylor, S. W., and Jaffé, P. R. (1990). Biofilm growth and the related changes in the physical properties of a porous medium: 1. Experimental investigation. *Water Resour. Res.* 26, 2153–2159. doi: 10.1029/wr026i009p02153
- Thullner, M., Zeyer, J., and Kinzelbach, W. (2002). Influence of microbial growth on hydraulic properties of pore networks. *Transport Porous Media* 49, 99–122. doi: 10.1023/A:1016030112089
- Todd, D. K., and Mays, L. W. (2005). *Groundwater Hydrology (3rd ed.)*. Hoboken, NJ, USA: John Wiley & Sons.
- Tur-Piedra, J., Ledo, J., Diego-Feliu, M., Queral, P., Marcuello, A., Rodellas, V., et al. (2024). Spatial and seasonal fluctuations in fresh submarine groundwater discharge revealed by marine continuous resistivity profiling. *Sci. Rep.* 14, 24854. doi: 10.1038/s41598-024-75984-z
- Viso, R., Spence, M., Schreiber, B. C., Hedeon, D., King, H., and Garrison, C. (2010). Geological controls on submarine groundwater discharge in Long Bay, South Carolina (USA). *Contin. Shelf Res.* 30, 335–341. doi: 10.1016/j.csr.2009.11.014
- Wang, W., Cui, L., Geng, X., Luo, M., Yu, S., Wang, Z., et al. (2025). Numerical simulations of tidal beach seawater-groundwater circulations using dimensionless method. *J. Hydrol.* 646, 132372. doi: 10.1016/j.jhydrol.2024.132372
- Wang, L., Dai, Y., Liu, W., Zhou, S., Long, X., Xi, Z., et al. (2024). Deep learning transient electromagnetic inversion for seawater intrusion. *J. Geophys. Eng.* 21, 1810–1821. doi: 10.1093/jge/gxae107
- Wang, X., Geng, X., Sadat-Noori, M., and Zhang, Y. (2022). Editorial: Groundwater-seawater exchange and environmental impacts. *Front. Water* 4. doi: 10.3389/frwa.2022.928615
- Williams, E. L., Kratt, C. B., Rodolfo, R. S., Lapus, M. R., Lardizabal, R. R., Bangun, A. S., et al. (2024). Multi-scale thermal mapping of submarine groundwater discharge in coastal ecosystems of a volcanic area. *Geophys. Res. Lett.* 51, e2024GL111857. doi: 10.1029/2024GL111857
- Xin, P., Robinson, C., Li, L., Barry, D. A., and Bakhtyar, R. (2010). Effects of wave forcing on a subterranean estuary. *Water Resour. Res.* 46, W12505. doi: 10.1029/2010WR009632
- Yu, X., and Michael, H. A. (2022). Impacts of the scale of representation of heterogeneity on simulated salinity and saltwater circulation in coastal aquifers. *Water Resour. Res.* 58, e2020WR029523. doi: 10.1029/2020WR029523
- Yu, X., Xin, P., Lu, C., Robinson, C., Li, L., and Barry, D. A. (2017). Effects of episodic rainfall on a subterranean estuary. *Water Resources Research* 53, 5774–5787.
- Yu, S., Zhang, X., Li, H., Wang, X., Wang, C., and Kuang, X. (2022). Analytical study for wave-induced submarine groundwater discharge in subtidal zone. *J. Hydrol.* 612, 128219. doi: 10.1016/j.jhydrol.2022.128219
- Zhang, J., Lu, C., Shen, C., Liu, Y., Werner, A. D., and Zhang, C. (2024). Flow and transport in coastal aquifer-aquitard systems: Experimental and numerical analysis. *Water Resour. Res.* 60, e2023WR035200. doi: 10.1029/2023WR035200
- Zhao, S., Li, M., Burnett, W. C., Cheng, K., Li, C., Guo, J., et al. (2022). *In-situ* radon-in-water detection for high resolution submarine groundwater discharge assessment. *Front. Mar. Sci.* 9. doi: 10.3389/fmars.2022.1001554
- Zheng, Y., Yang, M., and Liu, H. (2024). Coastal groundwater dynamics with a focus on wave effects. *Earth Sci. Rev.* 256, 104869. doi: 10.1016/j.earscirev.2024.104869