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Special Section:
Forcing, response, and impacts of coastal storms in a changing climate

Key Points:

- Vertical saltwater intrusion following coastal floods threatens fresh groundwater in an age of rising seas and intensifying storms
- We review salinization and flushing processes identified with field and modeling methods and identify future research opportunities
- Knowledge gaps can be addressed through multidisciplinary studies to advance science and inform water resources management and policy

Supporting Information:

Supporting Information may be found in the online version of this article.

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Vertical Saltwater Intrusion in Coastal Aquifers Driven by Episodic Flooding: A Review

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Abstract Low-elevation coastal areas are increasingly vulnerable to seawater flooding as sea levels rise and the frequency and intensity of large storms increase with climate change. Seawater flooding can lead to the salinization of fresh coastal aquifers by vertical saltwater intrusion (SWI). Vertical SWI is often overlooked in coastal zone threat assessments despite the risk it poses to critical freshwater resources and salt-intolerant ecosystems that sustain coastal populations. This review synthesizes field and modeling approaches for investigating vertical SWI and the practical and theoretical understanding of salinization and flushing processes obtained from prior studies. The synthesis explores complex vertical SWI dynamics that are influenced by density-dependent flow and oceanic, hydrologic, geologic, climatic, and anthropogenic forcings acting on coastal aquifers across spatial and temporal scales. Key knowledge gaps, management challenges, and research opportunities are identified to help advance our understanding of the vulnerability of fresh coastal groundwater. Past modeling studies often focus on idealized aquifer systems, and thus future work could consider more diverse geologic, climatic, and topographic environments. Concurrent field and modeling programs should be sustained over time to capture interactions between physical processes, repeated salinization and flushing events, and delayed aquifer responses. Finally, this review highlights the need for improved coordination and knowledge translation across disciplines (e.g., coastal engineering, hydrogeology, oceanography, social science) to gain a more holistic understanding of vertical SWI. There also needs to be more education of communities, policy makers, and managers to motivate societal action to address coastal groundwater vulnerability in a changing climate.

Plain Language Summary Along the world's coastlines, seawater flooding on the land surface by storms and high tide events can drive the downward infiltration of seawater into coastal aquifers that are an important source of fresh groundwater. Rising sea levels and the intensification of coastal storms are expected to exacerbate seawater flooding events globally. The salinization of fresh groundwater along the coast following floods is often "out of sight, out of mind," but this process threatens freshwater resources that sustain dense coastal human populations and valuable, sensitive ecosystems. This paper reviews prior studies that have applied monitoring and/or computer modeling methods to better understand processes and controls on vertical saltwater intrusion. Our review details how surface flood dynamics, groundwater processes, environmental characteristics, and human activities combine to create complex patterns of salinization and flushing over space and time. From our synthesis we identify future research needs, including long-term, globally dispersed monitoring and collaboration across scientific disciplines. We further emphasize the need for communication with local stakeholders about this topic to motivate informed management and research initiatives to understand and reduce the vulnerability of coastal fresh groundwater resources in a changing climate.

1. Introduction

Fresh groundwater is a critically important resource in coastal zones as it supports the water demands of dense and rapidly growing coastal populations (Cunillera-Montcusí et al., 2022; Hauer et al., 2020; Sawyer et al., 2016; Small & Nicholls, 2003). Fresh groundwater also supports productive but vulnerable coastal ecosystems (Barbier et al., 2011; Sousa et al., 2016). Seawater flooding in low-elevation coastal areas can deliver large volumes of seawater inland, which can rapidly salinize fresh groundwater resources and ecosystems in terrestrial coastal zones that are not adapted to high salinity (Anderson, 2002; Gingerich et al., 2017; Post & Houben, 2017). Salinization from coastal flood events can have far-reaching effects on ecosystem services, populations, and economies

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(e.g., Sherren et al., 2021). For instance, even minor groundwater salinization along the coast can result in the deterioration or transgression of ecosystems (e.g., ghost forests) or crops (Briggs et al., 2021; Guimond & Michael, 2021), and can render fresh groundwater resources unfit for human consumption, forcing the closure of pumping wells for industrial, agricultural, and domestic purposes (Michael et al., 2017).

Anthropogenic climate change is driving sea-level rise and changing the frequency, intensity, duration, and spatial extent of extreme coastal storms that already impact thousands of kilometers of coastline annually (Bevacqua et al., 2020; Bhatia et al., 2019; Emanuel, 2013; IPCC, 2021; Kossin, 2018; Peduzzi et al., 2012). Dynamic shoreline morphology and coastal development combined with groundwater pumping-induced land subsidence compound the effects of climate change and exacerbate seawater flooding events (Almar et al., 2021; Frederikse et al., 2020; Nicholls et al., 2021). Coastal flooding disasters due to extreme flooding from tsunamis, tropical cyclones, and other marine storms impact millions of people annually through the loss of resources, infrastructure, livelihood, and life (Barbier, 2015; Barbier et al., 2011; Vousdoukas et al., 2020; Woodruff et al., 2013). These coastal disaster impacts are often evaluated at the land surface in the context of populations, infrastructure, and economic indicators (e.g., gross domestic product), while the unseen salinization of fresh groundwater resources is seldom documented or quantified (Barbier, 2015; Guimond & Michael, 2021; Hauer et al., 2020; Neumann et al., 2015; Sousa et al., 2016). Nevertheless, potable water access is critical for preserving human life within disaster response objectives, and thus groundwater salinization poses an additional disaster response challenge as it can limit potable water availability and increase water treatment costs.

The migration of saltwater into fresh aquifers by surface and subsurface flow paths is known as saltwater intrusion (SWI). SWI is a major water security concern in coastal regions, and it is being exacerbated by changing atmospheric, marine, and anthropogenic forcing (Ataie-Ashtiani et al., 2013; Ketabchi et al., 2016; Werner et al., 2013). Subsurface lateral SWI, which is the landward movement of the freshwater-saltwater interface, occurs over timescales ranging from months to millennia and is caused by a reduction in the land-sea hydraulic gradient from pumping, decreased aquifer recharge, and rising sea levels (Werner et al., 2013). Lateral SWI has been extensively investigated due to its potential to deteriorate freshwater resources (Ferguson & Gleeson, 2012) and degrade salt-intolerant coastal ecosystems (Fernandes et al., 2018; Tully et al., 2019). Vertical (i.e., downward) SWI occurs after seawater inundates land surfaces and infiltrates into underlying fresh groundwater over long and short timescales. Over geological timescales, transgressions in global sea level cause vertical and lateral SWI that influences the current distribution of fresh and saline groundwater along the coast (Ataie-Ashtiani et al., 2013; Han et al., 2020; Kooi et al., 2000; Loaiciga et al., 2012; Rotzoll & Fletcher, 2013). Over short timescales, rapid, temporary coastal flooding causes incidents of vertical SWI (e.g., Anderson, 2002) that have received less attention in prior investigations and global-scale analyses than lateral SWI and long-term vertical SWI (Holding & Allen, 2015b; Kooi et al., 2000). However, seawater flooding events threaten existing freshwater resources by driving salinization on considerably shorter time scales that preclude reactive management responses (Mahmoodzadeh & Karamouz, 2019; Yang et al., 2013). In general, vertical SWI threatens potable water supply in coastal areas and drives the degradation or inland retreat of ecosystems dependent on fresh groundwater (Brinson et al., 1995; Fagherazzi et al., 2019; Kearney et al., 2019).

In light of projected increases in coastal population density and the frequency and intensity of coastal seawater flooding (IPCC, 2021; Neumann et al., 2015), there is a need to review and synthesize the current state of knowledge on flood-driven vertical SWI (herein referred to as vertical SWI) in coastal aquifers. This review aims to provide a solid knowledge base from which research gaps can be identified and sustainable management strategies can be developed to increase the resilience of coastal resources, ecosystems, and communities to seawater flooding events. Management of coastal fresh groundwater resources often suffers from unclear objectives as existing conceptual models for vulnerability frameworks often only consider lateral SWI from sea-level rise and over-pumping (Ferguson & Gleeson, 2012; Klassen & Allen, 2017). However, in many coastal areas, the risks posed by episodic, flood-driven vertical SWI are potentially greater and more immediate than that of lateral SWI (Paldor & Michael, 2021; Xiao & Tang, 2019). The goal of this review is to synthesize prior monitoring and numerical modeling approaches to investigate vertical SWI, detail salinization and flushing processes, identify associated knowledge gaps, spur new research directions, and highlight coastal groundwater management challenges and opportunities. By focusing on vertical SWI, this paper complements other SWI review papers that primarily address lateral SWI (e.g., Ketabchi et al., 2016; Werner et al., 2013).

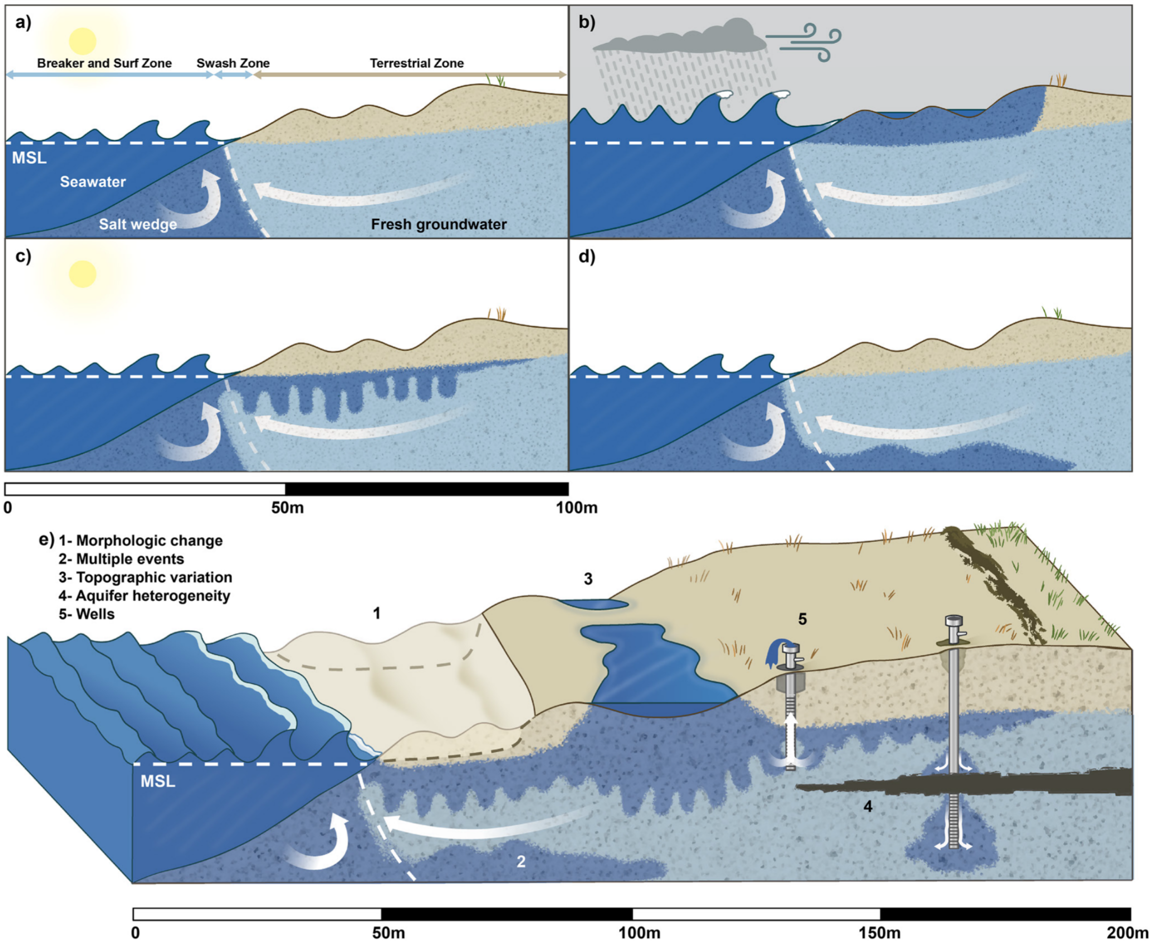

Figure 1. Conceptual model of the evolution of vertical saltwater intrusion (SWI) following seawater flooding on a low-elevation coastal aquifer system. (a) Pre-flood conditions show a coastal aquifer in equilibrium with the ocean and atmosphere; (b) temporary increases in sea level cause flooding to overtop coastal barriers, inundate the land surface, and infiltrate into the unsaturated zone; (c) post-event salinization by density-dependent flow drives seawater vertically into the aquifer while the freshwater-saltwater interface moves seaward due to increased aquifer hydraulic head; (d) recovery occurs when infiltrated seawater is flushed from the aquifer with lateral flow and the interface position recovers (with deeper SWI present). Panel (e) includes complicating factors that exacerbate vertical SWI (see legend). White arrows represent groundwater flow paths. Offshore saltwater circulation is driven by the density gradient across the freshwater-saltwater interface, and fresh groundwater flow to the sea is driven by onshore hydraulic gradients.

2. Brief Overview of Processes and Vertical SWI Studies

This section provides a brief overview of vertical SWI dynamics (Figure 1) to lay the foundation for the later sections of this review. Pre-event groundwater conditions (Figure 1a) are disturbed when temporary high sea levels from tsunamis, storm surges, extreme high tides, high-amplitude waves, or the convergence of these forcings occurs (Figure 1b), resulting in coastal flooding that triggers vertical SWI (Anderson, 2002; Bilskie et al., 2014; Post & Houben, 2017). Seawater on the land surface infiltrates (Figure 1c) and migrates into the subsurface, displacing and mixing with fresh groundwater in the coastal aquifer (Figure 1d). Subsurface migration and mixing are driven by density gradients between the denser saltwater and underlying freshwater, as well as vertical hydraulic gradients between pooled seawater and fresh groundwater at depth (Holding & Allen, 2015b; Terry & Falkland, 2010). The distribution of fresh groundwater is strongly controlled by topography and coastal morphology, and morphological changes during a flooding event (Figure 1e) can cause complex feedbacks

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that can increase the total volume of infiltrated seawater (Passeri et al., 2015; Schneider & Kruse, 2006; Yu et al., 2016; Zhang et al., 2016). Natural remediation of salinized groundwater resources occurs as fresh meteoric water recharges the aquifer after a flooding event (Figure 1d), causing the saline plume to sink, disperse, and discharge to streams, wells, and the ocean (Holding & Allen, 2015b; Post & Houben, 2017). Flooding, vertical salinization, and flushing are naturally successive and occur over different timescales (Figures 1a–1d). These processes and their timescales depend on a variety of environmental factors, including the event characteristics, coastal morphological conditions, and the aquifer characteristics (Cardenas et al., 2015; Gingerich et al., 2017; Xiao et al., 2016; Yang et al., 2015).

Monitoring and modeling vertical SWI are complicated as SWI involves a variety of processes: density-dependent and variably-saturated flow, coupled solute transport, terrestrial surface flow, coastal hydrodynamics and associated short-term sea-level fluctuations (e.g., Ataie-Ashtiani et al., 1999), coastal morphodynamics, groundwater pumping, and climate change. These processes are often interdependent, operate at different time scales, and have complex integrated feedbacks that must be considered across disciplines (Figure 1e) (Klassen & Allen, 2017). However, processes have traditionally been studied in different academic disciplines, including coastal engineering, physical oceanography, coastal geomorphology, and hydrogeology, and this approach has narrowed our ability to holistically understand and predict vertical SWI. Coastal flooding and vertical SWI occur rapidly, with little warning; however, these short-lived events (hours-days) can cause widespread impacts on fresh groundwater resources that can sometimes persist for decades (Bailey & Jenson, 2014; Violette et al., 2009).

2.1. Summary of Previous Studies of Vertical SWI

The earliest reports of vertical SWI into coastal freshwater aquifers came from water quality monitoring programs that observed large and prolonged increases in the salinity of water supply wells after seawater flooded the land surface (Anderson, 2002, and 1942 data analyzed by Post & Houben (2017)). Since these early reports, field investigations have captured incidents of vertical SWI across a range of settings as detailed in Table 1. However, field investigations of vertical SWI following coastal floods are limited given the paucity of coastal groundwater monitoring infrastructure, insufficient advanced warning, restricted access to flooded coastlines, loss/damage of monitoring infrastructure during flooding events, and the tendency to focus disaster relief initiatives and assessments on aboveground impacts (Adger et al., 2018). Further, field investigations have not captured incidents of vertical SWI across a range of settings and drivers given the breadth of causes (e.g., tides, storms, tsunamis), geographic distribution of coastal floods, and the random nature of these events. To fill these gaps and improve our understanding of vertical SWI dynamics across a range of environmental settings, numerical models have been applied to simulate the complex flow and solute (salt) transport dynamics that have not yet been captured with direct observations.

Figure 2 shows that the global distribution of vertical SWI field and site-specific modeling studies is limited and that past studies have been clustered in (a) small islands that depend on fresh groundwater as a primary water resource, (b) coastal areas disproportionately impacted by large flood events (e.g., the hurricane-battered Atlantic seaboard and the Indian Ocean coastline impacted by the 2009 Indian Ocean tsunami), and (c) areas with high population density (e.g., near coastal megacities). There are many regions of the world where no studies have been conducted. For instance, although Canada has the world's longest coastline, no studies of vertical SWI along Canada's shoreline were identified. Also, our extensive review of the English peer-reviewed literature did not uncover any studies focused on the African coastline. Figure 2 also reveals that fewer field monitoring investigations have been conducted compared to investigations exclusively applying numerical models. This may be due to the financial and logistical challenges associated with monitoring dynamic environments experiencing vertical SWI. More recently, studies have been conducted that combine field and modeling techniques, as field data are often used to parameterize, calibrate, and validate numerical models. Combining field, laboratory, and numerical modeling approaches is resource intensive but the most effective way to achieve process-based understanding and develop transferable frameworks to assess coastal aquifers at risk of vertical SWI.

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Table 1
Summary of Field Monitoring Studies of Vertical Saltwater Intrusion (SWI)

Location	Trigger	Surge height (m)	Inland flood extent (m)	Monitoring equipment[a]	Aquifer type[b]	Monitoring period	Observed or est. time to full recovery	Citation
North Carolina, USA	Hurricane Emily, 1993	2.75–3.65	1,000	SW	UNC, HET, L	4 years	–	Kaihotsu et al. (2017)
Samar Island, Philippines	Super typhoon Haiyan, 2013	5–6	1,250	PW, MW, ERT	UNC, C, HET, L	2–8 months	5–10 years	Cardenas et al. (2015)
Louisiana, USA	Hurricane Katrina and Rita, 2005	3.6 & 1.3	>10,000	PW	UNC, C, HET, L	9 months	–	Carlson et al. (2008)
Emilia-Romagna Italy	Winter storm, 2015	1	100	TDR, MW	UNC, HET, L	26 days	–	Giambastiani et al. (2017)
Kwajalein Atoll, Marshall Isl.	Extratropical storm, 2008	0.53 (ponded water)	–	SW	UNC, HET, L	2 years	22 months	Gingerich et al. (2017)
Spiekeroog, Germany	Storm tides, 2013	3.64	500	SW, PWS	UNC, HOM	3 years	–	Holt et al. (2017)
Tohoku, Japan	Sanriku Tsunami	10.70	10,000	SW, SI	UNC, HOM	4 years	4 years	Wilson et al. (2011)
Florida, USA	Hurricane Irma, 2017	2.00	–	ERT, MW	UNC, HET, L	8 months	–	Kiflai et al. (2020)
Kachelotplate, Germany	Storm tides, 2007	1.35	–	MW, PWS	UNC, HOM	4 months	–	Klaassen et al. (2008)
Sri Lanka	Indian Ocean Tsunami, 2004	3–8	1500	PW, DW	UNC, HOM	8 months	3 years	Illangasekare et al. (2006)
Louisiana, USA	Hurricane Katrina and Rita, 2005	3.6 & 1.3	>10,000	PW	UNC, C, HET, L	9 months	-	Van Biersel et al. (2007)
Pukapuka Atoll, Cook Islands	Cyclone Percy, 2005	–	2,000	PW, MLBH, DW, EM	UNC, C, HET, L	2 years	–	Terry and Falkand (2010)
Batticaloa, Sri Lanka	Indian Ocean Tsun., 2004	5–12	1,000	DW, MW	UNC, HET, L	1 year	–	Vithanage et al. (2009)
Batticaloa, Sri Lanka	Indian Ocean Tsun., 2004	5–12	1,000	MW, DEW, EM	UNC, HET, L	2 years	15 years	Vithanage, Engesgaard, Villholth, and Jensen (2012)
Tamil Nadu, India	Indian Ocean Tsun., 2004	5–12	500	PW	UNC, HET, L	4 months	3–7 years	Violette et al. (2009)
Cabretta Island, USA	Tropical Storm Fay	3	100	MLBH, RA, N	UNC, C, HET, L	2 months	–	Wilson et al. (2011)
Sand Engine, Netherlands	Storm tides	3–5.4	80	MW, ERT	UNC, HET, L	3 months	–	Huizer et al. (2017)
Baltrum, Germany	Vincinette Storm, 1962	4.1	800	DW, MLB, EM	UNC, HET, L	8 years	4 years	Post and Houben (2017)

Note. Notation modified from Mahmoodzadeh and Karamouz (2017).
[a]SW-supply well, DW-dug well, PW-private well, DEW-deep well, MW-monitoring well or piezometer, DP-drive point piezometer, MLBH-multi-level borehole, TDR-time domain reflectometer probes, SI-stable isotopes, Ra-radium isotopes, N-nutrients, EM-electromagnetic geophysics, ERT-electrical resistivity tomography geophysics. [b]UNC-unconfined aquifer, C-confined aquifer, HOM-homogenous aquifer, HET-heterogenous.

3. Monitoring and Modeling Techniques for Vertical SWI

3.1. Field Techniques to Monitor Vertical SWI

Field investigations have captured the salinization and recovery (flushing) of coastal aquifers in response to seawater flooding events across a range of temporal and spatial scales (Table 1, Figure 2). Characterizing the complex drivers and dynamics of vertical SWI requires multidisciplinary monitoring approaches applying a range of techniques, as data from individual techniques can be subject to multiple interpretations that may increase our

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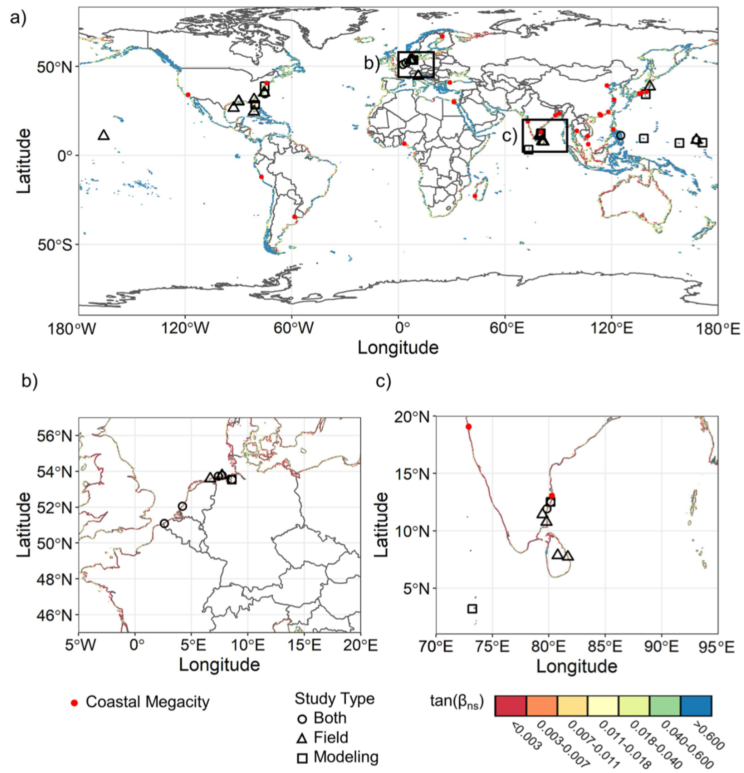

Figure 2. (a) The global distribution of field (Table 1) and site-specific modeling (Table S1, electronic supplement) studies of flood-driven vertical saltwater intrusion (SWI) into coastal aquifers. The locations of coastal megacities (population >10,000,000) and the distribution of nearshore coastal slopes ($\tan\beta_{ns}$) are also indicated. Insets of regions with a high density of studies are shown for (b) western Europe and (c) southern India and Sri Lanka. Coastal slope was obtained from Athanasiou et al. (2019) who calculated slope as the tangent of β_{ns}, where β_{ns} is the ratio of cross-shore elevation to horizontal length of the cross-shore profile.

uncertainty in system understanding. Effective monitoring should capture the spatial heterogeneity and temporal evolution of vertical SWI, and thus monitoring requires point and spatially distributed measurements over time. Terrestrial field studies have included groundwater head and salinity measurements in wells, aerial and ground-based geophysical surveys, and environmental tracers (Figures 3a and 3b). Following large floods, survivor accounts, flood lines, and soil salinity surveys also provide invaluable ancillary data to complement coastal flood and aquifer salinization monitoring.

The most common method for in situ monitoring of aquifer salinization and flushing following seawater inundation is through instruments installed in hand-dug wells, piezometers, monitoring wells, and supply wells (Figure 3b; Table 1). Such in situ "well-based" measurements are limited in their *spatial* resolution. However, when instrumented with conductivity-temperature-depth (CTD) loggers, wells can provide high-resolution time series that collectively provide valuable insights into the *transient* nature of episodic vertical SWI dynamics (Anderson, 2002; Gingerich et al., 2017; Illangasekare et al., 2006; Van Biersel et al., 2007; Violette et al., 2009). While the interpretation of pressure and electrical conductivity data from wells to reveal groundwater table rise and salinization is relatively intuitive, studies have also shown that temperature data from CTD loggers in wells can also be used to trace seawater infiltration/exfiltration and freshwater-saltwater interface movement (Grünenbaum et al., 2020; Taniguchi, 2000). A key advantage of direct, groundwater measurements from wells is that they do not require inversion as is needed to interpret geophysical data.

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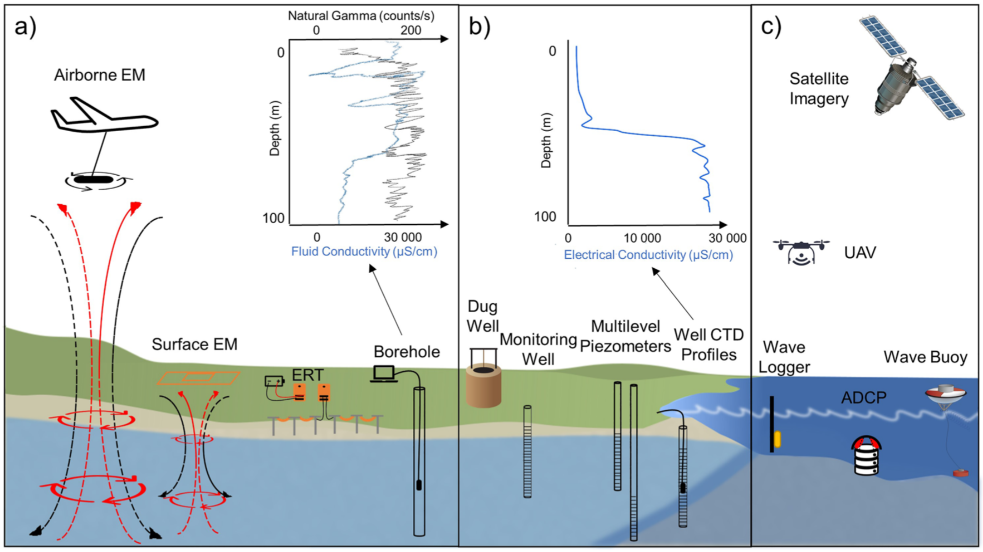

Figure 3. Monitoring techniques for vertical saltwater intrusion (SWI). Potential methods include (a) geophysical techniques, (b) hydrologic measurements, and (c) nearshore surface water and aerial measurements. (a) Geophysical methods include airborne and ground-based electromagnetic (EM) techniques as well as surface and borehole electrical resistivity tomography surveys (ERT) (borehole geophysics profiles based loosely on Mack & Degnan, 2003). (b) Hydrologic and salinity monitoring is conducted in dug wells, drilled monitoring wells, and multi-level piezometers equipped with stationary conductivity, temperature, and depth (CTD) loggers to monitor salinization or slowly lowered CTD loggers in small, unmixed, fully screened or uncased wells. (c) Nearshore monitoring is conducted with wave loggers, buoys, and acoustic Doppler current profilers (ADCP). This pane also highlights the collection of aerial imagery from unmanned aerial vehicles (UAV) and satellites.

Despite the advantages of direct, in situ well measurements, there are also challenges associated with interpreting data from coastal wells (Figure 3b). For example, hydraulic head measurements in coastal wells must be corrected for density variations to ensure a standard framework for comparison (Post et al., 2007). Also, measurements of water level and electrical conductivity in partially screened wells and piezometers represent the head and salinity at the screened interval provided there is adequate flow through the screened interval (Horn, 2002), and not conditions at the location of the water table or the CTD logger depth as is sometimes assumed. Further, in both fully and partially screened wells and piezometers, if groundwater is not flowing rapidly across the screen, the conductivity measurement may not be representative of the conditions in the aquifer but instead reflect stratification and dynamics within the well. In contrast, the temperature measurements from a CTD logger represent the groundwater temperature at the sensor depth, because the well casing material blocks the flow of water and solute but allows for radial heat conduction. As a result, the vertical salinity profile recorded by lowering a CTD sensor in a cased well does not represent the true aquifer salinity profile; however, the thermal profile concurrently recorded by the CTD logger does represent the aquifer thermal profile in the absence of well mixing (Kurylyk et al., 2019). Because the location of the freshwater-saltwater interface influences groundwater flow patterns (Figure 1) and resultant heat advection, such temperature profiles can theoretically yield insight into interface location and dynamics (Shin & Hwang, 2020; Taniguchi, 2000) and potentially overcome challenges with salinity profiles from cased wells. Further, wells that are uncased or have long screens can allow for short-circuiting across geologic units and facilitate vertical salinity and head mixing (e.g., Shalev et al., 2009, Figure 1e). Vertical SWI also causes systematic changes in the chemical composition of groundwater, and thus environmental tracers (e.g., salinity, chloride, electrical conductivity, stable isotopes, age tracers) can be an effective way to monitor salinization and flushing processes (Jiao & Post, 2019; Wilson et al., 2011). However, environmental tracers alone typically cannot provide conclusive evidence of vertical SWI due to the complexity of chemical reactions and site-specific biogeochemistry.

Geophysical monitoring techniques that provide measurements of bulk electrical conductivity are well suited to mapping saline and fresh groundwater zones based on the relationship between salinity and resistivity (low resistivity seawater and high resistivity freshwater) (Figure 3a). Electrical resistivity tomography (ERT) methods

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use electrodes installed at the surface or in boreholes to induce a current; the potential between the electrodes is measured, and subsurface conductivity is inferred from an inversion software (Singha et al., 2022). ERT electrode spacing can be adjusted to provide high-resolution resistivity measurements at depth (e.g., Palacios et al., 2020). Fixed arrays can also be installed and applied through time, making ERT techniques useful for spanning space and time when studying vertical SWI and aquifer flushing influences (Huizer et al., 2017; Palacios et al., 2020). ERT surveys enable the development of two-dimensional resistivity distributions to assess vertical and cross-shore porewater salinity variations.

Electro-magnetic (EM) geophysical tools use a transmitter to induce an electrical current at a location and a receiver to measure the resulting magnetic field (Jiao & Post, 2019). Data are interpreted using inversion software to generate a resistivity model. EM surveys can be ground-based, which often yield higher resolution data, but improved accuracy has increased the uptake of airborne techniques that increase spatial coverage (Fitterman & Deszcz-Pan, 1998). As stratigraphy also impacts subsurface resistivity, multiple geophysical methods and direct measurements (e.g., stratigraphy or salinity) are often needed to interpret resistivity distributions. Complementary geophysical approaches, such as combining time-domain and frequency-domain EM surveys, can be used to assess vertical SWI dynamics at multiple spatial scales (Figure 3a; Briggs et al., 2021). Geophysical evaluations at different spatial scales may also provide the opportunity to investigate vertical SWI processes across a range of temporal scales (i.e., shallow, recent salinization and older, deeper saline plumes). EM geophysical surveys in pre-storm conditions can also yield the geometry of the stable freshwater-saltwater interface (Figure 1a), which can be used to help calibrate and parameterize steady-state groundwater models that are then applied in transient runs to investigate the impacts of storms and vertical SWI (Pavlovskii et al., 2022). In general, geophysical methods provide the advantage of yielding spatially continuous subsurface salinity data in at least one dimension following flooding events; however, these surveys are often limited to discrete points in time, have uncertainty from the variability of inversion interpretations, and have received limited uptake in prior field investigations of vertical SWI (Table 1) (Cardenas et al., 2015; Huizer et al., 2017; Kiflai et al., 2020).

While vertical SWI field studies may include terrestrial groundwater hydraulic head and salinity, environmental tracers, and geophysics, such measurements are rarely paired with nearby measurements of coastal hydrodynamics (e.g., using wave buoys, wave loggers, acoustic Doppler current profilers, or satellites; Figure 3c) that generate vertical SWI events (Yu et al., 2016). Similarly, few studies pair vertical SWI monitoring with measures of morphologic change from unmanned arial vehicles and satellites (Figure 3c). The lack of paired hydrogeologic, hydrodynamic, and morphologic data in vertical SWI studies is in part because nearshore ocean monitoring must capture events that arise rapidly and are challenging to predict in space and time, whereas terrestrial monitoring can occur post event. Additionally, the absence of studies with paired offshore and terrestrial data may also be partially attributed to the tendency of researchers to stay within traditional disciplinary boundaries.

3.2. Numerical Modeling Techniques to Simulate Vertical SWI

Numerical models are irreplaceable tools to investigate present-day and future vertical SWI processes, drivers, and management alternatives on local to global scales. Advancements in process-based understanding and computational capacity have further bolstered the ability of numerical models for simulating computationally intensive SWI dynamics. Numerical models have been extensively applied to simulate lateral SWI and the effects of pumping scenarios, coastal infrastructure changes, and sea-level rise on freshwater and saltwater distributions in coastal aquifers (as reviewed by Sorek and Pinder (1999) and Werner et al. (2013)). More recently they have also been applied to simulate coastal flooding and vertical SWI into coastal aquifers (Table S1, electronic supplement). Numerical modeling codes applied to simulate vertical SWI include SUTRA (Provost & Voss, 2019), SEAWAT (Langevin et al., 2008), FEFLOW (Diersch, 2013), and HydroGeoSphere (Therrien et al., 2010). All these models simulate variable-density groundwater flow and transport, but they have had variable success at simulating real-world seawater flooding and concomitant vertical SWI because of their differing capacities for simulating unsaturated zone and surface hydraulic processes (Table 2).

These general-purpose modeling codes apply finite difference and/or finite element methods to convert mathematically complex governing equations to systems of simultaneous equations for variable-density flow (often including the unsaturated zone) and solute transport under different boundary conditions (Figure 4). Although most of these codes were not specifically developed for coastal applications, such codes have been modified to consider processes in coastal aquifers including the effects of tides and waves on groundwater flow and salt

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Table 2
Common Modeling Codes That Can Be Used to Simulate Vertical Saltwater Intrusion (SWI) and Their Capabilities (Modified From Werner et al., 2013)

Model name	Accessibility[a]	Numerical method	Saturation	Surface hydraulic processes	Near-shore ocean dynamics	Citation
FEFLOW	$, GUI, code not available for editing	Finite element	Variably saturated	No	No	Diersch (2013)
HydroGeo-Sphere	$, code not available for editing	Finite element (control volume)	Variably saturated	Yes, non-linear wave equations	No[b]	Therrien et al. (2010)
MOCDENS3D	Open access, editable code	Finite difference	Fully saturated	No	No	Oude Essink (1998)
SEAWAT	Open access, GUI, editable code	Finite difference	Fully saturated	No	No	Langevin et al. (2008)
SUTRA	Open access, GUI, editable code	Finite element/difference	Variably saturated	No	No	Provost and Voss (2019)

[a]$-license fees, GUI- graphical user interface. [b]While HydroGeoSphere can simulate surface hydraulics, it does not have specific wave mechanics or coastal storm routines. Periodic tidal forcing can be accommodated as a transient boundary condition in any of these codes.

transport (e.g., Robinson et al., 2007; Xin et al., 2010). Models, including SUTRA, SEAWAT, and FEFLOW, that do not include surface domains and are thus unable to explicitly simulate nearshore hydrodynamics and surface flooding can still be applied to simulate vertical SWI dynamics by representing floods as specified head or recharge boundary conditions with seawater concentration (Figure 4; Bailey, 2015; Chui and Terry, 2012, 2015; Gingerich et al., 2017). This approach requires an accurate estimate of the flooding extent and depth and/or the volume of infiltrated seawater. This is challenging because flood area and depth depend on hydrodynamics, topography, and surface retention, as highlighted in Figure 1 (Gingerich et al., 2017; Huizer et al., 2017; Post & Houben, 2017; Violette et al., 2009). Such processes should ideally be considered in a coastal surface hydrodynamic model or be directly measured. As such, models applying this approach likely incorrectly estimate infiltrated seawater volumes and the consequent extent of aquifer salinization and recovery duration.

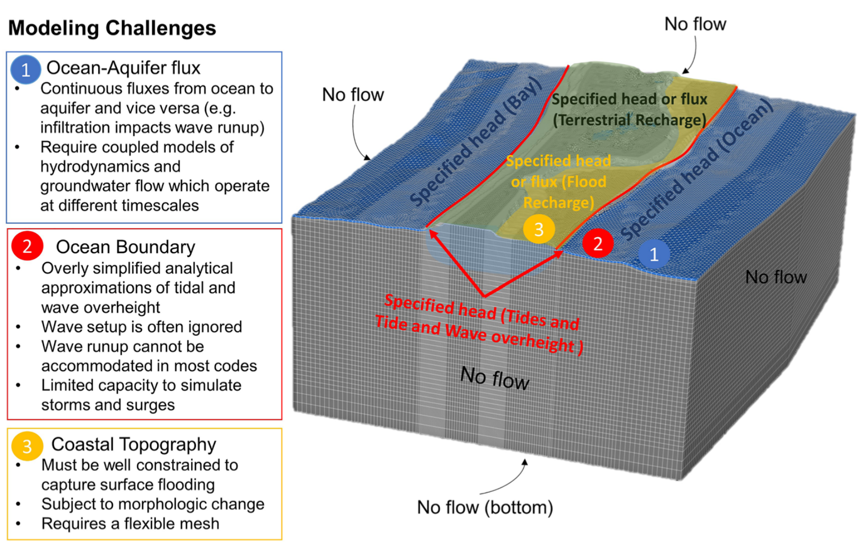

Figure 4. An example of a three-dimensional numerical model domain (adapted from Pavlovskii et al., 2021) of a sandy barrier island including the typical boundary conditions applied for simulating vertical saltwater intrusion (SWI). Modeling challenges specific to vertical SWI are identified in the boxes.

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Recently, Elsayed and Oumeraci (2018a) overcame challenges associated with the lack of surface routines in groundwater models by applying a more advanced approach that used the results of the nearshore hydrodynamic model XBeach (Roelvink et al., 2010) as a boundary condition for a MODFLOW groundwater model. A similar approach was used to couple XBeach with SUTRA (Storlazzi et al., 2018). Other studies have applied HydroGeoSphere, which can simulate coupled surface and subsurface density-dependent fluid flow in a variably saturated system during flooding using non-linear shallow-water equations (Therrien et al., 2010). This approach for simulating surface hydrodynamics ignores short wave effects (wave run-up, run-down, and breaking) for the surface water domain, which can be important drivers of coastal barrier breaching. In HydroGeoSphere, surface conditions can be transferred to the subsurface domain to simulate vertical SWI dynamics (Paldor & Michael, 2021; Yang et al., 2015; Yu et al., 2016). None of the groundwater modeling codes considered in this review allow for morphologic change, which is a general groundwater model limitation (Sections 4.1.2). Despite limitations, studies have employed groundwater models to assess the impacts of coastal flooding on vertical SWI and recovery including the effects of topography, aquifer geometry and properties, climate impacts, and flood characteristics (Table S1).

4. Process-Based Understanding Revealed Through Field and Modeling Investigations

4.1. Influence of Surface Conditions and Processes on Vertical SWI

Vertical SWI is influenced by multiple surface drivers and conditions that vary spatially and temporally and cause complex mixing patterns between fresh and saline groundwater. Flooded seawater is the source of vertical SWI, so understanding how surface flood characteristics influence the spatial and temporal patterns of vertical SWI is critical. Coastal morphology also influences seawater flooding and hydrogeological processes in coastal aquifers. This is particularly important along coastlines that experience frequent morphologic changes that can control vertical SWI and aquifer flushing. As described in the following sections, field and numerical modeling investigations have revealed the extent to which surface hydrodynamics and coastline morphology prior to and following a flood can influence vertical SWI dynamics in coastal aquifers.

4.1.1. Surface Characteristics of Floods

Coastal floods vary in terms of their area, depth, and duration, all of which influence the volume and rate of vertical SWI. Modeling investigations have found that of these characteristics, the spatial extent of land surface inundation has the largest impact on the total volume of aquifer salinization (Bailey, 2015; Chui & Terry, 2012; Huizer et al., 2017; Yu et al., 2016). Coastal flooding due to storm surge can be exacerbated during periodic high water levels that occur, for example, at spring high tides (Ataie-Ashtiani et al., 1999). Field studies have indicated that the spatial extent of surface flooding determines the area where vertical SWI will occur, and that seawater ponding will intensify seawater infiltration (Kiflai et al., 2020; Terry & Falkland, 2010; Yu et al., 2016). Aquifer salinization can extend beyond the surface extent of flooding if flood waters cross a groundwater divide (Liu & Tokunaga, 2020). The flood water depth controls the vertical hydraulic gradient that drives infiltration and downward flow into a fresh aquifer. Flood duration is not as important as the total volume of infiltrating seawater, owing to the difference in the timescales between flood events (hours to days) and natural remediation intervals (months to years) (Chui & Terry, 2013; Elsayed & Oumeraci, 2018b; Post & Houben, 2017). These findings were confirmed by the field-informed modeling investigation of Violette et al. (2009), who found that infiltration following coastal flooding only partly accounted for the volume of vertical SWI, and the total volume of vertical SWI could only be fully explained from sustained infiltration from local depressions. In contrast to the extent of flooding, which increases the plan view area of aquifer salinization, long periods of surface water ponding can drive seawater to greater depths in coastal aquifers due to the sustained saline recharge source and density differences (Chui & Terry, 2013). Infiltrated water may also temporarily cause elevated groundwater levels that push the saltwater-freshwater interface seaward, which in turn triggers lateral SWI when the interface rebounds years later (Paldor & Michael, 2021).

4.1.2. Surface Morphology and Dynamics

Nearshore bathymetry and coastal topography exert strong controls over the propagation and retention of floods across low-elevation coastal areas (Figure 1). Topography controls wave run-up, overtopping potential, flood extent, flood recession, surface water (seawater) ponding, and groundwater hydraulic gradients, all of which

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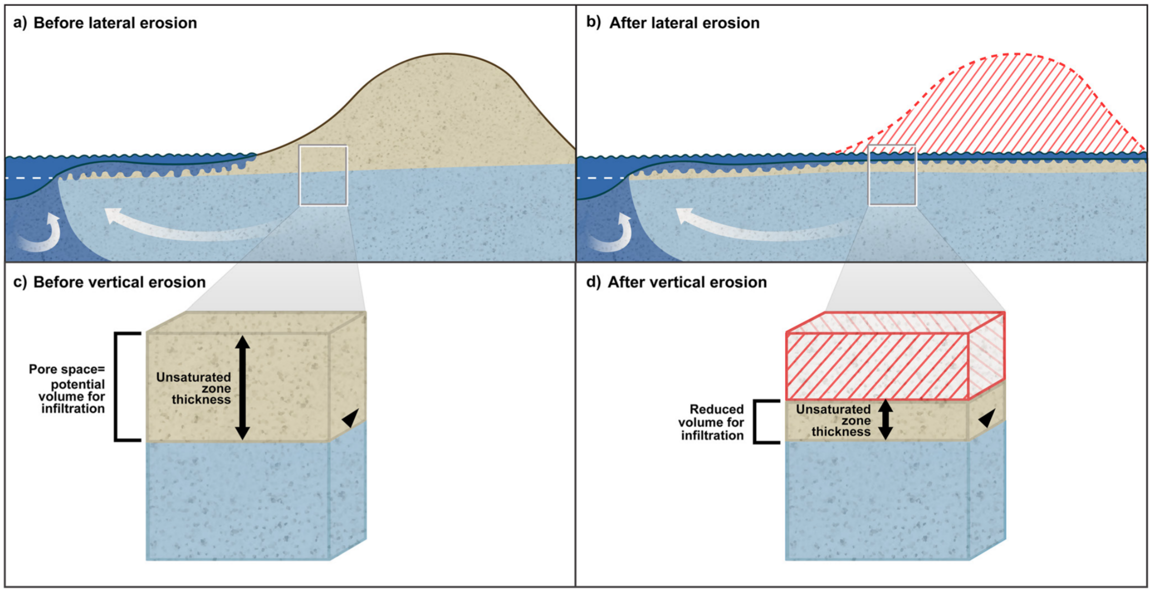

Figure 5. Conceptual diagram of coastal morphodynamic impacts on vertical saltwater intrusion (SWI) with a focus on the contrast between (a) an intact coastline, (b) a laterally eroded coast with extended surface flooding due to the removal of a foredune, (c) an intact vertical profile, and (d) a vertically eroded profile with reduced infiltration capacity.

impact vertical SWI and recovery (Anderson & Lauer, 2008; Bailey, 2015; Yu et al., 2016). Wave run-up and surface flooding extend further inland along low-elevation coastlines compared with high-elevation coastlines (Alsumaiei & Bailey, 2018; Anderson & Lauer, 2008). Coastal vegetation can further play an important role in dissipating wave energy, flood extent, and vertical SWI (Guimond & Michael, 2021). Behind coastal berms, topography strongly influences the occurrence and depth of surface ponding and underlying vertical hydraulic gradients (Ramsey et al., 2011). Mesoscale topographic features (m to km) therefore play an important role in determining the distribution and total volume of seawater flooding on a coastal landscape and the subsequent infiltration of seawater into aquifers, even after most of the surface flood subsides (Chui & Terry, 2015; Gingerich et al., 2017; Urbano & Thibault, 2005; Yu et al., 2016). Under topographic depressions, concentrated saline plumes form that are slow to flush (Chui & Terry, 2015). Microscale topographic variations (cm to m) also influence seawater storage and infiltration patterns; however, as they occur on small scales, their widespread impact is limited and they are impractical to consider within larger-scale models (Le & Kumar, 2017; Yu et al., 2016). The orientation of topographic features relative to the coast also influences their impact on the pattern and volume of vertical SWI. For instance, features aligned parallel to the coast will intensify vertical SWI if breached because of their tendency to retain seawater (Yu et al., 2016). Further, following a flood, topographically driven fresh groundwater flow strongly influences the persistence of salt contamination within aquifers as it can limit the formation of saline plumes, stabilize the system, and rapidly flush infiltrated seawater (Anderson, 2002; Post & Houben, 2017; Vithanage, Engesgaard, Jensen, et al., 2012).

Coastal morphology is continuously evolving, and topographic features across a range of spatial scales can erode and accrete under waves, storm surges, and floods (Figure 5; Elsayed & Oumeraci, 2018b; Houser et al., 2008; Huizer et al., 2017; Morton & Sallenger, 2003). Given the influence of topography on coastal floodwater retention and vertical SWI, morphologic change can impact groundwater salinization and recovery and, in some cases, reinforce and exacerbate flooding patterns and impacts to ecosystems and populations. A review by Passeri et al. (2015) highlighted that low-elevation coasts prone to erosion will likely experience increased coastal submergence and flooding over time. Such changes will likely increase the amount of vertical and lateral SWI as the coast adjusts (Holt et al., 2019). This is expected, as lateral erosion of a coastal barrier has the potential to increase the landward extent and volume of seawater that can flood and infiltrate (Figures 5a and 5b). Figure 5 depicts a general case where erosion leads to a greater flooding extent and more floodwater retention. However,

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the influence of morphologic change may be more complex than illustrated in Figure 5 as eroding coastal topography impacts the geomorphologic connectivity of a coastline and as such can impact the volume and duration of flooding (Yu et al., 2016). For example, a smoother, eroded surface with fewer depressions may limit the amount of ponded seawater. Also, when pronounced erosion events occur during coastal storms, coastal aquifers may be in disequilibrium, and in some cases, this can lead to a reduction in background hydraulic gradients and aquifer thinning that exacerbates vertical SWI (Schneider & Kruse, 2003).

4.2. Groundwater Salinization Processes

Monitoring and modeling have revealed that subsurface salinization can be observed within hours to days following a flooding event (e.g., Anderson, 2002), while peak salinization at the water table is often not observed until some period (e.g., 1 month) after an event (Cardenas et al., 2015; Violette et al., 2009). This time lag occurs as seawater continues to gradually percolate through the vadose zone of the flooded extent even after the flood has receded. Vertical SWI patterns vary in space and time as salinization is controlled by vertical hydraulic gradients, free convection, and aquifer properties. Initially vertical hydraulic gradients between flooded seawater and freshwater at depth drive salinization and saturation of the vadose zone (Section 4.2.1). Once infiltrated, density differences between seawater and freshwater drive free convection that leads to complex salinity patterns (Section 4.2.2) that are eventually flushed by dispersion and background groundwater flow.

4.2.1. Salinization of the Vadose Zone

Several studies have shown the important role of the vadose zone for vertical SWI into fresh, unconfined coastal aquifers (e.g., Holding et al., 2016). Flooded seawater infiltrates and saturates the vadose zone rapidly as floodwater creates high vertical hydraulic gradients that drive the rapid infiltration of floodwater down to fresh groundwater at depth. Once saturated, the subsurface cannot support high infiltration rates, and flooded seawater can be lost via evapotranspiration and return flow to the ocean or local depressions. Thus, the thickness of an aquifer's vadose zone impacts the volume (infiltration capacity) and timing of vertical SWI into a fresh coastal aquifer (Chui & Terry, 2012; Liu & Tokunaga, 2020), similar to how antecedent water table depth plays a key role in flood retention in inland watersheds (Biron et al., 1999). The vadose zone thickness varies with the landscape and season. For example, the vadose zone may be thin in a low-elevation, sedimentary environment and thick in a steep fractured aquifer (Holding & Allen, 2015b).

Erosion can reduce vadose zone dimensions and the infiltration volume during a flooding event (Figures 5c and 5d), while accretion can result in a thicker vadose zone. Also, because the water table rises and falls between wet and dry seasons, the timing of flood events between seasons can impact the SWI volume (Bailey & Jenson, 2014). Soil salinity following a flooding event remains elevated for a prolonged period and may even increase due to evapotranspiration. Residual soil salinity (e.g., a result of evapoconcentration) can result in a second pulse of saline water when subsequent precipitation leaches salt into the fresh groundwater (Sivakumar & Elango, 2010; Violette et al., 2009; Williams, 2010). Unsaturated zone dynamics may not need to be included in a model if the infiltration occurs rapidly and the flux of infiltrated seawater can be accurately estimated (Chui & Terry, 2012). However, such accurate estimation is seldom possible, and generally speaking, excluding or poorly parameterizing an aquifer's vadose zone will result in inaccurate simulations of vertical SWI (Liu & Tokunaga, 2020).

4.2.2. Free Convection

The salinity of infiltrated seawater in a coastal aquifer is often at least slightly lower than that of seawater as it is diluted by precipitation and mixing with fresh groundwater; however, infiltrated water is still denser than the deeper fresh groundwater. Through field observations and laboratory experiments, Illangasekare et al. (2006) found that infiltration is initially driven by forced convection from hydraulic head gradients, but as the surface hydraulic head dissipates, free convection of seawater from density differences dominates vertical flow. Thus, convection dynamics are critical for understanding vertical SWI processes.

Free convection is a form of fluid and solute transport that can occur in coastal aquifers when episodic, periodic, or long-term transgressions in sea level cause more dense seawater to overlie freshwater (Jiao & Post, 2019; Simmons, 2005). Free convection has received significant attention in the scientific literature because many natural and anthropogenic processes result in unstable density stratifications in groundwater systems (Simmons, 2005).

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Infiltrated seawater overlying less dense fresh groundwater after a flood is one such example of unstable density stratification (Cardenas et al., 2015; Post & Houben, 2017; Post & Kooi, 2003; Terry & Falkland, 2010). Laboratory investigations and numerical modeling (with little to no support from field programs) have indicated that unstable density distribution can cause convective fingers to form at the interface between infiltrated seawater and underlying freshwater. This fingering causes seawater to be transported to greater depths (Figures 1c and 1e), emplacing it further within the underlying fresh aquifer (Xie et al., 2012). The formation of convective fingers depends on the density contrast, permeability, and competing transport from hydraulic gradients and dispersion that dissipate density-driven flow (Xie et al., 2011). The general criterion for free convection is represented by a dimensionless Rayleigh number, *Ra*:

$$Ra = \frac{\Delta p g k H}{\mu D_e} \quad (1)$$

where $\Delta\rho$ is the difference in density between fresh and saline water (M L^{-3}), g is gravitational acceleration (L t^{-2}), k is intrinsic permeability of the porous media (L^2), H is the aquifer thickness (L), μ is dynamic fluid viscosity (M L^{-1} t^{-1}), and D_e is a coefficient accounting for dispersion and diffusion (L^2 t^{-1}) (Xie et al., 2011). This form of the Rayleigh equation is often applied along the coast using standard values for the density of freshwater (~1000 kg m^{-3}) and seawater (~1025 kg m^{-3}). In macroscopic, homogenous systems a Rayleigh number above 6,000 is assumed to indicate free convection; however, transience, aquifer heterogeneity, and flow limit the applicability of this criterion in field applications (Post & Kooi, 2003; Simmons et al., 2001). The velocity of convective finger descent has a large control on the rate and extent of vertical SWI, and relationships have been established to predict migration rates of individual fingers and long-term salinization (Post & Kooi, 2003). In general, patterns and rates of convective finger descent are complicated by aquifer anisotropy, heterogeneity, diffusion, and background lateral groundwater flow and have been the subject of several review papers (e.g., Simmons et al., 2001; Xie et al., 2012).

4.2.3. Influence of Aquifer Properties

Numerical modeling studies have demonstrated that the hydraulic and storage properties of the vadose and saturated zones play a key role in controlling the volume and flow of fresh groundwater and, therefore, the infiltration and flushing of saline water (Liu & Tokunaga, 2020). The infiltration rate and movement of saline groundwater is strongly influenced by the aquifer hydraulic conductivity. Generally, high-permeability aquifers are more susceptible to initial vertical SWI and salinization (Anderson & Lauer, 2008; Holding & Allen, 2015b; Yang et al., 2015), while low-permeability aquifers experience lower infiltration rates, fewer density-driven instabilities, and shallower/reduced SWI, which combine to preserve potable freshwater resources at depth (Bailey & Jenson, 2014; Chui & Terry, 2012; Vithanage, Engesgaard, Jensen, et al., 2012). Field observations reveal that shallow, high-permeability aquifers are salinized rapidly, but these also recover more quickly compared to lower-permeability aquifers (Terry & Falkland, 2010). Aquifer storage has received limited attention but is expected to cause a nonuniform hydraulic response that will cause enhanced mixing via time dependent velocity fields, similar to what has been observed in coastal aquifers influenced by tides (Pool et al., 2014).

Subsurface heterogeneities lead to complex salinization patterns (Mahmoodzadeh & Karamouz, 2019). Modeling studies have shown that local aquifer heterogeneity complicates flow paths for infiltrating seawater. Solute transport and fingering increase dispersion and thus the aquifer volume impacted by vertical SWI (Post & Houben, 2017; Yang et al., 2015, 2018). Holding et al. (2016) demonstrated that horizontally aligned high-permeability zones limit the spatial extent of saline plume migration, whereas vertically aligned high-permeability zones promote vertical migration of saline water. Groundwater flow occurs preferentially in high-permeability layers, whereas low-permeability layers act as barriers to flow and thus lead to the compartmentalization of fresh and saline water (Holding et al., 2016). Also, in heterogeneous aquifers, low-permeability zones can retain saline water, while high-permeability zones are flushed more rapidly through preferential flow paths (Bailey, 2015; Cardenas et al., 2015; Holding & Allen, 2015b; Yang et al., 2018). Further, in heterogenous aquifers, the effects of dynamic ocean forcing (e.g., tides) on the distribution of salinity in the aquifer are reduced (Pool et al., 2015).

Other aquifer properties specified in numerical models, such as anisotropy and dispersivity, are known to impact vertical SWI but their effects have not been widely examined. Chui and Terry (2012) modeled the effect of aquifer anisotropy and found that isotropy does not promote faster mixing immediately after a flooding event but increases mixing in late-stage recovery. Numerical model results are highly sensitive to aquifer dispersivity

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parameters as high dispersivity promotes mixing and increases the contaminated aquifer volume (Bailey & Jenson, 2014; Chui & Terry, 2012). Post and Houben (2017) found that high dispersivity and diffusion parameters cause modeled saline plumes to migrate deeper, thus increasing the recovery time. In general, aquifer heterogeneity, anisotropy, and dispersivity are challenging to measure in the field and parameterize in a model, but misrepresenting these parameters can cause inaccurate estimates of vertical SWI and recovery. Moisture retention and the cation exchange capacity of different soils and sediments may also affect leaching of salt post-event (e.g., Seibert et al., 2018), although, to our knowledge, no studies have investigated these processes across field sites and soil/sediment types. For this reason, it is important that studies conduct sensitivity analyses to assess how individual aquifer parameters can influence vertical SWI and recovery (Chui & Terry, 2012).

4.3. Flushing Processes

Understanding aquifer flushing processes is critical to predict aquifer recovery and restore potable water supplies. Field investigations of aquifer recovery (flushing) following vertical SWI (Figures 1c and 1d) rarely capture the complete (years to decades) return to pre-event conditions due to the challenge of maintaining long-term monitoring programs (Table 1). Nevertheless, critical insights into the processes that drive and enhance aquifer flushing have been gained through both field and modeling studies. Initially, the spread of infiltrated saline water is driven by density differences, but recharged fresh precipitation and background land-sea hydraulic gradients drive aquifer flushing and dominate recovery (Holding & Allen, 2015b; Post & Houben, 2017). Also, fresh recharge following a coastal flood floats above infiltrated seawater, and this layering limits flushing and can be maintained through time by density differences (Post & Houben, 2017).

Coastal storms are often associated with high precipitation rates that dilute saline floodwater, displace infiltrated seawater, decrease aquifer salinity, and increase aquifer recovery rates (Terry & Falkland, 2010; Vithanage, Engesgaard, Jensen, et al., 2012). Conversely, dry periods and associated evaporation following a coastal flood event can increase the salinity of standing floodwater, which can ultimately increase the total depth of salinization because of the increased density difference between the fresh and saline water (Lu, 2021). For example, Gingerich et al. (2017) monitored and modeled aquifer recovery in the Republic of the Marshall Islands and found that partial recovery occurred in the wet season, while pronounced dry seasons and notably low annual precipitation rates considerably prolonged aquifer recovery for up to 22 months. It is likely that snowmelt dynamics (initial storage and melt timing/rate) also play a role in aquifer flushing after vertical SWI in cold regions; however, studies are generally lacking in cold regions (Figure 2). In general, precipitation events following coastal floods are critical for more rapid aquifer recovery, while prolonged dry periods can aggravate aquifer salinization (Anderson & Lauer, 2008; Villholth et al., 2010; Vithanage, Engesgaard, Jensen, et al., 2012).

The seasonal timing of vertical SWI also impacts aquifer recovery. Studies have shown that in the wet season, high antecedent moisture content and aquifer recharge rates reduce vertical SWI and accelerate aquifer recovery, whereas, in the dry season, higher infiltration and low flushing rates increase vertical SWI (Bailey & Jenson, 2014). As a result, the timing of an event within seasonal cycles impacts the rate of early-stage aquifer recovery (Alsumaiei & Bailey, 2018; Bailey, 2015; Bailey & Jenson, 2014; Xiao et al., 2019). Gingerich et al. (2017) observed that the modeled return to potable water levels occurred 5 months faster if an event occurred in the wet season as opposed to the dry season. The impacts of seasonal factors on aquifer recovery emphasize the importance of using event-representative recharge for model boundary conditions instead of average recharge conditions to ensure satisfactory representation of antecedent conditions and recovery behavior (Gingerich et al., 2017). These model findings examining the effects of seasonal changes in recharge also have implications for the impact of natural climate oscillations, such as El Niño and La Niña (Briggs et al., 2021), on aquifer recovery.

Aquifer recovery can be complicated by land surface topography and anthropogenic actions as illustrated in Figure 1e. Generally, aquifer flushing occurs faster with increasing distance from the coast; however, flushing of the aquifer further inland can be delayed by topographic and associated groundwater flow divides that prevent groundwater discharging to the coast (Cardenas et al., 2015; Vithanage, Engesgaard, Jensen, et al., 2012). Topographic lows in the coastal landscape can pool seawater, which can provide a focused and persistent source of salinized groundwater recharge that prolongs aquifer recovery (Terry & Falkland, 2010).

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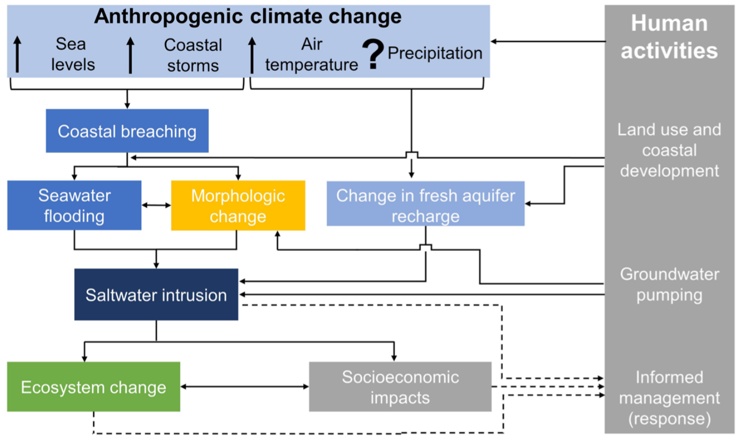

Figure 6. Propagation of impacts from climate change and coastal human activities leading to vertical saltwater intrusion (SWI) and coastal zone change. The resulting impacts to coastal ecosystems and socioeconomic indicators motivate responses through informed management (dashed arrows). Other feedbacks are possible, such as linkages between ecosystem change and socioeconomic impacts and coastal barrier overtopping. Light blue boxes indicate atmospheric and near-surface hydro(meteoro)logy considerations, dark blue indicates marine processes, green indicates ecosystem impacts, yellow indicates coastal morphodynamics, and gray indicates the social considerations for this topic.

4.4. Complications to Vertical SWI Processes From Anthropogenic Influence

4.4.1. Anthropogenic Interference and Remediation

Human activities have drastically altered the global coastline (He & Silliman, 2019; Williams et al., 2021), and investigations assessing how these alterations interact to lessen or exacerbate vertical SWI are critical as coastal populations continue to grow (Figure 6). Salinization of wells is often observed in the hours immediately following a seawater flooding event, although it typically takes much longer for seawater to percolate through the vadose zone (Bailey & Jenson, 2014; Cardenas et al., 2015). Often, the rapid salinization of wells occurs through local direct, focused flow paths via open or damaged boreholes, ditches, and wells (Figure 1e) (Bailey & Jenson, 2014; Holding & Allen, 2015b; Illangasekare et al., 2006). Poorly sealed wells can facilitate the rapid influx of seawater into deeper confined aquifers (Cardenas et al., 2015) that would not have been contaminated for months, if at all, had the wells not been present (Figure 1e).

Following vertical SWI, water resources managers are faced with the challenge of meeting potable water demands. To remediate wells contaminated by salt and potentially bacteria, extensive aquifer pumping, and chlorination are often performed (Carlson et al., 2008; Kaihotsu et al., 2017; Van Biersel et al., 2007). Disaster response efforts to reduce aquifer recovery times and restore potable water supply by pumping salinized groundwater and chlorinating wells can complicate flushing dynamics (Carlson et al., 2008; Illangasekare et al., 2006; Van Biersel et al., 2007). For instance, active pumping wells can draw saline water radially inward and influence the pattern of saltwater fingering (Figure 1e). These remediation techniques have had variable success as excessive pumping can also result in up-coning from a saline plume at depth or the lower salt wedge, and disposed pumped saline water on the land surface can reinfiltrate and lead to re-salinization of the aquifer (Illangasekare et al., 2006; Vithanage, Engesgaard, Jensen, et al., 2012). Further, studies have revealed that pumping to meet consumptive demands can prolong aquifer salinization relative to undisturbed recovery scenarios, emphasizing the importance of minimizing aquifer disturbance following salinization (Alsumaiei & Bailey, 2018; Gingerich et al., 2017; Vithanage et al., 2009). Studies have also shown that it is not uncommon for stratification or increases in salinity to continue to occur long after flooding events and remediation efforts. For example, Illangasekare et al. (2006) suggested that persistent SWI often occurs because of the multiple timescales and volumes of seawater that (a) enter wells directly, (b) enter through the vadose zone, and (c) are pumped during remediation, and how these seawater volumes compare to (d) the volume and rate of fresh recharge.

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Alternative interventions, including pumping pooled seawater and applying artificial freshwater recharge, have been attempted and have successfully reduced aquifer recovery periods (Gingerich et al., 2017; Post & Houben, 2017; Vithanage et al., 2009). Pumping seawater pooled in topographic depressions after a flood event or implementing artificial freshwater recharge may be effective approaches to decrease the volume of infiltrated seawater, and thus reduce the time to achieve potable water standards or full aquifer recovery (Chui & Terry, 2012; Gingerich et al., 2017). Numerical models have also been applied to assess the effectiveness of preventative measures to minimize the impacts of coastal flood events, including surface and subsurface barriers and subsurface drainage networks (Elsayed & Oumeraci, 2018a; Yang et al., 2018). Although surface barriers are effective at reducing vertical SWI, they may also reduce natural remediation (e.g., by reducing fresh recharge) and increase risks to surface water bodies and erosion as they can increase overland flow (Le & Kumar, 2017). Subsurface drainage networks may be able to reduce the total volume of vertical SWI by collecting infiltrating seawater and discharging it to the coast (Elsayed & Oumeraci, 2018a). Although not completely effective at preventing vertical SWI, this technique may be able to confine SWI to shallow depths, but it may also result in long-term lateral SWI because it lowers the local water table. In addition to "hard infrastructure" simulations have shown that green infrastructure alternatives, such as salt marshes, have the potential to reduce flood frequency and extent, and minimize vertical SWI impacts (e.g., Guimond & Michael, 2021).

4.4.2. Anthropogenic Climate Change Impacts on Vertical SWI

Numerical models serve as valuable tools for investigating the "what if" effects of future climate change scenarios on vertical SWI. Figure 6 represents the cascading impacts of anthropogenic climate change on vertical SWI as described further in this section. Data analyses suggest that the trends in storm surge elevations and sea-level rise are comparable (Calafat et al., 2022), but disentangling their impacts on lateral and vertical SWI is challenging. Numerical models considering sea-level rise, coastal storms, and vertical SWI have found that higher sea levels will result in more extensive flooding (spatial extent and depth) and greater vertical SWI (Figure 6; Xiao & Tang, 2019). Other modeling studies suggest that sea-level rise will drive a long-term thinning of the vadose zone in topography-limited coastal groundwater systems and will thereby reduce the volume of infiltrating seawater during a coastal flooding event (Chui & Terry, 2013; Holding & Allen, 2015a). On the other hand, higher sea levels relative to coastal aquifer water tables lead to lower hydraulic gradients that are expected to reduce aquifer flushing and prolong salinization following a vertical SWI event (Terry & Chui, 2012). In addition to rising sea levels, the increasing frequency and intensity of storms have the potential to dominate future coastal aquifer salinization (Paldor & Michael, 2021; Xiao & Tang, 2019), at least in low-elevation zones. For example, Xiao and Tang (2019) used HydroGeoSphere to compare the relative impact of coastal storms and sea-level rise on coastal aquifer salinization and found that episodic vertical SWI caused by storms may have a greater future impact on coastal freshwater resources than sea-level rise.

Discussions so far have been limited to the effect of a single storm event; however, as the global climate changes, the recurrence time between large storms and associated coastal flooding events is decreasing (Almar et al., 2021). As the frequency of coastal flood events increases, so does the potential for successive events to impact a coastal aquifer before full recovery is achieved (Anderson & Lauer, 2008; Paldor & Michael, 2021). Some studies have observed a second peak in salinity after the initial vertical SWI event because wet season precipitation can flush residual soil salinity into the aquifer (e.g., Violette et al., 2009), or because a second seawater flood event can occur and re-salinize the surface and subsurface (Holt et al., 2017). Additional inputs of saline water during aquifer recovery cause complex patterns in the subsurface salinity distribution, and in some cases lead to the presence of shallow and deep saline plumes (Figure 1e). In general, multiple flood events separated by short time intervals may result in persistent salinization due to repetitive vertical SWI (Figure 1e). Model results have shown that with more frequent coastal floods (lower return periods), the recovery of the aquifer may be slower relative to the return period (Paldor & Michael, 2021). In an island environment, repetitive surges can result in multiple fresh groundwater lenses that form as salinization and recovery occur for each event (Holt et al., 2017).

Climate change is also anticipated to alter global precipitation and evapotranspiration regimes. Changes to precipitation and evapotranspiration will collectively influence fresh groundwater recharge patterns in space and time, and thereby impact aquifer recovery dynamics following vertical SWI as described in Section 4.3 (Figure 6; Green et al., 2011). In summary, changes in atmospheric, hydrodynamic, and hydrogeologic conditions in the face of climate charge are projected to increase incidents and impacts of vertical SWI and have the potential to critically threaten coastal water security in the coming decades.

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5. Research Opportunities

Our review highlights that research efforts have focused on understanding the drivers, physics, and impacts of vertical SWI. However, despite recent field and modeling advancements, knowledge gaps remain. While prior studies have shown that topography, geology, climate, and anthropogenic factors strongly influence vertical SWI and flushing patterns, there are no existing frameworks available to reliably predict impacts across a range of conditions and thereby help guide suitable remediation actions. We separate knowledge gaps and research opportunities into monitoring, modeling, and management opportunities that could help improve fundamental understanding of vertical SWI and thereby inform management alternatives and increase future coastal freshwater resilience (Figure 6). This discussion is based on technological advancements in monitoring and modeling as such advancements will help address scientific questions and yield new process-based insight into vertical SWI. By monitoring the impact of *past* flooding events, we can understand drivers, processes, and risks in the present day. Through modeling we can help interpret field data and gain better insight into these past events, and project *future* vertical SWI risks and evaluate adaptation and mitigation approaches.

5.1. Monitoring Opportunities

There are significant opportunities for future research to address existing knowledge gaps with more extensive and long-term monitoring. Past hydrodynamic, morphodynamic, and hydrogeologic datasets of combined ocean, land surface, and aquifer conditions preceding, during, and following large coastal flooding events are limited in their spatial and temporal resolution and scale, as detailed in Section 3.2. There is a general need for investment in baseline mapping of coastal fresh groundwater resources and infrastructure to provide a foundation for global SWI monitoring and a datum from which to assess future change. Extensive global monitoring networks and geophysical mapping will help address research questions focused on the global distribution of vertical SWI risks across settings and hydrodynamic drivers, relative impacts of vertical and lateral SWI, transport paths and residence times of saline water from infiltration to flushing, and the global SWI trends in a changing climate. To achieve a global understanding, this review (see past studies in Figure 2) has identified that more studies are particularly needed in continental coastal environments, coastlines with complex geologies and topographies (rather than relatively homogeneous beaches), urban areas with infrastructure and altered land cover, and colder climates where sea ice and ground ice play a key role in ocean forcing and/or coastal groundwater dynamics (e.g., Charkin et al., 2017; Guimond et al., 2021, 2022). Thus, there is a host of future opportunities to develop and advance monitoring approaches.

Future research should also explore diverse field techniques, with a focus on low-cost applications for long-term monitoring. Investigations that consider water level, salinity, geophysical, and environmental tracers in tandem to quantitatively assess vertical SWI patterns in space and time are rare (Table 1). Traditionally, coastal monitoring networks are designed to capture lateral SWI, but these should be adapted to capture vertical SWI by pairing shallow wells that capture infiltration processes with deeper wells that can monitor the freshwater-saltwater interface movement, saline plumes, and flushing processes. Further, monitoring networks must include more robust installations for dynamic coastal environments to prevent the damage and loss of instruments and data during intensive storms. Conducting time-lapse geophysical surveys (e.g., EM-based) in the vicinity of these wells before and after storms can help connect the discrete data from the wells into a spatially continuous understanding of aquifer salinization/recovery.

Improvements in sampling techniques and analytical methods for environmental tracers have increased the resolution and accuracy of these methods to better identify water origin and residence time. These data will be critical as we attempt to understand the biogeochemical impacts and feedbacks of vertical SWI. Advancements enable the upscaling of these methods to spatial scales relevant for management (Garcia-Orellana et al., 2021). There are also opportunities to develop and employ other environmental tracers, such as heat, to monitor the fluxes between ponded surface water and groundwater, to estimate fresh or saline groundwater exfiltration rates along a coastline, or to assess the effects of morphologic change (Gilfedder et al., 2021; LeRoux et al., 2021; Wilson et al., 2016). There is a particular need for detailed maps of nearshore bathymetry and coastal topography to inform groundwater model development, monitor coastal change, and predict flooding incidents (Almar et al., 2021). In an age of remote sensing and big data, there is the opportunity to map antecedent (pre-flood) topography and bathymetry as benchmarks to relate surface and subsurface disturbances and thereby better quantify and explain vertical SWI impacts and recovery. Advances in satellite systems and UAVs are drastically increasing monitoring coverage

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and resolution, and the cost of these data is declining, with some satellite imagery freely accessible. Further, advancements in land-based and airborne geophysical tools (Figure 3) now enable 3D subsurface mapping at local and regional scales, but time-lapse surveys are required to assess temporal changes in salinity distributions in response to coastal floods.

Coastal storm events, their drivers, and their impacts lie at the nexus of multiple scientific disciplines, including climate science, ecology, oceanography, coastal geomorphology, hydrology, and hydrogeology (Figure 6). These distinct disciplines often operate within disciplinary bounds, and as such, few field-based hydrogeologic investigations have explicitly monitored coastal hydrodynamic drivers or morphodynamic change. For example, hydrogeologists have traditionally focused on the impacts of vertical SWI on fresh groundwater resources and have often overlooked the pronounced ecosystem impacts of soil and porewater salinization. Coastal oceanographers often focus on the marine impacts of seaward flow rather than the terrestrial effects of landward inputs of seawater. This disciplinary compartmentalization presents a challenge because the dynamics of interest to the different disciplines often operate on vastly different temporal and spatial scales. For example, surface hydrodynamic monitoring typically focuses on the well-constrained period of a flood, while aquifer salinization is persistent and requires monitoring over longer periods, and even then, the impacts of successive storms are difficult to disentangle. These challenges highlight the need for multidisciplinary and long-term coastal groundwater studies that integrate nearshore processes with terrestrial dynamics (Figure 6). Such studies will be the most effective way to answer interrelated scientific and management questions related to the geochemical, hydrodynamic, morphologic, and ecologic controls and feedbacks in the context of vertical SWI.

Increasingly, multidisciplinary teams are assembling and working in collaboration to rapidly collect data before, during and immediately following storm events (e.g., Nearshore Extreme Events Reconnaissance, https://neerassociation.org), but such initiatives are in their early stages, and will benefit from further expansion across disciplinary and geographic boundaries. Submarine groundwater discharge is a parallel research topic to SWI, and as demonstrated in several recent review papers (e.g., Moore, 2010; Robinson et al., 2018; Santos et al., 2021), this field has attempted to integrate researchers from across disciplines over the last decade. The recent, rapid growth in the understanding of submarine groundwater discharge demonstrates the value of converging research expertise in the topic of aquifer-ocean interactions. Investment in extensive, long-term coastal monitoring is costly and requires public and political support. Thus, improved knowledge translation and education on coastal groundwater resources and vulnerabilities is needed to inform coastal managers and the public on the impacts and urgent need to better understand, monitor, and manage vertical SWI.

5.2. Modeling Opportunities

Modeling studies of vertical SWI generally suffer from data paucity, as they often consider archetypal or generalized coastal aquifers and rely on limited topographic and geologic characterization. Few studies have adequate data to accurately constrain, calibrate, and evaluate model performance. Model simplifications are suitable for conceptualizing general processes, identifying controlling parameters, and predicting possible impacts of long-term changes such as climate change. However, they are often not suitable for addressing specific questions related to, for example, accurate flushing timescales at a particular site or the potability of groundwater following vertical SWI. Ongoing work is required to answer for what settings and drivers model simplification are and are not appropriate for when attempting to reliably reproduce vertical SWI processes. There is an opportunity to advance modeling practice by pairing intensive field studies with numerical modeling investigations to expand our understanding and to use these models for site-based management purposes. Investigations that take an interdependent approach at integrating findings from numerical models and field monitoring are the most effective at reconciling system uncertainties, which is critical for understanding processes, performing predictive analysis, and advancing coastal aquifer management objectives.

Despite the significant advancements that have been made in process-based understanding and modeling of vertical SWI (Jiao & Post, 2019), little quantitative guidance exists for specifying domain discretization, tidal and wave overheight boundary conditions, nearshore hydrodynamics, flood distribution, surface flows, and morphologic change. There is an opportunity to enhance modeling codes and applied groundwater modeling guidelines to better represent these processes. First, by creating numerical modeling tools that accommodate moving boundaries and flexible meshes, coastal groundwater models will be better able to represent the interactions of surface processes (i.e., erosion, flood inundation, and infiltration) and adequately simulate small-scale vertical SWI

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phenomena (e.g., density-driven fingering) while maintaining tractable mesh density at depth where processes are slower. Tide and wave overheights are often omitted or treated as constants based on analytical solutions such as that of Nielsen (1990), and thus there is a need to improve the representation of these processes and their variability across a range of conditions in numerical models.

In a flooding scenario, nearshore hydrodynamics, surface flows, infiltration, and groundwater flow are naturally successive fluxes that are continuous through time and should be considered as fully coupled processes (Elsayed & Oumeraci, 2018b; Yang et al., 2013, 2015). However, no models to date accommodate all these fluxes, and therefore there is a significant opportunity for future models that couple these processes without requiring the models to be run in series (e.g., coastal hydrodynamic model run with output applied as boundary conditions to a groundwater model). Pairing models or developing models with the capacity to simulate coupled coastal hydro- and morphodynamics with variable-density groundwater flow and solute transport would have a profound impact on this research field as such a coupled approach would have the capacity to simulate how multiple system features change with time. However, such a code would be computationally demanding and would require considerable data for model parameterization and assessment.

Many modeling investigations to date focus on the sensitivity of aquifers to a single environmental variable or driver; however, conditions are often linked and interact with complicated feedbacks (Figure 6). There is a need to further evaluate the sensitivity, relative importance, and interaction of controlling factors. Studies should evaluate what the combined impacts of waves, tides, sea-level rise, topography, pumping, and climate change are to vertical SWI. For example, increased coastal flooding is anticipated globally under the influence of climate change, but few local or regional studies have assessed the sensitivity of coastal groundwater systems to a range of climate scenarios and hydroclimatic variables (sea-level rise, increased surges, changes to recharge), which is a common approach when assessing the impacts of climate change on inland hydrologic systems. Such predictions could be used to identify vulnerable coastal regions and thus inform the installation of coastal groundwater monitoring infrastructure today. Furthermore, a uniform framework for assessing coastal aquifer sensitivity to climate change has not been proposed, making it difficult to quantitatively compare studies across sites or scenarios.

Studies on vertical SWI should also consider coupling hydrogeological, geochemical, ecological, and sociological impacts (Figure 6). Studies in this review focus on aquifer salinization by vertical SWI; however, changing salinity levels in coastal aquifers have far-reaching impacts on geochemical processes, ecosystem functioning, and society. Few studies have considered the potential for coastal flooding to contaminate aquifers beyond salinization impacts (e.g., mobilization and/or transport of bacteria, pathogens, nutrients, heavy metals) (Rakhimbekova et al., 2018; Sun et al., 2015). The impact of coastal floods and subsequent SWI is anticipated to have prolonged impacts and cause large shifts in coastal ecosystems, but only a few groundwater models consider this (e.g., Guimond & Michael, 2021). Addressing these research opportunities is critical for future coastal water resource management and will help bring coastal groundwater resources to the forefront when considering the influence of climate change on coastal communities.

5.3. Coastal Aquifer Management

Technological advancements in coastal aquifer monitoring and numerical modeling have increased our understanding of vertical SWI, but progress in management initiatives lags in part due to ineffective knowledge translation between scientific disciplines, the public, and policy makers (Figure 6). Improved collaboration between researchers and practitioners from multiple disciplines and sectors as well as stakeholders is needed to combine different expertise and perspectives and work cooperatively to better understand and manage the complex, interrelated dynamics of coastal flooding and vertical SWI (Figure 6). Future work should focus on assessing how vertical SWI impacts coastal communities and integrating findings in broad coastal vulnerability frameworks to inform tractable management plans (Dolan & Walker, 2006). Related to this, there is a present opportunity to include vertical SWI threats in existing risk assessment frameworks to investigate current and future coastal vulnerability, similar to the work by Werner et al. (2013), Ferguson and Gleeson (2012), Michael et al. (2013), and Klassen and Allen (2017) on global coastal vulnerability to lateral SWI. Management decisions for vertical SWI require rapid assessment and site-specific approaches; therefore, it is important that data-informed decision frameworks are in place and can be effectively applied to impacted coastlines worldwide.

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Often large floods cannot be prevented, but their effects can be mitigated and remediated (Elsayed & Oumeraci, 2018a). Efforts to monitor and mitigate damage to infrastructure during coastal flooding is widespread and supported globally, while subsurface impacts of coastal flooding is more expensive and challenging to monitor, mitigate, and remediate. There is a need for indicator-based methodologies for decision makers that are data informed and can result in practical and feasible mitigation and remediation techniques. Mitigation and adaptation techniques for vertical SWI are particularly challenging as they require hydrogeologic understanding and consideration of site-specific socioeconomic and environmental factors. Future work must assess these options and consider questions related to performance-based indicators (e.g., what is the potential to preserve potable water?), economic feasibility (e.g., what are the costs for coastal communities?), social impacts (e.g., what populations or services will this impact?), and environmental impacts (e.g., are there any cascading hydrologic or ecologic impacts?).

Subsurface impacts are generally out of sight, out of mind to the public and managers, so disaster response efforts following a coastal flood typically focus on surface impacts (Holding et al., 2016). Any efforts related to vertical SWI tend to be reactive rather than proactive. Due to the nature of flooding events and vertical SWI, emergency planning is inefficient, and engineering and natured-based mitigation and adaptation efforts are required. Section 4.4.1 identifies the studies to date that have assessed remediation options for vertical SWI, and findings indicate that pumping pooled water and artificial recharge are promising options for remediation. However, more research is required to identify over what spatial and temporal scales these methods are effective and the long-term impacts to hydrologic conditions. Additional work should assess scientific questions related to the plausibility of other remediation techniques including shallow pumping, combined freshwater injection and offshore pumping to increase seaward gradients and flushing, and excavation to remove encroaching salt. Techniques to mitigate groundwater salinization due to future flood events have received less attention, but include coastal hardening or retreat, increasing coastal barrier heights, well relocation, regulations limiting groundwater extraction, re-enforcing and sealing wells, surface and subsurface barriers, subsurface drainage systems, and developing alternative freshwater supplies (e.g., surface water, desalinization). There are significant opportunities for more forward looking and less reactive approaches for coastal adaptation efforts in the context of vertical SWI, particularly those that recognize the continuum between engineering and nature-based solutions and the opportunity to tailor solutions to environmental settings (e.g., wave climate, surface topography, geology).

6. Summary

Coastal seawater flooding devastates 1000's of kilometers of shoreline annually, and coastal fresh groundwater resources are extremely vulnerable to contamination from these flood events. While prior studies of episodic flood-driven vertical SWI events have yielded valuable understanding of the drivers and impacts, aquifer salinization from extensive seawater flooding events is largely overlooked in the public sphere and even in the broader coastal zone sciences. Vertical SWI is characterized by drivers (episodic surges, waves) and processes (seawater fingering and post-event flushing) that are distinct from lateral SWI. Thus, the breadth and complexity of processes controlling vertical SWI cannot be effectively captured with monitoring and modeling tools/practices designed for lateral SWI. Also, field monitoring programs along the world's coastlines provide important data on the driving mechanisms (erosion, flooding) of vertical SWI, yet these monitoring programs generally do not capture the resultant aquifer salinization. Coastal flooding, vertical SWI, and recovery occur over large areas along the nexus of the ocean, land, and atmosphere and span timescales ranging from minutes to decades. The unpredictability of coastal flooding events has further limited our ability to detect and monitor vertical SWI incidents that consequently remain largely "out of sight and out of mind." There is an urgent need for more long-term and large-scale coastal groundwater monitoring and mapping programs that are paired with numerical modeling tools to understand vertical SWI processes and inform appropriate management action.

Water quality and quantity problems from vertical SWI persist and are accelerating in the face of climate change. There are important gaps in scientific understanding stemming in part from a failure to integrate monitoring and modeling of marine-terrestrial interconnections across scientific disciplines. Salinization of fresh groundwater resources used for drinking water for coastal communities is an underappreciated aspect of coastal change, and coastal hydrogeology should be a core consideration in high-level coastal zone risk assessments. Vertical SWI risks will be further exacerbated in the future as (a) coastal floods will impact more of the global coastline more frequently, (b) shifts in air temperatures and hydrologic processes will impact aquifer recharge and flushing, and

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(c) cascading secondary effects from increased fresh groundwater consumption in a drying climate or in increasingly expanding coastal megacities will compound vertical SWI effects. To sustainably manage coastal aquifers as critical water supply reservoirs, improved process-based understanding is needed to underpin research and management programs and to inform the development and widescale application of emerging monitoring and modeling tools and technology. While advancements within the field have improved society's understanding of coastal fresh groundwater resources, gaps in our scientific understanding remain that provide exciting multidisciplinary research opportunities to help advance and link science, practice, and policy around the theme of coastal freshwater security in a rapidly changing world.

Data Availability Statement

New data were not used nor created for this research.

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References

Adger, W. N., Hughes, T. P., Folke, C., Carpenter, S. R., & Rockström, J. (2018). Social-ecological resilience to coastal disasters. In E. M. Hamin Infield, Y. Abunnasr, & R. L. Ryan (Eds.), *Planning for Climate Change: A Reader in Green Infrastructure and Sustainable Design for Resilient Cities* (pp. 151–159). Taylor & Francis. https://doi.org/10.4324/9781351201117

Almar, R., Ranasinghe, R., Bergsma, E. W. J., Diaz, H., Melet, A., Papa, F., et al. (2021). A global analysis of extreme coastal water levels with implications for potential coastal overtopping. *Nature Communications*, *12*(1), 3775. https://doi.org/10.1038/s41467-021-24008-9

Alsumaiei, A. A., & Bailey, R. T. (2018). Quantifying threats to groundwater resources in the Republic of Maldives Part II: Recovery from tsunami marine overwash events. *Hydrological Processes*, *32*(9), 1154–1165. https://doi.org/10.1002/hyp.11473

Anderson, W. P. (2002). Aquifer salinization from storm overwash. *Journal of Coastal Research*, *18*(3), 413–420. http://www.jstor.org/stable/4299090

Anderson, W. P., & Lauer, R. M. (2008). The role of overwash in the evolution of mixing zone morphology within barrier islands. *Hydrogeology Journal*, *16*(8), 1483–1495. https://doi.org/10.1007/s10040-008-0340-z

Ataie-Ashtiani, B., Volker, R. E., & Lockington, D. A. (1999). Tidal effects on sea water intrusion in unconfined aquifers. *Journal of Hydrology*, *216*(1–2), 17–31. https://doi.org/10.1016/S0022-1694(98)00275-3

Ataie-Ashtiani, B., Werner, A. D., Simmons, C. T., Morgan, L. K., & Lu, C. (2013). How important is the impact of land-surface inundation on seawater intrusion caused by sea-level rise? *Hydrogeology Journal*, *21*(7), 1673–1677. https://doi.org/10.1007/s10040-013-1021-0

Athanasiou, P., Van Dongeren, A., Giardino, A., Vousdoukas, M., Gaytan-Aguilar, S., & Ranasinghe, R. (2019). Global distribution of nearshore slopes with implications for coastal retreat. *Earth System Science Data*, *11*(4), 1515–1529. https://doi.org/10.5194/essd-11-1515-2019

Bailey, R. T. (2015). Quantifying transient post-overwash aquifer recovery for atoll islands in the Western Pacific. *Hydrological Processes*, *29*(20), 4470–4482. https://doi.org/10.1002/hyp.10512

Bailey, R. T., & Jenson, J. W. (2014). Effects of marine overwash for atoll aquifers: Environmental and human factors. *Groundwater*, *52*(5), 694–704. https://doi.org/10.1111/gwat.12117

Barbier, E. B. (2015). Climate change impacts on rural poverty in low-elevation coastal zones. *Estuarine, Coastal and Shelf Science*, *165*, A1–A13. https://doi.org/10.1016/j.ecss.2015.05.035

Barbier, E. B., Hacker, S. D., Kennedy, C., Koch, E. W., Stier, A. C., & Silliman, B. R. (2011). The value of estuarine and coastal ecosystem services. *Ecological Monographs*, *81*(2), 169–193. https://doi.org/10.1890/10-1510.1

Bevacqua, E., Vousdoukas, M. I., Zappa, G., Hodges, K., Shepherd, T. G., Maraun, D., et al. (2020). More meteorological events that drive compound coastal flooding are projected under climate change. *Communications Earth & Environment*, *1*(1), 47. https://doi.org/10.1038/s43247-020-00044-z

Bhatia, K. T., Vecchi, G. A., Knutson, T. R., Murakami, H., Kossin, J., Dixon, K. W., & Whitlock, C. E. (2019). Recent increases in tropical cyclone intensification rates. *Nature Communications*, *10*(1), 635. https://doi.org/10.1038/s41467-019-08471-z

Bilskie, M. V., Hagen, S. C., Medeiros, S. C., & Passeri, D. L. (2014). Dynamics of sea level rise and coastal flooding on a changing landscape. *Geophysical Research Letters*, *41*(3), 927–934. https://doi.org/10.1002/2013GL058759

Biron, P. M., Roy, A. G., Courschesne, F., Hendershot, W. H., Côté, B., & Fyles, J. (1999). The effects of antecedent moisture conditions on the relationship of hydrology to hydrochemistry in a small forested watershed. *Hydrological Processes*, *13*(11), 1541–1555. https://doi.org/10.1002/(sici)1099-1085(19990815)13:11<1541::aid-hyp832>3.0.co;2-j

Briggs, M. A., Cantelon, J. A., Kurylyk, B. L., Kulongoski, J. T., Mills, A., & Lane, J. W. (2021). Small atoll fresh groundwater lenses respond to a combination of natural climatic cycles and human modified geology. *Science of the Total Environment*, *756*, 143838. https://doi.org/10.1016/j.scitotenv.2020.143838

Brinson, M. M., Christian, R. R., & Blum, L. K. (1995). Multiple states in the sea-level induced transition from terrestrial forest to estuary. *Estuaries*, *18*(4), 648–659. https://doi.org/10.2307/1352383

Calafat, F. M., Wahl, T., Tadesse, M. G., & Sparrow, S. N. (2022). Trends in Europe storm surge extremes match the rate of sea-level rise. *Nature*, *603*(7903), 841–845. https://doi.org/10.1038/s41586-022-04426-5

Cardenas, M. B., Bennett, P. C., Zamora, P. B., Befus, K. M., Rodolfo, R. S., Cabria, H. B., & Lapus, M. R. (2015). Devastation of aquifers from tsunami-like storm surge by Supertyphoon Haiyan. *Geophysical Research Letters*, *42*(8), 2844–2851. https://doi.org/10.1002/2015GL063418

Carlson, D. A., Van Biersel, T. P., & Milner, L. R. (2008). Storm-damaged saline-contaminated boreholes as a means of aquifer contamination. *Ground Water*, *46*(1), 69–79. https://doi.org/10.1111/j.1745-6584.2007.00380.x

Charkin, A. N., Rutgers van der Loeff, M., Shakhova, N. E., Gustafsson, Ö., Dudarev, O. V., Cherepnev, M. S., et al. (2017). Discovery and characterization of submarine groundwater discharge in the Siberian Arctic seas: A case study in the Buor-Khaya Gulf, Laptev sea. *The Cryosphere*, *11*(5), 2305–2327. https://doi.org/10.5194/tc-11-2305-2017

Chui, T. F. M., & Terry, J. P. (2012). Modeling freshwater lens damage and recovery on atolls after storm-wave washover. *Groundwater*, *50*(3), 412–420. https://doi.org/10.1111/j.1745-6584.2011.00860.x

Water Resources Research 10.1029/2022WR032614

Chui, T. F. M., & Terry, J. P. (2013). Influence of sea-level rise on freshwater lenses of different atoll island sizes and lens resilience to storm-induced salinization. *Journal of Hydrology*, *502*, 18–26. https://doi.org/10.1016/j.jhydrol.2013.08.013

Chui, T. F. M., & Terry, J. P. (2015). Groundwater salinisation on atoll islands after storm-surge flooding: Modelling the influence of central topographic depressions. *Water and Environment Journal*, *29*(3), 430–438. https://doi.org/10.1111/wej.12116

Cunillera-Montcusí, D., Beklioğlu, M., Cañedo-Argüelles, M., Jeppesen, E., Ptacnik, R., Amorim, C. A., et al. (2022). Freshwater salinization: A research agenda for a saltier world. *Trends in Ecology & Evolution*, *37*(5), 440–453. https://doi.org/10.1016/j.tree.2021.12.005

Diersch, H. J. G. (2013). *FEFLOW: Finite element modeling of flow, mass and heat transport in porous and fractured media*. Springer Science & Business Media.

Dolan, A. H., & Walker, I. J. (2006). Understanding vulnerability of coastal communities to climate change related risks. *Journal of Coastal Research*, *3*(39), 1316–1323. https://www.jstor.org/stable/25742967

Elsayed, S. M., & Oumeraci, H. (2018a). *Modelling and management of storm-driven saltwater intrusion in freshwater aquifers: The case of near Bremerhaven, Germany*. Paper presented at Integrating ecosystems in coastal engineering practice (INECEP), Puerto Morelos, Mexico (pp. 150–168). Retrieved from https://cuvillier.de/de/shop/publications/7662

Elsayed, S. M., & Oumeraci, H. (2018b). Modelling and mitigation of storm-induced saltwater intrusion: Improvement of the resilience of coastal aquifers against marine floods by subsurface drainage. *Environmental Modelling & Software*, *100*, 252–277. https://doi.org/10.1016/j.envsoft.2017.11.030

Emanuel, K. A. (2013). Downscaling CMIP5 climate models shows increased tropical cyclone activity over the 21st century. *Proceedings of the National Academy of Sciences of the United States of America*, *110*(30), 12219–12224. https://doi.org/10.1073/pnas.1301293110

Fagherazzi, S., Nordio, G., Munz, K., Catucci, D., & Kearney, W. S. (2019). Variations in persistence and regenerative zones in coastal forests triggered by sea level rise and storms. *Remote Sensing*, *11*(17), 2019. https://doi.org/10.3390/rs11172019

Ferguson, G., & Gleeson, T. (2012). Vulnerability of coastal aquifers to groundwater use and climate change. *Nature Climate Change*, *2*(5), 342–345. https://doi.org/10.1038/nclimate1413

Fernandes, A., Rollinson, C. R., Kearney, W. S., Dietze, M. C., & Fagherazzi, S. (2018). Declining radial growth response of coastal forests to hurricanes and nor'easters. *Journal of Geophysical Research: Biogeosciences*, *123*(3), 832–849. https://doi.org/10.1002/2017JG004125

Fitterman, D. V., & Deszcz-Pan, M. (1998). Helicopter EM mapping of saltwater intrusion in Everglades National Park, Florida. *Exploration Geophysics*, *29*(1–2), 240–243. https://doi.org/10.1071/EG998240

Frederikse, T., Landerer, F., Caron, L., Adhikari, S., Parkes, D., Humphrey, V. W., et al. (2020). The causes of sea-level rise since 1900. *Nature*, *584*(7821), 393–397. https://doi.org/10.1038/s41586-020-2591-3

Garcia-Orellana, J., Rodellas, V., Tamborski, J., Diego-Feliu, M., van Beek, P., Weinstein, Y., et al. (2021). Radium isotopes as submarine groundwater discharge (SGD) tracers: Review and recommendations. *Earth-Science Reviews*, *220*, 103681. https://doi.org/10.1016/j.earscirev.2021.103681

Giambastiani, B. M., Colombani, N., Greggio, N., Antonellini, M., & Mastrocicco, M. (2017). Coastal aquifer response to extreme storm events in Emilia-Romagna, Italy. *Hydrological Processes*, *31*(8), 1613–1621. https://doi.org/10.1002/hyp.11130

Gilfedder, B. S., Waska, H., Wismeth, F., & Frei, S. (2021). Using heat as a tracer to map and quantify water infiltration and exfiltration along a complex high energy beach face. *Estuarine, Coastal and Shelf Science*, *250*, 107140. https://doi.org/10.1016/j.ecss.2020.107140

Gingerich, S. B., Voss, C. I., & Johnson, A. G. (2017). Seawater-flooding events and impact on freshwater lenses of low-lying islands: Controlling factors, basic management and mitigation. *Journal of Hydrology*, *551*, 676–688. https://doi.org/10.1016/j.jhydrol.2017.03.001

Green, T. R., Tahiguchi, M., Kooi, H., Gurdak, J. J., Allen, D. M., Hiscock, K. M., et al. (2011). Beneath the surface of global change: Impacts of climate change on groundwater. *Journal of Hydrology*, *405*(3–4), 532–560. https://doi.org/10.1016/j.jhydrol.2011.05.002

Grünenbaum, N., Ahrens, J., Beck, M., Gilfedder, B. S., Greskowiak, J., Kossack, M., & Massmann, G. (2020). A multi-method approach for quantification of in-and exfiltration rates from the subterranean estuary of a high energy beach. *Frontiers in Earth Science*, *8*, 571310. https://doi.org/10.3389/feart.2020.571310

Guimond, J., Mohammed, A., Walvoord, M., Bense, V., & Kurylyk, B. (2022). Sea-level rise and warming mediate coastal groundwater discharge in the Arctic. *Environmental Research Letters*, *17*(4), 045027. https://doi.org/10.1088/1748-9326/ac6085

Guimond, J. A., & Michael, H. A. (2021). Effects of marsh migration on flooding, saltwater intrusion, and crop yield in coastal agricultural land subject to storm surge inundation. *Water Resources Research*, *57*(2), e2020WR028326. https://doi.org/10.1029/2020WR028326

Guimond, J. A., Mohammed, A. A., Walvoord, M. A., Bense, V. F., & Kurylyk, B. L. (2021). Saltwater intrusion intensifies coastal permafrost thaw. *Geophysical Research Letters*, *48*(19), e2021GL094776. https://doi.org/10.1029/2021GL094776

Han, D., Cao, G., Currell, M. J., Priestley, S. C., & Love, A. J. (2020). Groundwater salinization and flushing during glacial-interglacial cycles: Insights from aquitard porewater tracer profiles in the North China Plain. *Water Resources Research*, *56*(11), e2020WR027879. https://doi.org/10.1029/2020WR027879

Hauer, M. E., Fussell, E., Mueller, V., Burkett, M., Call, M., Abel, K., et al. (2020). Sea-level rise and human migration. *Nature Reviews Earth & Environment*, *1*(1), 28–39. https://doi.org/10.1038/s43017-019-0002-9

He, Q., & Silliman, B. R. (2019). Climate change, human impacts, and coastal ecosystems in the Anthropocene. *Current Biology*, *29*(19), R1021–R1035. https://doi.org/10.1016/j.cub.2019.08.042

Holding, S., & Allen, D. M. (2015a). From days to decades: Numerical modelling of freshwater lens response to climate change stressors on small low-lying islands. *Hydrology and Earth System Sciences*, *19*(2), 933–949. https://doi.org/10.5194/hess-19-933-2015

Holding, S., & Allen, D. M. (2015b). Wave overwash impact on small islands: Generalised observations of freshwater lens response and recovery for multiple hydrogeological settings. *Journal of Hydrology*, *529*, 1324–1335. https://doi.org/10.1016/j.jhydrol.2015.08.052

Holding, S., Allen, D. M., Foster, S., Hsieh, A., Larocque, I., Klassen, J., & Van Pelt, S. C. (2016). Groundwater vulnerability on small islands. *Nature Climate Change*, *6*(12), 1100–1103. https://doi.org/10.1038/nclimate3128

Holt, T., Greskowiak, J., Seibert, S. L., & Massmann, G. (2019). Modeling the evolution of a freshwater lens under highly dynamic conditions on a currently developing barrier island. *Geofluids*, 9484657. https://doi.org/10.1155/2019/9484657

Holt, T., Seibert, S. L., Greskowiak, J., Freund, H., & Massmann, G. (2017). Impact of storm tides and inundation frequency on water table salinity and vegetation on a juvenile barrier island. *Journal of Hydrology*, *554*, 666–679. https://doi.org/10.1016/j.jhydrol.2017.09.014

Horn, D. P. (2002). Beach groundwater dynamics. *Geomorphology*, *48*(1–3), 121–146. https://doi.org/10.1016/S0169-555X(02)00178-2

Houser, C., Hapke, C., & Hamilton, S. (2008). Controls on coastal dune morphology, shoreline erosion and barrier island response to extreme storms. *Geomorphology*, *100*(3–4), 223–240. https://doi.org/10.1016/j.geomorph.2007.12.007

Huizer, S., Karaoulis, M. C., Oude Essink, G. H. P., & Bierkens, M. F. P. (2017). Monitoring and simulation of salinity changes in response to tide and storm surges in a sandy coastal aquifer system. *Water Resources Research*, *53*(8), 6487–6509. https://doi.org/10.1002/2016WR020339

Illangasekare, T., Tyler, S. W., Clement, T. P., Villholth, K. G., Perera, A. P. G. R. L., Obeysekera, J., et al. (2006). Impacts of the 2004 tsunami on groundwater resources in Sri Lanka. *Water Resources Research*, *42*(5), W05201. https://doi.org/10.1029/2006WR004876

Water Resources Research 10.1029/2022WR032614

IPCC. (2021). *Climate change 2021: The physical science basis. Contribution of working group I to the sixth assessment report of the intergovernmental panel on climate change*. Cambridge University Press.

Jiao, J., & Post, V. (2019). *Coastal hydrogeology*. Cambridge University Press. https://doi.org/10.1017/9781139344142

Kaihotsu, I., Onodera, S., Shimada, J., & Nakagawa, K. (2017). Recovery of groundwater in the Sanriku region contaminated by the tsunami inundation from the 2011 Tohoku earthquake. *Environmental Earth Sciences*, *76*(6), 1–7. https://doi.org/10.1007/s12665-017-6569-x

Kearney, W. S., Fernandes, A., & Fagherazzi, S. (2019). Sea-level rise and storm surges structure coastal forests into persistence and regeneration niches. *PLoS One*, *14*(5), e0215977. https://doi.org/10.1371/journal.pone.0215977

Ketabchi, H., Mahmoodzadeh, D., Ataie-ashtiani, B., & Simmons, C. T. (2016). Sea-level rise impacts on seawater intrusion in coastal aquifers: Review and integration. *Journal of Hydrology*, *535*, 235–255. https://doi.org/10.1016/j.jhydrol.2016.01.083

Kiflai, M. E., Whitman, D., Ogurcak, D. E., & Ross, M. (2020). The effect of Hurricane Irma storm surge on the freshwater lens in Big Pine Key, Florida using electrical resistivity tomography. *Estuaries and Coasts*, *43*(5), 1032–1044. https://doi.org/10.1007/s12237-019-00666-3

Klaassen, K., Bormann, H., Klenke, T., & Liebezeit, G. (2008). The impact of hydrodynamics and texture on the infiltration of rain and marine waters into sand bank island sediments—Aspects of infiltration and groundwater dynamics. *Senckenbergiana maritima*, *38*, 163–171. https://doi.org/10.1007/BF03055293

Klassen, J., & Allen, D. M. (2017). Assessing the risk of saltwater intrusion in coastal aquifers. *Journal of Hydrology*, *551*, 730–745. https://doi.org/10.1016/j.jhydrol.2017.02.044

Kooi, H., Groen, J., & Leijnse, A. (2000). Modes of seawater intrusion during transgressions. *Water Resources Research*, *36*(12), 3581–3589. https://doi.org/10.1029/2000WR900243

Kossin, J. P. (2018). A global slowdown of tropical-cyclone translation speed. *Nature*, *558*(7708), 104–107. https://doi.org/10.1038/s41586-018-0158-3

Kurylyk, B. L., Irvine, D. J., & Bense, V. F. (2019). Theory, tools, and multidisciplinary applications for tracing groundwater fluxes from temperature profiles. *Wiley Interdisciplinary Reviews: Water*, *6*(1), e1329. https://doi.org/10.1002/wat2.1329

Langevin, C. D., Thorne, D. T., Dausman, A. M., Sukop, M. C., & Guo, W. (2008). *SEAWAT version 4: A computer program for simulation of multi-species solute and heat transport*. U.S. Geological Survey Techniques and Methods Book 6-A22.

Le, P. V. V., & Kumar, P. (2017). Interaction between ecohydrologic dynamics and microtopographic variability under climate change. *Water Resources Research*, *53*(10), 8383–8403. https://doi.org/10.1002/2017WR020377

LeRoux, N. K., Kurylyk, B. L., Briggs, M. A., Irvine, D. J., Tamborski, J. J., & Bense, V. F. (2021). Using heat to trace vertical water fluxes in sediment experiencing concurrent tidal pumping and groundwater discharge. *Water Resources Research*, *57*(2), e2020WR027904. https://doi.org/10.1029/2020WR027904

Liu, J., & Tokunaga, T. (2020). 3D modeling of tsunami-induced seawater intrusion and aquifer recovery in Niijima Island, Japan, under the future tsunami scenario. *Journal of Groundwater Hydrology*, *62*(2), 303–322. https://doi.org/10.5917/jagh.62.303

Loáiciga, H. A., Pingel, T. J., & Garcia, E. S. (2012). Sea water intrusion by sea-level rise: Scenarios for the 21st century. *Groundwater*, *50*(1), 37–47. https://doi.org/10.1111/j.1745-6584.2011.00800.x

Lu, H. (2021). Effect of evaporation on land salinization after storm surge overtopping embankment. *IOP Conference Series: Earth and Environmental Science*, *676*(1), 012032. https://doi.org/10.1088/1755-1315/676/1/012032

Mack, T., & Degnan, J. (2003). *Geophysical characterization of fractured bedrock at site 8, former pease air force base, Newington, New Hampshire*. USGS Open-File 02-279.

Mahmoodzadeh, D., & Karamouz, M. (2017). *Influence of coastal flooding on seawater intrusion in coastal aquifers*. Paper presented at World environmental and water resources congress 2017: Groundwater, sustainability, and hydro-climate/climate change, Sacramento, California (pp. 66–79). https://doi.org/10.1061/9780784480618.007

Mahmoodzadeh, D., & Karamouz, M. (2019). Seawater intrusion in heterogeneous coastal aquifers under flooding events. *Journal of Hydrology*, *568*, 1118–1130. https://doi.org/10.1016/j.jhydrol.2018.11.012

Michael, H. A., Post, V. E. A., Wilson, A. M., & Werner, A. D. (2017). Science, society, and the coastal groundwater squeeze. *Water Resources Research*, *53*(4), 2610–2617. https://doi.org/10.1002/2017WR020851

Michael, H. A., Russoniello, C. J., & Byron, L. A. (2013). Global assessment of vulnerability to sea-level rise in topography-limited and recharge-limited coastal groundwater systems. *Water Resources Research*, *49*(4), 2228–2240. https://doi.org/10.1002/wrcr.20213

Moore, W. S. (2010). The effect of submarine groundwater discharge on the ocean. *Annual Review of Marine Science*, *2*(1), 59–88. https://doi.org/10.1146/annurev-marine-120308-081019

Morton, R. A., & Sallenger, A. H. (2003). Morphological impacts of extreme storms on sandy beaches and barriers. *Journal of Coastal Research*, *19*(3), 560–573. http://www.jstor.org/stable/4299198

Neumann, B., Vafeidis, A. T., Zimmermann, J., & Nicholls, R. J. (2015). Future coastal population growth and exposure to sea-level rise and coastal flooding—A global assessment. *PLoS One*, *10*(3), e0118575. https://doi.org/10.1371/journal.pone.0118575

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. *Nature Climate Change*, *11*(4), 338–342. https://doi.org/10.1038/s41558-021-00993-z

Nielsen, P. (1990). Tidal dynamics of the water table in beaches. *Water Resources Research*, *26*(9), 2127–2134. https://doi.org/10.1029/WR026i009p02127

Oude Essink, G. (1998). MOC3D adapted to simulated 3D density-dependent groundwater flow. *Paper Presented at MODFLOW'98 Conference, Golden, CO* (pp. 291–303).

Palacios, A., Ledo, J. J., Linde, N., Luquot, L., Bellmunt, F., Folch, A., et al. (2020). Time-lapse cross-hole electrical resistivity tomography (CHERT) for monitoring seawater intrusion dynamics in a Mediterranean aquifer. *Hydrology and Earth System Sciences*, *24*(4), 2121–2139. https://doi.org/10.5194/hess-24-2121-2020

Paldor, A., & Michael, H. A. (2021). Storm surges cause simultaneous salinization and freshening of coastal aquifers, exacerbated by climate change. *Water Resources Research*, *57*(5), e2020WR029213. https://doi.org/10.1029/2020WR029213

Passeri, D. L., Hagen, S. C., Medeiros, S. C., Bilskie, M. V., Alizad, K., & Wang, D. (2015). The dynamic effects of sea level rise on low-gradient coastal landscapes: A review. *Earth's Future*, *3*(6), 159–181. https://doi.org/10.1002/2015EF000298

Pavlovskii, I., Cantelon, J., & Kurylyk, B. L. (2021). *Hydrological model of Sable Island National Park Reserve* (p. 36). Report to Parks Canada Agency, Centre for Water Resource Studies, Dalhousie University.

Pavlovskii, I., Cantelon, J., & Kurylyk, B. L. (2022). Coastal groundwater model calibration using filtered and amplified hydraulic information retained in the freshwater–saltwater interface. *Hydrogeology Journal*, *30*(5), 1551–1567. https://doi.org/10.1007/s10040-022-02510-8

Peduzzi, P., Chatenoux, B., Dao, H., De Bono, A., Herold, C., Kossin, J., et al. (2012). Global trends in tropical cyclone risk. *Nature Climate Change*, *2*(4), 289–294. https://doi.org/10.1038/nclimate1410

Water Resources Research 10.1029/2022WR032614

Pool, M., Post, V. E. A., & Simmons, C. T. (2014). Effects of tidal fluctuations on mixing and spreading in coastal aquifers: Homogeneous case. *Water Resources Research*, *50*(8), 6910–6926. https://doi.org/10.1002/2014WR015534

Pool, M., Post, V. E. A., & Simmons, C. T. (2015). Effects of tidal fluctuations and spatial heterogeneity on mixing and spreading in spatially heterogeneous coastal aquifers. *Water Resources Research*, *51*(3), 1570–1585. https://doi.org/10.1002/2014WR016068

Post, V. E. A., & Houben, G. J. (2017). Density-driven vertical transport of saltwater through the freshwater lens on the island of Baltrum (Germany) following the 1962 storm flood. *Journal of Hydrology*, *551*, 689–702. https://doi.org/10.1016/j.jhydrol.2017.02.007

Post, V. E. A., & Kooi, H. (2003). Rates of salinization by free convection in high-permeability sediments: Insights from numerical modeling and application to the Dutch coastal area. *Hydrogeology Journal*, *11*(5), 549–559. https://doi.org/10.1007/s10040-003-0271-7

Post, V. E. A., Kooi, H., & Simmons, C. (2007). Using hydraulic head measurements in variable-density ground water flow analyses. *Groundwater*, *45*(6), 664–671. https://doi.org/10.1111/j.1745-6584.2007.00339.x

Provost, A. M., & Voss, C. I. (2019). *SUTRA, a model for saturated-unsaturated, variable-density groundwater flow with solute or energy transport—Documentation of generalized boundary conditions, a modified implementation of specified pressures and concentrations or temperatures, and the lake*. U.S. Geological Survey Techniques and Methods 6-A52. https://doi.org/10.3133/tm6A52

Rakhimbekova, S., O'Carroll, D. M., Andersen, M. S., Wu, M. Z., & Robinson, C. E. (2018). Effect of transient wave forcing on the behavior of arsenic in a nearshore aquifer. *Environmental Science and Technology*, *52*(21), 12338–12348. https://doi.org/10.1021/acs.est.8b03659

Ramsey, E., Lu, Z., Suzuoki, Y., Rangoonwala, A., & Werle, D. (2011). Monitoring duration and extent of storm-surge and flooding in western coastal Louisiana marshes with Envisat ASAR Data. *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing*, *4*(2), 387–399. https://doi.org/10.1109/JSTARS.2010.2096201

Robinson, C., Li, L., & Barry, D. A. (2007). Effect of tidal forcing on a subterranean estuary. *Advances in Water Resources*, *30*(4), 851–865. https://doi.org/10.1016/j.advwatres.2006.07.006

Robinson, C. E., Xin, P., Santos, I. R., Charette, M. A., Li, L., & Barry, D. A. (2018). Groundwater dynamics in subterranean estuaries of coastal unconfined aquifers: Controls on submarine groundwater discharge and chemical inputs to the ocean. *Advances in Water Resources*, *115*, 315–331. https://doi.org/10.1016/j.advwatres.2017.10.041

Roelvink, D., Reniers, A. J. H. M., Van Dongeren, A., Van Thiel de Vries, J., Lescinski, J., & McCall, R. (2010). *XBeach model description and manual*. Unesco-IHE Institute for Water Education, Deltares and Delft University of Technology.

Rotzoll, K., & Fletcher, C. H. (2013). Assessment of groundwater inundation as a consequence of sea-level rise. *Nature Climate Change*, *3*(5), 477–481. https://doi.org/10.1038/nclimate1725

Santos, I. R., Chen, X., Lecher, A. L., Sawyer, A. H., Moosdorf, N., Rodellas, V., et al. (2021). Submarine groundwater discharge impacts on coastal nutrient biogeochemistry. *Nature Reviews Earth & Environment*, *2*(5), 307–323. https://doi.org/10.1038/s43017-021-00152-0

Sawyer, A. H., Michael, H. A., & Schroth, A. W. (2016). From soil to sea: The role of groundwater in coastal critical zone processes. *Wiley Interdisciplinary Reviews: Water*, *3*(5), 706–726. https://doi.org/10.1002/wat2.1157

Schneider, J. C., & Kruse, S. E. (2003). A comparison of controls on freshwater lens morphology of small carbonate and siliciclastic islands: Examples from barrier islands in Florida, USA. *Journal of Hydrology*, *284*(1–4), 253–269. https://doi.org/10.1016/j.jhydrol.2003.08.002

Schneider, J. C., & Kruse, S. E. (2006). Assessing selected natural and anthropogenic impacts on freshwater lens morphology on small barrier Islands: Dog Island and St. George Island, Florida, USA. *Hydrogeology Journal*, *14*(1), 131–145. https://doi.org/10.1007/s10040-005-0442-9

Seibert, S. L., Holt, T., Reckhardt, A., Ahrens, J., Beck, M., Pollmann, T., et al. (2018). Hydrochemical evolution of a freshwater lens below a barrier island (Spiekeroog, Germany): The role of carbonate mineral reactions, cation exchange and redox processes. *Applied Geochemistry*, *92*, 196–208. https://doi.org/10.1016/j.apgeochem.2018.03.001

Shalev, E., Lazar, A., Wollman, S., Kington, S., Yechieli, Y., & Gvirtzman, H. (2009). Biased monitoring of fresh water-salt water mixing zone in coastal aquifers. *Groundwater*, *47*(1), 49–56. https://doi.org/10.1111/j.1745-6584.2008.00502.x

Sherren, K., Ellis, K., Guimond, J. A., Kurylyk, B., LeRoux, N., Lundholm, J., et al. (2021). Understanding multifunctional Bay of Fundy dykelands and tidal wetlands using ecosystem services-a baseline. *Facets*, *6*, 1446–1473. https://doi.org/10.1139/FACETS-2020-0073

Shin, J., & Hwang, S. (2020). A borehole-based approach for seawater intrusion in heterogeneous coastal aquifers, eastern part of Jeju Island, Korea. *Water*, *12*(2), 609. https://doi.org/10.3390/w12020609

Simmons, C. T. (2005). Variable density groundwater flow: From current challenges to future possibilities. *Hydrogeology Journal*, *13*(1), 116–119. https://doi.org/10.1007/s10040-004-0408-3

Simmons, C. T., Fenstemaker, T. R., & Sharp, J. M. (2001). Variable density groundwater flow and solute transport in heterogeneous porous media: Approaches, resolutions and future challenges. *Journal of Contaminant Hydrology*, *52*(1–4), 245–275. https://doi.org/10.1016/S0169-7722(01)00160-7

Singha, K., Johnson, T. C., Day-Lewis, F. D., & Slater, L. (2022). Electrical imaging for hydrogeology. In *The Groundwater Project, Guelph, Ontario, Canada*. Retrieved from https://gw-project.org/books/electrical-imaging-for-hydrogeology/

Sivakumar, C., & Elango, L. (2010). Application of solute transport modeling to study tsunami induced aquifer salinity in India. *Journal of Environmental Informatics*, *15*(1), 33–41. https://doi.org/10.3808/jei.201000164

Small, C., & Nicholls, R. J. (2003). A global analysis of human settlement in coastal zones. *Journal of Coastal Research*, *19*(3), 584–599. https://www.jstor.org/stable/4299200

Sorek, S., & Pinder, G. F. (1999). Survey of computer codes and case histories. In J. Bear, A. Cheng, S. Sorek, D. Ouazar, & I. Herrera (Eds.), *Chapter 5 in seawater intrusion in coastal aquifers—Concepts, methods and practices* (pp. 399–461). https://doi.org/10.1007/978-94-017-2969-7_12

Sousa, L. P., Sousa, A. I., Alves, F. L., & Lillebø, A. I. (2016). Ecosystem services provided by a complex coastal region: Challenges of classification and mapping. *Scientific Reports*, *6*, 22782. https://doi.org/10.1038/srep22782

Storlazzi, C. D., Gingerich, S. B., Van Dongeren, A., Cheriton, O. M., Swarzenski, P. W., Quataert, E., et al. (2018). Most atolls will be uninhabitable by the mid-21st century because of sea-level rise exacerbating wave-driven flooding. *Science Advances*, *4*(4), eaap9741. https://doi.org/10.1126/sciadv.aap9741

Sun, H., Alexander, J., Gove, B., & Koch, M. (2015). Mobilization of arsenic, lead, and mercury under conditions of sea water intrusion and road deicing salt application. *Journal of Contaminant Hydrology*, *180*, 12–24. https://doi.org/10.1016/j.jconhyd.2015.07.002

Taniguchi, M. (2000). Evaluations of the saltwater-groundwater interface from borehole temperature in a coastal region. *Geophysical Research Letters*, *27*(5), 713–716. https://doi.org/10.1029/1999GL002366

Terry, J. P., & Chui, T. F. M. (2012). Evaluating the fate of freshwater lenses on atoll islands after eustatic sea-level rise and cyclone-driven inundation: A modelling approach. *Global and Planetary Change*, *88*(89), 76–84. https://doi.org/10.1016/j.gloplacha.2012.03.008

Terry, J. P., & Falkland, A. C. (2010). Responses of atoll freshwater lenses to storm-surge overwash in the Northern Cook Islands. *Hydrogeology Journal*, *18*(3), 749–759. https://doi.org/10.1007/s10040-009-0544-x

Therrien, R., McLaren, R. G., Sudicky, E. A., & Panday, S. M. (2010). *HydroGeoSphere: A three-dimensional numerical model describing fully-integrated subsurface and surface flow and solute transport*. Groundwater Simulation Group.

Water Resources Research 10.1029/2022WR032614

Tully, K., Gedan, K., Epanchin-Niell, R., Strong, A., Bernhardt, E. S., BenDor, T., et al. (2019). The invisible flood: The chemistry, ecology, and social implications of coastal saltwater intrusion. *BioScience*, *69*(5), 368–378. https://doi.org/10.1093/biosci/biz027

Urbano, L. D., & Thibault, C. (2005). *Pattern of saltwater contamination resulting from tsunami inundation of small islands*. Transactions of the 17th Caribbean Geological Conference, San Juan, Puerto Rico (pp. 40–48).

Van Biersel, T. P., Carlson, D. A., & Milner, L. R. (2007). Impact of hurricanes storm surges on the groundwater resources. *Environmental Geology*, *53*(4), 813–826. https://doi.org/10.1007/s00254-007-0694-x

Villholth, K. G., Jeyakumar, P., Amerasinghe, P. H., Manamperi, A. S. P., Vithanage, M., Goswami, R. R., & Panabokke, C. R. (2010). Tsunami impacts and rehabilitation of groundwater supply: Lessons learned from eastern Sri Lanka. In M. K. Jha (Ed.), *Natural and Anthropogenic Disasters* (pp. 82–99). Springer. https://doi.org/10.1007/978-90-481-2498-5_5

Violette, S., Boulicot, G., & Gorelick, S. M. (2009). Tsunami-induced groundwater salinization in southeastern India. *Comptes Rendus Geoscience*, *341*(4), 339–346. https://doi.org/10.1016/j.crte.2008.11.013

Vithanage, M., Engesgaard, P., Jensen, K. H., Illangasekare, T. H., & Obeysekera, J. (2012). Laboratory investigations of the effects of geologic heterogeneity on groundwater salinization and flush-out times from a tsunami-like event. *Journal of Contaminant Hydrology*, *136–137*, 10–24. https://doi.org/10.1016/j.jconhyd.2012.05.001

Vithanage, M., Engesgaard, P., Villholth, K. G., & Jensen, K. H. (2012). The effects of the 2004 tsunami on a coastal aquifer in Sri Lanka. *Ground Water*, *50*(5), 704–714. https://doi.org/10.1111/j.1745-6584.2011.00893.x

Vithanage, M., Villholth, K. G., Mahatantila, K., Engesgaard, P., & Jensen, K. H. (2009). Effect of well cleaning and pumping on groundwater quality of a tsunami-affected coastal aquifer in eastern Sri Lanka. *Water Resources Research*, *45*(7), W07501. https://doi.org/10.1029/2008WR007509

Vousdoukas, M. I., Ranasinghe, R., Mentaschi, L., Plomaritis, T. A., Athanasiou, P., Luijendijk, A., & Feyen, L. (2020). Sandy coastlines under threat of erosion. *Nature Climate Change*, *10*(3), 260–263. https://doi.org/10.1038/s41558-020-0697-0

Werner, A. D., Bakker, M., Post, V. E. A., Vandenbohede, A., Lu, C., Ataie-Ashtiani, B., et al. (2013). Seawater intrusion processes, investigation and management: Recent advances and future challenges. *Advances in Water Resources*, *51*, 3–26. https://doi.org/10.1016/j.advwatres.2012.03.004

Williams, B. A., Watson, J. E., Beyer, H. L., Klein, C. J., Montgomery, J., Runting, R. K., et al. (2021). The global rarity of intact coastal regions. *Conservation Biology*, *36*(4), e138374. https://doi.org/10.1111/cobi.13874

Williams, V. J. (2010). *The ecological effects of salt water intrusion on the agriculture industry after Hurricane Katrina*. Paper presented in Proceedings of the 2007 National Confrence on Environmental Science and Technology, Greensboro, NC. https://doi.org/10.1007/978-0-387-88483-7_14

Wilson, A. M., Moore, W. S., Joye, S. B., Anderson, J. L., & Schutte, C. A. (2011). Storm-driven groundwater flow in a salt marsh. *Water Resources Research*, *47*(2), W02535. https://doi.org/10.1029/2010WR009496

Wilson, A. M., Woodward, G. L., & Savidge, W. B. (2016). Using heat as a tracer to estimate the depth of rapid porewater advection below the sediment-water interface. *Journal of Hydrology*, *538*, 743–753. https://doi.org/10.1016/j.jhydrol.2016.04.047

Woodruff, J. D., Irish, J. L., & Camargo, S. J. (2013). Coastal flooding by tropical cyclones and sea-level rise. *Nature*, *504*(7478), 44–52. https://doi.org/10.1038/nature12855

Xiao, H., & Tang, Y. (2019). Assessing the "superposed" effects of storm surge from a category 3 hurricane and continuous sea-level rise on saltwater intrusion into the surficial aquifer in coastal east-central Florida (USA). *Environmental Science and Pollution Research*, *26*(21), 21882–21889. https://doi.org/10.1007/s11356-019-05513-3

Xiao, H., Wang, D., Hagen, S. C., Medeiros, S. C., & Hall, C. R. (2016). Assessing the impacts of sea-level rise and precipitation change on the surficial aquifer in the low-lying coastal alluvial plains and barrier islands, east-central Florida (USA). *Hydrogeology Journal*, *24*(7), 1791–1806. https://doi.org/10.1007/s10040-016-1437-4

Xiao, H., Wang, D., Medeiros, S. C., Bilskie, M. V., Hagen, S. C., & Hall, C. R. (2019). Exploration of the effects of storm surge on the extent of saltwater intrusion into the surficial aquifer in coastal east-central Florida (USA). *Science of the Total Environment*, *648*, 1002–1017. https://doi.org/10.1016/j.scitotenv.2018.08.199

Xie, Y., Simmons, C. T., & Werner, A. D. (2011). Speed of free convective fingering in porous media. *Water Resources Research*, *47*(11), W11501. https://doi.org/10.1029/2011WR010555

Xie, Y., Simmons, C. T., Werner, A. D., & Diersch, H. J. (2012). Prediction and uncertainty of free convection phenomena in porous media. *Water Resources Research*, *48*(2), W02535. https://doi.org/10.1029/2011WR011346

Xin, P., Robinson, C., Li, L., Barry, D. A., & Bakhtyar, R. (2010). Effects of wave forcing on a subterranean estuary. *Water Resources Research*, *46*(12), W12505. https://doi.org/10.1029/2010WR009632

Yang, J., Graf, T., & Ptak, T. (2015). Impact of climate change on freshwater resources in a heterogeneous coastal aquifer of Bremerhaven, Germany: A three-dimensional modeling study. *Journal of Contaminant Hydrology*, *177–178*, 107–121. https://doi.org/10.1016/j.jconhyd.2015.03.014

Yang, J., Graf, T., Herold, M., & Ptak, T. (2013). Modelling the effects of tides and storm surges on coastal aquifers using a coupled surface-subsurface approach. *Journal of Contaminant Hydrology*, *149*, 61–75. https://doi.org/10.1016/j.jconhyd.2013.03.002

Yang, J., Zhang, H., Yu, X., Graf, T., & Michael, H. A. (2018). Impact of hydrogeological factors on groundwater salinization due to ocean-surge inundation. *Advances in Water Resources*, *111*, 423–434. https://doi.org/10.1016/j.advwatres.2017.11.017

Yu, X., Yang, J., Graf, T., Koneshloo, M., O'Neal, M. A., & Michael, H. A. (2016). Impact of topography on groundwater salinization due to ocean surge inundation. *Water Resources Research*, *52*(8), 5794–5812. https://doi.org/10.1002/2016WR018814

Zhang, Y., Li, L., Erler, D. V., Santos, I. R., & Lockington, D. (2016). Effects of alongshore morphology on groundwater flow and solute transport in a nearshore aquifer. *Water Resources Research*, *52*(2), 990–1008. https://doi.org/10.1002/2015WR017420