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Over, Under, and Through: Hydrologic Connectivity and the Future of Coastal Landscape Salinization

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Key Points:

- Hydrologic connectivity from coasts to inlands and between surface- and groundwaters determines patterns of seawater intrusion
- Climate change and human landscape modifications alter patterns of seawater intrusion in surface- and ground-waters
- We propose an approach to understand and steps forward to advance the science to forecast complex patterns of landscape salinization

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Abstract

Seawater intrusion (SWI) affects coastal landscapes worldwide. Here we describe the hydrologic pathways through which SWI occurs - over land via storm surge or tidal flooding, under land via groundwater transport, and through watersheds via natural and artificial surface water channels—and how human modifications to those pathways alter patterns of SWI. We present an approach to advance understanding of spatiotemporal patterns of salinization that integrates these hydrologic pathways, their interactions, and how humans modify them. We use examples across the East Coast of the United States that exemplify mechanisms of salinization that have been reported around the planet to illustrate how hydrologic connectivity and human modifications alter patterns of SWI. Finally, we suggest a path for advancing SWI science that includes (a) deploying standardized and well-distributed sensor networks at local to global scales that intentionally track SWI fronts, (b) employing remote sensing and geospatial imaging techniques targeted at integrating above and belowground patterns of SWI, and (c) continuing to develop data analysis and model-data fusion techniques to measure the extent, understand the effects, and predict the future of coastal salinization.

Plain Language Summary

Sea level rise, extreme weather (droughts and storms), groundwater pumping, and human modifications to coastal waterways (ditching, tidal gates, dredging) all interact to drive complex patterns of seawater intrusion, which is the landward movement of seawater inland through both ground and surface waters. Here we describe the hydrologic pathways by which seawater is delivered to interior landscapes and how humans modify those pathways. We use the East Coast of the United States as an example of how different hydrologic pathways determine patterns and extent of seawater intrusion. We end with suggestions for how scientists can better understand and predict complex patterns of salinization and their effects on ecosystems.

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1. Building an Integrated Perspective on Coastal Landscape Salinization

Coastal communities and ecosystems worldwide are experiencing salinization from seawater intrusion (SWI; i.e., the landward movement of seawater through both surface water and groundwater). Coastal aquifer salinization is well recognized (Panthi et al., 2022), yet effects of SWI on freshwater ecosystems, agricultural land, and built infrastructure remain understudied, presenting critical research and management challenges (Habel et al., 2024; Herbert et al., 2015; Tully et al., 2019). In addition to contaminating groundwater, salinization transforms forests to coastal marshes, leaving behind ghost forests; reduces crop yield, leading to farm abandonment; and damages stormwater and drinking water infrastructure, creating public health concerns (Carr et al., 2024; Kirwan et al., 2025; Tully et al., 2019). Building a holistic understanding of how SWI affects coastal landscapes is essential given that salinization is a major driver of socio-environmental change (O'Donnell et al., 2024), with sea level rise (SLR) induced land inundation alone placing 150 to 250 million people at risk by 2100 across the globe (Kulp & Strauss, 2019) and 41 nations identified as vulnerable to human health risks associated with coastal salinization of drinking water (Mueller et al., 2024). Yet, patterns of salinization are difficult to predict, in part because of the complex and interrelated hydrologic delivery and retention mechanisms that drive them.

The magnitude, duration, and timing of water-mediated transfer of materials, termed hydrologic connectivity (Covino, 2017; Pringle, 2003), between coasts and interior landscapes drives SWI and resulting patterns of salinization. SWI occurs through three interdependent hydrologic connections between the land and sea: over land via storm surge or tidal flooding, under land via groundwater transport, and through watersheds via surface water channels, including rivers, streams, canals, and ditches (Figure 1). Hydrologic connectivity between above- and below-ground pathways is important (Cantelon et al., 2022), though the vast majority of research does not consider these interactions and often considers major hydrologic pathways in isolation. Here, we propose an approach to study spatiotemporal patterns of salinization across coastal landscapes that integrates the hydrologic connectivity over, under, and through the landscape, the bidirectional hydrologic connectivity between groundwater and surface water, and how humans modify these sea-land hydrologic pathways.

Climate change increases hydrologic connectivity between the coast and interior landscapes via SLR, which raises water tables and increases the inland extent of saline surface water and groundwater gradually over time, via drought (Panthi et al., 2024), which reduces freshwater recharge resulting in lateral SWI, and via storm surges, which episodically increase saline water transport to interior landscapes (Neville et al., 2024). Humans also directly modify hydrologic connectivity between land and sea via drainage and flood defense infrastructure (Neville et al., 2023), navigational dredging and channel modifications (Duberstein & Kitchens, 2007), river flow management (Matsoukis et al., 2023), and groundwater extraction (Ferguson & Gleeson, 2012).

Human modifications to coastal landscapes are typically designed to keep land dry for agricultural or urban development. These same strategies designed to keep land dry can actually exacerbate SWI with climate change, either by reducing hydrologic connectivity after extreme events or enhancing hydrologic connectivity during droughts. Flood defense structures (e.g., seawalls, bulkheads, and dikes) and activities that increase land elevation (e.g., earthmoving, beach nourishment) restrict hydrologic connectivity to reduce flooding during storm events or extreme tides. Dams and tide gates similarly restrict the movement of water downstream and upstream, respectively. However, flood defense structures, dams, and tide gates can also trap saline water that overtops them, exacerbating SWI after increasingly common extreme storm events (Neville et al., 2023). Retained salts in surface waters affect a range of ecosystem processes (Helton et al., 2019; Kaushal et al., 2025) and can slowly infiltrate to groundwater, increasing groundwater salinization through above-below ground connectivity (Yu et al., 2016).

Drainage systems of canals and ditches can increase the extent of SWI during periods of reduced freshwater flow and droughts. Drainage systems are typically designed to enhance hydrologic connectivity to coastal waters to efficiently transport water off the land surface and lower water tables, (e.g., draining wet landscapes for agricultural uses). After storms, during droughts, or when upstream freshwater inputs are reduced (e.g., dam storage, withdrawals), drainage systems, particularly in low relief landscapes of the coastal plain, can increase landscape susceptibility to salinization (Bhattachan et al., 2018; Manda et al., 2014). Likewise, river dredging and tide gates increase the tidal prism and can lead to greater salinization upstream (Ralston & Geyer, 2019). In heavily built environments, storm sewers, subway tunnels, and other subterranean conduits also increasingly convey seawater inland during high tides or extreme events (Gold et al., 2023).

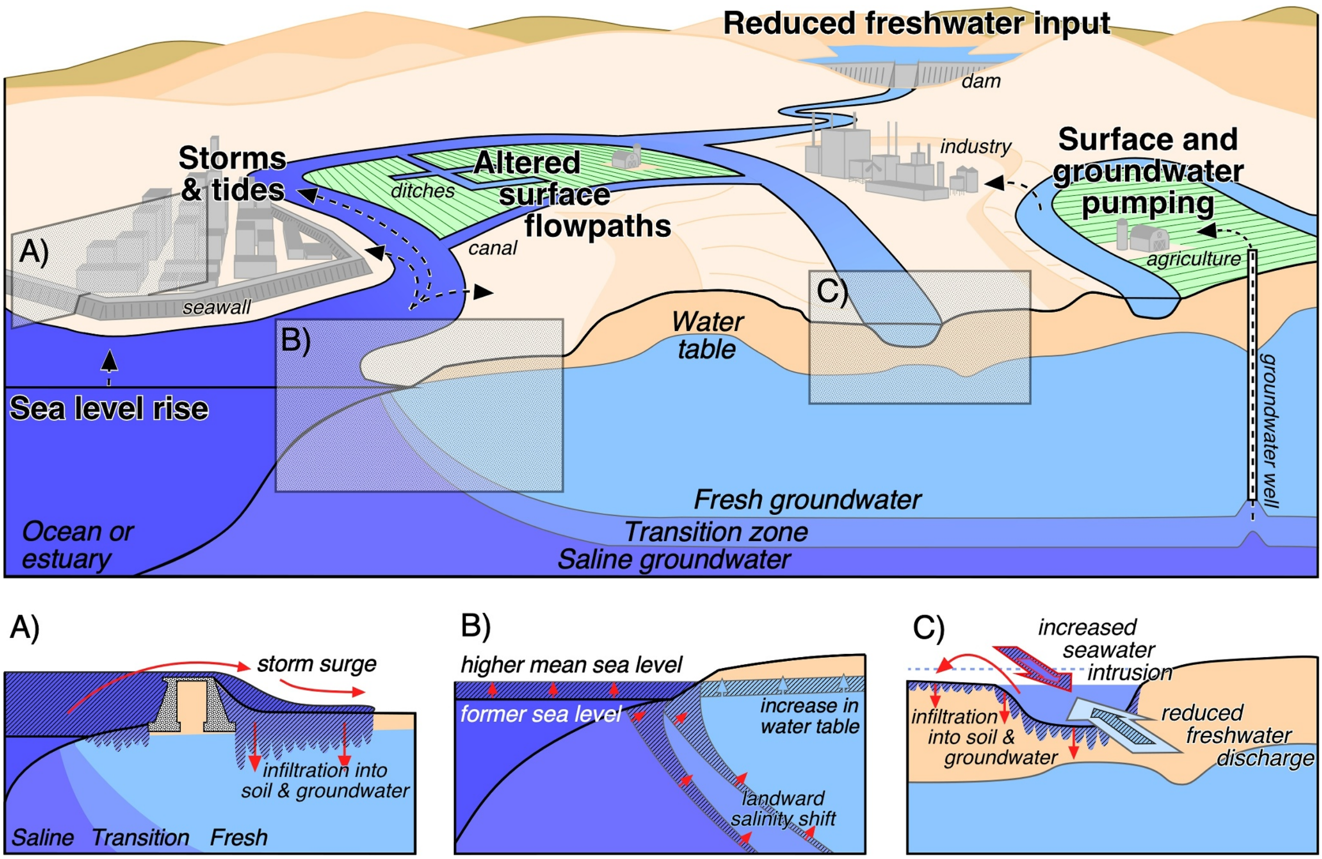

Figure 1. The landward movement of seawater occurs over land (storm surges and tides), under the ground (groundwater), and through surface waters (natural and built channels). Panels below the main figure illustrate the specific hydrologic connections between surface and groundwater salinization. (a) Storm surges can overtop coastal defenses (e.g., seawalls), leading to accumulation of seawater on land surface and its percolation into the groundwater. (b) SLR causes the landward movement of saline and brackish groundwater and a rise in the water table. (c) Reductions in freshwater flow due to drought, dams, and water extraction, and increasing connections due to dredging, channelization, and ditching cause SWI into surface waters and tidal floodplains, followed by downward movement of surface water into the groundwater. In Panels (a–c), red arrows show movement of saline waters and hatched areas indicate changes in water levels and/or flow.

Groundwater pumping is the primary human driver of SWI below-ground, with SLR orders of magnitude less important for most aquifers (Ferguson & Gleeson, 2012), though subsurface barriers have been proposed to protect groundwater from SLR induced groundwater salinization (Su et al., 2024). Groundwater pumping also affects SWI through surface channels, since the reduction in baseflow from groundwater extraction allows inland encroachment of saline water through streams (Peters et al., 2022). Thus, human hydrologic modification for agricultural and urban development can exacerbate the effects of SWI in many low-lying coastal areas.

2. Over, Under, and Through Case Studies

The East Coast of the United States exemplifies the interactions between natural and human-induced changes in hydrologic connectivity that limit our ability to measure, understand, and predict future salinization risks worldwide. The East Coast is experiencing some of the highest rates of relative SLR and land subsidence globally (Barnard et al., 2025; Sweet et al., 2022); has a wide natural range of coastal topography; and includes coastal communities that span rural agricultural to high-density urban. Thus, we have chosen the East Coast to highlight five ways that pathways of sea-land hydrologic connectivity and human modification to hydrologic connectivity create salinization challenges for communities in the region and across the planet (Figure 2).

2.1. Groundwater Pumping and Irrigation Infrastructure Enhance Surface-To-Subsurface Salinization

Coastal Delaware relies primarily on groundwater for irrigation and water supply, and SWI is a growing challenge for water managers and communities. Near the city of Dover, groundwater extraction for municipal, industrial,

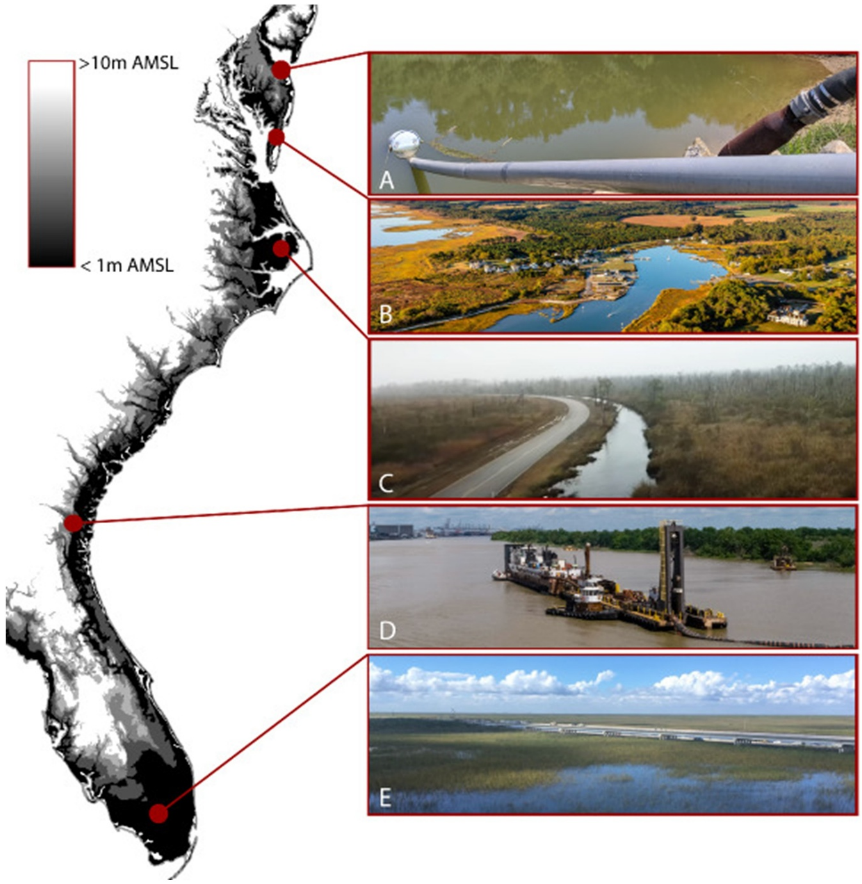

Figure 2. Examples of factors contributing to SWI in vulnerable landscapes (<1 m above mean sea level [ASML]) discussed in the main text, including pumping infrastructure in Delaware (a), low-relief landscapes in Virginia (b), legacy drainage canals in North Carolina (c), dredging in Georgia (d), and a combination of factors in Florida (e). Photographs used with permission from: (a) R. McQuiggan, Delaware Geological Survey, (b), Gordon Campbell, At Altitude Gallery, (c) Luke Groskin, Science Friday, (d) Georgia Ports Authority, and (e), J. Kominoski, Florida International University. Basemap derived from NASA Shuttle Radar Topography Mission (SRTM, 2013).

and agricultural uses combined with inland encroachment of saline surface water threaten water resources and crop yields (He & Andres, 2018). Groundwater pumping can reverse hydraulic gradients, changing net gaining streams to net losing streams, which can induce water movement from saline coastal wetlands or from increasingly saline tidal streams into the surficial aquifer (He & Andres, 2018; Hingst et al., 2024). Even smaller-scale agricultural water infrastructure that connects fresh and saline surface waters can cause surface salinization that intrudes into freshwater aquifers over time. For example, marsh-connected irrigation ponds can intersect shallow aquifers and quickly salinize them following high tide and surge events, with saline water further migrating into deep aquifers (Hingst et al., 2023).

2.2. Natural Infiltration of Saline Storm Surge Water Increases Groundwater Salinization

Storm surges move seawater over the landscape and through surface channels but can also drive patterns of groundwater salinization through the infiltration of saline storm water from surface to groundwaters. In one modeled watershed, SWI primarily occurs at the interface of tidal streams and uplands, where unsaturated soils facilitate seawater infiltration into groundwater, based on a combined storm surge and ecohydrologic model on the Eastern Shore of Virginia (Borstlap et al., 2024). The greatest seawater infiltration occurs when large surges inundate areas around the margins of tidal creeks that have dry antecedent soil water conditions. Thus, the smaller storm surge of Hurricane Joaquin (2015) resulted in more seawater infiltration than did Hurricane Isabel (2003), due to much drier antecedent conditions in 2015 than in 2003. Areas with steeper slopes tended to experience faster recovery rates, facilitated by increased lateral flow driven by groundwater gradients that flush seawater.

2.3. Legacy Canal Systems Enhance Hydrologic Connectivity in Low Relief Landscapes, Increasing Salt Transport Through Surface Waters

In coastal North Carolina, extensive ditching enabled agricultural development over the past century. Ditches can increase landscape vulnerability to SWI by facilitating inland seawater movement (Bhattachan et al., 2018; Manda et al., 2014), while also slowing the recession of saline waters where flow is constricted or dammed by pipes and roadways (Duberstein & Kitchens, 2007), extending the recession of salinity following storm surge pulses to nearly 10 days as opposed to 3–4 days where flow control structures are larger (Neville et al., 2023). Geophysical imaging has shown that belowground high conductivity plumes emanate from some ditches but not others, highlighting the heterogeneous influence of surface ditches on groundwater SWI. Removing legacy water control structures can also lead to unintentional consequences. For example, removal of a drainage ditch pump for a coastal wetland restoration increased hydrologic connectivity between the land and estuary, enabling seawater to penetrate into a previously freshwater area, decreasing wetland nitrogen retention and potentially increasing nitrogen loading to sensitive coastal waters (Ardon et al., 2013).

2.4. Channel Dredging and Water Control Structures Exacerbate Saline Water Inflow to Upstream Freshwater Ecosystems

Ports and navigation require water control structures and repeated channel dredging to facilitate shipping by vessels that have increased in size. Dredging shipping channels increases their cross-sectional area, and increases land-sea hydrologic connectivity, pushing more tide upstream and increasing salinity upstream of dredging (Ralston & Geyer, 2019). For example, along the Savannah River, both repeated dredging and 14 years of tide gate operations led to dramatic upstream salinization and conversion of tidal freshwater marsh to brackish marsh (Duberstein & Kitchens, 2007; Wetzel & Kitchens, 2007). The subsequent removal of the tide gate reduced upstream salinity and helped reestablish the tidal freshwater plant community. Although marsh vegetation communities have shown plasticity by recovering after multiple years of elevated salinity, the effects of infrastructure, SLR, and episodic drought have permanently converted many forested areas to oligohaline marsh (Krauss et al., 2009).

2.5. Interacting Modifications to Hydrologic Connectivity Drive SWI

South Florida is among the most hydrologically modified regions worldwide, combining the pathways described in the above case studies—groundwater pumping induced salinization, infiltration of saline storm surge water, and enhanced hydrologic connectivity through modified canals and channels. SWI in the Everglades has expanded substantially inland in both surface and groundwater, exacerbated by groundwater extraction from the porous limestone aquifer and SLR coupled with reduced freshwater inflows, mediated by a complex systems of canals and levees designed to prevent flooding (Dessu et al., 2021). Over the last several decades, freshwater restoration has begun to modify the vast network of canals that restricts freshwater flow from the marsh interior to increase water depths and surface hydroperiods (Sarker et al., 2020). However, the rate of SWI is outpacing freshwater restoration efforts. Hurricanes and tropical storms that increase the magnitude and delivery of seawater inland also alter the exposure and vulnerability of coastal wetlands in the Everglades to SWI (Feher et al., 2020; Lagomasino et al., 2021).

3. The Way Forward

The examples presented here are not unique but instead represent phenomena that occur globally and with increasing frequency, highlighting the critical need to advance the science of coastal landscape salinization. To date, prior research has not quantified hydrologic pathways at adequate spatial and temporal resolution to provide robust predictions of SWI and reliably inform coastal management (O'Donnell et al., 2024). To address this need, we propose a coordinated approach that includes a cross-site, cross-disciplinary collaborative scientific network to build understanding of the complex drivers and patterns of SWI through the following.

3.1. Targeted Deployment of Well-Distributed Sensor Networks for Monitoring How Hydrologic Connectivity Influences Patterns of Salinity at Local to Global Scales

Data on general patterns of salinity in coastal landscapes is limited; a recently published salinity database for non-oceanic waters (Thorslund & van Vilet, 2020) lacked data for large portions of the world. Even in regions where data are available (e.g., United States), collection efforts could be (a) expanded to encompass locations where altered hydrologic connectivity creates areas that are particularly vulnerable to SWI and (b) intentionally designed to track the spatially and temporally dynamic SWI front. Such a network should fully encompass the mechanisms of hydrologic delivery and their interactions, by integrating measurements from wells, soils, and surface waters across seasonal and hydrologic conditions. Standard practices will be important with researchers committed to following common protocols and sharing data. Even where data are collected, disparate formats and lack of accessibility often limit data usefulness (Panthi et al., 2022), so efforts should include integrating existing data sets. This common approach for data collection will maximize the utility of shared data.

3.2. Leverage Remote Sensing and Geophysical Imaging Technologies Across Scales to Measure the Extent and Understand the Impacts of SWI

Remote sensing data sets (satellite, airborne, and drone) cannot directly provide depth-resolved subsurface salinity, but can be leveraged for proxy information on SWI and its effects at various scales. Satellites provide information on precipitation, vegetation health, topography, sea surface height, nearshore salinity and ocean density that can provide contextual information for SWI estimation (e.g., Adams et al., 2024). Vegetation and coastal morphology can be observed from optical imagery and can track changes in how hydrologic connectivity alters SWI progression. Thermal infrared remote sensing can track groundwater flow paths to oceans and estuaries that provides insights into the terrestrial hydraulic gradient, which is essential for identifying areas at higher risk of SWI (Tamborski et al., 2015; Young & Pradhanang, 2021). Geophysical imaging techniques (e.g., seismic, electric, electromagnetic, and gravity) can reveal subsurface structures and hydrogeologic characteristics that influence belowground SWI. Integrating the surface and subsurface approaches through statistical or modeling methods will help advance our understanding of the complex processes driving SWI over, under, and through landscapes.

3.3. Continued Development of Data Analysis and Model-Data Fusion Techniques

Data streams, whether from integrated sensor networks or remote sensing and geophysical imaging technologies, will not advance the science of SWI alone. Pipelines that integrate diverse data sets across space and time to inform spatially explicit hydrogeochemical models powered by machine learning and other artificial intelligence approaches are likely to play a key role in predicting pathways and trajectories of SWI. Calls for and examples of this type of approach are emerging for SWI research (Myers-Pigg et al., 2025; Panthi et al., 2022). Integrating surface processes, including infiltration, flood inundation, and erosion with subsurface flow dynamics will enable a more comprehensive representation of the physical mechanisms driving SWI.

Because the challenges described above are exacerbated by human modifications to hydrologic connectivity, changing water management strategies to fully embrace the mechanisms by which SWI occurs has the potential to ameliorate the impacts of SWI in coastal landscapes and communities. Ultimately, our vision is that explicitly incorporating land-sea and above-below ground hydrologic connectivity into our measurements and models will contribute solutions to inform adaptive coastal management that can mitigate the extent and severity of SWI and improve the outlook for people living in the coastal zone and the natural ecosystems that surround them.

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Data Availability Statement

Data were not used, nor created for this research.

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