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Terrestrial Groundwater Drives Coastal Ecosystem Shifts

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Key Points:

- Decreased terrestrial groundwater levels drive persistent salinity increases in shallow aquifers that vegetation relies on
- Storm events, often identified as drivers of saltwater intrusion, are linked to aquifer freshening
- Upland head decline causes more spatially and temporally extensive saltwater intrusion in aquifers than storm events

Supporting Information:

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

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Abstract Saltwater intrusion (SWI) is accelerating along coastlines globally. This process is visually evident in low-lying regions as conversion of forests and agricultural fields to saltmarsh. Marsh migration is largely attributed to ocean forcings such as sea-level rise and storm surges. Here we show that terrestrial hydrology may also be a major driver of coastal ecosystem change. Data from the Delmarva Peninsula, USA show that declining upland groundwater head weakens the hydraulic gradient, causing shallow saline groundwater to push inland from coastal marshes. This drives SWI into coastal freshwater forests and farms at magnitudes that can exceed SWI from storms. We show that storm events often contribute to groundwater freshening through rainfall that restores the hydraulic gradient and flushes saline groundwater. Our findings highlight terrestrial groundwater as a primary control on root-zone saltwater intrusion and suggest that changes in upland head may be a dominant, yet overlooked, driver of marsh migration.

Plain Language Summary Along global coastlines, rising sea levels combined with frequent and intense coastal storms are causing saltwater to intrude into coastal freshwater ecosystems (i.e., saltwater intrusion). Saltwater intrusion is pushing marshes inland (i.e., marsh migration), resulting in a loss of coastal forests and agricultural lands along the Delaware, Maryland, and Virginia (Delmarva) Peninsula. Although marsh migration has been attributed to sea level rise and storms, our research suggests that changes in the terrestrial water level may play a larger role in driving saltwater intrusion into fresh groundwater than previously understood. Additionally, we found that storm events, through substantial rainfall, can contribute to groundwater recovery following periods of low upland water level by flushing out the saltwater. This insight shifts our understanding of coastal change, highlighting terrestrial hydrology as a primary driver of shallow saltwater intrusion and subsequent marsh migration in this region.

1. Introduction

Marsh migration, which is the landward transgression of coastal wetlands into adjacent upland freshwater ecosystems, is one of the most visible ecological consequences of changing coastal hydrology along low-lying shorelines. Along the U.S. Mid-Atlantic, over 587 km^2 of forest have been converted to marsh between 1984 and 2020, largely due to salinity and hydrologic stress that exceed the tolerance of upland vegetation (H. Chen et al., 2023; Y. Chen and Kirwan, 2024; M. Kirwan and Gedan, 2019; Krauss et al., 2018). This shift in land cover has critical implications for biodiversity, carbon cycling, land use, and coastal resilience.

Marsh migration is typically attributed to saltwater intrusion (SWI), which is the inland movement of saline water into freshwater zones (Fagherazzi et al., 2019; Werner & Simmons, 2009), and root zone saturation, which can cause anoxic stress and vegetation decline (DeBell et al., 1984). These mechanisms are typically triggered by two dominant oceanic drivers: (a) sea-level rise (SLR), a slow "press" disturbance that pushes the freshwater-saltwater interface inland (Werner, 2017; Werner & Simmons, 2009), and (b) storm surges, fast "pulse" disturbances that cause episodic flooding and salinization (Cantelon et al., 2022; Giambastiani et al., 2017; Guimond & Michael, 2021; Nordio et al., 2023; Paldor & Michael, 2021). Though these oceanic drivers act on different timescales, they are often jointly studied as key contributors to wetland transgression (Miller et al., 2021).

However, oceanic processes may not fully explain the range of salinization dynamics observed across low-lying coastal systems. Intermediate-timescale processes, such as seasonal declines in upland groundwater levels, can weaken hydraulic gradients and allow saline groundwater to move inland through the subsurface; a mechanism previously documented in deeper, regional aquifers (Michael et al., 2005). However, its role in shallow, near-surface systems directly connected to vegetation rooting zones remains largely unexplored. These shallow

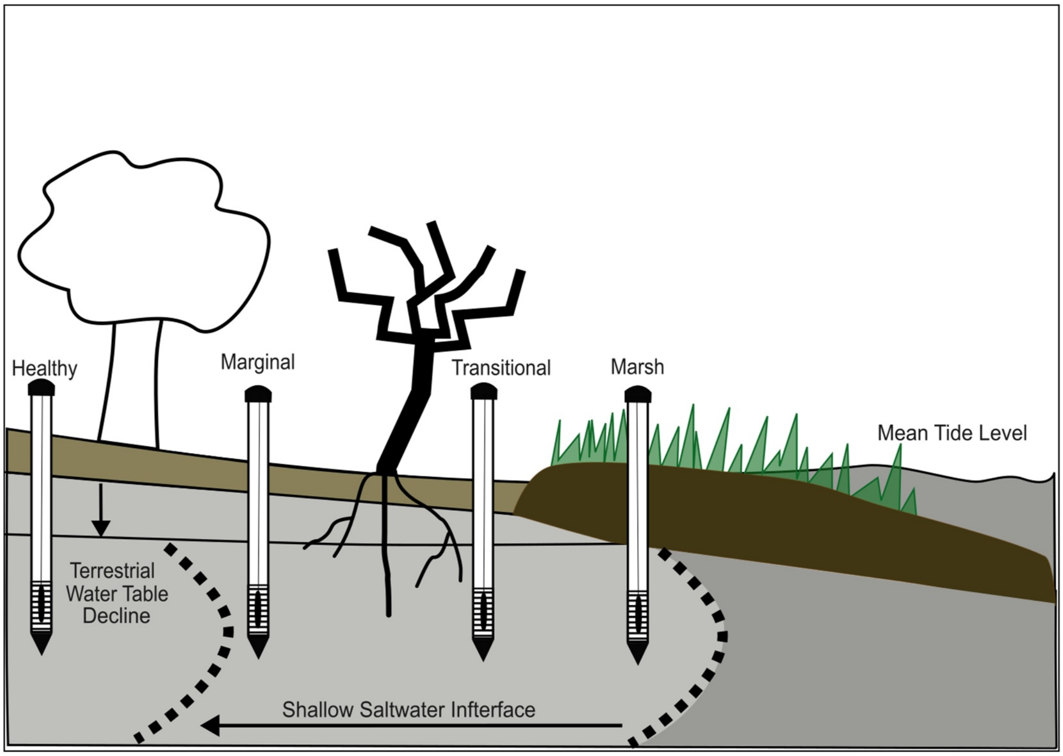

Figure 1. Lateral saltwater intrusion (SWI) in the surficial aquifer is driven by the hydraulic gradient between upland groundwater head and sea level. A drop in the upland head can induce lateral SWI. This study is designed to measure hydrologic processes causing vegetation shifts along the transition between marshes and coastal uplands. Each zone (marsh, transitional, marginal, healthy) is instrumented with piezometers to measure groundwater level and salinity.

aquifers are ecologically significant (Glanville et al., 2023), more dynamic than their deeper counterparts (Guzy et al., 2025; Winter et al., 2000), and highly sensitive to evapotranspiration (ET), recharge variability, and drought (Condon et al., 2020; Hare et al., 2021). Despite their importance to forest and crop health, they have received relatively little attention in SWI literature, which remains focused on deeper aquifers relevant to water supply (Barlow & Reichard, 2010; Hingst et al., 2023; Michael et al., 2017; Paldor & Michael, 2021).

Emerging research suggests that coastal wetland vulnerability may be overly attributed to oceanic drivers, overlooking the role of terrestrial groundwater dynamics. Recent work by Montalvo et al. (2024) showed that seasonal variability in terrestrial head influences marsh porewater salinity, with groundwater inflow buffering salinity during wet seasons and tidal influence increasing during dry periods. Similarly, upland water table fluctuations can exert stronger control over marsh redox conditions than tides, influencing oxygen availability, decomposition, and nutrient cycling (Guimond, 2025; Guimond et al., 2025). However, these studies focused on the marsh platform, neglecting to consider how terrestrial groundwater fluctuations affect the marsh-upland transition zone. Specifically, they did not assess whether shallow groundwater beneath the marsh salinizes during dry periods or how changes in the hydraulic gradient drive inland saltwater movement.

In this study, we provide new evidence that fluctuations in the terrestrial water table drive SWI in shallow aquifers where it has direct ecological consequences. Our results show that even modest declines in landward hydraulic gradients can trigger salinization that persists longer and extends farther inland than salinization from coastal storms (Figure 1). Unlike tidal or storm-driven flooding, this process does not saturate the soil, but instead exposes vegetation to salinity stress, which is known to reduce growth and survival in freshwater plant communities (DiCara & Gedan, 2023; McDowell et al., 2022; Munns & Tester, 2008). We examine this pattern across Delaware (DE), Maryland (MD), and Virginia (VA) on the Delmarva Peninsula using groundwater and salinity data from six field sites equipped with marsh-to-upland piezometer transects. Our findings reveal that this third, terrestrial driver of SWI and marsh migration, distinct from SLR and storm surge, may dominate salinization dynamics in shallow systems under specific hydrologic conditions.

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2. Materials and Methods

2.1. Site Description

The Delmarva Peninsula experiences relative SLR rates 2–3 times the global average (~3.4 mm/yr) due to glacial isostatic adjustment (DeJong et al., 2015; Engelhart et al., 2009). The Peninsula is fringed by tidal salt marshes and has a shallow, sandy surficial unconfined aquifer (generally <6 m thick).

2.2. Site Instrumentation and Data Collection

To study shallow aquifer dynamics, instrumented transects spanning marsh-upland zones with varying land use types, slopes, and coastal exposures were established in Delaware, Maryland, and Virginia (Figures 1 and 2a). Forest sites feature ghost forests (Figure 2c) whereas farm sites show salt-damaged, abandoned crops (Figure 2b). Each transect includes four zones based on vegetation health (Figure 1): (a) *healthy*: vegetation is alive with no visible salt stress; (b) *marginal*: trees show stress (leaf loss), crops are shorter and patchy; (c) *transitional*: dead trees, salt crusts, and barren fields present; and (d) *marsh*: dominated by halophytes (*Spartina patens* and/or *Phragmites australis*) and fine sediments.

Each zone was equipped with 1.5-inch (3.8 cm) diameter PVC piezometers with 12-inch (30.5 cm) screens. Conductivity, temperature, and depth loggers (Solinst M3001 Levelogger 5) recorded groundwater every 15 min, with specific conductance (SPC) as a proxy for salinity. Monitoring began between March 2021 and July 2022, depending on the site, with continuous data through July 2024. Barometric pressure (Solinst M3001 Barologger 5) was measured at each site to compensate groundwater levels. Water table elevations and SPC for all zones are available in Supporting Information S1 (Figures S4b, S4c, S6b, S6c, S8b, S8c, S10b, S10c, S12b, S12c, S14b, and S14c). Full data processing methods are detailed in Supporting Information S1 (Text S2) and (Pratt et al., 2025).

Additional environmental data contextualized groundwater fluctuations. Rainfall was derived from NOAA stations (DE: 72408813707, MD: 72398093720, VA: 72402093739), while tides obtained from USGS gages (DE: 01484085, MD: 01485755, VA: 01484746) (NOAA National Centers of Environmental Information, 1999; U.S. Geological Survey, 1997, 2012, 2018). Evapotranspiration (ET) data came from the Delaware Environmental Observation System at the Harrington site (Delaware Environmental Observing System, 2022). County-level drought status was obtained from the U.S. Drought Monitor (USDM) for Kent County (DE), Somerset County (MD), Accomack County (VA farm), and Northampton County (VA forest), using classifications ranging from D0 (Abnormally Dry) to D2 (Severe Drought) (National Drought Mitigation Center at University of Nebraska-Lincoln et al., 1999; Noel et al., 2020).

Additionally, we conducted an event-based analysis across sites using NOAA precipitation recurrence intervals (NOAA's National Weather Service, 2025) (≥1-year storm) and the top 1% of observed tides to define surge, precipitation, and combined events. For each event, we quantified pre- and post-event changes in hydraulic gradient and salinity to assess storm impacts compared to terrestrial drivers (see Text S3 for details in Supporting Information S1).

2.3. Hydraulic Gradient Calculation

Hydraulic gradients (*dh/dl*) were calculated between all upland zones and the marsh, where *dh* is the head difference and *dl* is the distance between piezometers. A positive gradient indicates flow toward the marsh, while a declining but positive gradient signals weakening flow. A negative gradient indicates full reversal, with groundwater moving inland. SWI can begin before full reversal, as reduced freshwater discharge enables inland saltwater migration. While gradients from all upland zones are in Supporting Information S1 (Figures S4a, S6a, S8a, S10a, S12a, and S14a), the main results focus on gradients between the healthy and marsh zones.

3. Results

Hydraulic gradients at all six sites declined or reversed for extended periods in 2022 and 2023, though not uniformly across all zones (Figure 3, Figures S1 and S2 in Supporting Information S1). Notable salinization during periods of declining hydraulic gradients was observed at three of the six sites (Figure 3). Salinization likely occurred at all sites based on the declining gradients and reversals, but whether salinization was detected

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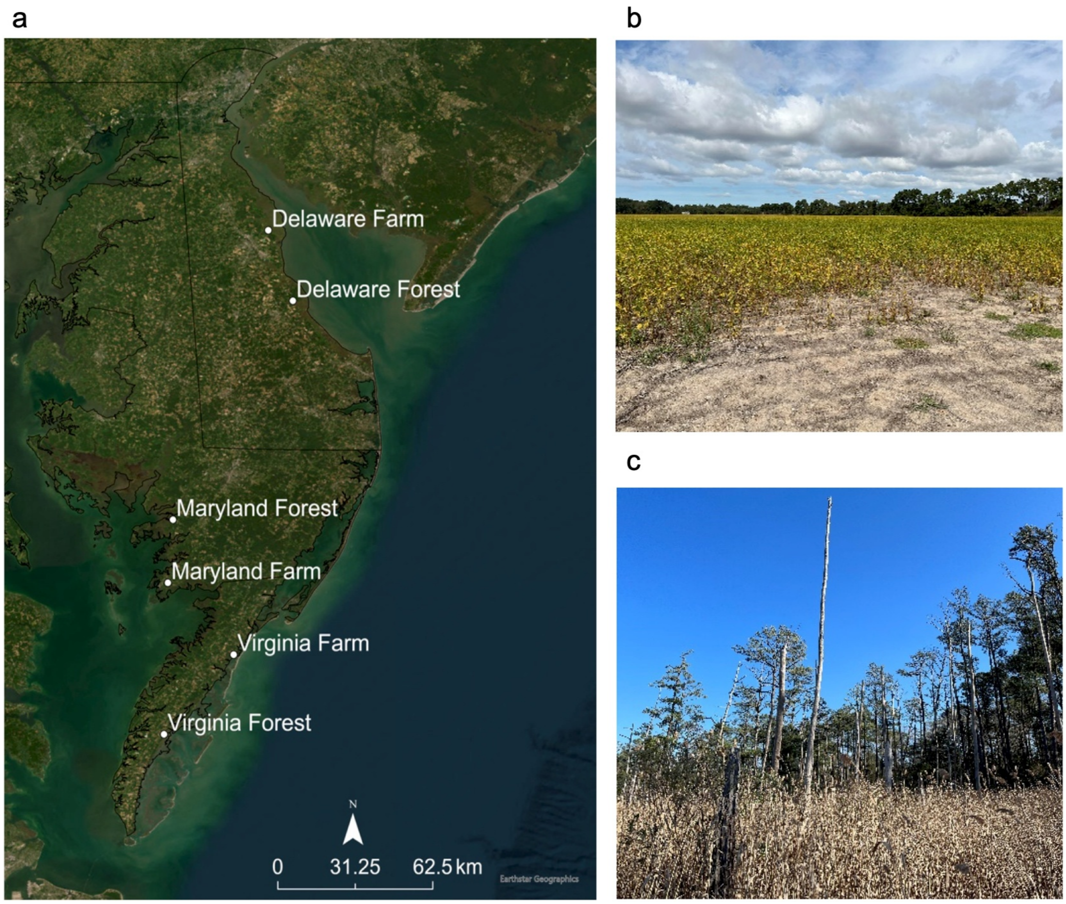

Figure 2. (a) Monitoring locations along the Delmarva. (b) Transition zone along the Virginia farm soybean field. (c) Transition zone/ghost forest at the Maryland forest site.

depended on the piezometer's position relative to the initial position of the freshwater-saltwater interface. Below are details for the three sites with observed salinization.

3.1. Delaware Forest

In 2022, from July to December, the gradient between healthy and marsh zones remained below average (<0.006) for 151 days, with no break exceeding seven consecutive days of above-average gradient. During this period, salinity significantly increased in the transitional, marsh, and, later, marginal zones. Similarly in 2023, the gradient was below average from May to July (52 days) and again from August to December (113 days), both coinciding with salinity increases in the same zones.

The 2022 gradient decline aligned with a D0 drought period from August to October, while the 2023 gradient decline corresponded with a D0–D1 drought from May to July. In both years, the healthy-to-marsh gradient decreased by an average of 0.004 m/m (Tables S1 and S2 in Supporting Information S1). Groundwater SPC remained static until the gradient declined, triggering SPC increases of 5.5, 15.3, and 19.5 mS/cm in 2022 and 3.3, 9.7, and 4.4 mS/cm in 2023 in the marginal, transitional, and marsh zones, respectively. In 2022, salinization in the transitional and marsh zones began in July and persisted for 7 months, reaching the marginal zone by October, lagging the transitional zone by 3 months. SPC took ~200 days to recover, driven by 15.6 cm of rainfall from Hurricane Ian in early October (Figure 3 and Figure S3 in Supporting Information S1). The storm's coincident surge (0.59 m above daily average) did not contribute to salinization (Figure S2 in Supporting Information S1). In 2023, salinization began in late May/early June, lasting 6–8 months, with saltwater reaching the marginal zone by August. Recovery was driven by above-average December rainfall (+11 cm above the 30-year mean) (Leathers, 2024), which restored the gradient and facilitated flushing.

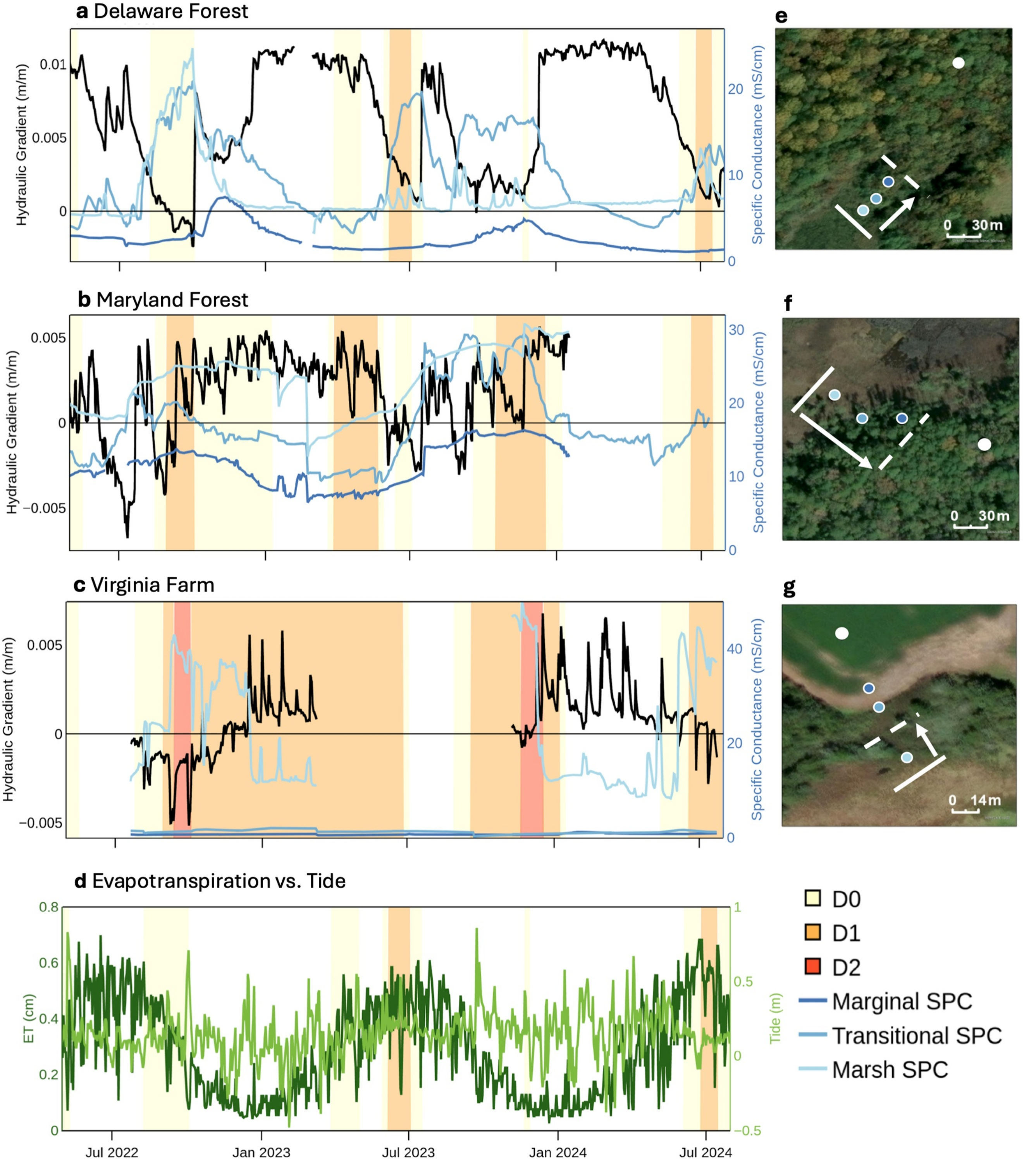

Figure 3. Hydraulic gradients, groundwater specific conductance (SPC), and U.S. Drought Monitor drought periods for three sites with observed salinization during upland water level decline: (a) Delaware (DE) Forest, (b) Maryland Forest, (c) Virginia Farm. The black line represents marsh-to-healthy zone gradient, where positive values indicate groundwater flow toward the marsh, declining values indicate weakening flow, and negative values indicate full reversal (inland flow). Blue lines show groundwater SPC in marsh, transitional, and marginal zones. Shaded yellow/orange areas mark drought severity (D0, D1, D2). Panels (e–g) show site transects, with solid white lines marking the estimated initial salt front and dashed indicating its observed ending position. Map colors correspond to zones in (a–c). (d) Shows evapotranspiration (dark green line) and tide level (light green line) from DE; representative of all three sites.

3.2. Maryland Forest

At the Maryland Forest, the healthy-to-marsh gradient declined by an average of 0.004 m/m from June to September 2022 (98 days), and by 0.001–0.002 m/m during two periods in 2023: May to September (112 days) and October to November (26 days) (Figure 3 and Table S1 in Supporting Information S1). In 2022, groundwater SPC increased between March and September by 5.7, 9.9, and 7.4 mS/cm in the marginal, transitional, and marsh zones respectively. In 2023, SPC increased from late May/early June through 2024, with large increases of 8.9, 19.9, and 17.7 mS/cm in the same zones (Figure 3 and Table S2 in Supporting Information S1).

Some declining-gradient periods coincided with droughts (e.g., August-December 2022), while others (e.g., March-June 2022) did not. The most declines occurred during peak ET, likely driving groundwater level declines even without below average precipitation (Figure 3).

In September 2022, a two-day storm with 8 cm of rainfall helped restore oceanward flow and flush the aquifer (Figure 3 and Figure S3 in Supporting Information S1). Despite an associated elevated tide (0.27 m above daily average), salinization did not occur (Figure S2 in Supporting Information S1). Hurricane Ian delivered another 7.5 cm of rain over 6 days with an associated elevated tide (0.41 m above daily average) and contributed to aquifer flushing, though SPC remained elevated for 229–300 days. In 2023, rainfall in late November (4.36 cm) initiated flushing, yet elevated SPC persisted for 217–341 days.

3.3. Virginia Farm

At the Virginia Farm, declining gradients from July to December 2022 and November to December 2023 aligned with D0–D2 (severe) droughts. Due to data loss in summer 2023, gradient calculations were unavailable, though SPC was elevated in November when monitoring resumed. Average gradient decline was 0.002 m/m in 2022 and 0.0006 m/m in 2023, lasting at least 145 days in 2022 (likely longer, as monitoring began after the decline had started) (Figure 3 and Tables S1 and S2 in Supporting Information S1). Unlike other sites, only the marsh experienced significant salinization, with SPC increasing by 31.0 and 34.7 mS/cm in 2022 and 2023, respectively, the highest SPC increase among sites. In 2022, SPC remained elevated for 157 days. However, a 5 cm rain event in December rapidly restored the gradient, flushing the aquifer and returning SPC to pre-event levels within 8 days, the fastest recovery across sites (Figure 3 and Figure S3 in Supporting Information S1). This storm was accompanied by a surge (0.54 m above daily average), but no salinization occurred (Figure S2 in Supporting Information S1). In 2023, a coastal winter storm delivered 16.9 cm of precipitation, restoring groundwater SPC to pre-event levels.

3.4. Storm Event Salinity and Gradient Effects

Across sites discussed above, surge events (categorized as surge-only or surge with precipitation) more often coincided with aquifer freshening than salinization. The marginal, transitional, and marsh zones at all sites were analyzed. At the DE Forest, six events in these three zones (18 total responses) resulted in 12 responses with either a decrease or no change in salinity (62%). Similar outcomes were observed at the MD Forest and VA Farm sites, where 61% of responses indicated salinity decline or no change (Tables S3–S5 in Supporting Information S1). We note that many "surge-only" events included sub-threshold rainfall that likely contributed to recovery, suggesting our classification may underestimate the role of storm precipitation.

In contrast, declining upland head resulted in substantially higher and more prolonged salinity increases than surge events. Across all three sites, average SPC increases during upland gradient declines were 6.7 mS/cm (marginal), 13.7 mS/cm (transitional), and 13.3 mS/cm (marsh), persisting 176–262 days (Tables S6–S8 in Supporting Information S1). Surge-driven events produced smaller increases of 0.31, 0.52, and 0.11 mS/cm, lasting 12–26 days in the marsh, transitional, and marsh zones, respectively (Tables S6–S8 in Supporting Information S1).

4. Discussion

Shallow aquifers are highly sensitive to short-term and seasonal groundwater fluctuations, responding rapidly to changes in recharge, ET, and climate variability. Our results demonstrate that even brief upland head declines, without full gradient reversal, can induce shallow groundwater salinization, triggering prolonged salinization in transitional and marginal zones. This sensitivity is likely amplified in low-lying coastal areas where hydraulic gradients are small. Therefore, only slight declines in upland water levels are needed to shift or reverse groundwater flow direction, increasing vulnerability to lateral saltwater intrusion during dry seasons or droughts. This is especially important for marsh-adjacent ecosystems like forests and farms, where vegetation depends on stable, fresh groundwater. Unlike previous studies emphasizing salinization from storm surges or SLR, our findings reveal a distinct terrestrial driver of root-zone salinization operating on intermediate timescales (seasonal to annual). While this may not significantly affect deeper water resources, it may have profound ecological consequences and may be a key overlooked driver of marsh migration.

Coastal groundwater-dependent ecosystems, like marsh-adjacent forests, help buffer flooding from storm surges, reduce erosion, and support biodiversity (Chang & Mori, 2021), while coastal farms provide key economic resources. Along the Delmarva, dominant species such as loblolly pines (*Pinus taeda*) and corn have a shallow rooting depths (0.5–2 m) (Adegbidi et al., 2004; Fan et al., 2016), making them reliant on shallow groundwater (Liu et al., 2018). Our findings demonstrate that declining gradients allow saltwater to reach these rooting zones, with salinization persisting over 300 days, which may be long enough to induce chronic stress and potential mortality (DiCara & Gedan, 2023). At the Delaware Forest site, observations indicate that the salt front advanced 7.9 m from the transitional to marginal zone over 253 days of declining gradient. Darcy's Law estimates using average gradients and measured hydraulic conductivity predicted a 5.9-m advance over the same period (Text S1 and Tables S9 and S10 in Supporting Information S1). This agreement between observed and predicted salt front movement strengthens the conclusion that upland head declines can drive lateral SWI in shallow systems. Although our data set is not long enough to confirm progressive salt front migration, the salinized zones, particularly transitional and marginal, often correspond to areas where freshwater vegetation is degraded. This suggests that shallow aquifer salinization, driven by upland head decline, may contribute to long-term marsh migration over time. Longer-term monitoring that integrates groundwater with vegetation change is needed to determine whether seasonal salinization leads to sustained inland salt front movement.

Although upland head declines frequently co-occur with drought, our results reveal that groundwater depletion lags atmospheric and soil moisture deficits, so drought conditions often emerge before observed groundwater declines. The USDM assesses drought severity using precipitation, soil moisture, streamflow, and vegetation, but does not incorporate well-based groundwater levels. Instead, it integrates GRACE satellite data, which lacks resolution to detect localized groundwater depletion in shallow coastal aquifers. This gap is consistent with the “drought cascade” concept (Changnon, 1987; Entekhabi, 2023), where groundwater responds more slowly to atmospheric and soil moisture loss.

Here, we use USDM as a regional water deficit indicator, not a predictor of saltwater intrusion or gradient shifts. While drought can cause groundwater decline, gradient shifts may also result from seasonal fluctuations in precipitation, high ET, recharge variability, and groundwater extraction. For example, in summer 2022, groundwater declined at multiple sites without corresponding USDM drought classification—particularly at the Maryland forest site. These mismatches highlight that localized summer rainfall may not offset high ET, leading to groundwater loss even without declared drought. Furthermore, while ET contributes to groundwater decline and may cause evapoconcentration of salt, that cannot alone explain the observed increases in salinity, which must be due to advection of saline groundwater. Evapoconcentration primarily affects the shallow unsaturated zone, where capillary action may draw saline water upward, causing surface salt accumulation (Geng & Boufadel, 2017). These interactions illustrate the complexity of shallow aquifer systems, where groundwater levels are shaped by individual rain events, inter-storm periods, and vegetation water use, acting alongside broader seasonal trends.

In transitioning zones, where freshwater vegetation lacks salinity tolerance, increased groundwater salinity likely functions as a stressor that accelerates ecosystem transition. These events may create tipping points, pushing systems past ecological thresholds and initiating marsh migration. This reinforces the need to study shallow coastal aquifers separately from deeper, slower-responding groundwater systems that have dominated SWI and drought research, as shallow groundwater exhibits greater sensitivity to short-term climatic and ecological variability (Bloomfield & Marchant, 2013; Changnon, 1987; Entekhabi, 2023).

Our work provides new insight into the role of storm events and their effects on subsurface salinity. While storm surges are recognized as primary drivers of SWI, our findings suggest a more complex relationship between storms and shallow groundwater salinity. Surges can introduce saltwater into shallow aquifers, especially when groundwater levels are low. However, hurricane-associated precipitation often counteracts this by increasing recharge, raising water tables, and restoring oceanward flow.

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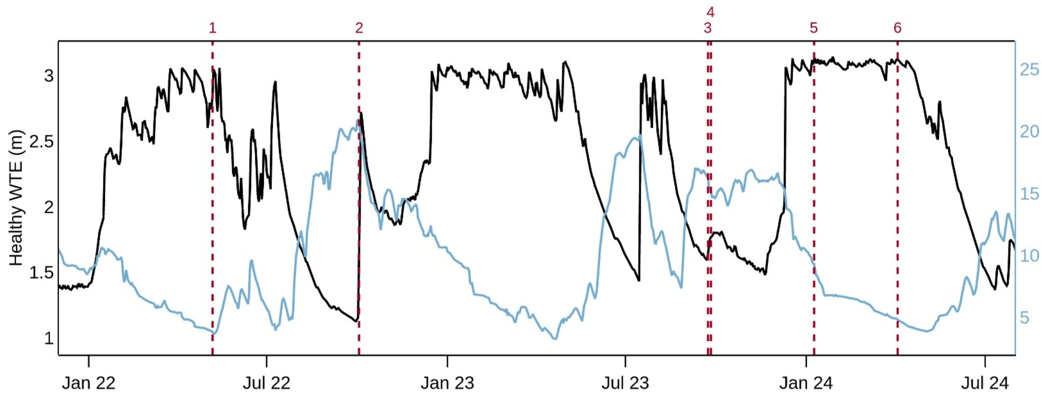

Figure 4. Water table elevation in the upland healthy piezometer (black) and groundwater specific conductance (SPC) in the transitional zone at the Delaware Forest site (blue). Red dashed lines indicate the highest 1% of surge events during the recorded period as calculated in Tables S3–S5 in Supporting Information S1; (1) Surge, (2) Surge, (3) Surge + Precipitation, (4) Surge, (5) Surge, (6) Surge. The groundwater SPC in the transitional zone (closest to the marsh) is more affected by drops in upland groundwater level than surge events.

This pattern was consistent across the Delmarva, where hurricane season follows summer, and low upland groundwater levels may create a window of heightened vulnerability to vertical SWI due to an expanded unsaturated zone. Yet, our data show that storm rainfall frequently mitigates this by refilling the aquifer with freshwater (Figure 3 and Figure S3 in Supporting Information S1). At the Delaware Forest site, there were six surge events between May 2022 and April 2024 which did not coincide with sustained salinity increases (Figure S2, Tables S3 and S6 in Supporting Information S1). Based on these observations, salinization more closely tracked preceding upland head declines than the surge themselves. Figure 4 illustrates this pattern: salinity in the transitional zone more closely follows upland head than surge events (also see Figures S16 and S17 in Supporting Information S1), highlighting the dominant role of terrestrial hydrology. While seasonal sea level variation may contribute to vulnerability, upland groundwater declines (2 m) far exceeds seasonal sea level fluctuations (0.17 m) (NOAA Tides & Currents, 2025). Additionally, conductivity begins to increase in July, coinciding with upland groundwater decline rather than peak mean sea level in September. This can more clearly be observed in a zoomed in version of Figure 3 that is provided in Supporting Information S1 (Figure S18), where conductivity increases coincide with gradient decline and storm events, which increase the hydraulic gradient, promoting flushing. Together, this suggests that terrestrial head loss, not sea level variability, is the primary driver of seasonal gradient decline (Figure S19 in Supporting Information S1). However, periods of elevated sea level that coincide with low terrestrial groundwater may further increase salinization risk.

Many events display overlapping surge, rainfall, and declining gradients, complicating attribution. However, across sites, salinization typically aligned with upland head declines, even when storms occurred. Future work untangling the relative contributions of overlapping drivers will be critical for understanding ecosystem response to compound events.

Interactions between groundwater dynamics, vegetation stress, and climate variability create complex feedbacks that influence long-term coastal ecosystem resilience (M. L. Kirwan et al., 2025). Vegetation dieback may increase surface evaporation (Hall et al., 2022; Whitcraft & Levin, 2007), exacerbating groundwater decline, while flooding can flush salts or induce root-zone anoxia (Ding et al., 2023), further stressing vegetation. These stressors may cause elevation loss through root zone collapse and organic matter decay, reinforcing marsh encroachment (M. L. Kirwan et al., 2025). Our findings emphasize that press (SLR), pulse (storms), and intermediate (upland head) drivers often co-occur and interact, so their individual contributions to forest and agricultural decline remain unclear.

Future research should explore how these drivers combine to influence long-term SWI, and marsh migration, especially as rising temperatures and ET intensify terrestrial groundwater stress. Understanding these compound and sequential stressors is critical for predicting future ecosystem vulnerability and requires better integration of terrestrial groundwater dynamics into coastal salinization studies.

5. Conclusions

In this study, we use established monitoring sites along the Delmarva Peninsula to study responses of the marsh-upland-aquifer-system to hydrologic forcings. Groundwater monitoring reveals that declines in upland head are an important, unseen driver of coastal salinization, acting on intermediate timescales that have largely been overlooked. We show that even small declines in hydraulic gradients along the marsh-upland ecotone induce lateral SWI, with salt persisting in the surficial aquifer system for up to 9 months before recovering. We highlight the importance of fall storms in freshening, rather than salinization, of aquifers. Declining upland water tables cause more salinization of the surficial aquifer than storms and have been widely overlooked in coastal environments where precipitation may be sufficient. Yet precipitation can be insufficient to overtake ET losses in dense vegetation, driving groundwater declines. This study shifts the paradigm of coastal ecosystem change by identifying terrestrial groundwater hydrology as a potentially dominant driver of root-zone salinization compared to oceanic forcing, particularly under dry or high-ET conditions.

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

Data Availability Statement

All data will be available in Hydroshare upon publication available as described in Pratt et al. (2025) from the following data sets (Pratt et al., 2021, 2022a, 2022b, 2022c; Pratt, Michael, Nordio, & Fagherazzi, 2024; Pratt, Michael, Sprague-Getsy, & Bacmeister, 2024).

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