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Frequent Storm Surges Affect the Groundwater of Coastal Ecosystems

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Abstract Recent studies have focused on the effect of large tropical cyclones (hurricanes) on the shore, neglecting the role of less intense but more frequent events. Here we analyze the effect of the offshore tropical storm Melissa on groundwater data collected along the North America Atlantic coast. Our meta-analysis indicates that both groundwater level and specific conductivity significantly increased during Melissa, respectively reaching maximum values of 1.09 m and 25.2 mS/cm above pre-storm levels. Time to recover to pre-storm levels was 10 times greater for groundwater specific conductivity, with a median value of 20 days, while groundwater level had a median recovery time of 2 days. A frequency-magnitude analysis indicates that the percent of time with salinization is higher for Melissa than for energetic hurricanes. Given the high frequency of these events (return period of 1–2 years), and the long time needed for groundwater conditions to return to normal levels, we conclude that increasingly frequent moderate storms will have a significant impact on the ecology of vegetated shorelines.

Plain Language Summary Salinization and flooding events due to sea level rise and storm surges threaten coastal ecosystems, changing groundwater characteristics. Moderate and more frequent storm surges can have a significant impact on coastal ecology, similar to larger tropical cyclones. Salinity and water table elevation need time to recover to normal conditions. The recovery time is compared to the frequency of these moderate storm surge events to determine the effect on the coastal groundwater.

1. Introduction

Along the coast, salinization and flooding caused by sea level rise (SLR) and storm surges result in the radical conversion of ecosystems, in response to a host of new hydrological, geomorphological, ecological, and biogeochemical dynamics (Tully et al., 2019). Saltwater intrusion and flooding events kill mature trees and suppress germination and seedling survival in forested areas, encouraging their retreat (Antonellini & Mollema, 2010; Fagherazzi, Anisfeld, et al., 2019; Fagherazzi, Nordio, et al., 2019; Kirwan & Gedan, 2019; Munns & Tester, 2008; Pezeshki, 1992; Schieder & Kirwan, 2019; Williams et al., 1999). These events also determine the gradual or sudden decline of croplands (Tully et al., 2019; Williams et al., 1999) and can slow down the leaf growth of less tolerant tree species in coastal urban green spaces (Hallett et al., 2018).

Lateral saltwater intrusion, where saltwater migrates inland through subsurface pathways, is considered one of the most impactful drivers for the salinization of most coastal areas over the long term (Barlow & Reichard, 2009). Though less widely studied, storm surge events, despite occurring on short temporal scales, can have greater impact through vertical saltwater intrusion, caused by flooding and rapid vertical infiltration of saltwater. Recovery time (RT) (the duration of time between initial storm-surge inundation to the return of the groundwater specific conductivity to baseline conditions) and penetration depth (maximum depth reached during vertical infiltration) are dependent on aquifer characteristics (Yang et al., 2018). Anderson (2002) estimated an aquifer recovery period greater than 3 years for a major hurricane overwash in a barrier island. The RT of the coastal aquifer in the Pukapuka Atoll after the category 5 cyclone Percy in 2005 was estimated to be around 1 year (Terry & Falkland, 2010). A similar event, occurred in a lower-permeability surficial aquifer, was felt up to 8 years after (Xiao et al., 2019). In 2013, saltwater intrusion due to supertyphoon Haiyan contaminated sandy aquifers of Samar Island, Philippines. The RT was estimated in 1–2 years (Cardenas et al., 2015). The effects of the 2004

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tsunami were felt in a shallow sandy aquifer in Sri Lanka 1–1.5 years after the event (Vithanage et al., 2012). Salinization triggered by hurricanes Katrina and Rita persisted until 10 months after landfall in the groundwater system of coastal Louisiana (Van Biersel et al., 2007).

Vulnerability of coastal areas has been shown to decrease when recharge and hydraulic gradients increase (Yang et al., 2018). Topography itself has an impact on groundwater salinization. Saltwater accumulated in depressions increases the mass of infiltrated salt, whereas connected channels can promote more extensive salinization (Yu et al., 2016).

Many studies have focused on the hydrological, ecological, and geomorphological consequences of hurricanes, characterized by large storm surges (Fagherazzi, Anisfeld, et al., 2019; Fagherazzi, Nordio, et al., 2019; Fernandes et al., 2018; Gardner et al., 2002; Middleton, 2016). Recently, more attention has been paid about the effects of frequent and moderate storm events on coastal areas (Beebe et al., 2022; Wilson et al., 2011, 2015). However, the coupling between hydrological processes and coastal ecosystems has not been studied in detail. Beebe et al. (2022) estimated the consequences of a moderate storm on submarine groundwater discharge (SGD), with the formation of an anomalous seawater intrusion in the groundwater system. Wilson et al. (2015) determined the magnitude and the main processes controlling temporal variations in tidally driven SGD caused by moderate storm surges. However, most of these studies focus on a specific site, and do not provide a broad picture of the groundwater response at the regional scale in different coastal environments. Here, we sought to quantify the effect of more frequent events on coastal groundwater dynamics, extending the analysis at the regional scale in very different settings, and to discuss the consequences of moderate storm surge events on the coastal ecosystems. Between 11 and 14 October 2019, tropical storm Melissa hit the North Atlantic shoreline from North Carolina to Massachusetts. The storm developed over the western Atlantic Ocean, never made landfall, and evolved from subtropical storm to tropical storm on 12 October (Figure 1). Coastal water levels reached between 1 and 1.5 m above predicted levels (National Oceanic and Atmospheric Administration [NOAA]). An event of the magnitude of tropical storm Melissa has a return period (RP), or frequency, of about 1–2 years. Here we synthesized available groundwater level and specific conductivity measurements collected in the North Atlantic region between 9 and 15 October 2019, to assess the effects of a frequent, medium-intensity storm surge on coastal groundwater at a regional scale.

2. Methods and Data

Methods and data used are explained in Texts S1 and S2 in Supporting Information S1.

3. Results

3.1. Increase in Groundwater Level Correlates With Distance From the Shore and Ground Elevation

Groundwater data were analyzed in wells distributed along the North Atlantic coast from North Carolina to Massachusetts (Figure 1, Tables S1–S3, Text S1 in Supporting Information S1). The increase in groundwater level during the storm surge was significantly correlated with distance from the coast ($R^2 = 0.61$, $p < 0.05$) (Figure 2a) and ground surface elevation ($R^2 = 0.57$, $p < 0.05$) (Figure 2b). As expected, the effect of the storm on groundwater levels diminishes at greater distances from the coast and higher ground elevations. Storm effects on groundwater reached a minimum value of 5 cm at 4 km from the coast and at a ground surface elevation of 11 m on NAVD88 (Figure 2a). Groundwater increments could also be attributed to freshwater contributions from rainfall. Therefore, the analysis was repeated excluding stations that recorded high rainfall rates (Data). The relationship did not significantly change when these stations were excluded (Figures S1c and S1d, Texts S1 and S2 in Supporting Information S1). A multiple regression analysis considering both topographic elevation and distance from the coast as independent variables was significant (adjusted-$R^2 > 0.65$, $p < 0.01$) (Table S4, Text S2 in Supporting Information S1). The mean and maximum water specific conductivity of the groundwater were not significantly correlated to elevation, distance from the shore, or well depth ($R^2 < 0.3$, $p > 0.05$) (Figures S3, S4, and Text S2 in Supporting Information S1).

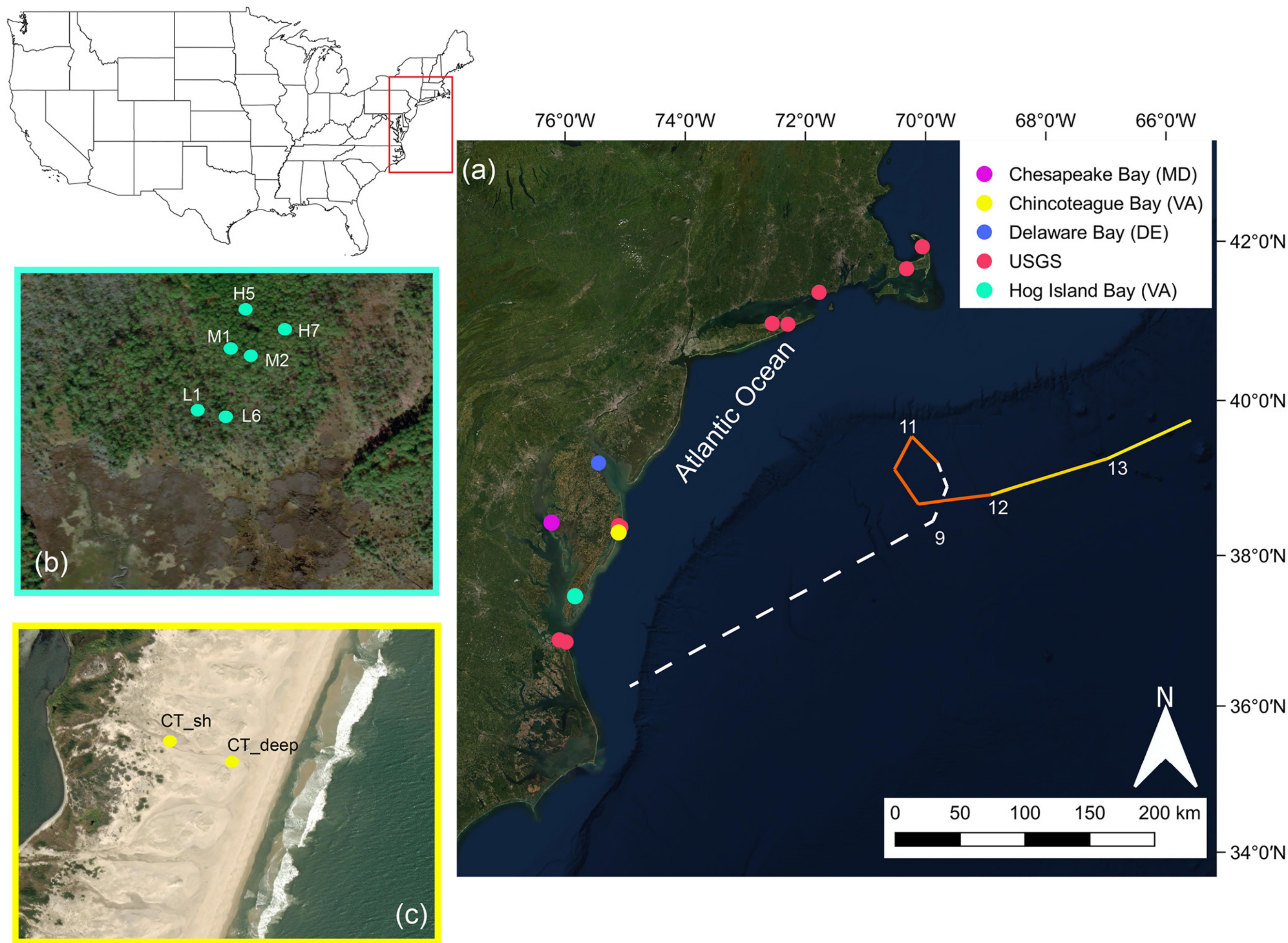

Figure 1. Well locations along the North Atlantic coast. Melissa storm track between 11 and 14 October 2019, according to National Oceanic and Atmospheric Administration (a). Before 11 October the storm was classified as extratropical (dashed white line). The storm was classified as subtropical between 11 and 12 October (orange lines) and as tropical from 12 to 14 October (yellow lines). (b) Well distribution in a forested area in Hog Island Bay; (c) well distribution on a beach in Chincoteague Bay.

3.2. Groundwater System Recovery After Storm Surge Event

Groundwater level and specific conductivity were significantly different before and after the storm ($t(3.24) > t_{crit}(2.09)$, $p < 0.05$ for groundwater level and $t(3.82) > t_{crit}(2.31)$, $p < 0.05$ for groundwater specific conductivity), suggesting that the pre-storm conditions did not immediately re-establish (Figures 3, 4a, and 4b). The median value of groundwater level after the storm was 6.25 cm with respect to pre-storm values. The median specific conductivity before the storm was 13.74 mS/cm, in comparison to a median specific conductivity of 31.50 mS/cm after the storm (Figure 4b). Overall, conductivity values reached along the North Atlantic coast during the Melissa storm event are comparable to seawater conductivity values, ranging from 20 in Chesapeake Bay (NOAA buoy id: 8635750) and 39 mS/cm in Delaware coast (NOAA buoy id: 8557380). Variability in groundwater levels before the storm is significantly higher than after, likely because of differences in vegetation, soil, and land use. Once the storm surge occurred, groundwater levels and specific conductivity became similar across sites.

The groundwater recovery duration from the Melissa surge varied significantly by site ($t(2.78) > t_{crit}(2.31)$, $p < 0.05$). Our analysis suggests that groundwater levels recovered faster than groundwater specific conductivity. The median RT was 2.2 days for groundwater levels, in comparison to 20 days for specific conductivity (Figure 4c). Additionally, RT of groundwater specific conductivity was more variable across sites. In particular, recovery times for conductivity estimated in clay soil were much higher than those estimated in sandy soil. In the

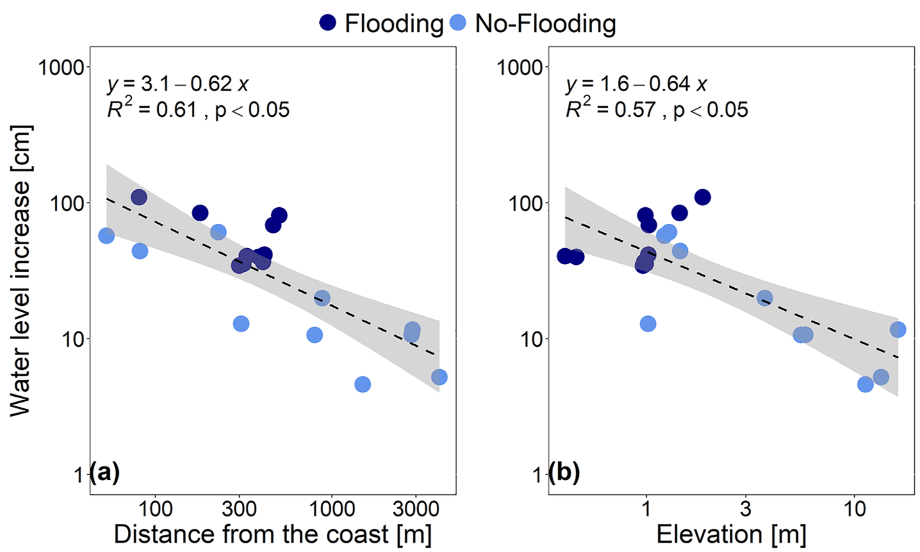

Figure 2. Increase in groundwater level during Melissa versus distance from the (a) coast and (b) ground elevation. Shaded areas represent 0.95 confidence interval. Flooding = sites flooded from above during Melissa, No-Flooding = sites not flooded from above.

clay forested area close to Hog Island Bay (VA) (Figure 1, Table S1 in Supporting Information S1), characterized by soil macropores and often wet, mean time to recover was 23 days. In the marshland in Leipsic (DE) (Figure 1, Table S1 in Supporting Information S1), characterized by clay soil, a smaller conductivity increase, due to the storm surge event, dampened by marshland vegetation friction, run out in a mean RT of around 4 days. In the sandy beach in Chincoteague Bay (DE) (Figure 1, Table S1 in Supporting Information S1), the estimated RT was around 17 hr on average. The RT of groundwater specific conductivity had an interquartile range of 26 days, nine times larger than the interquartile range of groundwater level RT (Figure 4c). Recovery time for both groundwater level and conductivity were found to be not correlated with distance from the ocean, ground elevation, and well depths (not shown). Moreover, recovery timescale of groundwater level was not clearly correlated to sediment type at the wells' screen, suggesting a possible strong influence of external inputs, local morphology, and vegetation (Figure S5 in Supporting Information S1).

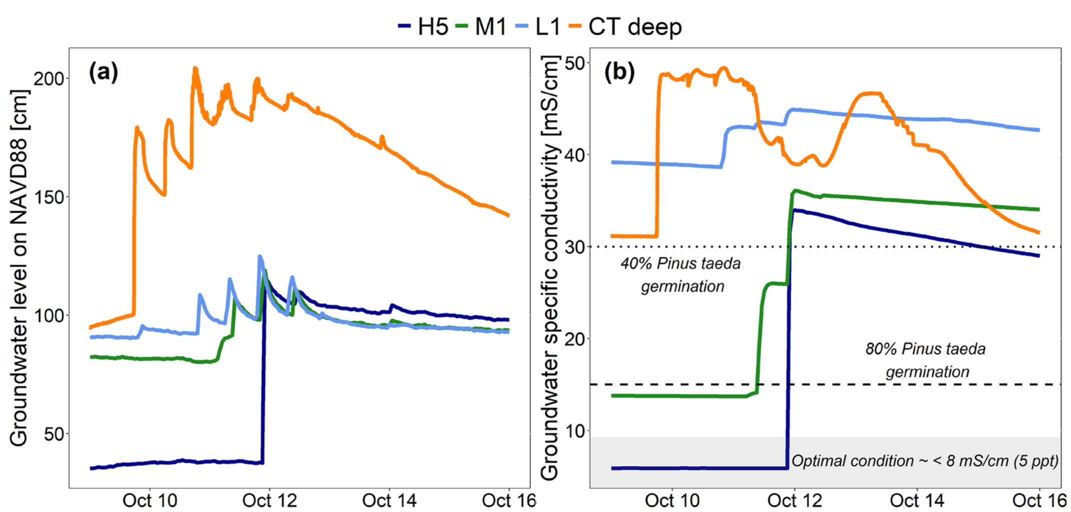

Figure 3. (a) Groundwater level and (b) specific conductivity data in Hog Island forested areas H5, M1, and L1 and in the deep well CT along the Chincoteague beach. Specific conductivity thresholds for *Pinus taeda* forests under controlled conditions are identified according to Woods et al. (2020). Photosynthetic activity of *P. taeda* is optimal when specific conductivity conditions are below 5 ppt in unsaturated soil conditions (Poulter et al., 2008; Woods et al., 2020).

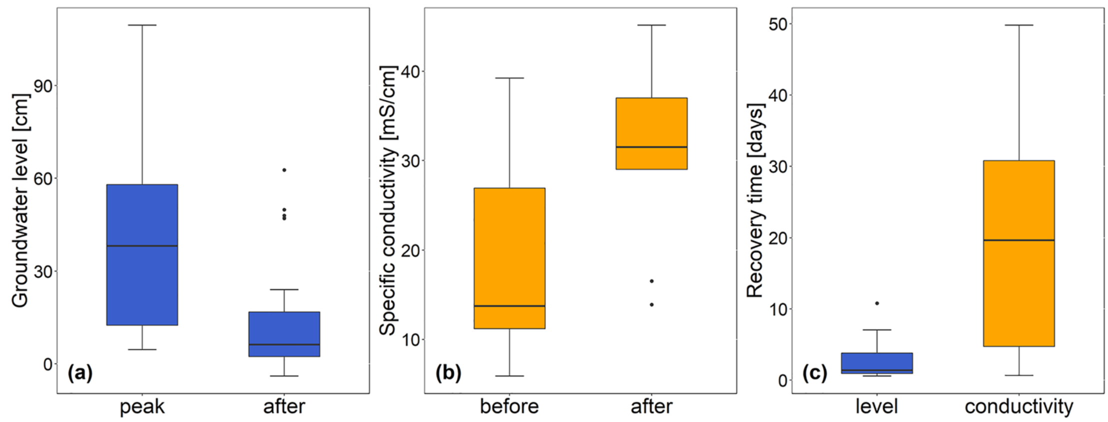

Figure 4. (a) Peak and after storm groundwater levels compared to pre-storm values, (b) groundwater specific conductivity values before and after a storm surge event. (c) Recovery timescale for groundwater level and specific conductivity.

Ratios between groundwater recovery timescale and RP for the Melissa storm were compared to similar ratios derived from the literature for other storms that affected coastal sites around the world (Figure 5). Ratios represent the percent of time during which the system is characterized by an anomalous conductivity and accounts for both the frequency and magnitude of the events. The different hydrological settings of the study sites justify the ratio variability. Despite the low storm surge, Melissa ratios were similar to ratios representing very energetic hurricanes of category 3 and 4. This is because the RP of Melissa is much lower than a hurricane, thus increasing the percent of time with salinization. During Melissa, the ratio reached a value of 0.054 in clay soils, the highest values calculated in the analysis. Here, clay soil and the presence of soil macropores, mostly created by uprooting of dead trees and dense understory vegetation, encourage water retention and water infiltration during storm events, significantly increasing groundwater conductivity and making recovery times longer. A lower ratio of 0.022 estimated in a marsh in Leipsic (DE clay soil) (Figure 1, Table S1 in Supporting Information S1) was related to a smaller conductivity increase occurred during the storm surge event. The smallest value of 0.01 was reached in a sandy beach in Chincoteague Bay (DE) (Figure 1, Table S1 in Supporting Information S1), due to the weaker ability of the soil to retain water.

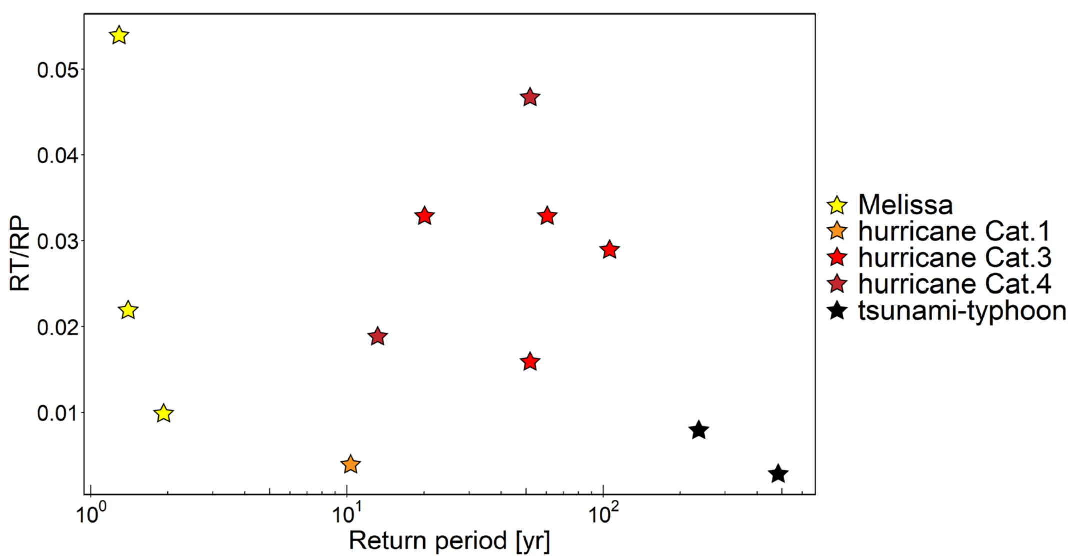

Figure 5. Ratios between recovery time and return period for different storm events. Data were derived from the literature (Anderson, 2002; Cardenas et al., 2015; Hedgespeth et al., 2021; Keim et al., 2007; Kiflai et al., 2020; McDowell et al., 1996; Sawyer et al., 2014; Terry & Falkland, 2010; Van Biersel et al., 2007; Vithanage et al., 2012; Wachnicka et al., 2020; Williams, 1993).

4. Discussion

The medium-intensity storm surge (RP ~1–2 years) of Tropical Storm Melissa affected coastal groundwater levels and specific conductivity at a regional scale along the eastern shore of the United States. The groundwater level increase due to the storm surge is significantly larger in wells closer to the ocean and at lower elevation. Nine wells at four sites, reaching a maximum distance of 500 m from the coast, comprise a representative sample of coastal environments on the northeastern seaboard. In our analysis we quantify the overall effect of a moderate storm surge event on coastal groundwater systems located in different landscapes. For instance, similar or smaller events can be significantly felt in barrier islands, where run-up mechanisms encourage an increase in groundwater level and conductivity. The same events can be slightly or no felt in inland marshland areas, where the water signal reaching the wells is dampened. Tidal pumping and wave setup are the main driving forces of groundwater flow through the beach and they tend to exacerbate the storm surge effects on sloping surfaces (Evans & Wilson, 2017; Nielsen, 1999). On the other hand, during its flow from the ocean to a coastal forest bordering a marshland, the water energy dissipates due to marsh vegetation friction, and the storm surge effect is reduced (Leonardi et al., 2018; Nordio and Fagherazzi, 2022; Stark et al., 2015). While we are able to draw general conclusions from this limited sample, these results highlight the value of additional intensive groundwater monitoring in the coastal zone, to capture the dynamics of SLR and coastal saltwater intrusion. Since medium intensity storm events have been occurring more frequently in the last century (Knutson et al., 2010; Landsea et al., 2010), they could change groundwater characteristics and consequently undermine ecological communities.

Our data suggest that a medium-intensity storm surge can negatively affect groundwater dynamics, preventing a complete recovery once the storm surge stops. Soil needs time to drain to restore the levels present before the storm surge. Drainage can require between 1 and 10 days in the absence of similar events. As the soil starts to drain, the salt concentration in the groundwater tends to decrease. The recovery timescale in shallow aquifers is around 10 times higher for specific conductivity than for groundwater level. Inter-storm arrival times (Khaertidova & Longobardi, 2013) and hydrogeological characteristics control RT (Knutson et al., 2010; Terry & Falkland, 2010; Yang et al., 2018). Evapotranspiration rate can also accelerate the groundwater level recovery (Gardner et al., 2002). At the same time, storm surge salinization is exacerbated by both evaporation and evapotranspiration processes. In intertidal coastal areas, salinity values are often higher than those recorded in seawater (Geng & Boufadel, 2015; Geng et al., 2016, 2021; Rajmohan et al., 2021). This especially occurs in the upper intertidal zone, that is less affected by tides and waves inundation, so that the new water can dilute pore water salinity (Geng et al., 2016). When meteorological conditions are favorable to high evaporation (i.e., high temperature and low humidity) capillary fringe increase soil moisture in the upper soil layer, encouraging water evaporation and consequently salt concentration (Geng & Boufadel, 2015; Geng et al., 2016, 2021). Groundwater modeling conducted on sandy beaches suggests a doubling in salinity in the intertidal zone when evaporation is considered (Geng & Boufadel, 2015). Geng and Boufadel (2015), showed that after maximum salinity values are reached during a spring tide, salinity decreased slowly due to the brackish water surrounding the beach site. After storm surge events, salinity values are higher, and evapotranspiration likely increases salinization with deleterious effects for non-salt tolerant ecosystems. The estimated time to recover from a medium-intensity storm surge event is shorter than the RT after a hurricane (Cardenas et al., 2015; Vithanage et al., 2012). However, hurricanes are less frequent, and therefore the relative time during which salinization occurs is shorter.

Specific conductivity dynamics follow the groundwater level and an upward salt flux toward the root zone can trigger changes in plant health (Mohamed et al., 2000; Munns & Tester, 2008). A recovery timescale of months for groundwater specific conductivity can be crucial for salt-intolerant vegetation, particularly if it occurs with a RP of only 1 or 2 years. In this scenario, along forested areas close to marshland, mature trees can defoliate or die (Fagherazzi, Anisfeld, et al., 2019; Fagherazzi, Nordio, et al., 2019). *Pinus taeda* dominates maritime forests in the southern portion of our study region (Hog Island and Chesapeake Bay sites). This tree is moderately flood-tolerant (Pezeshki, 1992) and able to establish and survive in specific conductivity conditions up to 5 ppt (~8 mS/cm at 20°C) (Poulter et al., 2008; Woods et al., 2020). Seedlings are more sensitive to specific conductivity increase while mature trees can show greater salt tolerance (Kirwan et al., 2007; Poulter et al., 2008). Woods et al. (2020) observed that, under controlled conditions in a growth chamber, *Pinus taeda* germination was unaffected at up to 10 ppt (~17 mS/cm at 20°C) salinity and germination was reduced by half when salinity was 20 ppt (~32 mS/cm at 20°C). The groundwater specific conductivity levels reached during the Melissa storm surge were between two and five times higher than the tolerated conductivity levels. These high salinity levels can affect photosynthetic dynamics, stomatal conductance, and biomass production (Pezeshki, 1992). Stress due to inundation can compound the stress of saltwater exposure (Pezeshki, 1992; Poulter et al., 2008). Pitch pine (*Pinus rigida*), black oak (*Quercus velutina*), and white oak (*Quercus alba*) dominate forests at the Wellfleet site (Hall et al., 2002; Smith et al., 2011). Pitch pines are quite intolerant to salt spray (Griffiths & Orians, 2004) and succumb to total immersion in two to 4 weeks (Craine & Orians, 2006). Oaks, however, can survive but only at conductivity levels up to 4 mS/cm (Kotuby-Amacher et al., 2000). In farmland sites, salinity levels tolerated by the crops are generally up to 2 ppt (∼4 mS/cm at 20°C) (Tully et al., 2019), much lower than salinity levels reached during Melissa. Storm surge events not only directly affect the survival of native species, but also encourage encroachment of more flooding and salt tolerant plants that establish in the disturbed ecosystem (Noto & Shurin, 2017).

According to our analysis, the estimated groundwater recovery times are sufficiently lower than the RP of Melissa so we can suppose that, in absence of external competitors, once original conditions are re-established, vegetation regeneration restarts. However, SLR and global warming will decrease the RP of these storms in the near future, and a subtropical storm event like Melissa will have more drastic consequences. For example, with a sea level increase of 50 cm, the magnitude of a storm surge like Melissa could become comparable to storm surges that today have a return time between 5 and 14 years (Figure S6 in Supporting Information S1). Therefore, moderate but frequent storm events could affect ecosystems survival, frequently changing hydrological conditions and consequently stressing photosynthetic activity of native species (Budke et al., 2008; Vreugdenhil et al., 2006). Although major hurricanes and storms have catastrophic consequences on society and economy, moderate but frequent storm surge events also contribute to ecological change.

Our analysis indicates that the groundwater level and specific conductivity are similar across the studied wells after Melissa, suggesting more homogeneous groundwater post-storm conditions. This mainly occurs in shallow aquifers. Hydrological variability can be a crucial driver of biodiversity at most scales of analysis (Konar et al., 2013). Therefore, this homogenizing phenomenon might drastically reduce biodiversity and consequently affect ecosystem functioning (Konar et al., 2013). At some coastal locations, SLR and frequent tropical storms are already reshaping the landscape with an irreversible impact on biodiversity (Allen & Lendemer, 2016; Burkett et al., 2008), and consequently affect socio-economic development (Midgley, 2012; Sylvain & Wall, 2011). Here we put forward the hypothesis that homogenization of conductivity and groundwater levels driven by moderate storms can be partly responsible for loss of biodiversity.

The United States Geological Survey (USGS) stations used herein do not include specific conductivity measurements. The paucity of available conductivity data hampered our analysis on the extent of groundwater salinization due to Tropical Storm Melissa. Conductivity monitoring across a broad swath of the coastal zone is imperative to detect how climate change affects coastal groundwater resources. Our study is unique because in the past, salinization and flooding due to storm surge events have been investigated at the continental scale using only numerical models (Guimond & Michael, 2021; Knutson et al., 2010; Paldor & Michael, 2021; Yang et al., 2018). This research illustrates the value of field studies of saltwater intrusion and highlights a broader need for large-scale data sets.

5. Conclusions

Our analysis demonstrates that frequent storm surges (RP ∼1–2 years) affect groundwater at a regional scale. Groundwater level and specific conductivity increased after Tropical Storm Melissa up to 4 km inland. The change in groundwater level decreased with elevation and distance from the coast. Recovery time of groundwater specific conductivity was 10 times greater than the RT of water level in shallow wells. A frequency-magnitude analysis indicates that the percent of time with salinization after Melissa is of the same order if not higher than the relative salinization periods of energetic hurricanes and tsunamis, highlighting the potential damage of moderate but frequent storms on coastal ecosystems.

Long high-conductivity periods can trigger forest dieback and favor the encroachment of new vegetation species. Groundwater level and specific conductivity after the storm surge were more uniform. This homogenizing process can trigger loss in biodiversity, encouraging the establishment of monotonic halophyte vegetation. Large-scale efforts to monitor groundwater conductivity in the coastal zone can help to characterize the effect of ever-more frequent storms on groundwater and related ecosystems to inform resource management.

Data Availability Statement

Part of the data supporting findings of this research are openly available in the Long Term Ecological Research-Virginia Coast Reserve (LTER-VCR) at https://doi.org/10.6073/pasta/942a5a981e6e986c5fa1a9a9cd2eb8b7, in the National Oceanic and Atmospheric Association (NOAA) repository at https://www.noaa.gov/ and in the United States Geological Survey (USGS) repository at https://doi.org/10.5066/P9XQ27F5 and https://doi.org/10.5066/F7P55KJN.

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