The results indicate that the salinity variations in tidal estuaries impact significantly on estuary–aquifer interaction and need to be accounted for to properly assess salinity and flow dynamics and groundwater residence times of riparian zones.

So if we know that salinity variations in tidal estuaries significantly impact estuary-aquifer interactions, then we need to know how these interactions have changed through time and how they are projected to change in the future.

Prime et al. [14] demonstrated that modeled flood extent is grossly underestimated when cumulative (and nonlinear) multiple flood pathway impacts are not considered, and that resulting costs grow disproportionately.

Saltwater intrusion and the degree of upland salinization are driven by five main factors: the position of sea-level relative to the land and water table, the frequency and magnitude of storms and tides, the frequency and duration of drought, water use (e.g., surface and groundwater withdrawals for drinking water and irrigation), and hydrologic connectivity (e.g., tide gates, levees, agricultural, diversions, and roadside ditches, and canals; figure 1). Because each of these five factors are themselves variable in space, time, frequency, and duration, the process of ecosystem salinization is extremely dynamic and can occur slowly or quickly, depending on

Cooper, 1959; Glover, 1959; Moore, 1996; Weinstein et al., 2007). Areas around streams, 45

rivers, lakes and coastal environments represent zones of interaction and transition 46

between the two systems, where dissolved constituents such as pollutants can be diluted, 47

exchanged, transformed or degraded. Identifying predominant processes affecting solute 48

exchange across transition zones is therefore critical (Bear et al., 1999; Oz et al., 2011; 49

Post, 2005).

(Tully et al. 2019)

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(Bhattachan et al. 2018)

Where wetlands have been drained and tilled, elevation loss through soil oxidation and enhanced hydrologic connectivity via ditch and canal systems may exacerbate both the frequency and the extent of saltwater intrusion by facilitating the movement of water between interior coastal landscapes and the sea (Hackney and Yelverton, 1990; Turner, 1997; Doyle et al., 2007; Manda et al., 2014; White and Kaplan, 2017).

In low relief landscapes, it is primarily freshwater flow that limits the movement of saline water inland, against the intuitive land-to-sea gradient. During periods of extended drought, a lack of flow together with strong landward winds off the coast can push saline water inland (e.g., Day et al., 2007; Anderson and Lockaby, 2012; Ardon et al., 2013).

Here we develop a tool, the Saltwater Intrusion Vulnerability Index (SIVI), which combines the effects of sea level rise with freshwater flow routing and accumulation in order to assess the vulnerability of coastal ecosystems to saltwater intrusion via surficial drainage ways. In this study, we apply SIVI to a portion of the Albemarle-Pamlico Peninsula (APP), a coastal landscape in North Carolina where most of the landscape is below 1.5 m mean sea level in elevation with respect to National Geodetic Vertical Datum (Moorhead and Brinson, 1995; Titus and Richman, 2001).

In this study, we examine the extent to which artificial drainage infrastructure has altered the potential for salt- water intrusion in the APP. We hypothesize that current drainage infrastructure supporting agriculture in this region has increased the vulnerability to saltwater intrusion in surface waters in this region by altering patterns of flow routing and flow accumulation. We use a high-resolution digital elevation model (DEM) and related geospatial datasets to identify and remove artificial drainages and other human infrastructure. We perform geospatial analyses on the original DEM with artificial drainages and the modified DEM without artificial drainage infrastructure. We use these analyses to estimate the effect of highly connected artificial drainages on hydrological flow in a low gradient coastal landscape, and we discuss implications for major land uses within the region.

In this study, we showed that artificial drainages not only increased the drainage density of the landscape but also altered flowpaths in ways that reduce the ability of fresh- water flows to counter the effects of saltwater intrusion. Even in areas that lacked local artificial drainages, hydro- logic flows were affected due to the large-scale nature and connectivity of flow networks.

(Nobi and Gupta 1997)

The simulation of the regional flow and solute transport in a hydraulically connected stream-aquifer system has received very little attention.

(Poulter, Goodall, and Halpin 2008)

Drainage networks were originally built to drain wet-lands and lower water tables to encourage human settlement, agricultural use or forestry ( Holden et al., 2004; Lilly, 1980). These drainage networks now have the potential to act as conduits that contribute to inland flooding during storms and salt-intrusion during episodes of sea level rise.

(Smith, Hafner, and Niles 2017)

Tidal marshes with higher marsh accretion rates and capacity for inland migration offer the potential for long-term persistence, particularly in estuaries with moderate to high tidal ranges (Kirwan et al., 2016). The Delaware Estuary, in concept, should represent a sea level rise-resilient tidal marsh system, with moderate (1.6e1.8 m) tidal range (Galperin and Mellor, 1990), high suspended sediment loads (Cook et al., 2007) and large frontage of undeveloped tidal marsh/upland ecotone (Smith, 2013) to allow for inland transgression (Kirwan et al., 2016). Despite these attributes, large acreages of these marshes have converted to open water and a significant proportion of the remaining marsh is in degraded condition (Kearney et al., 2002).

We estimate that more than half Delaware Estuary tidal marshes were subject to impoundment for farming from early colonial period through the early 20th century. By comparing formerly farmed marshes with marshes that were never impounded, we demonstrate that impoundment has left lasting impacts, with important implications for tidal marsh resiliency to sea level rise. The primary impact is lower marsh surface elevation, which in turn has resulted in a reduction of high marsh vegetation and the loss of approximately 4000 ha of marsh to open water, comprising the largest single contributor to marsh loss in the study area.

(Masterson and Garabedian 2007)

This article presents an analysis of a hypothetical aquifer consisting of a shallow, permeable, fresh water lens system similar to those found along the Atlantic coast of the United States to demonstrate that the nontidal portions of ground water fed streams can affect the changes in nearby water levels and the depth to the underlying fresh water/salt water interface resulting from sea-level rise.

The effects of sea-level rise on water levels, streamflow, and the position and movement of the fresh water/salt water interface were determined by simulating a change in the altitude of sea level of 2.65 mm/year from 1929 to 2050. The effect of the resulting increase in tidal influence in the stream with rising sea level was determined by two simulations—stream stage remaining constant through the simulation period and stream stage increasing with an increase in sea level.

The decline in the water table altitude relative to local sea level can be explained by the presence of the ground water fed stream, which prevents the surrounding water table from rising appreciably above the altitude of the streambed. As the water table rises in response to sea-level rise, the amount of ground water discharge to the stream increases because the increased height of the water table adjacent to the stream results in increased streamflow rather than a higher water table altitude at the stream.

Ground water fed, or gaining, streams prevent the adjacent water table from rising much above the altitude of the streambed. As the water table rises in response to sea-level rise, the amount of ground water discharge to the stream increases because the increased height of the water table adjacent to the stream generates more stream-flow rather than a higher water table altitude. Our simulation results show that the discharge to this stream when we assumed that the stream was not tidally influenced nearly doubled in response to sea-level rise from 1929 to 2050. As stream stage rose in the lower reach of the stream during the tidal simulation, there was a corresponding decrease in streamflow. The difference in total streamflow between the tidal and nontidal simulations was about 15% by 2050.

The assumption that the primary threat to coastal aquifer systems from rising sea levels is the increased potential for surface inundation of saline water in low-lying areas does not consider the potential for a decrease in fresh water lens thickness from a net decrease in water levels relative to an increased sea-level position. This net decrease in water levels results in a decrease in the depth to the fresh water-salt water interface as described by the Ghyben-Herzberg relation.

The extent to which water level altitudes decline relative to an increased sea-level position is directly related to the proximity of ground water fed streams and whether the streams are tidally influenced. As the water table rises in response to a rise in sea level, the amount of ground water discharge to streams increases because the increased height of the water table adjacent to the streams generates more streamflow rather than a higher water table altitude. The effect that ground water fed streams have on water levels and the depth to the fresh water-salt water interface diminishes as the extent of tidal influence in streams prop-agates inland with the rising sea levels.

(Mazi, Koussis, and Destouni 2016)

To relatively simply address and quantify the SWI response to forcing changes, Koussis et al. (2012 ) developed an analytical framework that extends previous analytical solutions (Strack1976 ). This extended framework has been used, for instance, to assess the proximity of prominent Mediterranean aquifers to the site-specific critical thresholds that determine the above-mentioned tipping points under prevailing aquifer conditions.

(Lenkopane et al. 2009)

The results indicate that the salinity variations in tidal estuaries impact significantly on estuary–aquifer interaction and need to be accounted for to properly assess salinity and flow dynamics and groundwater residence times of riparian zones.

So if we know that salinity variations in tidal estuaries significantly impact estuary-aquifer interactions, then we need to know how these interactions have changed through time and how they are projected to change in the future.

(Montagna, Palmer, and Pollack 2013)

Given the unprecedented change in the water cycle caused by human and cli- mate systems, there are clear needs to manage water resources in the coastal zone using an ecosystem-based approach to protect human health and well-being by sustaining coastal resources. Considerable scientific information is needed to man- age coastal ecosystems, such as: What affect will altered freshwater inflow have on coastal resources? What are the relative magnitudes of effects driven by human activities versus climate change? The focus of management initiatives must shift to land planning efforts that conserve water, prevent polluted runoff and groundwa- ter contamination, restore the physical integrity in aquatic ecosystems by increas- ing natural flow regimes, and promote and protect ecosystem services that could potentially be produced (Ruhl et al. 2003). Despite

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