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SANTA CRUZ

SEASONAL CHANGES IN TERRESTRIAL FRESHWATER INPUTS IMPACT SALT MARSH HYDROLOGY

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Maya Shiri Montalvo

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The Thesis of Maya Montalvo is approved:

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Asst. Professor Margaret Zimmer, chair

____
Professor Andrew Fisher

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Research Professor Adina Paytan

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Peter Biehl
Vice Provost and Dean of Graduate Studies

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Abstract

SEASONAL CHANGES IN TERRESTRIAL FRESHWATER INPUTS IMPACT SALT MARSH HYDROLOGY

by

Maya Shiri Montalvo

Salt marshes exist at the terrestrial-marine interface, serving as hotspots for nutrient cycling of tidal and freshwater inputs and providing critical ecosystem services. Tidal inputs are understood to play a dominant role in salt marsh pore water mixing, and terrestrially derived freshwater inputs are increasingly recognized as important sources of water and solutes to intertidal wetlands. However, there remains a critical gap in understanding of the role of shallow terrestrial freshwater inputs on salt marsh hydrology, with implications for plant productivity and biogeochemical cycling. Here, we examine the hydrologic behavior, pore water salinity, and pickleweed (*Sarcocornia pacifica*) productivity across three marsh positions in an estuary along the central coast of California to understand how seasonal changes in terrestrial freshwater inputs impact salt marsh processes. We found that salt marsh pore water salinity, pickleweed productivity, and water level tidal signal dampening (i.e. shallow subsurface saturation) are closely coupled with elevated upland water level during the winter and spring, and dominated by tidal inputs during the summer and fall, indicating a seasonal switch in salt marsh hydrologic connectivity with the terrestrial upland. Terrestrial freshwater inputs to the salt marsh depend on water level in the adjacent upland, which fluctuates seasonally and is driven by seasonal and interannual precipitation inputs — highlighting the sensitivity of salt marsh hydrology to climate change.

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1. Introduction

Salt marshes are intertidal wetlands that exist at the land-sea interface, where dynamic mixing of marine and terrestrial waters occurs. Salt marshes are highly productive ecosystems that provide critical services for coastal ecology and biogeochemical processes (Shepard et al., 2011), such as storm buffering (Valiela & Cole, 2002), carbon sequestration (Mitsch & Gosselink, 2000), and nutrient cycling (Verhoeven et al., 2006; Velinsky et al., 2017; Wang et al., 2020). Traditionally, focus has been on identifying the role of tidal conditions, and more recently sea level rise, on wetland function (Moore, 1999; Wilson & Gardner, 2006), however the impact of groundwater and other terrestrial freshwater inputs on wetland hydrology remains understudied (Guimond & Tamborski, 2021).

Groundwater-surface water exchange in coastal environments has often been examined as part of submarine groundwater discharge (SGD) (Santos et al., 2012; Wilson et al., 2015a). However, deep groundwater flow paths in SGD studies are often not connected to or circumvent salt marshes; there has been less focus on the role of shallow terrestrial freshwater sources that are disconnected from regional aquifers, comprising an important knowledge gap in understanding of hydrologic controls on salt marsh function (Breier et al., 2009; Robinson et al., 2017; Taniguchi et al., 2019). In this paper, we seek to improve our understanding of the impact of seasonal freshwater inputs on hydrologic behavior in marsh systems. Unraveling the role of seasonal shallow freshwater inputs to salt marshes is especially relevant due to climate change, as sea level rise and shifting climate regimes alter hydrologic inputs to coastal systems, and has implications for wetland ecology and biogeochemical processes.

Freshwater from terrestrial sources has been identified as a critical component of surface water - groundwater interactions in salt marshes, and influences salt marsh ecology and biogeochemistry. Tidal forcing dominates groundwater flow in coastal wetlands (Wilson & Gardner, 2006), however water table elevations in adjacent uplands control hydraulic gradient directions (Guimond et al., 2021), which has implications for pore water flow and solute exchange (Xin et al., 2022). Shallow groundwater inputs to salt marsh systems impact marsh soil saturation, salinity, and pore water quality (Gardner & Reeves, 2002). Changes in soil and pore water conditions strongly impact salt marsh vegetation zonation and plant productivity (Pennings et al., 2005; Wilson et al., 2015b; Moffett et al., 2010), which are linked with and have implications for salt marsh biogeochemistry and nutrient processing (Valiela et al., 1978; Nuttle & Hemond, 1988; Wilson & Morris, 2012; Santos et al., 2021).

This paper aims to identify the role of shallow seasonal freshwater inputs on salt marsh hydrology and to identify linkages between marsh hydrology and marsh salinity and vegetation. To address knowledge gaps concerning the impact of seasonal freshwater inputs on marsh hydrologic behavior, we developed a study transect across a salt marsh in the Elkhorn Slough, an estuary located along the central coast of California. The study transect comprises an upland and three marsh positions delineated based on elevation and degree of tidal inundation. We instrumented each study position with piezometers for routine pore water sampling to assess chemistry, and in situ pressure sensors to monitor changes in pore water level. We collected soil cores from each of the marsh positions to characterize subsurface soil stratigraphy and structure, and downhole nuclear magnetic resonance surveys were conducted at each marsh position to identify changes in pore water availability and porosity with depth. We conducted monthly surveys of salt marsh vegetation biomass metrics and collected spectral imagery using an unmanned aerial vehicle (UAV) to monitor spatial and temporal changes in vegetation activity.

2.1 Background

2.1.1 Elkhorn Slough

The Elkhorn Slough is a shallow estuary that terminates into the Monterey Bay National Marine Sanctuary along the central coast of California (Figure 1). The Elkhorn Slough is California's second largest estuary, 11 kilometers long from mouth to head and 3.8 km^2 in area. The estuary is dominated by a mixed semidiurnal tidal cycle and does not have a perennial surface water input at its head; instead, the Salinas River meets the Elkhorn Slough at its mouth (Figure 1A) and is the main freshwater input to the estuary (Wong, 1989). The dominant land use surrounding the Elkhorn Slough is agricultural, and consists of row crops such as strawberries, lettuce, and brussels sprouts. Intensive agricultural practices have resulted in excessive nutrient inputs to the estuary and Monterey Bay, negatively impacting water quality and resulting in eutrophic conditions in some areas (Jeppesen et al., 2018). The region is dominated by a Mediterranean climate, receiving the majority of its rainfall during the winter and spring, and little to none during the summer and fall. This strong seasonality results in precipitation inputs being out of phase with the growing season during the summer and fall, which provides an opportunity to study seasonal changes in salt marsh hydrologic behavior. The Elkhorn Slough receives an average annual rainfall of 600 mm/year, though this can vary greatly (200-1,150 mm/year) with wet years receiving significantly more rainfall and drought periods lasting 2-6 years (Caffrey et al., 2002).

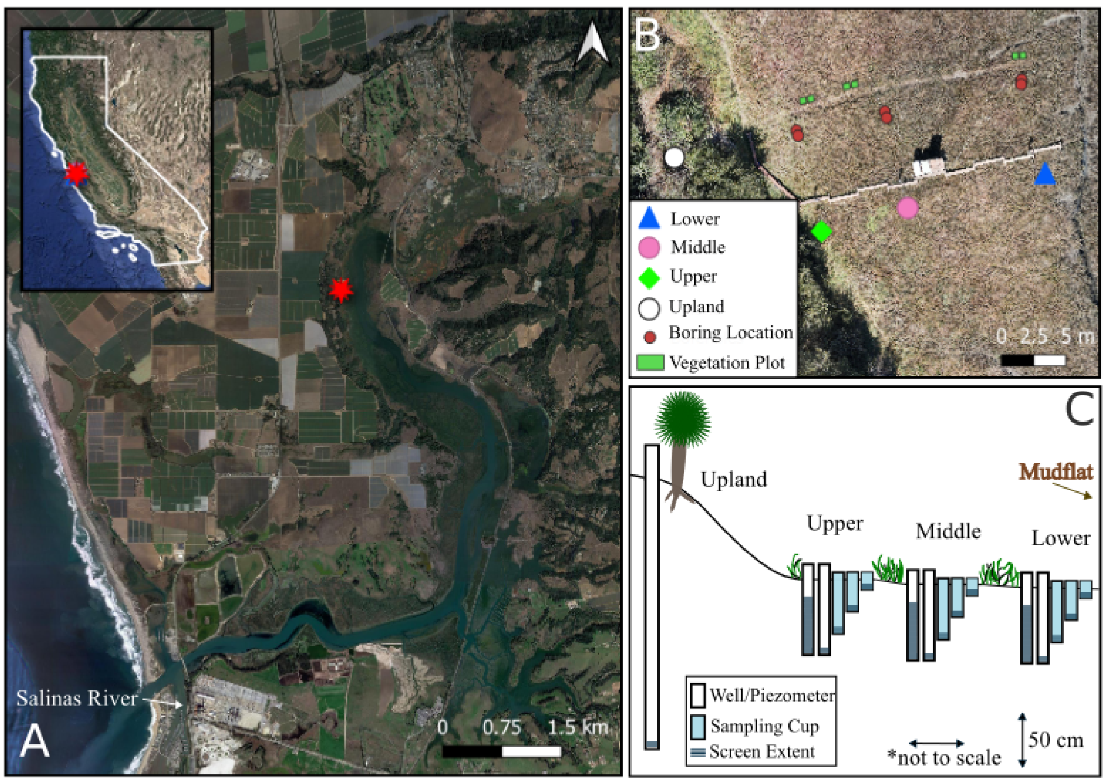

Figure 1. Map of study site at the Elkhorn Slough (36°49′00″N, 121°46′00″W). The red star in panel A shows the location of the Cowell Ranch study site relative to the estuary. The study transect with vegetation survey plots and delineated upland and marsh positions are shown in panel B. Water level data collection and water quality sampling infrastructure are shown in panel C (note: horizontal distance not to scale).

2.1.2 Cowell Ranch study site

We conducted this study at the Elkhorn Slough National Estuarine Research Reserve (ES NERR), with most work being completed at an emergent salt marsh, Cowell Ranch (36°51'5.93"N, 121°45'44.62"W), located in the upper northwest reach of the estuary approximately 9 km from the mouth (Figure 1A). The site is tidally influenced and unrestricted, and lies along the intertidal zone with a local tidal range of -0.54 to 2.21 m (relative to NAVD88). The experimental transect of four distinct study positions spans 25 meters between the terrestrial uplands and the lower boundary of the salt marsh (Figure 1B). The portion of transect spanning the salt marsh was delineated by elevation into upper (1.71 m - relative to NAVD88), middle (1.65 m), and lower (1.59 m) salt marsh positions based on differences in average tidal inundation duration: 5.4%, 7.2%, and 9.6%, respectively. We designated a terrestrial upland study position ~5 m from the upland-marsh margin at an elevation of 2.78 m.

An instrumentation nest was installed at each marsh study position consisting of co-located wells, piezometers, and sampling cups. A single piezometer was installed in the upland position (Figure 1C, section 2.2.4). We collected high-resolution *in-situ* water level measurements and conducted monthly water quality sampling campaigns at each site. Additionally, we identified representative upper, middle, and lower marsh positions based on elevation along an adjacent transect approximately 10 m to the north to conduct monthly vegetation surveys, characterize subsurface soil properties from soil cores, and survey the subsurface using nuclear magnetic resonance (NMR) (Figure 1B).

The salt marsh vegetation is dominated by pickleweed *(Sarcocornia pacifica)*, a perennial halophyte native to North America, while the upland consists of coastal scrub vegetation, pacific willow *(Salix laevigata)*, and coast live oak *(Quercus agrifolia)* woodland. Pickleweed can tolerate low (~3 ppt) to high (>40 ppt) pore water salinities, with optimal productivity observed around 28 ppt (Watson & Byrne, 2009). Pickleweed productivity is highest during the summer and fall growing seasons, with plant senescence and dormancy occurring during the late fall through winter. The plots designated for vegetation surveys are composed exclusively of pickleweed, but other species exist along the upland and upper marsh margin, such as alkali heath *(Frankenia salina)* and salt grass *(Distichlis spicata)*.

2.2. Methods

2.2.1 Soil characterization

We collected two soil cores at each of the marsh positions in February and March 2021 to characterize subsurface soil properties (Figure 1C). We extracted these 5 cm diameter soil cores using a Russian Peat Borer (Aquatic Research Instruments, Idaho, USA) during low tide conditions. We extracted the soil cores in 50 cm intervals until we reached the depth of refusal at each of the marsh positions: 1.7 m, 2 m, and 3 m deep in the upper, middle, lower marsh position, respectively. Each borehole was converted to a piezometer by installing 2" Schedule 40 polyvinyl chloride (PVC) screen and casing to tightly fit the borehole diameter, except for one upper marsh borehole which was backfilled with sphagnum peat moss. Core sections were photographed upon extraction, then wrapped in plastic wrap and placed in PVC cradles to maintain their moisture content and physical integrity. The cores were stored at 4°C and subsampled within two days of extraction. Soil analyses began immediately after subsampling. Subsamples were collected at 5 cm intervals for the top 70 cm-bgs, and at 10 cm intervals for the remaining portion. We analyzed the sediment for bulk density (ρ), soil moisture content (θ), organic matter content (OM), content and stable isotopic composition of organic carbon and nitrogen, and particle size. Results for ρ, θ, and OM are reported in this study. The methods for the soil analyses were adapted from the LacCore Grain Size Pretreatment SOP (2007), Belknap & Kraft (1977), Kemp & Haven (2013), and Kirwan et al. (2011) .

We used an olive pitter to collect a uniform cylindrical volume (V) at each of the subsampling depths, determined wet weight (WW), dried at 100°C for a minimum of 12 hours, and re-weighed for dry weight (DW_1). We calculated bulk density and soil moisture content as:

Eq. 1 $$\rho = \frac{DW_1}{V}$$

Eq. 2 $$\theta = \frac{(WW - DW_1)}{DW_1} * 100\%$$

We gently crushed the dry weight sample using a mortar and pestle, dried and re-weighed to find the new dry weight (DW_2), burned at 500°C for 12-15 hours in a muffle furnace, and weighed the post-ignition weight (BW) in order to calculate OM:

Eq. 3 $$OM = \frac{DW_2 - BW}{DW_2} * 100\%$$

2.2.2 Partitioning of soil water

We used nuclear magnetic resonance (NMR) logging to determine the partitioning of soil water at high-resolution measurements in the upland and salt marsh positions with a Dart 140J NMR Logging Probe (Vista Clara, Inc.). The technology has been used extensively in the oilfield to estimate reservoir porosity and permeability (e.g. Kleinberg), and with the advent of portable instrumentation (Walsh et al., 2013), NMR logging has been used to estimate properties of groundwater aquifers (Knight et al., 2015). More recent research has demonstrated the use of NMR in the unsaturated vadose zone and in organic soils (Costabel and Hiller, 2021, Minsley et al. 2016).

An in-situ NMR relaxation measurement directly detects hydrogen in pore fluids. The signal amplitude can be used to directly quantify the fluid volume (i.e. volumetric water content) and the relaxation time (T_2) is influenced by the ratio between the pore water volume and the wetted grain surface area. Mobile water in large pores has a longer T_2 and more bound water in small pores has a shorter T_2. In saturated materials, the NMR volumetric water content reflects the porosity and the T_2 relaxation times are interpreted as a proxy for pore size distribution.

In this study, NMR surveys were conducted in November 2021, one week after receiving ~27 mm of rain following the end of the dry season, in the salt marsh soil core extraction boreholes (one survey per salt marsh position) and in one upland borehole adjacent to the piezometer (Figure 1C). The sensor detects the NMR response from the formation within two thin cylindrical shells, approximately 13 cm and 15 cm in diameters, and approximately 10 cm in height. Stepped measurements were acquired in 10 cm vertical intervals from the bottom of each borehole to the ground surface.

The NMR data was acquired and processed using a dual-Tr sequence with adaptive reference noise cancellation to mitigate the impact of noise from nearby scientific equipment. In a standard NMR interpretation framework, T_2 cutoff times were used to subdivide the continuous T_2 distributions into discrete bins of more bound water (e.g. in compacted clays) and more mobile water (e.g. water in loosely compacted sediment or permeable sand). We designate three cutoff times for binning: water with $T_2 < 10$ ms is designated as most bound ("immobile"), water with $T_2 > 50$ ms is designated as "mobile," and water with T_2 between these values is designated as intermediate ("capillary").

2.2.3 Subsurface and tidal hydrology

To elucidate hydrologic behavior in the upland and salt marsh positions, we established a network of co-located wells and piezometers in the salt marsh, and a deep monitoring piezometer in the upland (Figure 1C). The wells and piezometers were constructed using PVC pipe and a slotted PVC screen wrapped with polyester mesh. The salt marsh wells and piezometers were screened 60 cm and 15 cm from the bottom of the pipe, respectively, and installed to a depth of 70 cm-bgs. The upland position piezometer was installed to a depth of 2.5 m-bgs. The wells and piezometers were instrumented with Solinst 3001 LT M5 pressure transducers (Solinst, Ontario, Canada) to collect pressure and temperature data (5 minute interval) from December 2019 through April 2022. To account for barometric pressure, we deployed a Solinst 3001 Barologger M5 pressure sensor in the upland region. Transducer data were downloaded every ~2 months, and pressure data were corrected for barometric variations and converted to water depth. Water depths were converted to water level along the transect relative to the NAVD 88 datum. Gaps (1-3 weeks) present in the upland piezometer water level due to slow recovery after water quality sampling were interpolated using a linear interpolation function from the *imputeTS* R software package (Steffen Moritz, 2021). In this paper, we will refer to the shallow subsurface (<4 m-bgs) water measured in the upland position as groundwater, separate from the deep (>30 m-bgs) regional groundwater pumped for agricultural use.

We used publicly available tidal water level from the Vierra Mouth gauge (36° 48' 39.96"N, 121° 46' 45.12"W), a tidally unrestricted gauge site located at the mouth of the estuary and maintained by ES NERR. We downloaded 15 minute corrected tidal water level and daily precipitation from the NERR Centralized Data Management Office (CDMO) website for December 2019 through April 2022. Precipitation data from the Caspian Weather Station (36°48'56" N, 121°44'18" W) at ES NERR was also acquired through the CDMO site for the study period.

2.2.4 Geochemistry

We conducted routine porewater sampling every 2-5 weeks from January 2020 to April 2022 using sampling infrastructure installed along the transect. We developed a network of sampling cups to collect pore water from shallow subsurface water. We constructed the sampling cups as “closed” chambers by capping a 5 cm internal diameter PVC pipe at both ends to minimize the interaction of pore water with atmospheric air. We used a PVC cap on the bottom end, and on the top end we used an epoxy layer. We placed a 0.5 cm internal diameter tubing through the epoxy layer to the bottom of the sampling cup, and used this tubing to extract water samples from the sampling cup. We introduced an additional vent tube of the same diameter through the epoxy layer to avoid vacuum forming during pumping and allow air to escape as water entered the cup. We installed a set of sampling cups at depths of 10 cm, 30 cm, and 50 cm at each marsh position (Figure 1C). Tubing was run from the sampling cups and upland piezometer to a central transect workbench to enable sampling of each location using Geopump peristaltic pumps (Geotech Environmental Equipment, Inc.). At the start of each sampling campaign, we purged all sampling locations until they were empty and allowed them to refill before collecting the pore water samples. We analyzed samples for nutrients (specifically NO_3 and NH_4), dissolved organic carbon (DOC), dissolved gasses (N_2, Ar), and major cations and anions. We used an Orion Star A329 Portable Multiparameter Meter (Thermo Scientific, Massachusetts, USA) to collect in situ measurements of temperature, salinity, specific conductance, TDS, dissolved oxygen, and pH. A total of 100, 99, 86, and 27 measurements were collected for the lower marsh, middle marsh, upper marsh, and upland, respectively. In this study, we will only be focusing on specific conductance (used as a proxy for salinity) results as indicators of spatiotemporal variability in salt marsh hydrology.

2.2.5 Vegetation

In order to resolve potential impacts of variability in salt marsh hydrology, we conducted monthly vegetation surveys of the upper, middle, and lower marsh positions. We established vegetation study plots along a separate study transect (~ 7 m north of primary transect) that represent each of the marsh positions based on their surveyed elevations. For each location, we established two replicate plots (Figure 1B). We used a 0.5 m by 0.5 m quadrat to collect four measurements per plot of pickleweed stalk length, stem width, and canopy height; we also measured the green (turgid), woody (brown, senesced), and bare percent cover of the platform within each plot. The vegetation in each of these study plots was composed solely of pickleweed *(Sarcocornia pacifica)*, a perennial halophyte.

We conducted unmanned aerial vehicle (UAV) imagery surveys in conjunction with the vegetation surveys to pair spatiotemporal changes in the normalized difference vegetation index (NDVI) with vegetation survey measurements. We operated a DJI Phantom 5 Pro UAV to collect monthly true-color (RGB), and used a multispectral Double 4k Sensor S/N 0024 camera (Sentera, Minnesota, USA) to collect Red and near-infrared (NIR) bands of the marsh platform. Survey imagery results were processed using a MATLAB script to calibrate and calculate NDVI results. We calibrated Red and NIR bands using calibration equations provided by Sentera:

Eq. 4 $$Red = -0.966 * NB + 1 * NR$$

Eq. 5 $$NIR = 4.35 * NB - 0.286 * NR$$

where

$NB = blue\ (3rd)\ channel$

$NR = red\ (1st)\ channel$

We applied a shapefile created in QGIS 3.22.0 containing georeferenced quadrats to the calibrated images to calculate monthly NDVI results for each of the vegetation plots:

Eq. 6 $$NDVI = \frac{NIR - Red}{NIR + Red}$$

We were unable to capture NIR drone imagery over the growing season in 2021 due to maintenance on the multispectral camera, and several survey dates throughout the study period had to be removed due to wrack (accumulation of organic material and debris transported and deposited by tides) covering the marsh vegetation study positions.

3. Results

3.1 Marsh sediment characterization

Subsurface sediment volumetric water content, organic matter, and bulk density varied by marsh positions and with depth (Figure 3). Generally, we saw that soil moisture content and OM had an inverse relationship with bulk density across all sediment profiles. A local peak in bulk density was also observed near 30 cm-bgs in the upper (1.3 g/cm^3), middle (0.8 g/cm^3), and lower (0.3 g/cm^3) marsh positions. The upper marsh had the highest bulk density values (~1.7 g/cm^3) throughout the sediment profile, except for a minimum observed at the ground surface and at the 50 cm depth. In the upper marsh position, soil moisture content and OM were greatest at the ground surface (90% and 50%, respectively). soil moisture content and OM values significantly decreased with depth and remained low (40% and 5%, respectively), except for a local maxima at 45-55 cm depth (66% soil moisture content and 22% OM). The middle marsh position showed more variability in bulk density, soil moisture content, and OM with depth than the upper marsh position. The bulk density values in the middle marsh were consistently low (0.2-0.8 g/cm^3) throughout the sediment profile, but increased to a value of 1.7 g/cm^3 at a depth of 220 cm. The lower marsh position had consistently low bulk density values ranging from 0.1 to 0.3 g/cm^3. Peak soil moisture content was observed at the lower marsh position ground surface at a value of 110%, before decreasing with depth to a consistent range of 50% to 90%, and an average value of 80%. We observed variations in OM (30-70%) with depth in the lower marsh, with a general increasing trend with depth.

The lower marsh position had the highest capillary (low conductivity) and mobile water contents (high conductivity and availability), and lowest immobile content (very low conductivity, unavailable for plant use) (Figure 3). The middle marsh position showed an increase in immobile water content and decrease in mobile water content with depth after 40 cm-bgs. The upper marsh position had the lowest values of capillary and mobile water content out of the three marsh positions, with clay water content increasing with depth below 50 cm-bgs. A peak in shallow capillary and mobile water contents was observed around 30 cm-bgs for both the upper and middle marsh positions, and maximum clay content values were observed for both positions around 50 cm. The lack of observations near the ground surface (<10 cm-bgs) is likely due to the low tidal conditions during the survey, during which the marsh platform was not inundated and likely drained at the surface. The water content measured in the upland position, which is located outside the marsh platform, was mostly within clay pore spaces, with very little to no water measured in capillary and mobile pore spaces (<5%, except for between 100 and 190 cm-bgs). A minimum in total water content (<20%) was observed at 50 cm-bgs in the upland position, and was composed of water stored primarily in immobile clay pores paces. Peaks in water stored in mobile pore spaces were observed at 130 and 160 cm-bgs. Additionally, a maximum of total water content at 40% stored in clay/immobile pore spaces was observed at 190 cm-bgs.

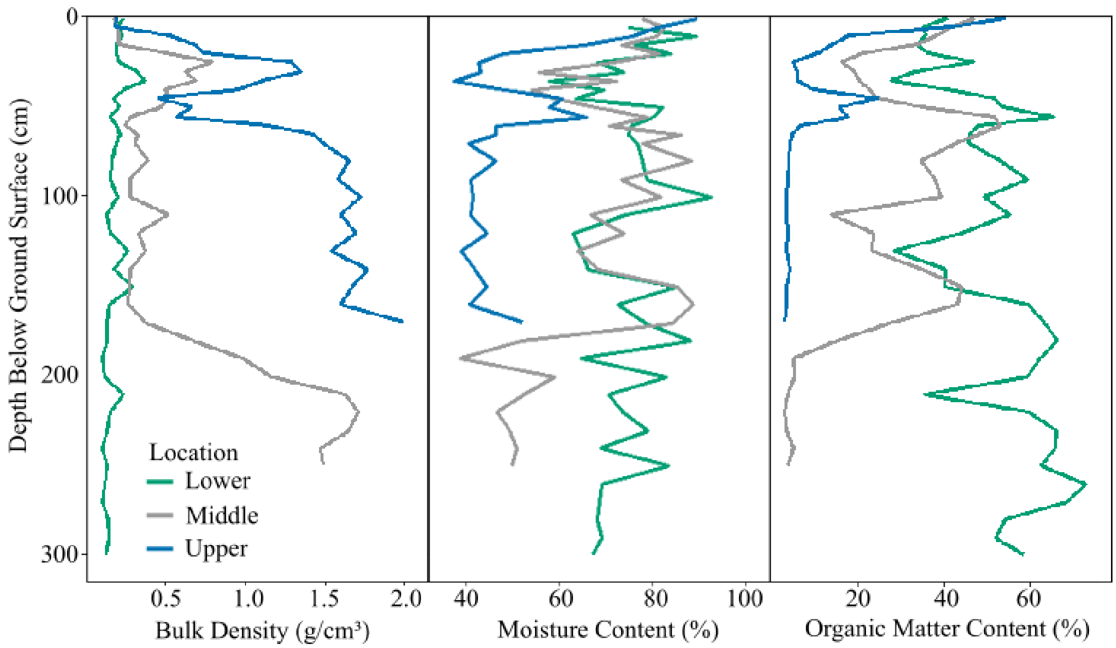

Figure 2. Vertical profiles of bulk density, soil moisture content, and organic matter content for the upper, middle, and lower marsh positions.

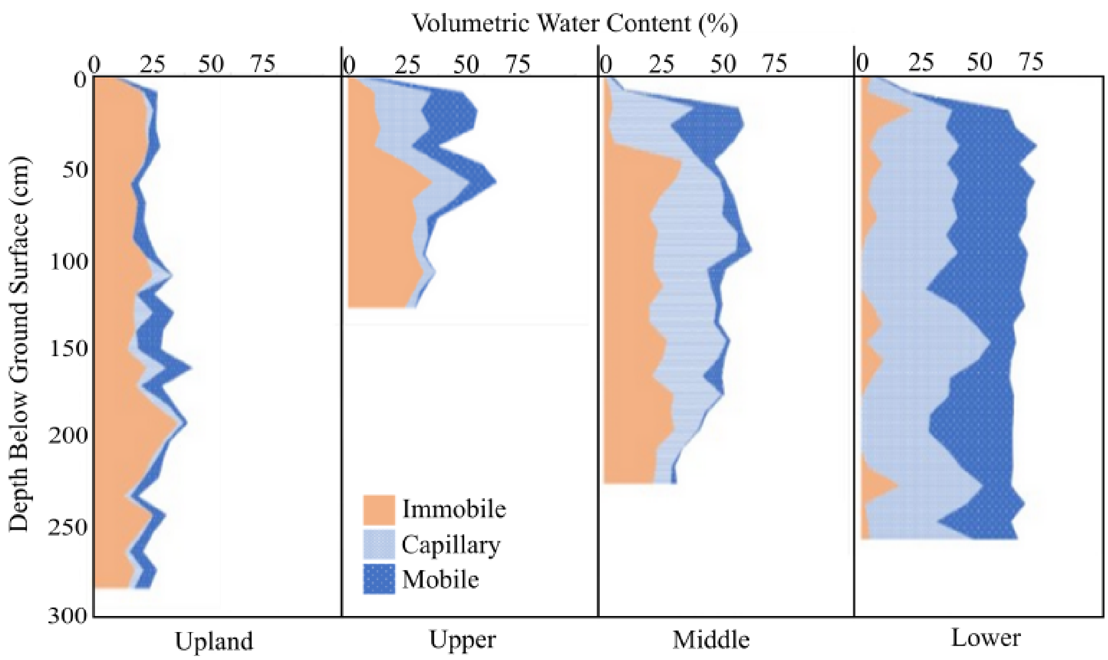

Figure 3. Vertical profiles of volumetric water content in sediment at the upland and three marsh positions measured by the nuclear magnetic resonance survey. Water

content is categorized by how tightly it is stored: immobile (orange), capillary pores (light blue), and mobile pores (dark blue). Survey was conducted in November 2021 during low tide conditions when the marsh was not inundated.

3.2 Precipitation and tidal conditions

Precipitation totals for water years 2020, 2021, and 2022 (up to April 25) were 455 mm, 280 mm, and 380 mm, respectively (Table 1). All precipitation fell as rain. The majority of rainfall occurred during the November to May, and maximum daily values were seen during the winter season, consistent with a Mediterranean climate (Figure 4). Water year 2020 had the lowest peak daily rainfall value of 48 mm on April 5, and received most of its precipitation during December through January, and in late March through early April. Water year 2021 received low amounts of precipitation (<15 mm/day) from October through February, however it had the highest peak rainfall over the study period of 78 mm on January 27. Water year 2022 had a peak daily rainfall of 73 mm on December 13, and received the majority of its precipitation during October through December. Notably, water year 2022 received no significant precipitation during the months of January and February.

The measured tidal range at the mouth of the estuary over the study period (Oct 2019 - Apr 2022) ranged from a maximum of 2.21 m to a minimum of -0.54 m (relative to NAVD88). The tidal stage during the study period had a mean of 0.94 ± 0.50 m and median of 0.72 m. The lower marsh was tidally inundated for almost twice the amount of time as the upper marsh (9.6% compared to 5.4%), with the middle marsh inundated for 7.2% of the time. The upland position at its elevation of 2.76 m did not receive any tidal inundation.

3.3 Subsurface hydrology

The terrestrial upland groundwater level fluctuated seasonally: the highest levels were observed during the winter and spring, and lowest levels occurred during the summer and fall (Figure 4). The water level in the upland position reached the ground surface during peak saturation 2.78 m, and fell below 1.6 m (below the elevation of the salt marsh platform) during the peak dry season in water year 2021. Rapid increases in water level occurred during periods with significant precipitation. Tidal impacts on upland water level were not observed during the winter and spring seasons, however small fortnightly fluctuations (±2 to 5 cm) were observed when water level was low during the summer and fall seasons (Figure 4).

Water level dynamics in the marsh displayed seasonal differences, with dampened tidal signals during wetter winter and spring conditions and strong tidal signals during drier summer and fall conditions. A dampened response to tidal inundation was observed in all three marsh positions during the winter and spring seasons (Figure 4). In particular, the water level was at or above the ground surface elevation (dashed black line in Figure 4) at the upper and middle marsh positions during the winter and spring seasons, resulting in tidal signal dampening. Dampened tidal responses in the marsh subsurface were coincident with periods when the upland position water level was elevated near to the ground surface. In the summer and fall seasons, when the upland water level was low, fortnightly tidal cycle signal responses were observed in the marsh subsurface water level records. Clear diel and fortnightly tidal signals were observed in the lower marsh position throughout the study period, but an increase in the minimum water level was observed during the winter and spring months, which may have dampened the tidal signal due to marsh saturation. The period of tidal dampening varied across marsh positions, with generally longer saturation periods in the upper and middle marsh positions (Table 1). The longest extent of upper marsh saturation (203 days) was observed during water year 2020, the wettest year of the study. The period of upper and middle marsh signal dampening was shortest in water year 2022, despite water year 2021 having the driest winter and spring seasons and the least amount of precipitation during our study. However, both water years 2021 and 2022 received well below the annual average for the area (~600 mm/year). Tidal dampening in the salt marsh was observed to end when water level in the upland position was higher than at the beginning of signal dampening (Table 1).

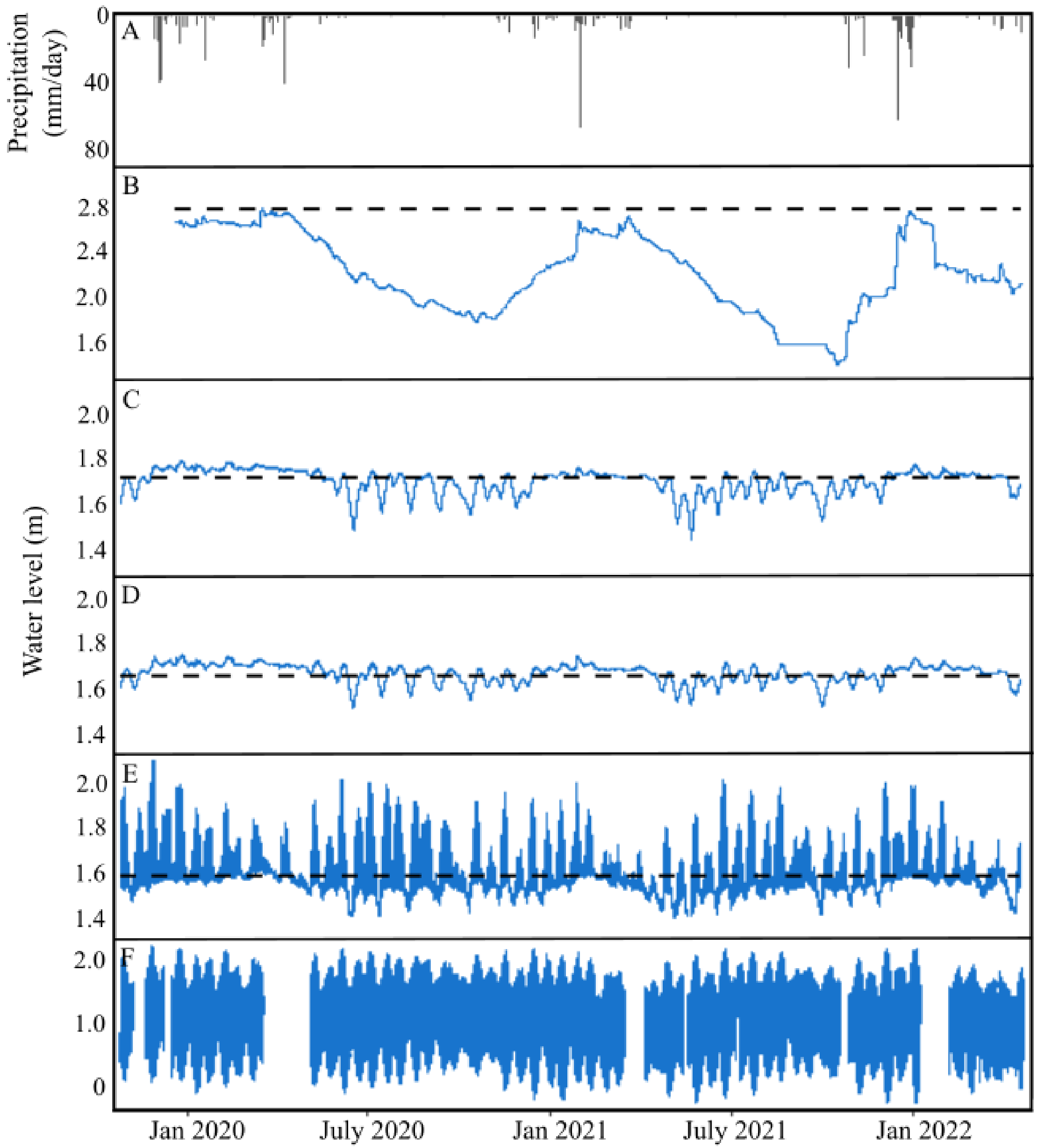

Figure 4. Plot of daily precipitation (mm) from Caspian Weather Station located in ESNERR (A), and water level (m relative to NAVD88) for the upland (B), upper marsh (C), middle marsh (D), lower marsh (E), and tidal level at the Vierra Mouth gauge site (F). Dashed black lines in panels B-E represent the ground surface elevation at the respective position. Date ranges shown are October 26, 2019 to April 20, 2022, with the exception of no data before December 20, 2019 for the upland position (B).

Water Year	2020	2021	2022
Total Precipitation (mm)	455	280	380
Upper Marsh Saturation (Total Days)	24 Nov - 12 May (171)	10 Dec - May 2 (145)	4 Dec - 6 Apr (124)
Middle Marsh Saturation (Total Days)	22 Nov - 11 June (203)	12 Dec - 17 Apr (127)	4 Dec - 5 Apr (123)
Upland Water Level During Upper Marsh Saturation Start, End (m)	NA, 2.53	2.1, 2.38	2.03, 2.13

Table 1. Total precipitation, date ranges and length (total days) of marsh tidal signal dampening (i.e. saturation) at upper and middle marsh positions, and the water level in the upland position during upper marsh dampened signal range.

3.4 Salt marsh pore water geochemistry

Salt marsh pore water specific conductance was seasonally variable in the three marsh positions, with a decrease in conductivity observed during the winter and spring seasons and hypersaline conditions during the summer and fall. (Figure 5). The lower, middle, and upper marsh positions had mean pore water conductivity values of 51.0 ± 14.2 mS/cm, 54.2 ± 10.5 mS/cm, and 41.9 ± 17.8 mS/cm, respectively. Combining all time points, we found that conductivity varied significantly among the upper marsh (median=47.0 mS/cm), middle (median=54.7 mS/cm) and lower (median=53.0 mS/cm) marsh positions (Kruskal-Wallis test: $H=22.45$, $df=2$, $p<0.0001$). A pairwise Wilcoxon test showed that only the upper marsh conductivity differed significantly from the middle and lower marsh ($p<0.005$). The upper, middle, and lower marsh positions generally showed a decrease in pore water conductivity during the wet winter and spring months, and increase during the dry summer and fall months. Peak conductivity occurred during August, September, and October for all three marsh positions. Conductivity began to decrease during November and December in the lower and upper marsh positions, while the middle marsh position remained high (>60 mS/cm). Conductivity variability was found to be statistically significant among the winter (median=49.1 mS/cm), spring (median=38.9 mS/cm), summer (median=59.8 mS/cm), and fall (median=59.2 mS/cm) seasons (Kruskal-Wallis test: $H=102.88$, $df=3$, $p<0.0001$). The seasons were found to differ significantly between each other except for between the summer-fall seasons (Wilcoxon test: $p<0.001$). Conductivity values in the groundwater samples taken from the upland position remained low throughout the year with a mean conductivity value of 6.13 ± 2.32 mS/cm and a median value of 5.52 mS/cm. The mean estuarine surface water conductivity at the Vierra Mouth gauge (9 km from Cowell Ranch study site) remained relatively constant at 50 mS/cm, with low values around 47 mS/cm during the winter and high values approximately 52 mS/cm during the summer. Hypersalinity was observed in the three marsh positions during the late summer, fall, and early winter months, which exceeded the mean estuarine surface water conductivity (~50 mS/cm) at the Vierra Mouth. We observed the greatest decrease in conductivity in the upper marsh, with mean values around 20 mS/cm from January through April. The middle marsh position had the highest mean conductivity value (54.2 ± 10.5 mS/cm) with the least variability, and lagged behind the upper and lower marsh decreasing trend in the winter and early spring.

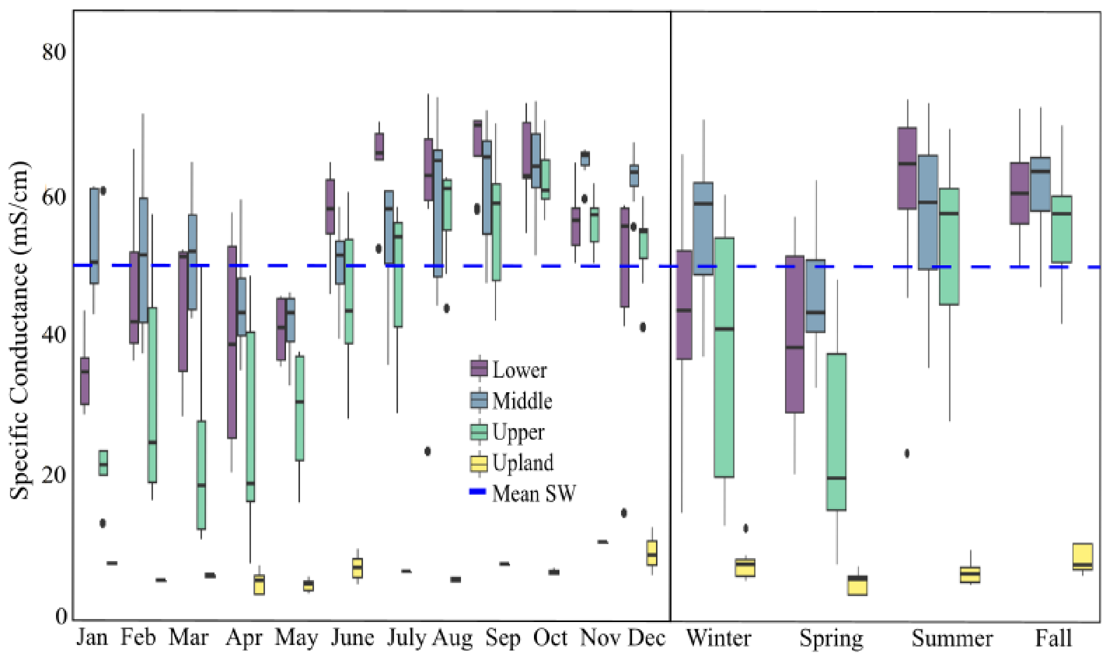

Figure 5. Box plots of in situ specific conductance values of upland groundwater and sediment porewater from the lower, middle, and upper marsh positions. Data are aggregated by month (panel A) and season (right panel B). Dashed blue line indicates the mean estuarine surface water specific conductance at the mouth of ES NERR. Solid black line within each box plot indicates the mean value.

3.5 Vegetation

Salt marsh pickleweed canopy height and stalk measurements varied across the platform, with the highest measurements at the upper marsh position and lowest at the lower marsh position (Table 2, Figure 6). The upper marsh had the highest canopy height and stalk length measurements for each survey date, with the middle marsh having the second highest and the lower marsh having the lowest (i.e. decreasing from the upper to lower marsh; Table 2, Figure 6). Variability in canopy height among the lower, middle, and upper marsh positions was found to be statistically significant (Kruskal-Wallis test: $H=218.77$, $df=2$, $p<0.0001$). The canopy height variability was determined to be significant between each of the marsh positions (Wilcoxon test:

$p<0.05$). Similarly, pickleweed stalk length variability was also determined to be statistically significant among the marsh positions (Kruskal-Wallis test: $H=83.327$, $df=2$, $p<0.0001$).Variability in stem width was significant between the marsh positions (Kruskal-Wallis test: $H=22.222$, $df=2$, $p<0.0001$). We found that both the stalk length and stem width variability was significant only between middle-lower and upper-lower positions, but not between the upper-middle positions (Wilcoxon test: $p<0.001$).

We observed seasonal trends in pickleweed canopy height, stalk length, and stem width measurements that generally tracked growing and dormant season behavior. Generally, we observed an increase in canopy height and stalk length during the spring and summer growing season, and a decrease during the winter dormant season (Figure 6). We found that canopy height variability across all sites was statistically significant among the winter (median=26 cm), spring (median=23 cm), summer (median=27 cm), and fall (median=24 cm) seasons (Kruskal-Wallis test: $H=26.351$, $df=3$, $p<0.0001$). The seasons were found to differ significantly for canopy height except for between the winter-fall and summer-fall seasons (Wilcoxon test: $p<0.05$). Variability in stalk length was found to be statistically significant between the winter (median=30 cm), spring (median=29 cm), summer (median=29 cm), and fall (median=35.2 cm) seasons (Kruskal-Wallis test: $H=72.143$, $df=3$, $p<0.0001$). Stem width variability among the winter (median=2.24 mm), spring (median=2.22 mm), summer (median=2.41 mm), and fall (median=2.84 mm) seasons was statistically significant (Kruskal-Wallis test: $H=44.783$, $df=3$, $p<0.0001$). Seasons that did differ significantly for both the pickleweed stalk length and stem width were the spring-fall, summer-fall, and winter-fall seasons, while the summer-spring, winter-spring, and winter-summer did not differ significantly (Wilcoxon test: $p<0.005$).

Vegetation cover across the salt marsh platform varied seasonally: green (turgid) cover dominated the marsh during the growing season, while the woody (partially to fully senesced) cover was dominant during the dormant season (Figure 7). Green cover varied significantly across the salt marsh for the fall (median=67%), winter (median=0%), spring (median=56%), and summer (median=56%) seasons (Kruskal-Wallis test: $H=161.66$, $df=3$, $p<0.0001$). Each of the seasonal interactions were found to be significant ($p<0.05$), except for between the summer-fall and summer-spring seasons (Wilcoxon test). Similarly, woody cover varied significantly across the marsh platform during the fall (median=22%), winter (median=78%), spring (median=33%), and summer (median=22%) seasons (Kruskal-Wallis test: $H=149.58$, $df=3$, $p<0.0001$), though only the summer-fall season interaction was found to be insignificant (Wilcoxon test: $p>0.05$). The total vegetation cover across the platform significantly varied seasonally, though at a lower significance level, for the fall (median=89%), winter (median=89%), spring (median=89%), and summer (median=89%) seasons (Kruskal-Wallis test: $H=10.984$, $df=3$, $p<0.05$), with significance found only for the summer-fall, summer-spring, and summer-winter season comparisons (Wilcoxon test: $p<0.05$).

Salt marsh vegetation NDVI was generally observed to be highest in the upper marsh and lowest in the lower marsh across the study period (Figure 8). The upper marsh had the highest weighted mean NDVI value (0.177 ± 0.110) across the study period out of the three marsh positions, and had the highest overall value (0.330) observed on April 21, 2021. The middle marsh position had a mean NDVI value of 0.171 ± 0.098, similar to the upper marsh, while the lower marsh had a distinctly lower value of 0.101 ± 0.166. We observed the highest NDVI values for all marsh positions during the April of 2021 and 2022, and November 2021. The lower marsh had the highest measured NDVI values out of all three positions during spring 2021, however we observed a sharp decrease in early summer 2021, and lower marsh NDVI observation remained lower than the middle and upper marsh for the remainder of the study (Figure 8).

	N	Median	Mean	Standard Deviation
Lower				
Canopy Height (cm)	242	23	22.3	2.04
Stalk Length (cm)	188	27	27.2	8.99
Stem Width (mm)	188	2.35	2.41	0.792
Green Cover (%)	130	44	40.8	29.2
Woody Cover (%)	130	33	39.1	30.5
Total Cover (%)	130	88.5	80.1	18.3
Middle				
Canopy Height (cm)	224	24	23.4	4.2
Stalk Length (cm)	185	33	33.6	7.09
Stem Width (mm)	185	2.73	2.76	0.743
Green Cover (%)	125	67	54.8	32.2
Woody Cover (%)	125	33	41.4	32.6
Total Cover (%)	125	100	96.2	6.81
Upper				
Canopy Height (cm)	213	32	30.5	5.7
Stalk Length (cm)	178	34	24.4	7.11
Stem Width (mm)	178	2.62	2.67	0.754
Green Cover (%)	140	33	38.8	30.3
Woody Cover (%)	140	33	38.6	30.7
Total Cover (%)	140	78	77.6	20.7

Table 2. Summary statistics of monthly vegetation survey measurements (canopy height, stalk length, stem width, green cover, woody cover, and total cover) for the

lower, middle, and upper marsh positions. Measurements collected from October 2019 to April 2022.

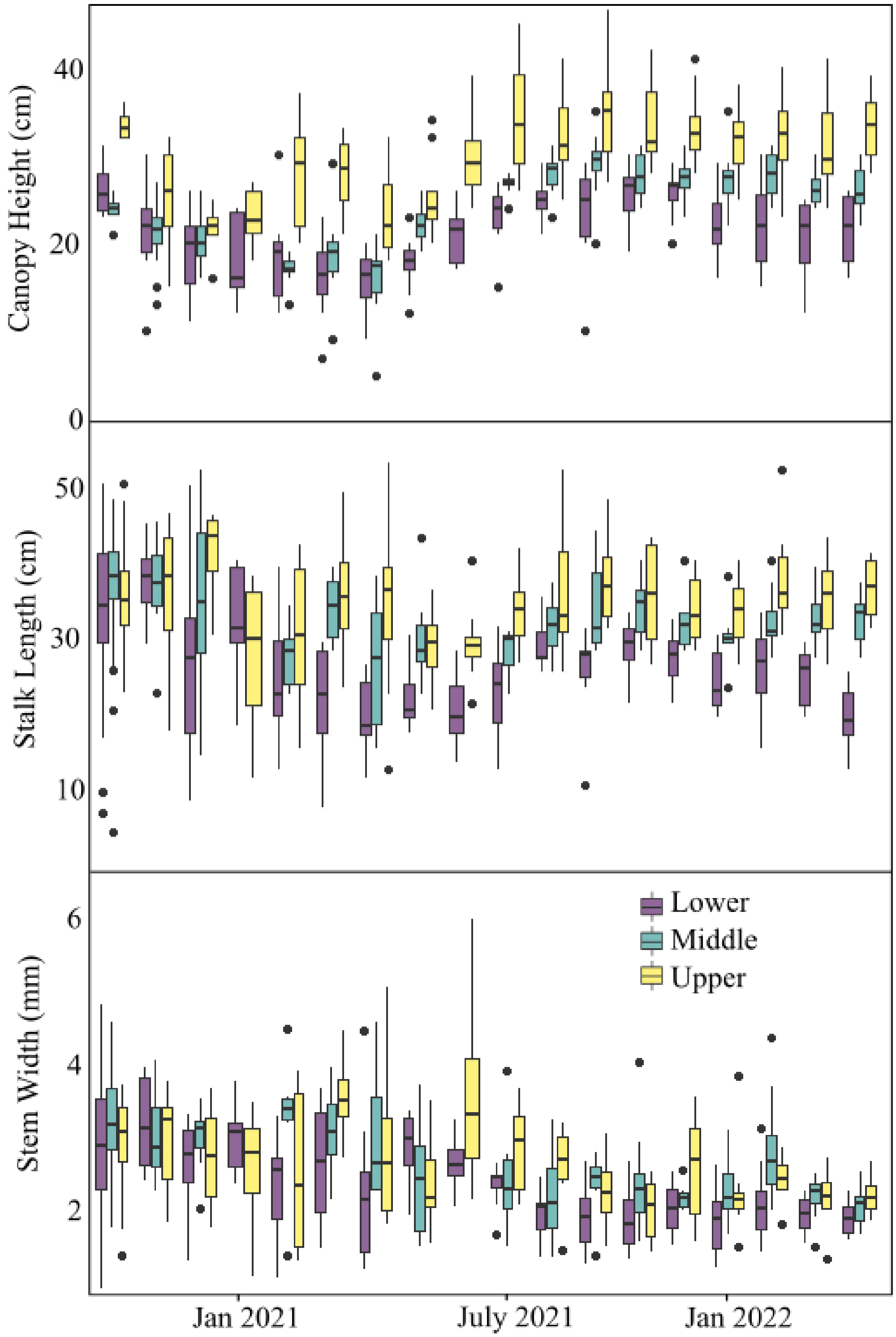

Figure 6. Box plots showing monthly canopy height, stalk length, and stem width for each marsh position. Black line within the box plot indicates the mean value.

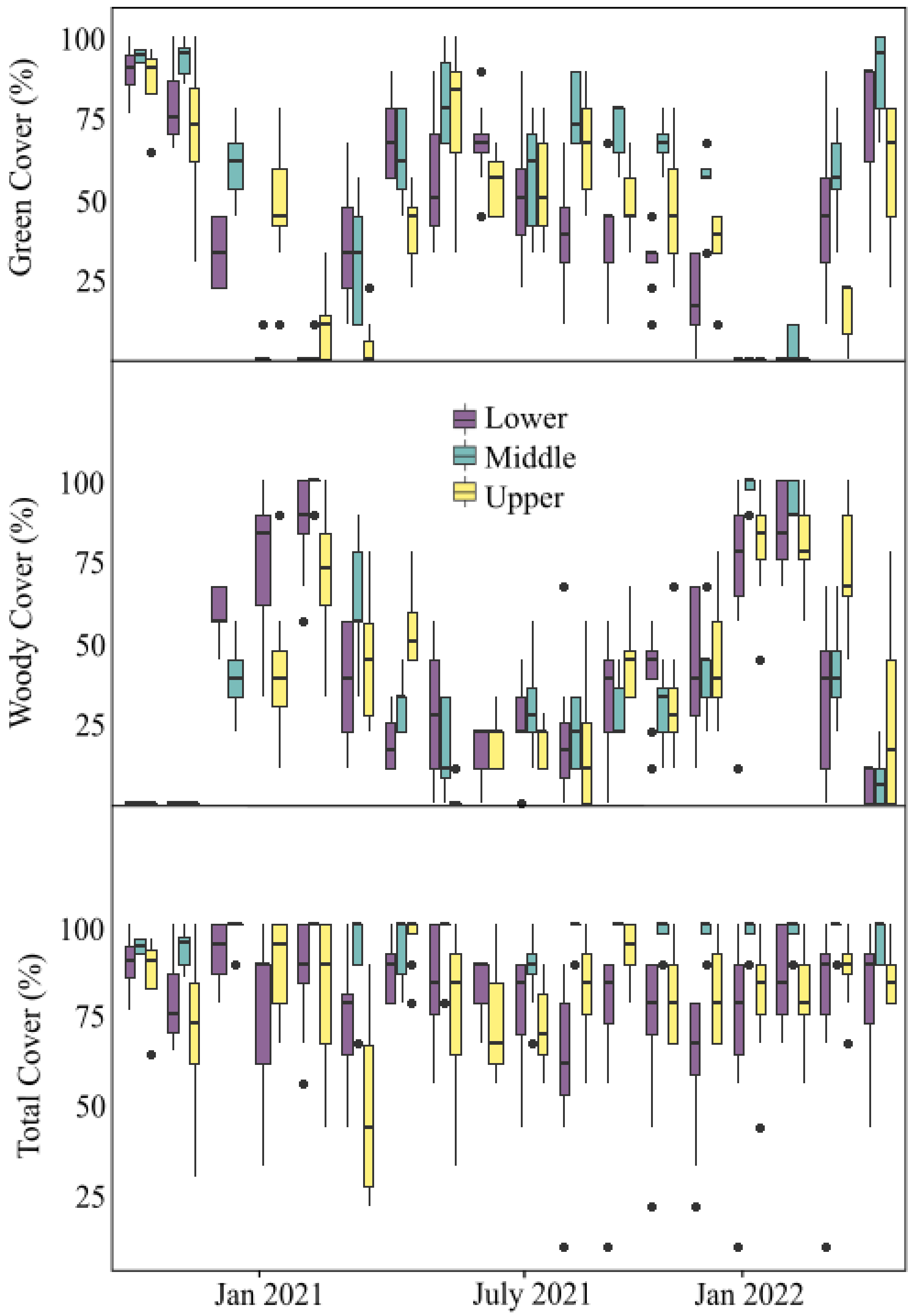

Figure 7. Box plots showing monthly green, woody, and total vegetation cover for each marsh position. Black line within the box plot indicates the mean value.

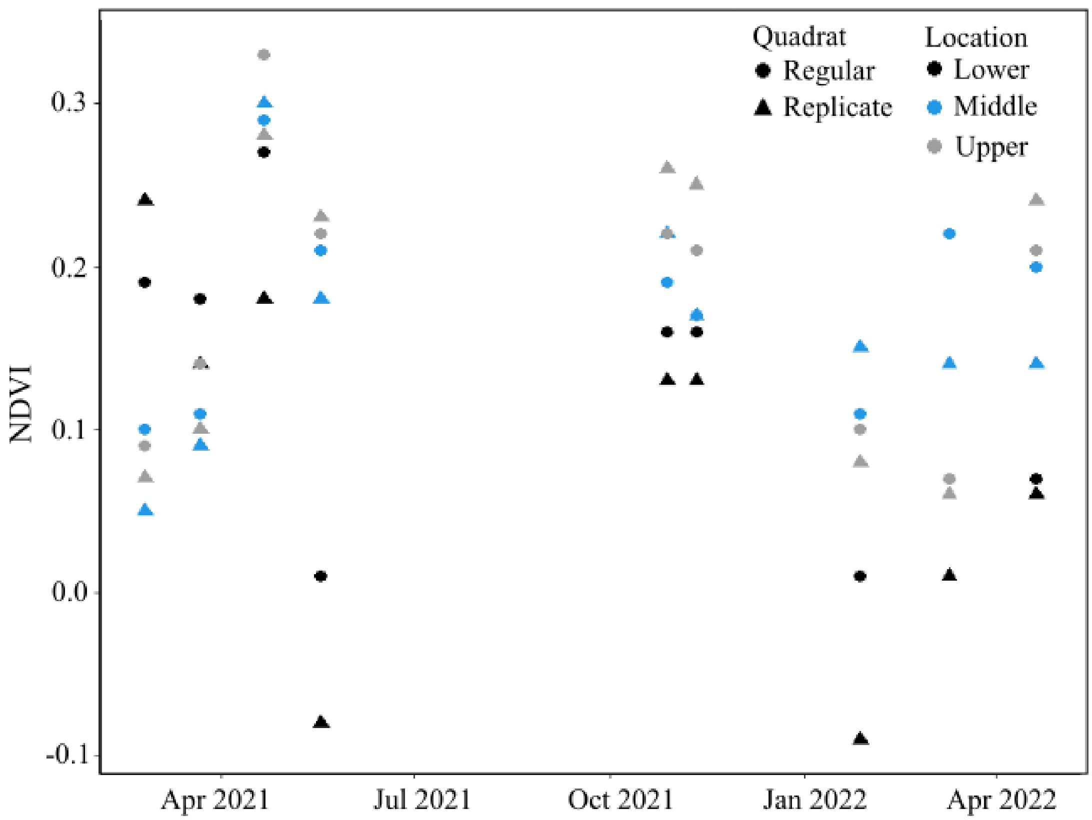

Figure 8. Plot of salt marsh normalized difference vegetation index (NDVI) at each marsh position and by survey regular (circle) and replicate (triangle) quadrat.

4. Discussion

4.1 Temporally bimodal salt marsh hydrology behavior driven by seasonal water source patterns

Our results suggest there is seasonal variability in dominant water sources contributing to the salt marsh, producing distinct bimodal hydrology and salinity states that have implications for salt marsh vegetation health and biogeochemistry. Here, we describe a conceptual model of this seasonal water source pattern and how we hypothesize it produces bimodal hydrologic behavior across the marsh platform. Specifically, we show that the highly-seasonal climate of Elkhorn Slough, where precipitation occurs predominantly in the winter, results in tidally dominated salt marsh hydrology during the summer and subdued and saturated marsh hydrologic conditions during the winter.

Precipitation inputs constrained to the wet winter and spring seasons increase upland groundwater levels, potentially driving observed salt marsh hydrologic patterns. Specifically, we observed a sustained increase in water level and dampening of tidal signals in the upper and middle salt marsh positions (Figure 4), despite no significant changes in the overall tidal regime between the wet and dry seasons. During this time, precipitation inputs recharge groundwater in the uplands, creating a subsurface hydraulic gradient from the upland towards the salt marsh when the upland water table exceeds the elevation of the salt marsh platform. The saturation of the salt marsh platform coinciding with high upland water levels during the winter and spring seasons suggests a hydrologic connectivity of shallow, lateral flow paths between the upland and salt marsh. That said, diel and fortnightly tidal cycles were observed in the lower marsh position throughout all seasons, though the base water level was higher in the wet season than during the dry season (Figure 4). This suggests the mechanisms driving wet season marsh hydrology are not uniform across the marsh platform.

While we hypothesize a dominant shallow hydraulic gradient from the upland towards the marsh during the wet winter and spring drives marsh saturation, with a reversal of this gradient towards the upland during the dry summer and fall. During the latter time period, we observed clear fortnightly tidal cycles in all marsh positions (Figure 4). This suggests that terrestrial water inputs play a role in dampening tidal signals, and that reduction of these inputs during the dry season amplifies the impact of tides on marsh hydrology.

Pore water pressure head in salt marshes has traditionally been conceptualized to be driven predominantly by tidal forcings, specifically by diel and fortnightly tidal inundation (Wilson & Morris, 2012). However, recent work has shown that the magnitude of tidal influence varies spatially and temporally due to factors such as salt marsh soil stratigraphy, topography, terrestrial surface and groundwater inputs, and vegetation zonation (Moffett et al., 2010; Guimond & Tamborski, 2021; Xin et al., 2022). This recent work supports our findings that tidal dominance temporally varies and may be a function of upland wetness and terrestrial water inputs. Guimond & Tamborski (2021) described how the direction of the hydraulic gradient between salt marshes and the upland can reverse depending on changes in the local groundwater table elevation; for example, the gradient can flow from the marsh towards the terrestrial upland when the upland groundwater level is low relative to the marsh platform elevation.

In addition to seasonal precipitation inputs, changes in tidal regime and the reduction of evapotranspiration rates may also be potential mechanisms driving the increase of pressure head and tidal signal dampening in the salt marsh subsurface during the wet winter and spring seasons. The increase in the marsh pressure head that we observed during the winter and spring seasons may be attributed in part to contributions from precipitation, however the extent of upper and middle marsh signal dampening (~4 months) during extended periods with little to no precipitation suggest that precipitation inputs are not the only driving force in the observed hydrologic behavior. The vertical infiltration of direct precipitation onto the salt marsh platform has been shown to elevate the salt marsh water table (i.e. recharge), however this impact is often observed to be short-lived, usually lasting hours to days following precipitation events (Gardner & Gaines, 2008).

The transition between the dampened tidal signal during the wet season and tidally dominated signal during the dry season in the upper and middle marsh piezometers occurred when the upland water level was above 2 m. We expected to see this transition occur when the upland water level decreased to 1.7 m, which is the elevation of the upper marsh position. However, the transition in dominant hydrologic behavior in the salt marsh occurred when the upland water level was higher than the marsh platform. This suggests that the hydrologic connectivity between terrestrial water sources and the marsh platform may be driven by a combination of groundwater elevation and soil stratigraphy that may create barriers to flow. Low permeability layers, such as clay lenses, can restrict the movement of water between the upland and upper marsh position. We observed a decrease in mobile water pore spaces and increase in immobile pore spaces at ~1 m and ~2 m bgs in the upland through the NMR survey, and increases in mobile water pore spaces between 1-2 m bgs, suggesting a shallow perched water table. Other potential mechanisms that may drive this transition during the spring-summer are salt marsh evapotranspiration and magnitude changes in upland vegetation water use. Evapotranspiration during the growing season reduces water content in surficial marsh sediments (Harvey & Nuttle, 1995), potentially contributing to the increase in fortnightly tidal cycle response in the marsh platform during the summer and fall months. Plant water use along the shallow freshwater flow path between the upland and upper marsh may decrease the height of the water table along the salt marsh margin if water loss through evapotranspiration outpaces freshwater inputs from the upland. The combined impact of this mechanism with evapotranspiration and subsurface soil structure may sever or diminish the hydrologic connection between the upland and salt marsh.

Spatial similarities in salt marsh saturation and pressure head tidal signal responses between the upper and middle marsh are likely due to the similarities in soil stratigraphy, despite their slight differences in elevation. We observed an abrupt increase in bulk density and soil moisture content stored in immobile pore spaces ~60 cm-bgs at the upper and middle marsh positions (Figure 3). This may restrict drainage of porewater in the shallow subsurface, contributing to marsh saturation and tidal signal dampening during periods with low evapotranspiration or increased water inputs. Additionally, we see that the upper and middle marsh positions reach high bulk density (~1.7 g/cm^3) and low OM (~5%) values at depth (Figure 2), suggesting a transition from marsh to terrestrial sediments around 70 cm and 170 cm bgs for the upper and middle marsh positions, respectively. In contrast, the low bulk density, high soil moisture content in mobile pore spaces, and high OM in the lower marsh position from the surface to 3 m bgs (depth limit of soil core collection), are suggestive of long-term accumulation of marsh sediments that facilitate rapid flushing of the marsh subsurface. These observations are supported by studies that have shown that salt marsh hydrologic behavior is affected by soil stratigraphy (Gardner, 2007), with high conductivity soils (e.g. marsh peat containing roots and burrows) facilitating rapid flushing of tidal inundation while low conductivity (e.g. clay-rich lenses) soils can limit subsurface flow and drainage (Xin et al., 2009; Wilson & Gardner, 2006; Wu et al., 2022).

Seasonal freshwater inputs from the upland to the salt marsh depend on the available water stored in the uplands, which fluctuates year-to-year based on total annual precipitation. Precipitation in the uplands recharges the local groundwater, filling subsurface water storage, and drives freshwater inputs into the salt marsh from the upland. When precipitation is reduced during drought periods, upland water storage is depleted, leading to a potential reduction in freshwater inputs to the salt marsh. Our study showed that during a drought year (water year 2021), peak winter upland water level was lower than during the previous year, which received significantly more precipitation. Additionally, the extent of salt marsh saturation and tidal signal dampening was shorter than that of the previous year. Furthermore, we observed that the system had the shortest saturated period during water year 2022, despite water year 2021 receiving the least amount of precipitation during the study period, suggesting that drought in the upland can have compounding interannual impacts on salt marsh hydrology. We posit that upland water storage was significantly depleted during the drought in water year 2021, and precipitation inputs during water year 2022 were not sufficient to recharge this storage deficit. These observations show how salt marsh hydrologic behavior is linked to annual precipitation inputs across a variety of time scales.

4.2 Seasonal freshwater inputs contribute to salt marsh salinity dilution

Tidal inundation flushes the salt marsh platform almost daily, driving pore water solute mixing and drainage. Our study suggests shallow groundwater flow from the upland towards the marsh dilutes salt marsh pore water salinity, and the upper marsh experiences the most dilution due to its proximity to the upland-marsh interface. We observed significant decreases in pore water specific conductance during the winter and spring seasons across all salt marsh positions, however the upper marsh position in particular experienced a steep decrease in pore water conductivity during the winter and spring that came within ~15 mS/cm of the measured upland groundwater conductivity (6.13 ± 2.32 mS/cm). In contrast, the middle and lower marsh pore water conductivity was around the mean marine surface water conductivity of 50 mS/cm during the winter, and ~40 mS/cm during April and May (Figure 5). Seasonal evapotranspiration reductions, mixing of tidal water with lower salinity, and low electrical conductivity precipitation inputs are potential drivers of dilution of the salt marsh pore water during winter. Evapotranspiration increases pore water conductivity through the removal of water in shallow salt marsh sediments during the growing season, leading to the concentration of salts in shallow sediments, causing pore water salinity to exceed the salinity of incoming tidal surface water. Decreases in evapotranspiration due to vegetation dormancy during winter and early spring reduces the amount of water removed from the salt marsh platform, and may contribute to the reduction of pore water salinity as tidal mixing dilutes precipitated salt in shallow marsh sediments. The reduction in electrical conductivity coincides with periods of salt marsh saturation and tidal signal dampening, regardless of precipitation inputs, suggesting that shallow freshwater flow paths from the upland combined with the reduction of evapotranspiration during the vegetation senescence period may cause the salt marsh pore water dilution.

Salt marsh pore water salinity increases significantly during the summer due to increases in evapotranspiration, but salt marsh hypersalinity may also indicate the absence of a hydrologic connection between the freshwater groundwater from the uplands and the marsh. Salt marsh pore water conductivity significantly increased between May and July, coinciding with the commencement of vegetation activation and transpiration, with mean pore water conductivity exceeding that of the tidal surface water for most of the summer and fall seasons. The observed increase also began when water level in the salt marsh piezometers displayed an unsaturated, tidally dominated hydrologic behavior in the shallow subsurface, and water level in the upland had fallen by ~1 m from peak conditions, approaching the elevation of the upper marsh. The upper marsh in particular experienced the greatest increase in pore water conductivity between spring and summer (Figure 5), despite having the closest proximity to the upper marsh, indicating that dilution from freshwater inputs is significantly diminished during the dry summer season. This may be due in part to the fact that the upper marsh receives the least tidal inundation, 5.4% compared to 9.6% in the lower marsh, which reduces salinity through tidal flushing of marsh sediments. Vegetation activation during the summer and fall growing seasons results in higher rates of plant transpiration, preferentially removing water from shallow sediments, while increases in daily air temperatures increases the evaporation of water from surficial marsh sediments, resulting in hypersaline (salinity exceeding that of tidal surface water) pore water conditions. Tidal inundation dilutes hypersaline soils, however the rate of evapotranspiration may outpace tidal dilution during the growing season. We hypothesize the lack of freshwater inputs to the salt marsh in conjunction with increased evapotranspiration during the summer and fall led to hypersalinity in the shallow salt marsh sediments.

We observed a temporal lag in the dilution of salt marsh pore water salinity from the upper to lower marsh. Conductivity in the upper marsh decreased from slightly greater than the mean estuarine surface water (~55 mS/cm) in December to ~20 mS/cm in January, suggesting that a "pulse" of freshwater first entered the marsh at the upper position in mid-winter and diluted the upper salt marsh pore water. This salinity reduction continued until May. The lower marsh position experienced decrease in conductivity between December (60 mS/cm) and January (35 mS/cm), and began increasing to near the mean surface water conductivity in February and March. The middle marsh conductivity remained high (50 mS/cm) in January, despite its closer proximity to the upland and upper marsh than to the lower marsh position. We observed a decreasing trend in middle and lower marsh pore water conductivity from March to May, while conductivity in the upper marsh increased. This observation suggests that a seasonal plume of freshwater from the upland decreased throughout spring as the water level lowered, due to increases of evapotranspiration in the upland and marsh vegetation. We observed increases in marsh vegetation activity during the spring, especially in the upper marsh, which indicates that evapotranspiration began concentrating salinity earlier in the upper marsh surface sediments. In contrast, vegetation activity in the lower and middle marsh remained low, allowing mixing with marine inputs through tidal inundation to continue to dilute salt-enriched middle and lower marsh positions. Soil characteristics in the upper marsh, such as high bulk density, low OM, and the majority of VWC stored in immobile pore spaces beginning at 70 cm bgs may slow the transport of freshwater plumes entering the tidal marsh from the upland. This may explain the extended period of pore water dilution in the upper marsh during the winter and spring, in addition to upland proximity and less tidal inundation, compared to the middle and lower marsh positions, which have a thicker historic salt marsh soil composition with depth that may allow for shorter residence times and flushing by tides. Soil stratigraphy controls solute transport through salt marsh sediments, with increased residence times in low conductivity soils while high conductivity soils facilitate quicker transport of solutes through the substrate (Wu et al., 2022).

4.3 Vegetation activity impacted by freshwater inputs

Terrestrial freshwater inputs have been shown to promote plant growth in salt marshes, which result in more vegetation productivity in marsh positions closer to the terrestrial upland (Moffett et al. 2012). Our study showed that vegetation in the upper marsh was overall more active and had higher biomass characteristics than the middle and lower marsh positions, and spring pulses of freshwater from the upland potentially catalyzed earlier activation of vegetation in the upper marsh (Figures 7-9). Monthly surveys of pickleweed *(Sarcocornia pacifica)* stalk length, stem width, and canopy height showed that the upper marsh had the highest values out of the three marsh positions throughout the study, especially during the spring and summer seasons. Similarly, we observed that the upper and middle marsh positions had the most green cover during the growing season compared to the lower marsh. Observations of NDVI from monthly drone imagery indicate that vegetation activity was highest in the upper and middle marsh positions throughout the study period, and were substantially greater than the lower marsh position during the winter and spring. The lower marsh position increased in NDVI from April to October, as expected, however observations show that the upper and middle marsh were significantly more active than the lower marsh position during vegetation senescence and dormancy in the winter and spring. The higher upper marsh NDVI values during the spring coincide with observations of increases in canopy height, stalk length, and stem width before decreasing again in late spring/early summer before the commencement of growing season. In other words, we see a "growth spurt" in the upper marsh pickleweed during spring, and this observation occurs when the salt marsh is saturated and the pore water specific conductance is low. We believe this spring growth spurt in the upper marsh may be attributed in part to freshwater inputs along the upland-salt marsh interface, in addition to receiving the least tidal inundation out of our studied marsh positions. Salt marsh platform flooding via tidal inundation limits plant growth due to abiotic stresses, such as anoxic conditions in the rootzone and waterlogging, leading to vegetation zonation across the marsh (Moffett et al., 2012). The observed differences in vegetation health between the three delineated marsh positions is primarily driven by tidal flooding, however subsurface freshwater inputs along the upland-marsh interface impact salt marsh plant productivity by changing pore water salinity, marsh sediment saturation, and nutrient availability

(Guimond & Tamborski, 2021). Pickleweed canopy height and biomass has been observed to increase with decreased salinity (Callaway & Zedler, 1998; Schile et al., 2011), and a hypersaline marsh in southern California was observed to have a 160% increase in pickleweed productivity following a freshwater flood (Zedler, 1983).

5. Conclusions and Implications

This study of salt marsh hydrologic behavior, pore water salinity, and vegetation activity along a perpendicular salt marsh transect in the Elkhorn Slough suggests that seasonal changes in upland water level impacts salt marsh hydrologic and biologic processes. We observe marsh saturation and dampening of the diel and fortnightly tidal signal in piezometers at each of the salt marsh positions, particularly in the upper and middle salt marsh positions, when upland water level is high during the wet winter and spring seasons. The extent of the tidal signal dampening appears to depend on upland water storage and how much precipitation the region received during the winter and spring season. Additionally, pore water specific conductance significantly decreased during the winter and spring most likely due to reduced evapotranspiration during vegetation dormancy, and through pore water dilution via shallow subsurface freshwater flow paths from the upland towards the salt marsh. The proximity of the upper marsh to the upland may advantage salt marsh vegetation due to increases in freshwater inputs during the spring, in addition to receiving less tidal inundation, than the lower marsh position.

Upland groundwater storage may be sensitive to interannual drought conditions, which has implications for how salt marshes may be impacted by climate change and rising sea level. Our study showed a multi-year impact of drought on salt marsh hydrologic behavior: precipitation following a drought year did not recharge upland groundwater storage, and resulted in reduced periods of salt marsh saturation and tidal signal dampening during the winter and spring months despite having received more precipitation than the prior year. This suggests a net decrease in freshwater inputs to shallow salt marsh sediments, with implications for vegetation activity and groundwater-pore water exchange.

Seasonal freshwater inputs from terrestrial upland sources may have implications for microbial communities and nutrient cycling (e.g., denitrifying potential) between marsh positions due to changes in pore water geochemistry and bimodal hydrologic behavior. Freshwater inputs to the upper marsh have been observed to potentially drive earlier activation of *Sarcocornia pacifica* during the spring than in the middle and lower marsh positions. In addition to receiving the least tidal inundation, decreased pore water salinity may allow for higher vegetation transpiration rates and changes in microbial nutrient-processing pathways. Previous studies have shown that surface freshwater inputs (e.g. rivers) are major sources of nutrients to wetlands, however the role of shallow subsurface flow paths from the uplands to salt marshes on biogeochemical processing is poorly understood.

This work suggests that salt marsh bimodal hydrologic behavior due to subsurface freshwater inputs may play a significant role in salt marsh processes, such as influencing nutrient pathways through plant and microbial activity. Additional work is needed to understand the impacts of seasonal groundwater inputs to salt marshes, and its sensitivity to a changing climate.

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