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A Fresh Take: Seasonal Changes in Terrestrial Freshwater Inputs Impact Salt Marsh Hydrology and Vegetation Dynamics

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Abstract
Salt marshes exist at the terrestrial-marine interface, providing important ecosystem services such as nutrient cycling and carbon sequestration. Tidal inputs play a dominant role in salt marsh porewater 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 the role of freshwater inputs on salt marsh hydrology, and how this may impact marsh subsurface salinity and plant productivity. Here, we address this knowledge gap by examining the hydrologic behavior, porewater salinity, and pickleweed (*Sarcocornia pacifica* also known as *Salicornia pacifica)* plant productivity along a salt marsh transect in an estuary along the central coast of California. Through the installation of a suite of hydrometric sensors and routine porewater sampling and vegetation surveys, we sought to understand how seasonal changes in terrestrial freshwater inputs impact salt marsh ecohydrologic processes. We found that salt marsh porewater salinity, shallow subsurface saturation, and pickleweed productivity are closely coupled with elevated upland water level during the winter and spring, and more influenced by tidal inputs during the summer and fall. This seasonal response indicates a switch in salt marsh hydrologic connectivity with the terrestrial upland that impacts ecosystem functioning. Through elucidating the interannual impacts of drought on salt marsh hydrology, we found that the severity of drought and historical precipitation can impact contemporary hydrologic behavior and the duration and timing of the upland-marsh hydrologic connectivity. This implies that the sensitivity of salt marshes to climate change involves a complex interaction between sea level rise and freshwater inputs that vary at seasonal to interannual timescales.

Keywords Salt marsh · Coastal hydrology · Freshwater inputs · Sea level rise · Terrestrial-marine interface · Climate change

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 ecosystem services (Sheppard et al. 2011), such as storm buffering (Valiela and Cole 2002), carbon sequestration (Mitsch and Gosselink 2000; Wang et al. 2020), and nutrient cycling (Verhoeven et al. 2006; Velinsky et al. 2017). Traditionally, research has been focused on identifying the role of tidal inundation, and more recently sea level rise (SLR), on wetland function (Moore 1999; Wilson and Gardner 2006). The impact of shallow groundwater and other terrestrial freshwater inputs on salt marsh hydrology remains understudied (Guimond and Tamborski 2021). In particular, we lack understanding of the impact of seasonal freshwater inputs (i.e., seasonal precipitation, shallow subsurface flowpaths, and perched water tables) on hydrologic behavior, and subsequent porewater salinity and vegetation dynamics, in marsh systems. This knowledge is especially relevant due to climate change, as SLR and shifting precipitation regimes are expected to alter hydrologic inputs to coastal systems with implications for marsh productivity and persistence (Drake 2014; Bittar et al. 2016; Blum et al. 2021). For example, tidal inundation has been shown to mediate

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groundwater table fluctuations and porewater salinity across salt marshes and, in turn, regulate ecological zonations and biogeochemical cycling (Fagherazzi et al. 2013). Sea level rise has also been shown to affect ecological, biogeochemical, hydrological, and sedimentological ecosystem components through increased inundation across the marsh platform, driving erosion, drowning, and landward marsh migration (Fagherazzi et al. 2020; FitzGerald and Hughes 2019). However, this ocean-centric focus has overshadowed the likely role of fresh groundwater inputs on salt marsh ecosystem function.

Groundwater-surface water exchange in coastal environments is often examined within the context of submarine groundwater discharge (SGD; Santos et al. 2021; Wilson et al. 2015a). However, groundwater flowpaths in SGD studies are often referring to deep flowpaths that are not connected to or circumvent salt marshes by exfiltrating 10–1000’s of meters offshore (Gallardo and Marui 2006). Compared to the generally larger scopes of SGD studies, researchers have also investigated groundwater-surface water exchange at the sediment-marsh interface, focusing on centimeter-scale advective processes occurring over short timescales (e.g., sub-hourly; Santos et al. 2012; Taniguchi et al. 2019). Thus, while SGD generally operates on large spatial scales, and porewater exchange investigates processes on very small spatial scales, there has been less focus on the seasonal role of shallow, subsurface freshwater sources that are disconnected from regional aquifers, comprising a critical knowledge gap in understanding of hydrologic controls on salt marsh function (Breier et al. 2009; Robinson et al. 2017). Conducting in situ field studies that quantify the specific role of freshwater inputs on wetland function can aid in our understanding of how these systems may respond to climate change impacts.

Freshwater-driven changes in salinity have long been recognized as a driver of marsh vegetation distribution (Xin et al. 2022). For example, freshwater and tidal-driven changes in sediment saturation and porewater salinity significantly impact salt marsh vegetation zonation and plant productivity (Pennings et al. 2005; Wilson et al. 2015b). The role of freshwater in influencing plant growth and vegetation distributions at the marsh-upland terrestrial boundary is of increasing interest as SLR continues to push marshes landward (Boorman 2019). However, a major focus of marsh ecohydrologic studies in the United States has been on Atlantic and Gulf Coast marshes, which are less topographically constrained (Mcowen et al. 2017). Previous work has shown that terrestrial freshwater inputs in West Coast tidal marshes provide avenues for migration into higher-elevation uplands that may otherwise not be possible in such steep systems (Wasson et al. 2013).

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 by asking the following questions:

1. *How do tidal and seasonal terrestrial water sources interact to drive spatio-temporal variability in marsh saturation states and porewater mobility?*
2. *How does spatio-temporal variation in saturation state drive ecosystem structure (e.g., salinity and plant growth) across a marsh elevation gradient?*

We collected hydrologic, vegetation, and geophysical measurements from a salt marsh transect in Elkhorn Slough, an estuary located within the Monterey Bay of California, USA. The warm, dry summers and cool, wet winters driven by the Mediterranean climate at our site allow us to address knowledge gaps concerning the impact of seasonal freshwater inputs on salt marsh behavior.

Background

Study Site

We conducted this study at the Elkhorn Slough, on the property of the Elkhorn Slough Foundation, a shallow estuary that terminates into the Monterey Bay National Marine Sanctuary along the central coast of California and is part of the NOAA National Estuarine Research Reserve (NERR) network (Fig. 1). The Elkhorn Slough is an 11-km-long estuary from mouth to head, and 3.8 km^2 in area. The estuary is dominated by a mixed semi-diurnal tidal cycle of approximately 2.7 m, with changes in amplitude over the tidal lunar cycle (Grande et al. 2022), and does not have a perennial surface water input at its head; instead, the main freshwater input to the estuary, the Lower Salinas River, meets the Elkhorn Slough at its mouth (Fig. 1A) (Wong 1989). Land use surrounding the estuary is dominated by intensive agriculture, resulting in degraded water quality and eutrophic conditions in some areas (Hughes et al. 2011; Jeppesen et al. 2018; Venkatesh et al. 2021). 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, resulting in precipitation inputs out of phase with the growing season. Elkhorn Slough receives an average annual rainfall of 520 mm/year (NOAA 2020), though this can vary greatly (200–1150 mm/year) with wet years receiving significantly more rainfall and drought periods generally lasting 2–6 years (Caffrey et al. 2002).

Within Elkhorn Slough, we instrumented an emergent salt marsh, Cowell Ranch, located in the upper northwest reach of the estuary, approximately 9 km from the mouth (36° 51′ 5.93″ N, 121° 45′ 44.62″ W; Fig. 1A). The site is tidally influenced and unrestricted, and lies along the intertidal zone

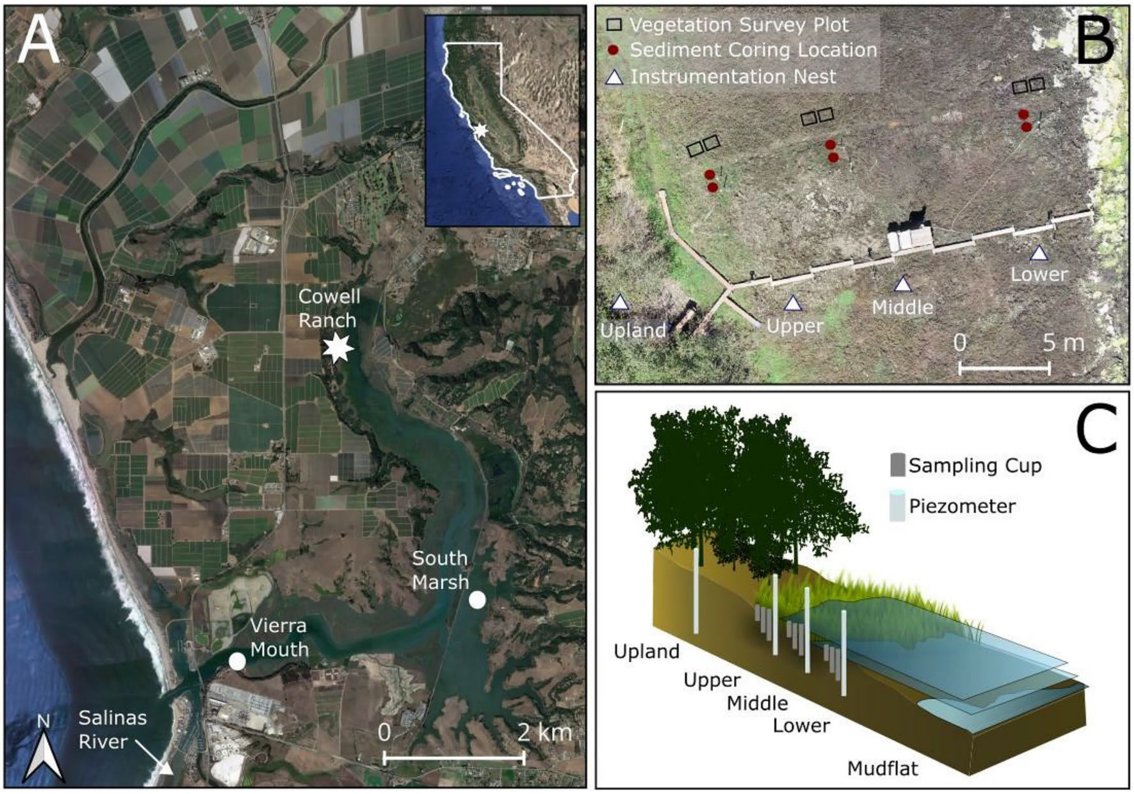


Fig. 1 Map of study site at the Elkhorn Slough in California, United States (36° 49′ 00″ N, 121° 46′ 00″ W). The white star in panel **A** shows the location of the Cowell Ranch study site relative to the estuary, and ESNERR Vierra Mouth and South Marsh monitoring stations are shown by white circle. The study transect with vegetation survey plots, sediment coring locations, and delineated upland and marsh positions are shown in panel **B**. Water level data collection and water quality sampling infrastructure shown in panel **C** (figure adapted from Grande et al. 2022)

with a local tidal range of approximately 3.5 m (− 1.9 to 1.6 m above mean sea level (m amsl)). The datum for amsl is calculated at the estuary mouth. The experimental transect spans 25 m horizontally between the terrestrial uplands and the lower boundary of the salt marsh (Fig. 1B). The portion of transect spanning the salt marsh was delineated by elevation into upper (0.76 m amsl), middle (0.71 m amsl), and lower (0.64 m amsl) 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 1.81 m amsl.

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 (Fig. 1C). The wells and piezometers were constructed using PVC pipe and a slotted PVC screen wrapped with polyester mesh (0.1 mm). 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 below the ground surface (bgs). The upland piezometer was installed to a depth of 2.5 m bgs. Additionally, we established another transect with upper, middle, and lower marsh positions delineated based on similar elevation, approximately ~ 7 m to the north of our original transect. We used this transect to conduct monthly vegetation surveys, characterize subsurface sediment properties from extracted sediment cores, and survey the subsurface using nuclear magnetic resonance (NMR) (Fig. 1B).

The salt marsh vegetation is dominated by pickleweed (*Sarcocornia pacifica*, also known as *Salicornia 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. The plots designated for marsh vegetation surveys are composed exclusively of pickleweed, but other species exist along the upland and upper marsh margin outside of the study transect, such as alkali heath (*Frankenia salina*), marsh jaumea (*Jaumea carnosa*), and salt grass (*Distichlis spicata*).

Methods

Marine Water Level and Salinity and Precipitation Conditions

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 instrumentation station located at the mouth of the estuary and maintained by ESNERR (NOAA NERRS 2023). We downloaded 15-min corrected tidal water level from the NERR Centralized Data Management Office (CDMO) web portal for the study period of December 2019 through April 2022. We are using tidal mouth as an example of tidal range; however, we recognize that the tidal level is modified by the propagation up the open channel and therefore the tidal level at our study site has slight differences in amplitude and frequency to the gage at the estuary mouth (Breaker et al. 2008). However, we are examining larger seasonal patterns in salt marsh hydrologic behavior, and assume the relatively consistent fortnightly tidal signals across the estuary to be sufficient for the analyses of this paper. We also downloaded 15-min surface water salinity data from the CDMO from the South Marsh station (36° 49′ 4.44″ N, 121° 44′ 21.84″ W) and daily precipitation data from the Caspian Weather Station (36° 48′ 56″ N, 121° 44′ 18″ W) through the CDMO portal (NOAA NERRS 2023). Potential evapotranspiration was downloaded from the California Irrigation Management Information System (CIMIS 2023).

Sediment Characterization

We collected two sediment cores at each of the three marsh positions in February and March 2021 to characterize subsurface sediment properties (Fig. 1C). We extracted these 5 cm diameter sediment cores using a Russian Peat Borer (Aquatic Research Instruments, ID, USA) during low tidal conditions. We extracted the sediment cores in 50-cm intervals to the depths of 1.7 m, 2 m, and 3 m deep in the upper, middle, and lower marsh position, respectively. These depths represent the depth to refusal, except for the lower marsh position where we reached the maximum length of our borer. We installed a 2-inch schedule 40 polyvinyl chloride (PVC) screen and casing into each borehole to create piezometers. We photographed core sections upon extraction then wrapped in plastic wrap and placed in PVC cradles to maintain their moisture content and physical integrity for transportation to the lab. We stored the cores at 4 °C and subsampled within 2 days of extraction by collecting subsamples at 5 cm intervals for the top 70 cm, and at 10 cm intervals for the remaining portion. We began sediment analyses immediately after subsampling and analyzed for bulk density (ρ), moisture content (θ), and organic matter (OM) content. We adapted sediment analysis methods from the LacCore Grain Size Pretreatment Standard Operating Procedure Triplett and Heck (2013), Belknap and Kraft (1977), Kemp and Haven (2013), and Kirwan et al. (2011).

Subsurface Hydrology

We instrumented the wells and piezometers with Solinst 3001 LT M5 pressure transducers (Solinst, Ontario, Canada) to collect pressure and temperature measurements every 5 min during the study period (December 2019 through April 2022). We corrected pressure data for barometric pressure using a Solinst 3001 Barologger M5 pressure sensor we installed in the upland region. We converted water level depths to water level along the transect relative to meters above mean sea level (m amsl). We interpolated data gaps in the upland piezometer water level, which occurred because of slow recovery after water quality sampling, using a linear interpolation function from the *imputeTS* R software package (Moritz and Bartz-Beielstein 2017). In this paper, we refer to the shallow subsurface (< 4 m bgs) water measured in the upland position as terrestrial subsurface water, separate from the deep (> 30 m bgs) regional groundwater pumped for agricultural use.

To understand the proportion of mobile and immobile water as well as estimate hydraulic conductivity within the uplands and marsh platform, we deployed nuclear magnetic resonance (NMR) logging down our boreholes on October 21, 2022, and April 5, 2023. This technology has been used extensively in oilfields to estimate reservoir porosity and permeability (e.g., Kleinberg and Vinegar 1996). With the advent of portable instrumentation (Walsh et al. 2013), NMR logging has been used to estimate properties of groundwater aquifers (Knight et al. 2016). More recent research demonstrated the use of NMR in the unsaturated vadose zone and in organic soils (Costabel and Hiller 2021; Minsley et al. 2016). In this study, we used a Dart NMR Logging System (DP175, Vista Clara Inc). This system operates at two different frequencies allowing detection of the NMR response from sediment within a 12–15-cm diameter sensitive zone. While these surveys occurred after the water level, salinity, and vegetation study period (December 2019–April 2022), they provide useful subsurface properties information that give additional context to our observations.

For each date, we deployed the NMR at each marsh position and the uplands using the existing piezometer infrastructure (Fig. 1C). We recognize that the variable nature of tidal systems can cause differences in water saturation through time, and we are thus using these two NMR surveys to identify a relative comparison of water distribution dynamics across the study transect. The water levels in the upland and upper and mid marsh position piezometers on the day of measurement in October 2022 were 120, 26, and 3 cm bgs, respectively. The water level for the lower marsh position on the day of the survey was unknown. The water levels in the upland and upper, mid, and lower marsh position piezometers on the day of measurement in April 2023 were 11, 0, 0, and 17 cm bgs, respectively. For each deployment, we took NMR measurements at 10 cm intervals from the bottom of each borehole to the ground surface. The dual-TR NMR pulse sequence was collected using acquisition parameters described in the Supplemental Information. The NMR data were processed using adaptive reference noise cancellation to mitigate the impact of noise from nearby scientific equipment. The initial NMR signal amplitude is used to directly quantify the fluid volume (i.e., volumetric water content) or porosity if the formation is saturated. The relaxation times estimated from NMR signal decay reflect molecular interactions in the pore fluid and between grain surfaces. These relaxation times (T_1 and T_2) are strongly correlated with the size of the pore space. Therefore, the observed relaxation time distribution is used to distinguish the quantity of water bound in small pores (short T_2) from more mobile water in large pores (long T_2). During the data processing, we designated three cutoff times for binning the output NMR data (T_2 cutoff times): water with $T_2 < 3$ ms is designated as clay water representing the most bound ("immobile"), water with $T_2 > 33$ ms is designated as "mobile," and water with T_2 between these values is designated as intermediate ("capillary").

Salt Marsh Porewater Conductivity

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 porewater from shallow subsurface water. We installed a set of sampling cups at depths of 10 cm, 30 cm, and 50 cm at each marsh position. Briefly, the sampling cups are a closed chamber with an approximate volume of 150 mL, built with 5 cm internal diameter (I.D.) screened PVC pipe capped at the bottom with a PVC cap and an epoxy resin plug at its top. We installed tubing (0.5 cm I.D.) from the bottom of the sampling cup through the sealed epoxy layer to allow for sampling, and used an additional vent of equal internal diameter to prevent a vacuum from forming during pumping, providing hydrostatic equilibrium with the surrounding water table in the cup (see Grande et al. 2023 for more details on sampling cup construction). To sample, we purged the cups using a Geopump peristaltic pump (Geotech Environmental Equipment, Inc.) until they were empty and allowed them to be refilled before collecting the porewater samples. We used an Orion Star A329 Portable Multiparameter Meter (Thermo Scientific, MA, USA) to collect in situ measurements of specific conductance, which we used as a proxy for salinity in this paper. We collected a total of 100, 99, 86, and 27 measurements for the lower marsh, middle marsh, upper marsh, and upland, respectively. Measurement totals varied across positions due to temporal differences in water availability (e.g., upper marsh was drier during low tide).

Vegetation

We conducted monthly vegetation surveys to compare temporal changes in plant productivity to observed seasonality in marsh hydrology. For each marsh position, we established two replicate plots that were composed solely of pickleweed *(Sarcocornia pacifica)* (Fig. 1B). We used a 0.5 m by 0.5 m quadrat to measure the percent cover of green (turgid), woody (brown, senesced), and bare area as well as four measurements per plot of pickleweed stalk length, stem width, and canopy height.

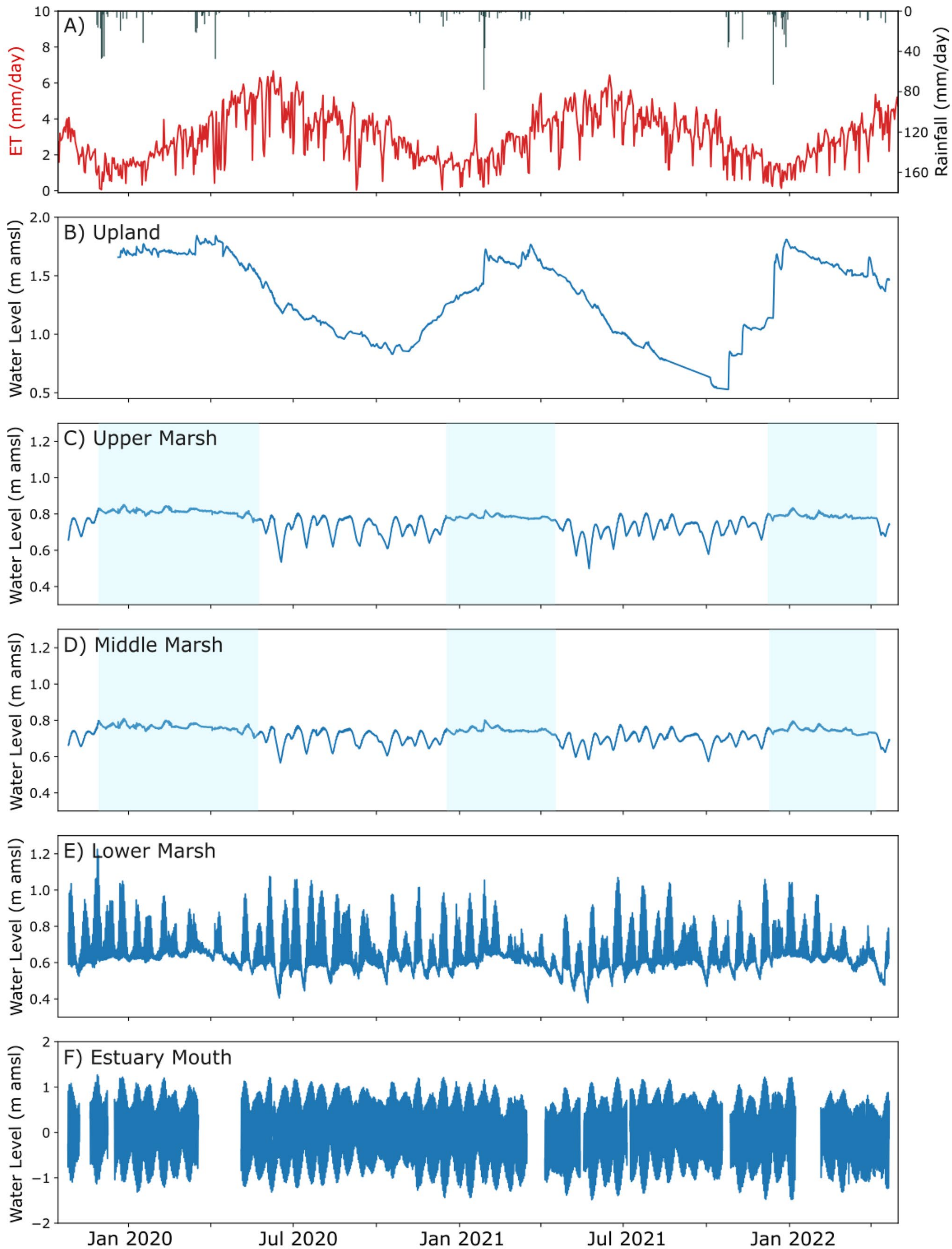
Statistical Analyses

We tested monthly measurements of porewater salinity and vegetation for variability across season and marsh position using Kruskal–Wallis and Wilcoxon tests as our results did not meet the assumptions of one-way or multivariate ANOVA tests. We developed a quasi-binomial general linear regression model (GLM) to understand the probability of green vegetation as a function of season and location along the transect. We included interaction terms between location and season to determine how they relate to each other. The model was created using the GLM function in R 4.2.3.

Results

Precipitation and Tidal Conditions

The majority of rainfall (92%) occurred between the months of November and May, and we observed the maximum daily values during the winter season, consistent with a Mediterranean climate (Fig. 2C, D). Precipitation totals for water years 2020, 2021, and 2022 (where water years are defined from October 1 to September 30) were 455 mm, 280 mm, and 421 mm, respectively (Table 1), with all precipitation falling as rain. All three water years were average or below the average precipitation totals for Elkhorn Slough. On a significant climatic note, water year 2022 received no significant precipitation during the months of January and February (second longest wet season, dry spell on record in California from Jan 8 to Mar 2, 54 days) which on average yields the highest rainfall totals of the year. The measured tidal range at the mouth of the estuary over the study period (Oct 2019–Apr 2022) ranged from a maximum of 1.27 m amsl to a minimum of −1.48 m amsl.


A)
ET (mm/day)
Rainfall (mm/day)
10
8
6
4
2
0
0
40
80
120
160
B) Upland
Water Level (m amsl)
2.0
1.5
1.0
0.5
C) Upper Marsh
Water Level (m amsl)
1.2
1.0
0.8
0.6
0.4
D) Middle Marsh
Water Level (m amsl)
1.2
1.0
0.8
0.6
0.4
E) Lower Marsh
Water Level (m amsl)
1.2
1.0
0.8
0.6
0.4
F) Estuary Mouth
Water Level (m amsl)
2
1
0
−1
−2
Jan 2020
Jul 2020
Jan 2021
Jul 2021
Jan 2022

◂**Fig. 2** Water level and precipitation time series from October 26, 2019, to April 20, 2022. Potential evapotranspiration and daily precipitation shown in panel (**A**). Water level for the upland (**B**), upper marsh (**C**), middle marsh (**D**), lower marsh (**E**), and estuary mouth (**F**). Shaded blue regions in panels **C** and **D** indicate time periods of sustained saturation in the upper and middle marsh

Marsh Sediment Characterization

Sediment water content, OM, and bulk density varied by marsh position and with depth (Fig. 3). Generally, we observed that water content and OM had an inverse relationship with bulk density across all profiles. The upper marsh and middle marsh sediment profiles transitioned from highly organic to mineral at 70 cm and 200 cm, respectively, while the lower marsh sediment profile had high OM content throughout the profile. The upper marsh had the highest bulk density values (~ 1.7 g/cm3) throughout the profile, except for a minimum observed at the ground surface and at the 50 cm depth. We also observed a local peak in bulk density near 30 cm bgs in the upper (1.3 g/cm3), middle (0.8 g/cm3), and lower (0.3 g/cm3) marsh positions (Fig. 3). This coincided with distinct troughs in OM and water content. Below the troughs, the profile of the upper marsh position had consistently low OM, high bulk density, and low water content with depth, while we observed variability at the middle and lower marsh positions.

Subsurface Hydrology

In the upland position, the terrestrial groundwater level fluctuated seasonally (Fig. 2A) with precipitation in the winter/spring and dry conditions in the summer. The subsurface water level in the upland position reached the ground surface during peak saturation at 1.84 m amsl in the wet season and fell below the elevation of the salt marsh platform (0.64 m amsl) during the peak of the dry, growing season in water year 2021. Rapid increases in water level occurred during periods with significant precipitation. In the upland water level time series, we did not observe a tidal signal. However, we did observe small fortnightly fluctuations (± 2 to 5 cm) during the summer and fall seasons, when the water level was low (Fig. 2).

In the marsh water level times series, we observed strong tidal signals during drier summer and fall periods, and dampened tidal signals during the wetter winter and spring periods (Fig. 2B). The dampened response to tidal inundation was observed in all three marsh positions during the winter and spring seasons (Fig. 2B). In particular, the water level was at or above the ground surface elevation at the upper and middle marsh positions during the winter and spring seasons, resulting in tidal signal dampening. In the summer and fall seasons, when the upland water level was low and evapotranspiration (ET) was elevated, 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, regardless of season, but minimum water levels were higher during the winter and spring months.

The period when the marsh reached a prolonged saturated state varied across marsh positions, with generally longer saturation periods in the upper and middle marsh positions while the lower marsh water level appeared to remain dominated by tidal inputs (Table 1; Fig. 2). The longest extent of upper marsh saturation (203 days) was observed during water year 2020, the wettest year in this study. The period of upper and middle marsh saturation was shortest in water year 2022, with water year 2021 having the driest winter and spring seasons and the least amount of precipitation during our study. However, water years 2021 and 2022 received 280 mm and 421 mm of precipitation, respectively, which was well below the annual average for the area of ~ 520 mm/year (NOAA 2020). We observed that the upland water level at the initiation of the upper marsh saturation period was between 1.1 and 1.2 m amsl. The upland water level at the end of the upper marsh saturation period was between 1.4 and 1.5 m amsl, showing that the water level in the upland position was higher than at the beginning of the upper marsh saturation period across water years 2021 and 2022 (Table 1).

Our results from the NMR surveys show distinct differences in the proportions of mobile, capillary, and immobile water across our landscape positions. The lower marsh position had the highest mobile and capillary water content and lowest

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. The lower marsh position is not included in the table due to no observed periods of sustained saturation

Water year	2020	2021	2022
Total precipitation (mm)	455	280	421
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 amsl)	NA, 1.4	1.2, 1.5	1.1, 1.5

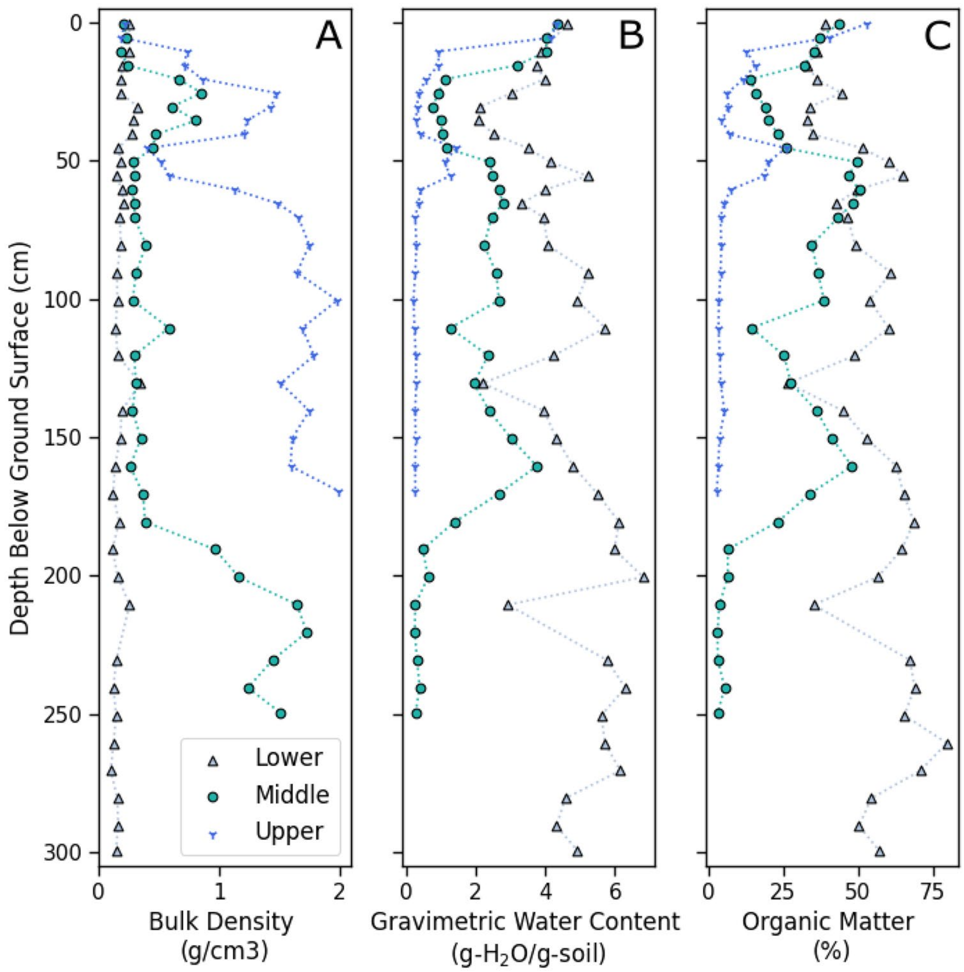


Fig. 3 Vertical profiles of bulk density (**A**), gravimetric water content (**B**), and organic matter content (**C**) for the lower (gray triangles), middle (green circles), and upper (blue forks) marsh positions. Total depth varies between marsh positions due to the depth of refusal deepening from the upper to lower marsh positions

immobile content (Fig. 4). The upper marsh position had the lowest values of capillary and mobile water content out of the three marsh positions, with immobile water fraction increasing with depth below 50 cm bgs. The water content measured in the upland position was mostly within clay pore spaces, with limited water measured in capillary and mobile pore spaces (Fig. 4).

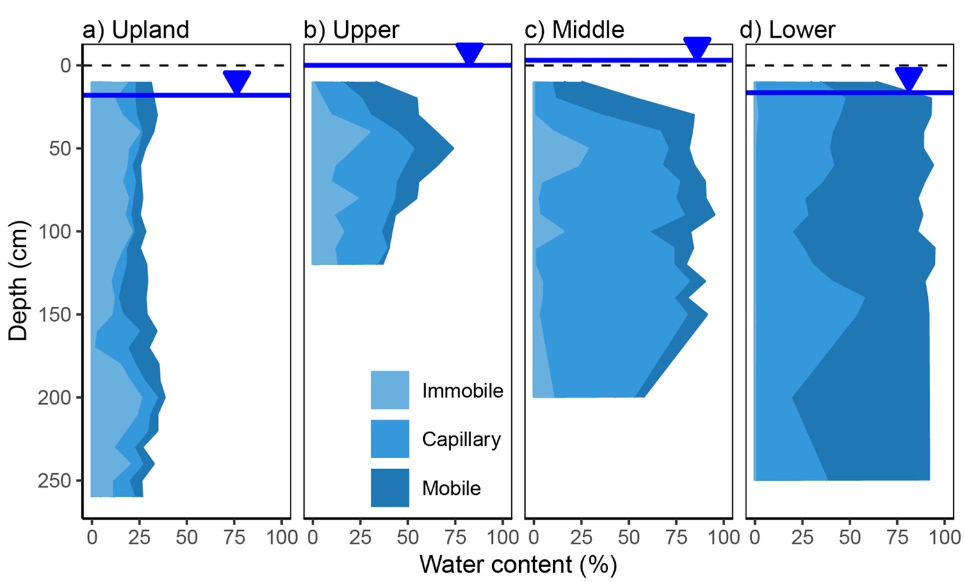


Fig. 4 Vertical profiles of immobile (light blue), capillary pores (blue), and mobile pores (dark blue) in sediment measured by the nuclear magnetic resonance (NMR) survey in April 2023 at the **A** upland, **B** upper marsh position, **C** middle marsh position, and **D** and lower marsh position (see Supplement for October 2022 survey). The top 10 cm of data were removed due to interference with air near the ground surface. Profile depths varied based on borehole refusal depths. Blue horizontal line and triangle represents water level as measured in the boreholes at the time of the survey

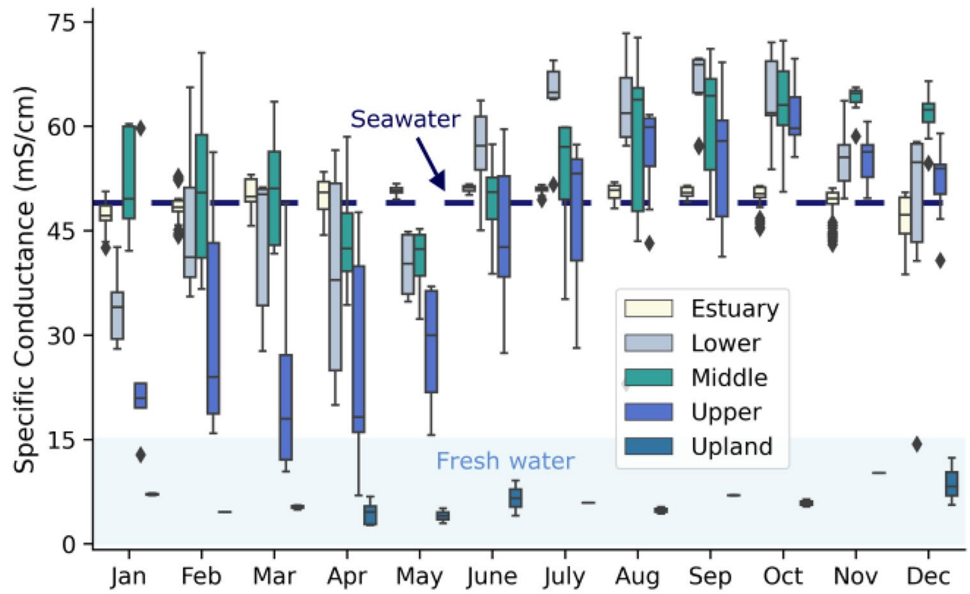


Fig. 5 Box plots of in situ specific conductance binned by month for the study period duration of upland groundwater (teal), estuary surface water (white), and sediment porewater from the lower (grey), middle (green), and upper (blue) marsh positions. Box plots for porewater include all sample depths. Dashed dark blue line indicates mean seawater conductivity (~49 mS/cm), shaded light blue box represents fresh water conductivity range (0–15 mS/cm). Estuarine surface water–specific conductance was measured at the ESNERR South Marsh water quality sampling station. Solid black line within each box plot indicates the median value

Specific Conductance

The mean estuarine surface water–specific conductance at the Vierra Mouth gauge (9 km from Cowell Ranch study site) was relatively constant at ~50 mS/cm across the study period, with minimum values around 47 mS/cm during the winter and maximum values around 52 mS/cm during the summer. Similarly, surface water–specific conductance at the South Mouth gauge (4 km from our study site) was also ~50 mS/cm during the dry season, with minimum values rarely reaching below ~40 mS/cm during peak winter precipitation events (Figs. 5, S2). Water from the upland piezometer had a mean ± standard deviation and median-specific conductance value of 6.13 ± 2.32 mS/cm and 5.52 mS/cm, respectively. The mean-specific conductance of the porewater at the upper marsh position over the entire study period (41.9 ± 17.8 mS/cm) was significantly lower than the middle (54.2 ± 10.5 mS/cm) and lower (51.0 ± 14.2 mS/cm) positions (Wilcoxon test, $p < 0.005$).

Salt marsh porewater-specific conductance was seasonally variable in the three marsh positions. We observed a decrease in specific conductance during the winter and spring seasons and an increase during the summer and fall, when marsh porewater-specific conductance was above Elkhorn Slough estuary water conductivity (Fig. 5). Peak-specific conductance occurred during September for lower and middle positions and October for the upper marsh (Fig. 5).

Specific conductance of all marsh positions varied between seasons with lower conductivity in the winter (median = 49.1 mS/cm) and spring (median = 38.9 mS/cm) than in the summer (median = 59.8 mS/cm) and fall (median = 59.2 mS/cm; Kruskal–Wallis test: $H = 102.88$, df = 3, $p < 0.0001$). The range of specific conductance values in porewater decreased in the fall compared to the winter, spring, and summer across all marsh positions (Fig. 5; Supplemental Table S1).

Vegetation

Salt marsh pickleweed canopy height and stalk measurements varied across the marsh, with the highest measurements at the upper marsh and lowest at the lower marsh position (Supplemental Table S2, Fig. 6). Median canopy height varied across the elevation gradient, with upper marsh position having the largest canopy height and lower marsh position having the smallest canopy height (Kruskal–Wallis test: $H = 218.77$, df = 2, $p < 0.0001$). The canopy height varied between each of the marsh positions mirroring the elevation gradient (upper > middle > lower; Wilcoxon test: $p < 0.05$). Stem length and width followed similar patterns and are described in the supplemental material (Supplemental Table S2; Supplemental Figs. S3, S4).

We observed seasonal trends in pickleweed canopy height that tracked growing and dormant season behavior. Generally, we found canopy height increased during the spring (median = 23 cm) and summer (median = 27 cm) growing season, and decreased during the winter dormant season (median = 26 cm; Kruskal–Wallis test: $H = 26.351$, df = 3, $p < 0.0001$; Fig. 6). However, seasonality did not result in significant differences in canopy height between the fall season and both winter and summer (Wilcoxon test: $p < 0.05$).

Vegetation cover across the salt marsh platform varied seasonally: green (turgid) cover dominated the marsh during spring and summer (i.e., the growing season), while the woody (partially to fully senesced) cover was dominant during the fall and winter (i.e., dormant season) (Fig. 7; Supplemental Table S2). Percent green cover was highest

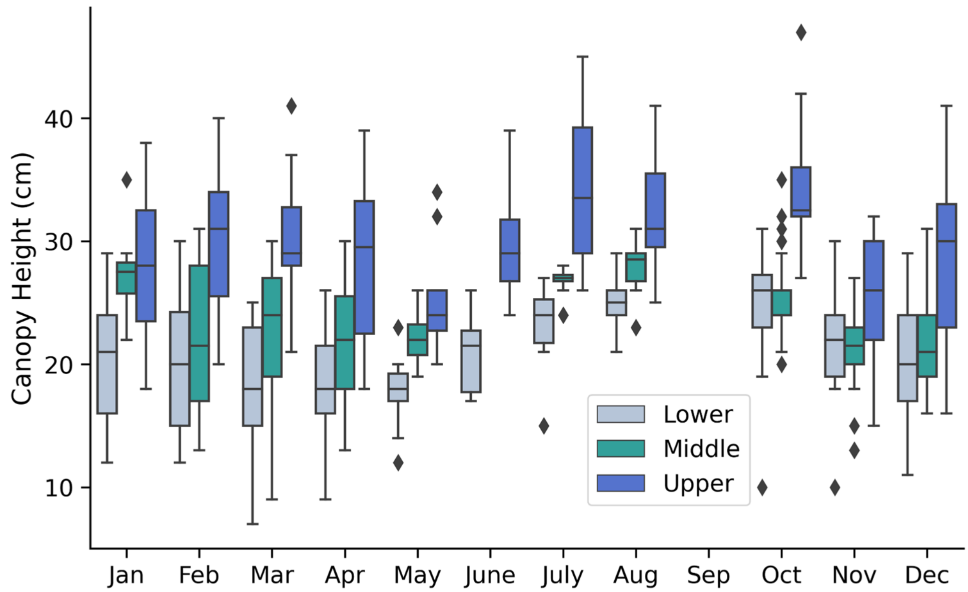


Fig. 6 Box plots showing monthly canopy height for each marsh position. Black line within the box plot indicates the median value

in the fall (median = 67%), dropping to the lowest in the winter (median = 0%), and then rebounding over the spring (median = 56%) and summer (median = 56%; Kruskal–Wallis test: $H = 161.66$, df = 3, $p < 0.0001$). Green cover was lower in the winter season than in the spring, summer, or fall seasons (Wilcoxon test: $p < 0.05$). We found that there is an interaction between season and plot with the upper (t-value: − 2.891, $p = 0.0041$) and middle (t-value: − 2.261, $p = 0.02$) marsh position significantly differing in the green cover of the spring (Supplemental Table S3). Normalized Differential Vegetation Index (NDVI) reflected similar trends as the field. Collected NDVI measurements from the upper and middle marsh stayed greener in the winter than the lower marsh sites (Supplemental Fig. S5).

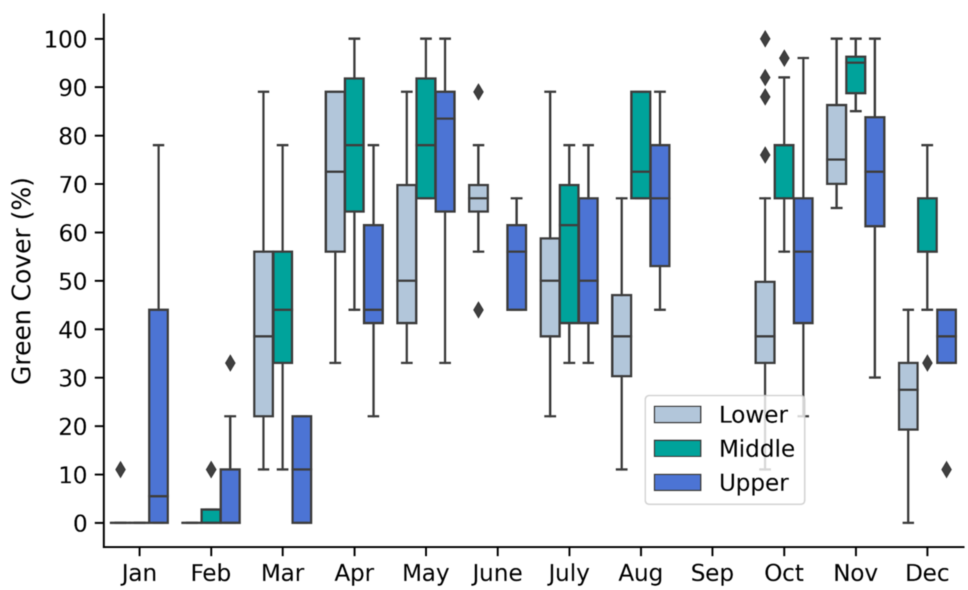


Fig. 7 Box plots showing monthly green vegetation cover for each marsh position. Black line within the box plot indicates the median value

Discussion

Spatio-temporal Differences in Marsh Sediment Saturation States Are a Result of Variability in Water Source Contributions and Subsurface Flushing Capacity

Traditionally, tidal forcings were thought to predominately drive the saturation state of salt marsh sediments, specifically diel and fortnightly tidal inundation dynamics (Wilson and Morris 2012). However, in systems with high seasonal precipitation variation (e.g., Mediterranean ecosystems) and close proximity to the terrestrial landscape, we posit that the saturation state of marsh sediments is a reflection of both the magnitude and timing of incoming water (both from fresh and marine sources) as well as the ability of the subsurface to move that water (e.g., hydraulic conductivity; Moffett et al. 2010; Guimond and Tamborski 2021). Along central coastal California, the marked seasonality and interannual variability in precipitation influence the magnitude and timing of freshwater inputs into marsh systems over seasonal to annual time scales. At our site, we observed continuously saturated conditions across much of the marsh platform during wet winter and spring months (Table 1; Fig. 2). During this time, precipitation can fall on and infiltrate directly into the marsh platform. However, the positive response of water level to precipitation events is often observed to be short-lived, usually lasting hours to days following precipitation events (Gardner and Gaines 2008) and thus cannot fully explain the observed prolonged (multiple months) elevated saturation state across much of the marsh platform. Instead, our observations of saturated salt marsh conditions coincide with periods of elevated upland subsurface water levels, suggesting freshwater contributions from the uplands drive marsh saturation, dampening the tidal signal (Fig. 2). Specifically, seasonal precipitation can recharge shallow subsurface zones within the adjacent terrestrial landscape, creating a hydraulic gradient from the upland toward the salt marsh (Fig. 2; Xin et al. 2022). This hydraulic gradient may reverse during the dry summer and fall, potentially when the elevation of the upland piezometer water level falls below the elevation of the marsh platform (Fig. 2). Such hydraulic gradient reversals lead to changes in dominant flowpath directions (Guimond and Tamborski 2021). While we are not able to calculate exact horizontal hydraulic gradients with our datasets due to differences in piezometer installation between the upland and marsh positions, water level observations suggest there is a connection between the directionality of major hydraulic gradients and tidal dampening. During periods of low groundwater levels, we observed clear fortnightly tidal cycles across the marsh platform (Fig. 2). This finding suggests that the decreased terrestrial water inputs during the dry season amplify the impact of tidal inundation on marsh hydrology.

Evapotranspiration may amplify seasonal behavior in the observed salt marsh saturation states. Evapotranspiration during the growing season reduces water content in surficial marsh sediments (Harvey and Nuttle 1995), potentially contributing to the increase in fortnightly tidal cycle response in the marsh platform during the summer and fall months. In addition, terrestrial plant water use may decrease the overall upland-to-marsh hydraulic gradient, reducing freshwater inputs during the transition from wet winter to dry summer months (Grande et al. 2023).

The proximity to the terrestrial landscape influences how contributions of different water sources (freshwater and marine water) contribute to the spatial variability in the saturation state behavior across the marsh platform. Tidal inundation drives rapid (daily to fortnightly) porewater exchange and drainage (Grande et al. 2023). During summer months, when freshwater contributions are limited, this tidal signal dominates across all marsh positions. During winter months, when freshwater contributions are elevated, the tidal signal is only observed in the lower marsh position, despite no drastic changes in tidal inundation between the wet and dry seasons. We argue that the spatial extent of the freshwater plume is limited, especially in drought years, and does not reach the lower marsh position at the research site, only dampening the tidal signal in the upper and middle marsh positions.

Differences in sediment characteristics across the marsh platform can influence variability in how water enters the subsurface as well as the residence time of water in the subsurface (Gardner 2007; Wu et al. 2022; Xin et al. 2009). The upper marsh has higher bulk density and lower OM, leading to lower overall porosity and capacity to store water (Fig. 3). This produces a sediment column that has minimal mobile water (Fig. 4) and presumably longer hydrologic residence times, which may explain the extended period of saturation in winter months. In contrast, the lower bulk density, higher OM, and more abundant mobile water pore spaces in the lower marsh position are suggestive of high conductivity marsh sediments that facilitate rapid hydrologic flushing of the marsh subsurface. This may help explain why we observe rapid fluctuations in water levels across the study period in the lower marsh.

Saturation States Affect Salinity and Vegetation Across the Elevation Gradient

Across marsh positions, we found that salinity was higher in the summer and lower in the winter months. We attribute this seasonal cycle to changes in the freshwater inputs to the marsh and variation in evapotranspiration.

Evapotranspiration increases porewater conductivity through the removal of water in shallow salt marsh sediments during the growing season (Hughes et al. 2012). Salt marsh porewater conductivity significantly increased between May and July, coinciding with the commencement of spring and summer plant growth and increased transpiration (Fig. 5), with mean porewater conductivity exceeding that of the tidal surface water for most of the summer and fall seasons. This process leads to the concentration of salts in shallow sediments (Nuttle and Hemond 1988; Miklesh and Meile 2018). Conductivity varied less in the summer than in the winter across all positions. This consolidation of variance points to the cross-site dominance of tidal inputs and evapotranspiration as drivers of salinity in the dry 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.

The seasonal changes in conductivity varied across the elevation gradient due to the seasonal dominance of tidal and freshwater inputs. During the summer months, tides dominate all sites and freshwater inputs are limited (Grande et al. 2023). The upper marsh experienced the greatest increase in porewater conductivity between spring and summer, indicating that any dilution from freshwater inputs was significantly reduced and plant activity was high during the dry summer season. This effect may be due in part to the fact that the upper marsh receives the least tidal inundation (5.4% annual tidal inundation duration) compared to the lower marsh (9.6%).

In the winter months, variance in porewater conductivity across the marsh increased, pointing to the difference in hydrologic drivers across the positions. The freshwater inputs to the marsh affect the upper marsh position more, with greater dilution of salinity and the lowest salinity between positions in the winter. The lower marsh position has some dilution effect, but the mechanism is less clear with tidal forcing dominating the saturation state of the lower marsh in the winter. As discussed in "Spatio-temporal Differences in Marsh Sediment Saturation States Are a Result of Variability in Water Source Contributions and Subsurface Flushing Capacity," sediment characteristics vary across the marsh platform, influencing the residence time of water. These characteristics influence the conductivity across the elevation gradient through affecting residence time and flushing of solutes. Specifically, the longer residence time of water in the upper marsh may explain the extended period of porewater dilution during the winter and spring, compared to the middle and lower marsh positions, which have higher OM and lower bulk density that may allow for shorter residence times and rapid tidal flushing of any dilute precipitation contributions.

Reduced tidal water salinity during winter may contribute to porewater salinity changes; however, Elkhorn Slough tidal water salinity data from ESNERR at the South Marsh station shows significant, but short-lived decreases during precipitation events, with specific conductance reaching a minimum of ~ 40 mS/cm for about a week in peak winter (NOAA NERRS 2023). Therefore, tidal water salinity is not likely to be the dominating control on seasonally decreased porewater salinity, as the low (< 35 mS/cm) specific conductance values we see in the upper and middle marsh positions are sustained throughout the winter and spring (Fig. 5). Additionally, if tidal water salinity was the dominant control on upper and middle marsh porewater dilution during the wet season, we would expect to see a relatively uniform porewater salinity across the marsh platform. We note that the South Marsh station is 4 km from our study site, and recognize it may not fully represent tidal conditions at the site.

Terrestrial freshwater inputs promote plant growth in salt marshes, which result in more vegetation productivity in marsh positions closer to the terrestrial upland (Moffett et al. 2012). We found that vegetation in the upper marsh had a taller canopy height than the middle and lower marsh positions (Fig. 6). Surveys of pickleweed 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 (Supplemental Figs. S3, S4; Supplemental Table S2). Spring pulses of freshwater from the upland potentially catalyzed earlier plant growth in the upper marsh, with greening occurring earlier for the upper marsh (January/February; Fig. 7). In other words, we see a "growth spurt" in the upper marsh pickleweed during spring (Fig. 7, Supplemental Figs. S4, S5), and this observation occurs when the salt marsh is saturated and the porewater specific conductance is low. The high green cover was maintained across much of the growing season, with the high and middle marsh having higher green cover than the low marsh. These results point to the importance of freshwater plumes in activating and maintaining the vegetation across seasons. In addition, these upper marsh areas receive 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 (Zedler 1983; Callaway and Zedler 1998; Schile et al. 2011).

System Memory and Climate Change Impacts on Marsh Function and Spatial Extent

Seasonal freshwater inputs from the adjacent uplands to the salt marsh depend on the available water stored in the uplands, which fluctuates year-to-year based on recharge from precipitation. During droughts, terrestrial water storage is depleted, leading to a potential reduction in freshwater inputs to the salt marsh. We observed this in our study, where water year 2021 was drier than the previous year, and the extent of wet season salt marsh saturation and tidal signal dampening was shorter than that of the previous year. Interestingly, we observed the shortest saturation period during water year 2022, despite water year 2021 receiving less precipitation (Fig. 2). This suggests that the severity of droughts can have compounding interannual impacts on salt marsh hydrology and that historic precipitation can influence contemporary hydrologic behavior. 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. The observed connection between terrestrial freshwater inputs, salt marsh hydrology, and vegetation productivity showcases the importance of year-to-year variability of precipitation in coastal systems with Mediterranean climates.

Precipitation ameliorates salinity conditions, fills storage deficits, and provides water for plants; however, the intensity and frequency of precipitation events may influence the resilience of salt marsh systems in the future. With anticipated increased intensity and reduced frequency of precipitation events in California (Swain et al. 2018), we may observe heightened strength of flushing events that momentarily decrease salinity in coastal ecosystems. We observed this in the daily surface water salinity record during our study period (Supplemental Fig. S2), which may help alleviate inhospitable hypersaline conditions in marsh sediments in winter (Fig. 5). However, such high-intensity events may reduce overall groundwater recharge by exceeding the subsurface infiltration capacity. Additionally, these less frequent events may have non-discernible effects on the extent of saturated conditions into spring, when marsh plants start growing. More long-term hydrologic research is needed to understand how changing precipitation regimes may impact the timing and delivery of freshwater contributions to salt marsh systems.

Sea level rise, a global hydrologic forcing, will alter both the tidal driver of the marsh saturation state and the extent of the salt marsh platform. With higher sea level, the effects of tidal forcing will be dominant farther inland (Bosserelle et al. 2022), possibly changing the dominance of hydrologic drivers across the elevation gradient. This shift will bring saline water and more frequent tidal oscillations across seasons into higher-elevation marsh positions. SLR will also shape the size and extent of the marsh. Elkhorn Slough has experienced devastating marsh loss through both anthropogenic alterations to the estuary and the ongoing effects of SLR (Van Dyke and Wasson 2005). As water levels continue to rise, we expect to see continuing erosion along the water's edge in west coast marshes, leading to a shortened marsh platform because of the high topography of the region (Thorne et al. 2018). Over time, we expect the salt marsh platform extent to narrow into thinner "bathtub rings" of fringing marsh along steeper uplands. Previously upper marsh positions may behave more like lower marshes, dominated by tidal forcing and with higher hydraulic conductivity. As marshes migrate towards the upland, distinct subsurface salinity patterns emerge due to seasonal upland freshwater input pulse; while increased connectivity to upland freshwater upwelling can facilitate marsh migration and support leading edge habitat, stark seasonal salinity patterns potentially threaten salt marsh plant viability as porewater conditions may become unsuitable for plant survival (Zhang et al. 2022). These changes will decrease the size and the heterogeneity of conditions within marshes, impacting the ecology, ecosystem services, and biogeochemistry of salt marshes. In addition to this narrowing marsh extent, we expect that the changing in timing and quantity of precipitation, specifically the projected contraction of wet season duration in this Mediterranean climate region due to climate change, will further threaten the critical requirements for salt marsh productivity and survival.

The West Coast of North America is especially vulnerable to extreme meteorological events such as drought, which impact groundwater recharge and in turn reduce the buffering effects of upland freshwater inputs. However, changes in precipitation patterns are happening across the continent with implications for changes in when and how freshwater is delivered to marsh systems. Thus, this work applies to coastal systems that have direct connections to freshwater sources, which we believe is the case for many upper marsh systems across wetland systems, with implications for considering upland memory and storage effects due to water cycle changes. Understanding the role that freshwater inputs play in regulating marsh health is critical for predicting how climate change is disrupting these systems, particularly while marshes are also experiencing drowning due to SLR.

Conclusions

We monitored spatio-temporal variability in subsurface saturation states and porewater mobility at a salt marsh in Elkhorn Slough (central coastal California) to understand hydrologic impacts on salinity and plant growth across a marsh elevation gradient. We found that the seasonality of precipitation inputs in this region drove observed differences in marsh saturation states across the salt marsh platform. Tidal inputs were the dominant driver of salt marsh hydrologic response during the dry season, and terrestrial upland subsurface water inputs saturated the upper and middle marsh positions during the wet season, dampening the tidal signal. We observed that the seasonally elevated groundwater level in the upland and the associated marsh saturation during the wet season lowered porewater-specific conductance in the upper and middle marsh, coinciding with earlier plant growth at these positions compared to the tidally dominated lower marsh. During the dry season, we observed daily and fortnightly tidal signals in piezometers across the entire marsh. This coincided with decreased terrestrial water level and increased porewater specific conductance, suggesting a compounding response from increased evapotranspiration and reduced terrestrial water inputs.

These observed hydrologic and plant responses indicate a seasonal shift in salt marsh hydrologic connectivity to the terrestrial upland that ultimately impacts ecosystem function. We found that the duration of hydrologic connectivity varied based on incoming precipitation amounts, suggesting that the severity of drought and historical precipitation can impact contemporary hydrologic behavior. Keeping in mind that lower coastal marsh elevations face increasing pressure from sea level rise, our results suggest the sensitivity of salt marshes to climate change involves a complex interaction between sea level rise and freshwater inputs that may vary at seasonal to interannual timescales. Continued work understanding how projected intensification of the water cycle may buffer, impede, or exacerbate coastal marsh structural or functional responses to sea level rise and changing climate conditions is critically needed.

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Data Availability Data used in this manuscript are available via Hydroshare (Montalvo, M. (2024a)) and ESS-DIVE Data Archive (Montalvo, M. (2024b)).

Declarations

Conflict of Interest The authors declare no competing interests.

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