Salinity increases with water table elevation at the boundary between salt marsh and forest

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Abstract

The migration of salt marshes into forests along coastal regions is nowadays well documented. Sea level rise and storms threaten coastal forests by increasing groundwater levels and salinity. Salinization is the main cause of forest conversion to salt marsh in North America. In this paper we study groundwater levels and salinity in two wells installed at the border between forest and salt marsh in the lower Delmarva peninsula, USA. The upper well is located in the regenerative forest, where recruitment is still possible, while the lower well is located in the persistent forest, where only mature trees survive. Groundwater in the upper well is fresh at the roots depth, while in the lower well the mean salinity is 8 ppt. Our data suggest that rainfall has an instantaneous effect on salinity and groundwater levels, but it does not affect salinity and groundwater levels on longer periods (weeks to months). Groundwater levels and salinity reflect the hydraulic gradient toward the marsh (a proxy for outgoing water fluxes), the uphill hydraulic gradient (a proxy for incoming water fluxes) and temperature (a proxy for evapotranspiration). Salinity increases when groundwater levels are high. To explain this result, we put forward the hypothesis that a high water table favors the flux of surficial, fresh water to the marsh, and loss of freshwater by evapotranspiration. These losses are likely replenished by saltier water moving at depth.

1. Introduction

Freshwater availability, flooding and soil salinity can be considered the main drivers of ecological zonation in many coastal regions (Thibodeau et al. 1998; Gardner et al. 2002; Wilson et al.2015). In temperate areas, these factors play a crucial role in structuring the salt marsh-forest interface (Fagherazzi et al. 2019). Being either not salt tolerant or not flood tolerant, coastal trees can be killed by increasing tidal flooding, leading to forest retreat and marsh expansion. Coastal forest retreat is generally driven by sea-level rise and storm events that affect the marsh-upland boundary at different spatial and temporal scales. Sea level rise progressively increases the salinity of costal zones, thus influencing vegetation recruitment (see Fagherazzi et al. 2019 for a review). Salt intrusion in aquifers can also be exacerbated by water withdrawals in populated areas (Pezeshki et al. 1990). Strong winds and storm surges, usually associated with tropical cyclones, can cause short-term damages and killing of trees, making space available for new vegetation. According to Duryea et al. (2007), strong winds are responsible for defoliation, breakage and uprooting of trees. Storm surges cause saltwater intrusion that suppresses seed germination, suffocates and inhibits root formation and tree survival (Fernandes et al. 2018). In general, tree seedlings are more susceptible to salt and flooding than mature trees whereas storm events directly affect the survival of all trees (Kearney et al 2018).

Rainfall events can have a positive effect on the forest bordering a salt marsh, reducing groundwater salinity by dilution (Sumner et al. 2005). However, as sea level increases, rainfalls could flood soils causing tree mortality from anoxia (Stanturf et al., 2007). When occurring simultaneously, rainfall and salt intrusion events result in specific dynamics. If the soil was already saturated with fresh water before a storm surge, it is unlikely that groundwater salinity increases (Gardner et al. 1992, Allen et al. 1996). Flooding events affect the available oxygen content in the soil, decrease the soil redox potential, and consequently slow the photosynthetic activity in flood intolerant vegetation species (Anderson and Pezeshki 1999). Salt intrusion in the soil undermines the growth of new leaves and accelerate the senescence of mature trees (Munns and Tester 2008). Evapotranspiration is also a main hydrological driver in coastal forests. Evapotranspiration creates an upward soil water flow with solute concentrating or precipitating near the soil surface, making salt ions available to be absorbed by roots (Mohamed et al. 2000). The relationship among precipitation, evapotranspiration, and tidal oscillations is fundamental to characterize groundwater levels and salinity in a forest and adjacent salt marsh. Tidal inputs directly affect groundwater discharge (Li and Berry 1999). When large storm surges occur, flooding often augment the salinity of the soil, affecting vegetation growth. Salt intrusion can also reach deep ground layers and the aquifer (Robinson et al 2007).

All hydrological inputs should be considered to determine groundwater dynamics during a storm. Although many studies have focused on the marsh-upland boundary dynamics (Fagherazzi et al. 2019) or have analyzed and interpreted salinity data for these regions (Gardner et al. 2002, Carter et al. 2008), the salinity dynamics at the marsh-upland interface remain unclear. The goal of this paper is to characterize variations in groundwater level and salinity in a coastal forest bordering a salt marsh. We will explore how rainfall, evapotranspiration, and storm surges might control both water levels and salinity for two wells. Our preliminary results indicate that groundwater dynamics at the marsh/forest interface can be complex and therefore will require extensive field campaigns in the future.

2. Study area

We focus our study on a coastal forest in the Eastern Shore of Virginia National Wildlife Refuge on the southern tip of the Delmarva Peninsula, in Virginia, United States (Fig. 1). The Delmarva Peninsula is bordered by the Atlantic Ocean on the eastern side and by Chesapeake Bay on the western and southern sides. This area is experiencing particularly high rates of sea level rise, around 5 mm/yr (Sallenger et al. 2012). The forest is dominated by loblolly pine (*Pinus taeda*), particularly common in the southeastern regions of the United States. At the salt marsh boundary, the forest changes to a woody shrubs zone, characterized by *Juniperus virginiana, Iva frutescens, Baccharis halimifolia* and *Myrica cerifera* (Fernandes et al. 2018). This zone borders, in turn, a salt marsh ecosystem, where *Spartina alterniflora* is the most representative species. The Delmarva peninsula climate varies between humid subtropical to the south, characteristic of Eastern Virginia, to humid continental to the north, characteristic of Northern Delaware and North-Eastern Maryland. The average annual maximum daily temperature in Cape Charles, close to our study area, is 19.4 °C, while the average annual minimum daily temperature is 10.6 °C. The average annual rainfall is around 1140 mm.

The Delmarva peninsula experiences a semidiurnal tidal cycle, with a mean low tide (MLW) of -0.40 cm and a mean high tide (MHW) of 0.393 cm on MSL at Kiptopeke station. The Delmarva peninsula is often affected by tropical cyclones and winter Nor'Easters that can cause coastal flooding. According to the Virginia Department of Emergency Management, the Delmarva peninsula has been hit by some of the strongest storm events since 2003. On September 18th, 2003 during Hurricane Isabel, sea level reached 1.34 m on NAVD88 at the NOAA Kiptopeke station. On November 13th, 2009 during Tropical Depression Ida and Nor'Easter, sea level reached 1.50 m. On August 27th, 2011 during Hurricane Irene, sea level reached 1.35 m and on October 29th, 2012 during Hurricane Sandy, sea level reached 1.48 m.

Over the years, storm events along with sea level rise have affected the ecological zonation of the marsh-forest interface, establishing a higher regenerative zone, rich of saplings, and a lower persistent forested zone, where only mature trees survive (Kearney et al. 2019). Sea level rise advances the salt marsh in the forest, while storm events move the lower boundary of the regenerative zone towards the upland. This ecological ratchet was fully described in Fagherazzi et al. (2019).

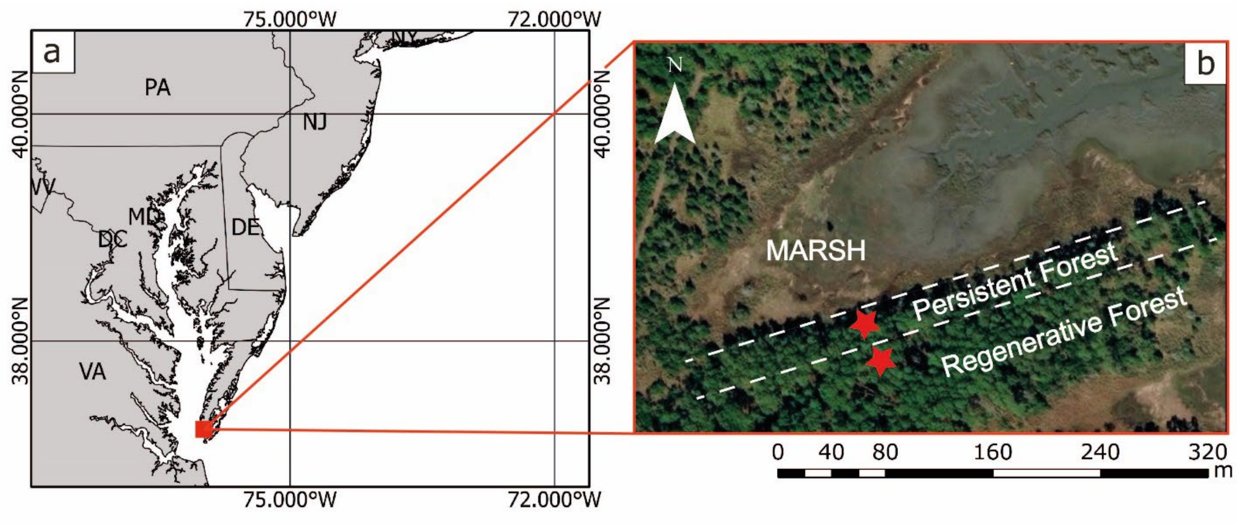

Figure 1: a) location of the study site in Virginia, USA, b) location of groundwater wells (red stars) (after the study of Kearney et al. 2019).

Data

Water level and conductivity were measured in two groundwater wells along a transect (Fig. 1b). The transect starts at the marsh boundary to the north and ends in the middle of the forest; it was chosen to be perpendicular to the gently sloping hillside reaching the regeneration zone.

A Schlumberger Water Service CTD diver, able to measure conductivity, temperature and water depth was installed in each well. A first well was placed at the lowest boundary of the pine forest in the persistent zone, where adult trees can survive but not saplings. The well is at 1.16 m ±0.14 m (lower well) and at a depth of 0.80 cm below the ground surface (elevation of 0.334 m on

NADV88). The second well was placed at the line of sapling at the beginning of the regenerative zone, at 1.24 m ± 0.13 m (upper well) and at a depth of 0.90 m below the ground surface (elevation of 0.507 m on NADV88). The wells were screened to the surface. According to McFarland and Scott (2006) the approximate altitude of the top of bedrock basement is between -1500m and -1800 m on NGVD29 (~NAVD88) in the Virginia Eastern shore. The general groundwater flow direction is towards Chesapeake Bay (McFarland & Scott 2006). Well positions on a slope (inclination angle estimated = 0.86 deg) suggest the general flow direction from the upper site to the marsh. In 2013 mean Chesapeake forest age ranged from 16 to 40 years. According to Fire Effects Information System (FEIS), *Pinus taeda* taproots grow between 1.2 to 1.5 m in depth. Therefore, the CTD depth of around 0.80cm in the lower well corresponds to the mean root depth.

Hourly water level data were collected from 08 January 2014 to 07 January 2015, and referenced to North American Vertical Datum 1988 (NAVD88). Hourly conductivity data were converted into hourly water salinity data using the conductivity-salinity algorithm provided by Fofonoff and Millard (1983), where data are reported in practical salinity scale 1978 (PSS78).

The soil of the study area has been characterized on the basis of cores collected in January, 2014. For both lower well site and upper well site, six soil samples at depth of 0 cm, 20 cm, 40 cm, 60 cm, 80 cm and 95 cm were taken. The particles size was analyzed using a Ro-Tap sieve shaker equipped with sieves of 2000 μm, 1000 μm, 500 μm, 250 μm, 125 μm and 63 μm. Finally, obtained data were processed using GRADISTATv8 program (Blott and Pye, 2001). Soil can be homogeneously classified as moderately sorted medium-fine sandy in the study area (Fig. 2).

Available hourly precipitation data (mm/hr) were collected by the Virginia Coast Reserve Long Term Ecological Research (VCR-LTER) at the Hog Island station (VCR97018). Because of the

38-kilometer distance between Hog Island station and the Eastern Shore of Virginia National Wildlife Refuge, precipitation data collected at this station might not capture all rainfall events. Daily temperature data collected at the same station are used to assess evapotranspiration effects on groundwater levels. Evapotranspiration was estimated using temperature-based approaches (Trajkovic 2005, Yates and Strzepe 1994), which might result in an overestimation in such humid conditions if the model used is not correctly calibrated (Trajkovic 2007). Sea level data were obtained from the NOAA Kiptopeke station (Identifier: 8632200). Kiptopeke station is located 5 kilometers from the study site, and the data are referred to NAVD88. Tidal data also capture storm surges.

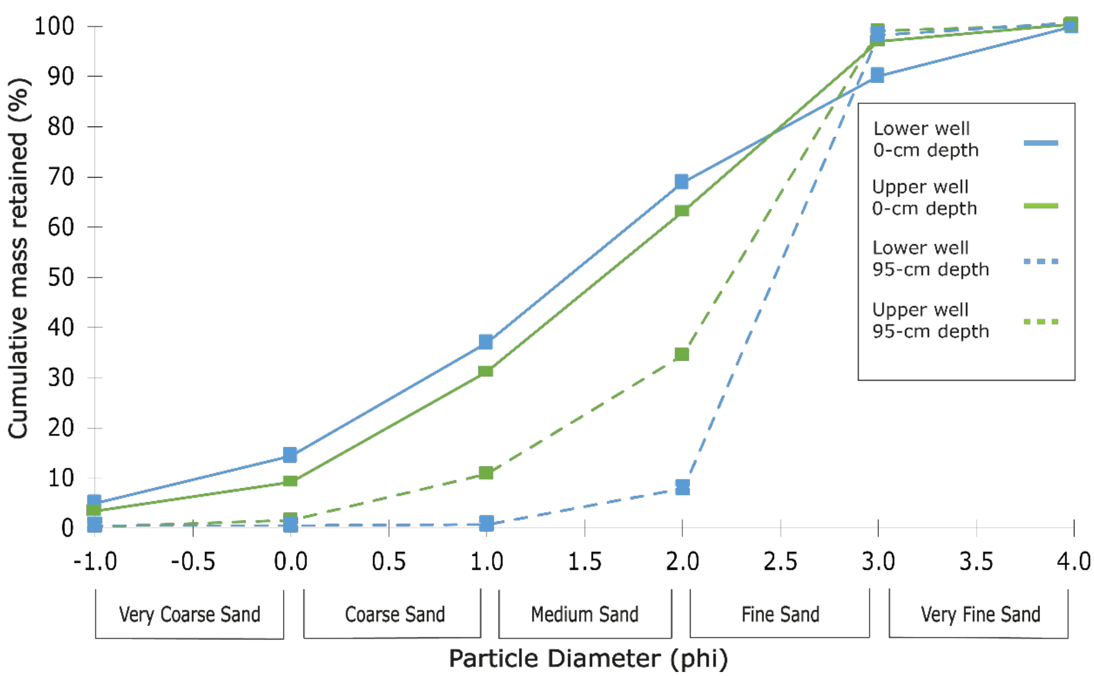

Figure 2: Cumulative frequency curves of sediment diameter at the upper and lower well in 2014.

3. Results

The groundwater table dynamics in both wells are similar (Fig. 3d), while salinity values indicate a significant difference (Fig. 3e). According to Kearney et al. (2019), the groundwater table (Fig. 3d) is generally below the ground surface, except for few days, when either occasional heavy rainfalls or long rainy periods occur (Fig. 3a). This happens several times during the year at the lower well, on 11 January, 13 February, 16 April, 16 May, 8 September and 24 December when the water level reaches the ground surface at 102 cm on NAVD88. On the other hand, flooding only occurs in the upper well on 8 September, when the groundwater level reaches the ground surface at 124 cm on NAVD88.

Overall groundwater table elevations vary from 36.9 cm to 112.6 cm above NAVD88 in the lower well and from 35.5 cm to 137.8 cm in the upper well. In the lower well, closer to the salt marsh, the salinity values are much higher than the values in the upper well. In particular, in the lower well the salinity ranges from 0.13 to 11.48 ppt, while in the upper well the salinity ranges from 0.01 to 0.29 ppt (Fig. 3e). A moving average carried out considering a window of 800 hours highlights the seasonal trend of groundwater table and groundwater salinity (Fig. 3d-e).

The most conspicuous precipitation events occur from April to September and range from a minimum of around 1 cm/hr in April to a maximum of 2.2 cm/h on September 7. The largest storm surge events of 69.7 cm occurred on November 2 and on December 9. Other storm surges events of around 50 cm occurred over the year (Fig. 3b). The corresponding moving average for observed sea water level range from a maximum of 31 cm in October to a minimum of -35 cm in November. Four temporal windows are selected to better analyze the most important features of the dataset. (Fig. 4,5).

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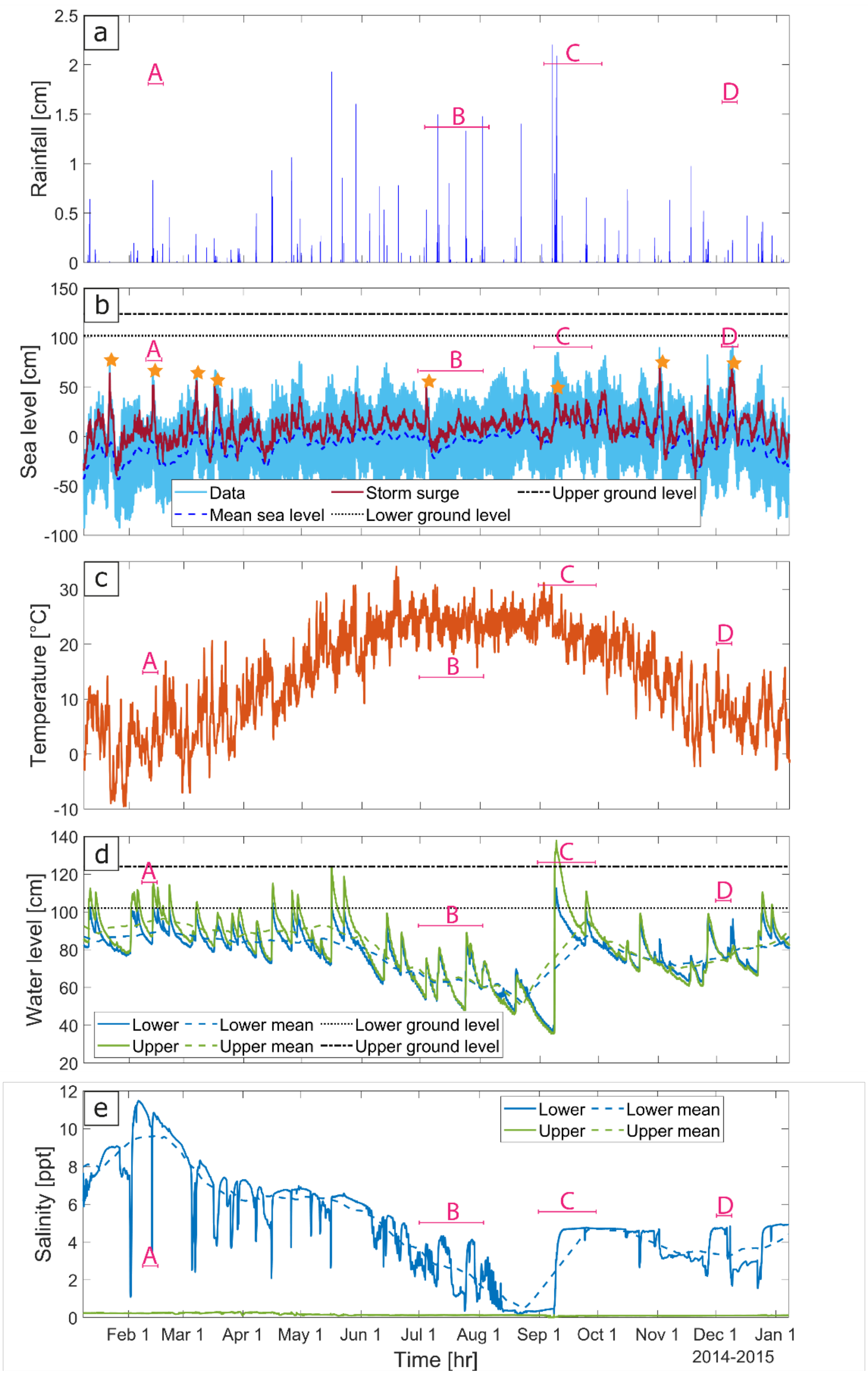

a
Rainfall [cm]
A
B
C
D
b
Sea level [cm]
Data
Storm surge
Upper ground level
Mean sea level
Lower ground level
c
Temperature [°C]
d
Water level [cm]
Lower
Lower mean
Lower ground level
Upper
Upper mean
Upper ground level
e
Salinity [ppt]
Feb 1
Mar 1
Apr 1
May 1
Jun 1
Jul 1
Aug 1
Sep 1
Oct 1
Nov 1
Dec 1
Jan 1
Time [hr]
2014-2015

Figure 3: a) Hourly precipitation at Hog Island station; b) observed tidal data with moving average and storm surges at Kiptopeke station (NOAA); c) hourly temperature at Hog Island station; d) groundwater level in the lower and the upper wells, corresponding moving averages and ground surface; e) salinity in the lower and upper wells with corresponding moving averages. Yellow stars in b) identify the most significant storm surges.

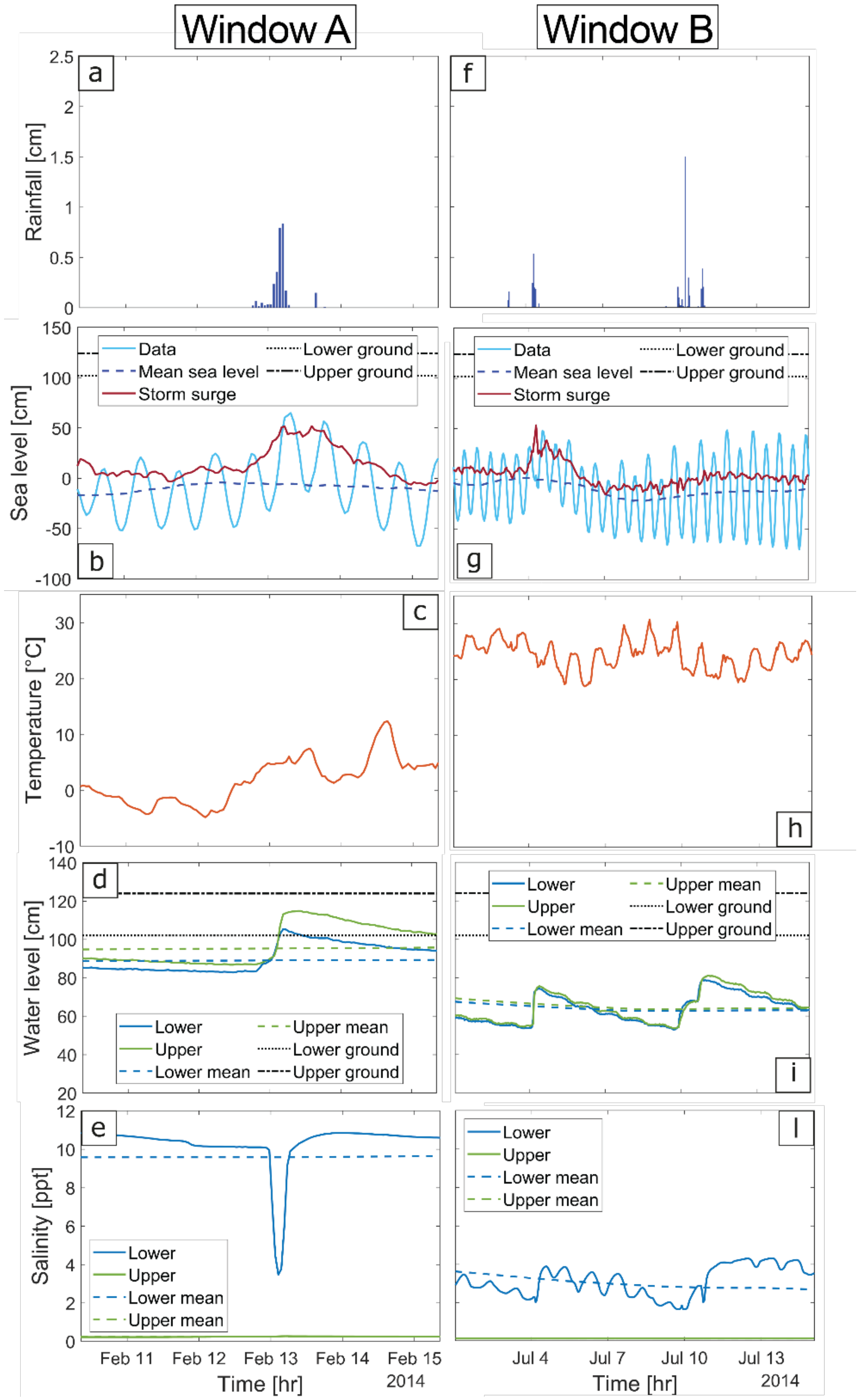
Window A
Window B
a
f
Rainfall [cm]
2.5
2
1.5
1
0.5
0
150
100
50
0
-50
-100
Sea level [cm]
Data
Mean sea level
Storm surge
Lower ground
Upper ground
b
g
c
h
Temperature [°C]
30
20
10
0
-10
140
120
100
80
60
40
20
Water level [cm]
d
i
Lower
Upper
Lower mean
Upper mean
Lower ground
Upper ground
12
10
8
6
4
2
0
Salinity [ppt]
e
l
Lower
Upper
Lower mean
Upper mean
Feb 11
Feb 12
Feb 13
Feb 14
Feb 15
2014
Time [hr]
Jul 4
Jul 7
Jul 10
Jul 13
2014
Time [hr]

Figure 4: Temporal windows with measured hydrological variables. Windows A from 10 February 2014 at 8.30 am to 15 February at 8.30 am, Windows B from 1 July 2014 at 1.30 am to 15 July at 1.30 am. a) Rainfall events; b) observed tidal data, moving average of observed tidal data, storm surge; c) hourly temperature at Hog Island station; d) groundwater level in the lower and upper wells, corresponding moving averages and ground surface; e) salinity in the lower and upper wells with corresponding moving averages. Note that: to better illustrate the data in t*he*

windows, the horizontal axes have different time interval.

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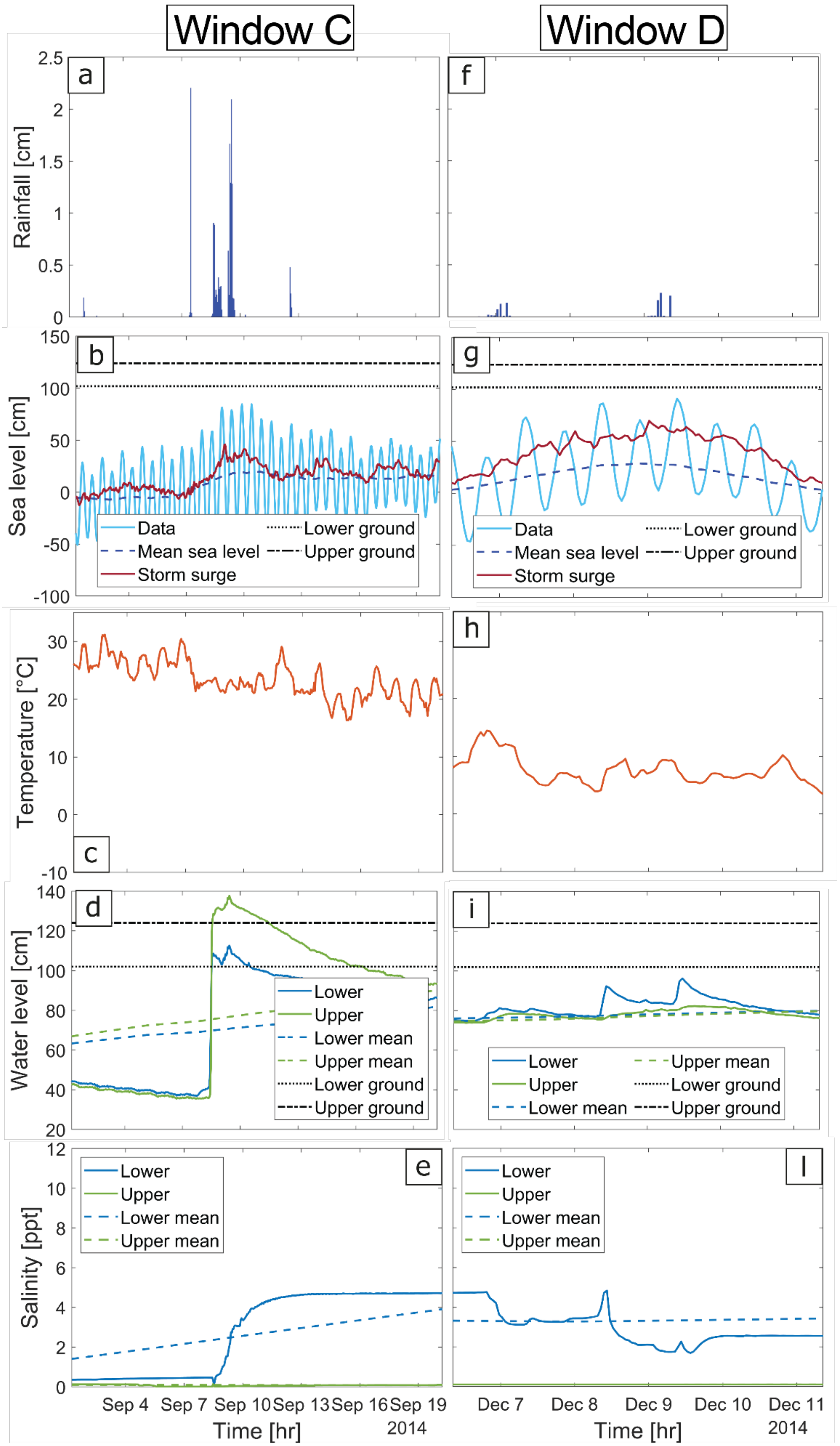


Window C
Window D
a
f
Rainfall [cm]
b
g
Sea level [cm]
Data
Mean sea level
Storm surge
Lower ground
Upper ground
c
h
Temperature [°C]
d
i
Water level [cm]
Lower
Upper
Lower mean
Upper mean
Lower ground
Upper ground
e
l
Salinity [ppt]
Sep 4
Sep 7
Sep 10
Sep 13
Sep 16
Sep 19
2014
Dec 7
Dec 8
Dec 9
Dec 10
Dec 11
2014
Time [hr]

Figure 5: Temporal windows with measured hydrological variables. Windows C from 1 September 2014 at 5.30 am to 20 September at 5.30 am and Windows D from 6 December 2014 from 8.30 am to 11 December at 8.30 am. a) Rainfall events; b) observed tidal data, moving average of observed tidal data, storm surge; c) hourly temperature at Hog Island station; d) groundwater level in the lower and in the upper wells, corresponding moving averages and ground surface; e) salinity data in the lower and upper wells with corresponding moving averages. Note that: to better illustrate the data in the windows, the horizontal axes have different time interval.

3.1 Precipitation and groundwater levels

In general, precipitation events are reflected in the groundwater level dataset as instantaneous increases (Fig. 6a). Cumulative rainfall is calculated for each precipitation event, neglecting the rainfall that moved as runoff when the soil was fully saturated. In both wells groundwater level significantly increases (R^2=0.311 p<0.05 in the lower well and R^2=0.497 p<0.05 in the upper well) as the rainfall amount increases. A consistent increase in water level from few centimeters to around 40 cm occurs when rainfall amounts are above 1 cm. From September 7 to September 9 precipitation events between 3 and 8 cm along with storm surges between 10 and 40 cm cause a water level increase of around 70 cm in the lower well and of around 100 cm in the upper well, exceeding the ground surface respectively of 10.6 cm and of 13.8 cm (Fig. 5d). A precipitation event of 2.62 cm occurred between February 12 and February 13, and it is reflected as an increase of 22 cm in the lower well and of 27.30 cm in the upper well (Fig. 4a,d). This event floods the ground surface at the lower location with 3.3 cm. A precipitation event of around 1 cm causes a groundwater increase of 3 cm in Window D (Fig. 5f,i). In Window B (Fig. 4f,1), a similar precipitation events cause groundwater increases between 5 cm and 12 cm. Therefore, groundwater level response to precipitation is not always the same. This can be explained by the presence of lateral water fluxes affecting the water table elevation and antecedent soil moisture conditions. Some precipitation events in Windows A (Fig. 4a,d), C (Fig. 5a,d) and D (Fig. 5f,i) are not reflected in the groundwater level. This discrepancy might be due to the location of the weather station, which is several kilometers away. After each precipitation event, water level tends to decrease due to hydrologic recession dynamics.

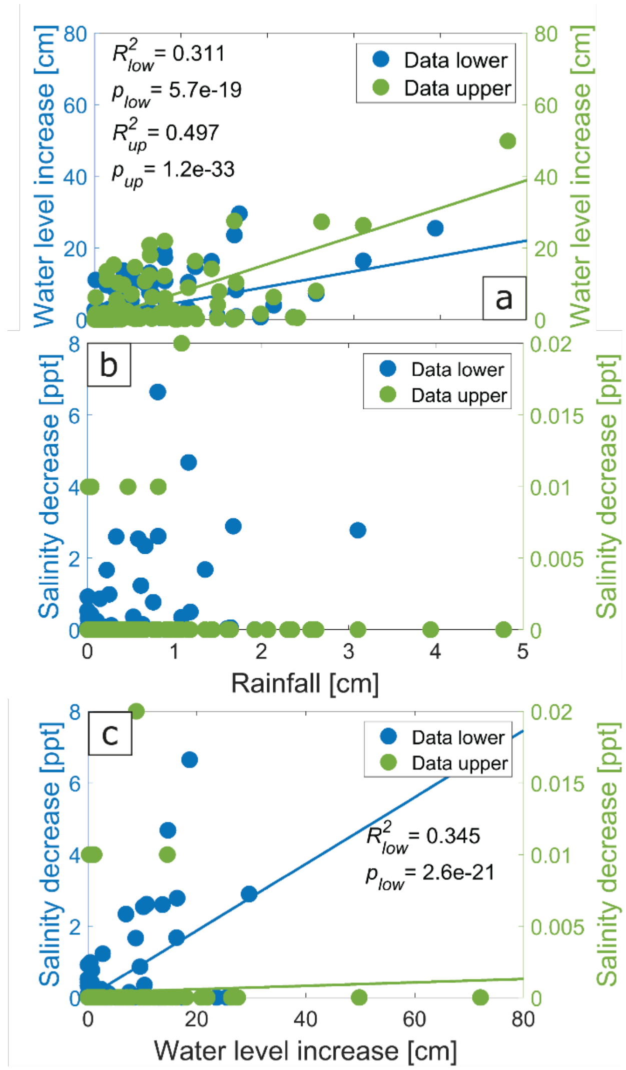


Figure 6: a) Groundwater level increments associated to cumulative rainfall amounts. Salinity drops associated to: b) cumulative rainfall amounts and c) ground water level increments. Salinity decreases on vertical axis are expressed as absolute values.

3.2 Evaporation and groundwater levels

According to Gardner et al. (2002), evapotranspiration triggers a daily step-like decrease in the elevation of the groundwater table. This typical trend can be seen during the warmer summer season, for example, in window B (Fig. 4i). During sunlight hours, evapotranspiration is higher, due to the combined effects of vegetation transpiration and soil evaporation; the higher the external air temperature the higher the decrease in groundwater level. The groundwater level in both wells remains quite constant during the nighttime hours. The daylight decrease is between 3 cm and 4 cm. An overall drop of 30 cm can be reached in this period, if the instantaneous increments due to precipitation are not strong enough to increase the average groundwater level (Fig. 4i). The evapotranspiration effect is reduced in the fall season. In window C (Fig. 5d), the groundwater level drops only 1 cm during the daylight hours. The step-like decrease associated to evapotranspiration is not present during the winter season.

3.3 Salinity

In the upper well, salinity is around zero and not related to precipitation events (Fig. 6b). Here, groundwater can be considered freshwater (Fig. 3e). In the lower well, the salinity trend is strictly connected to lateral fluxes of water. Precipitation events are reflected in the salinity record as instantaneous drops due to dilution effects of the additional rainfall water. The decrease in salinity is not correlated to rainfall amount (Fig. 6b). In Window A and Window B (Fig.4a,e,f,l) two similar rainfall amounts (2.62 cm and 2.35 cm) cause very different decreases in salinity (6.64 ppt and 0.20 ppt respectively). The second precipitation event in Window C (Fig. 5a,e), is not felt in the salinity record. Instantaneous drops in salinity are instead correlated to water level (R^2=0.345 $p<0.05$, Fig. 6c). Once again, the salinity drops are related to water level increases calculated neglecting runoff effects. In particular, when water level increases from 0 cm to 15 cm, the absolute value of salinity drops increase linearly from 0 ppt to 3 ppt. The highest values of 6.64 ppt in terms of salinity drop is reached during the precipitation event on 12 February (Fig. 4e). After each precipitation event, salinity value increases fast, tending to reach the value before rainfall dilution, and sometimes surpassing it.

In Window A, C, and D the salinity increase after storms seems to be associated to surge events. In Window A (Fig. 4b,e), a storm surge event of 51.7 cm increased the salinity of 1.69 ppt compared to the value before the storm, while in window C (Fig. 5b,e) a storm surge event of 45.9 cm slowly increased the salinity of 4.55 ppt. After this increase the salinity level remains higher. A storm surge event of 69.7 cm, occurred on December 8, increases the groundwater level and salinity respectively of 20 cm and 1.67 ppt in the lower well (Fig. 5i-l). This event leads groundwater level in the lower well to reach level higher than in the upper well, inverting the groundwater flux (negative hydraulic gradient). Rainfall events are not detected over this time.

Salinity increases when storm surge occurs, but the variables are not significantly correlated (Fig. 7a). Storm surge effects on salinity are tested considering maximum storm surges and their time duration, when no precipitation events occur (Fig. 7b). A significant correlation is found between storm surge duration and salinity increase for storm surge events higher than 40 cm (Fig. 7b).

In Window B (Fig. 4l) we detect a diurnal salinity oscillation due to evapotranspiration in a time period not affected by precipitation events. During sunlight hours, when evapotranspiration is higher and water level is decreasing, salinity tends to decrease, while during the nighttime when evapotranspiration is low and groundwater levels are constant salinity tends to increase. Moreover, in this time window neap-spring tidal modulation seems to affect variations in salinity. During the neap tide the average salinity is around 3 ppt while during the spring tide the salinity is around 4 ppt.

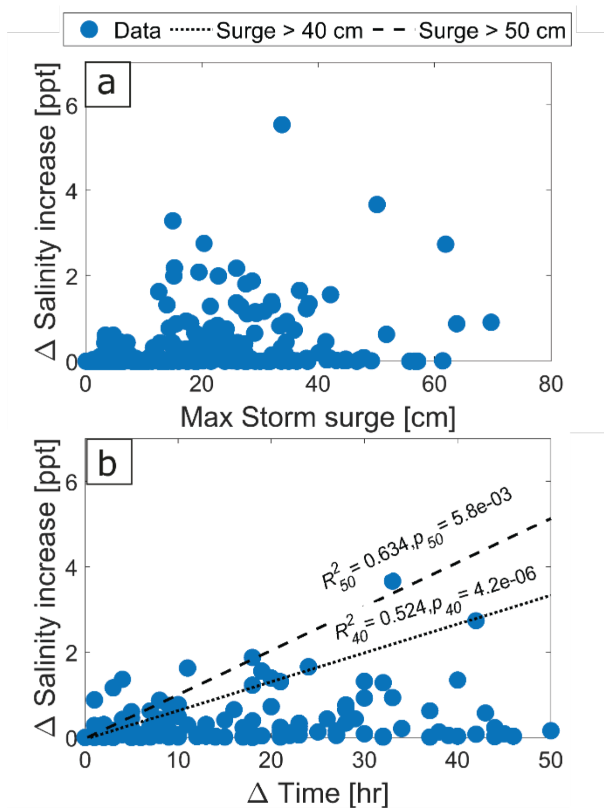


Figure 7: a) Salinity increments associated to maximum storm surge events and b) to storm surge duration in the lower well. Positive correlation between time duration and salinity increases for storm surge higher than 40 cm is shown.

3.4 Weekly and monthly relationships among groundwater level, groundwater salinity, evapotranspiration, sea level and rainfall.

The relationships between groundwater level, salinity, rainfall, seawater level and evapotranspiration are analyzed using a linear regression analysis. The variables are correlated considering a temporal window spanning from 1 hour to 2 months. All variables are averaged across the temporal windows. Monthly salinity is significantly correlated to monthly groundwater level in the lower well (Fig. 8a). The correlation is also significantly positive for all temporal windows, with R^2 values ranging from 0.475 to 0.832 (Fig. 8d). The relationships between groundwater level, and rainfall, temperature, upstream and downstream hydraulic gradients are presented in Fig. 9 ,10 and 11. The hydraulic gradients are considered here as a proxy for the flux of water reaching the lower well from upstream or discharging toward the marsh. Monthly groundwater levels are significantly correlated to temperature, upstream discharge from the upper well and downstream discharge to sea (Fig. 9). A significant negative correlation is present between groundwater level and temperature with a R^2 ranging from 0.336 for a one-week window to 0.533 for a one-month window on a yearly scale (Fig. 11a). Therefore, upstream hydraulic gradient has the strongest control on groundwater level, while rainfall is weakly correlated to groundwater levels. On a seasonal scale, correlation between groundwater level and upstream hydraulic gradient is always significantly positive for all seasons with R^2 values higher than 0.385 (Fig.11 b,c,d,e). The temperature effect is significant during summer (Fig.11 c) reaching R^2 values of 0.771 for a two-week window. Groundwater level is significantly correlated to downstream discharge in spring and summer with R^2 values higher than 0.331, for one-day and one-month temporal windows (Fig. 11 b,c).

In Figure 11 we report the determination coefficients between salinity, rainfall, temperature, upstream and downstream hydraulic gradients (Fig. 11 f, g, h, i, l). Monthly groundwater salinity is significantly correlated to temperature, upstream discharge from the upper well and downstream discharge to the marsh (Fig. 10). The correlation between salinity and hydraulic gradients is significantly positive with R^2 values higher than 0.315 for temporal windows ranging from 1 day to 1 month on a yearly scale (Fig. 11f). Salinity is negative correlated to temperature with R^2 values ranging from 0.341 to 0.461 for temporal windows from 1 hour to 1 month (Fig. 11f) on a yearly scale. Salinity and upstream hydraulic gradient are significantly correlated in summer and fall (Fig. 11 h,i). Downstream hydraulic gradient has the most remarkable effect on salinity during spring and summer (Fig. 11 g, h). Temperature variations are significantly felt in the salinity trend during winter and fall season (Fig. 11 i, l).

A multiple regression analysis is conducted considering only independent variables leading to significant effects on the dependent variables of groundwater level and salinity on a yearly scale (Table 1, 2). Groundwater level is correlated to temperature, upstream and downstream hydraulic gradients while groundwater salinity is correlated to groundwater level, upstream and downstream gradients and temperature. A first model considering all variables is proposed to describe groundwater level and salinity trends (Table. 1, 2). Multicollinearity leads to non-significant coefficients for some independent variables even if the regression as a whole is significant. Redundant information is provided by different variables. After looking for the best combinations among variables, two other models are proposed. Both salinity and groundwater level are analyzed in a multivariate space firstly with upstream and downstream hydraulic gradients, and then with upstream hydraulic gradients and temperature. For each temporal window adjusted R^2 values increase in comparison to single regressions. Analysis of residuals confirm that removing one or more variables from the multivariate dataset leads to information lost, and that the model well represents the groundwater level trend. Parameters obtained in the sub-models are significant ($p<0.05$) and give a positive effect on the analysis.

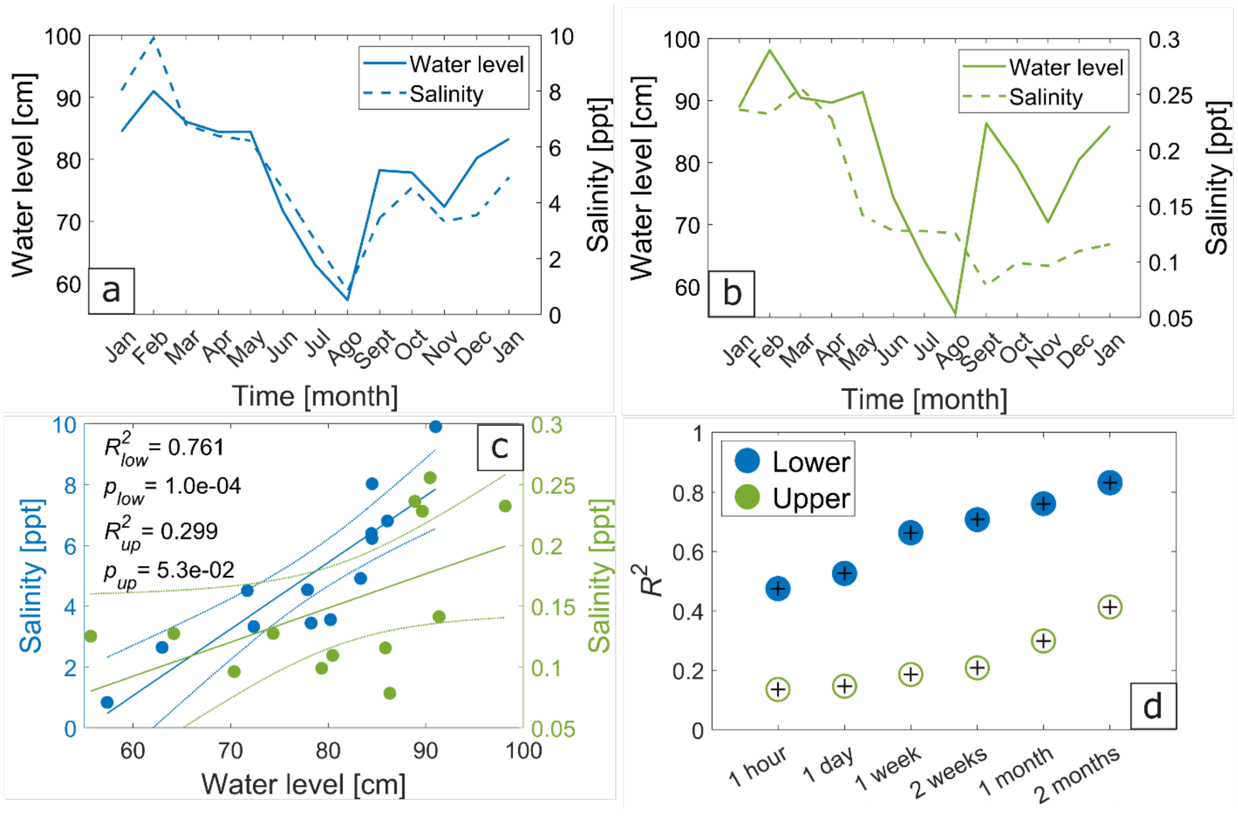
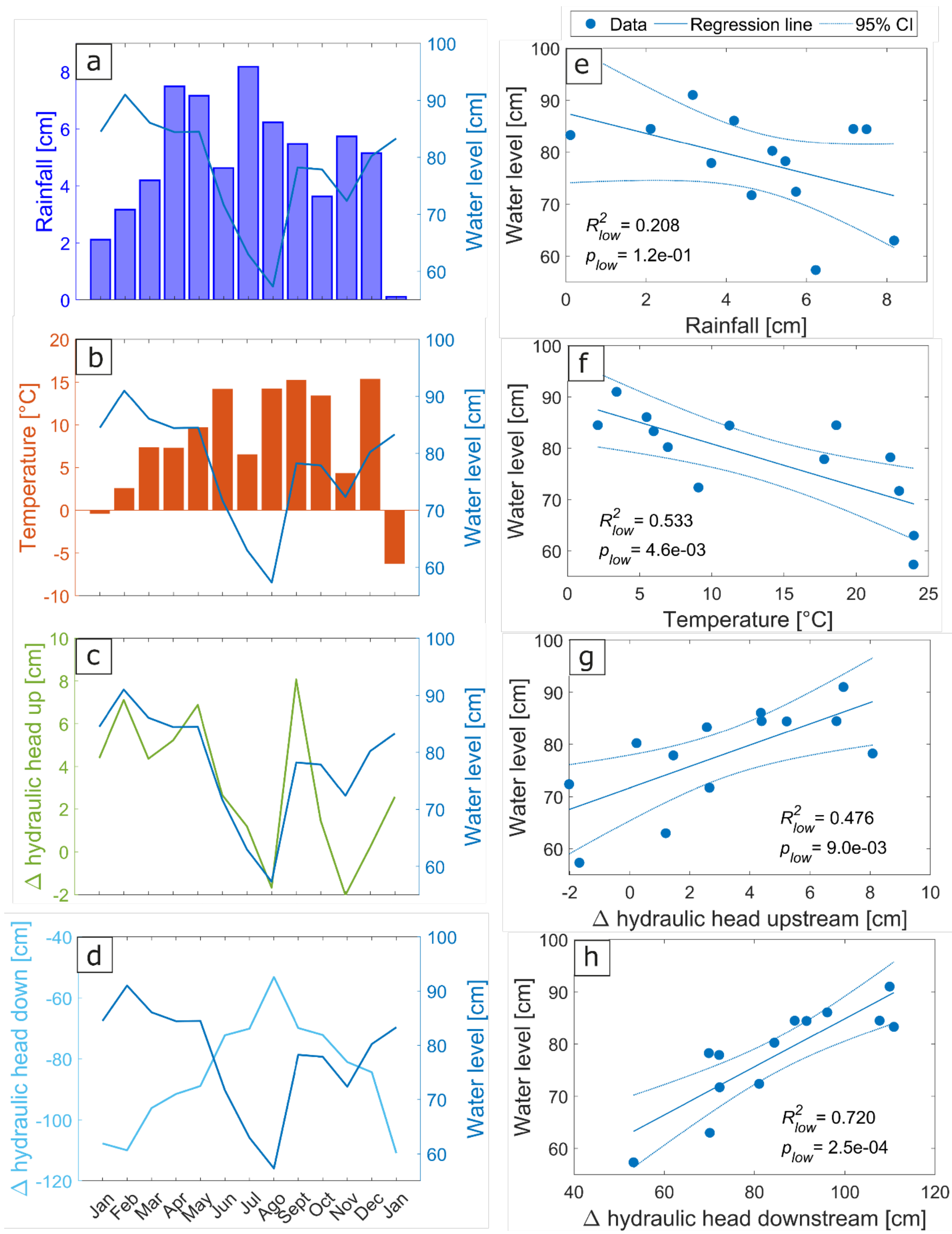


Figure 8: Monthly groundwater level and salinity in a) lower well and b) upper well. c) Linear regression results for monthly groundwater levels and salinity; d) R^2 values for different temporal windows from 1 hour to 2 months over the year. Filled circles represent significant R^2($p<0.05$), empty circles are not significant. The sign inside the circles indicates whether the correlation is positive or negative.



Data
Regression line
95% CI
a
Rainfall [cm]
Water level [cm]
b
Temperature [°C]
Water level [cm]
c
Δ hydraulic head up [cm]
Water level [cm]
d
Δ hydraulic head down [cm]
Water level [cm]
Jan Feb Mar Apr May Jun Jul Ago Sept Oct Nov Dec Jan
e
Water level [cm]
R^2_{low} = 0.208
p_{low} = 1.2e-01
Rainfall [cm]
f
Water level [cm]
R^2_{low} = 0.533
p_{low} = 4.6e-03
Temperature [°C]
g
Water level [cm]
R^2_{low} = 0.476
p_{low} = 9.0e-03
Δ hydraulic head upstream [cm]
h
Water level [cm]
R^2_{low} = 0.720
p_{low} = 2.5e-04
Δ hydraulic head downstream [cm]

Figure 9: a) Monthly cumulative rainfall; b) average temperature; c) averaged upstream hydraulic gradient; and d) averaged downstream hydraulic gradient related to monthly averaged groundwater levels. Linear regression analysis on monthly data are reported in e), f), g), h).

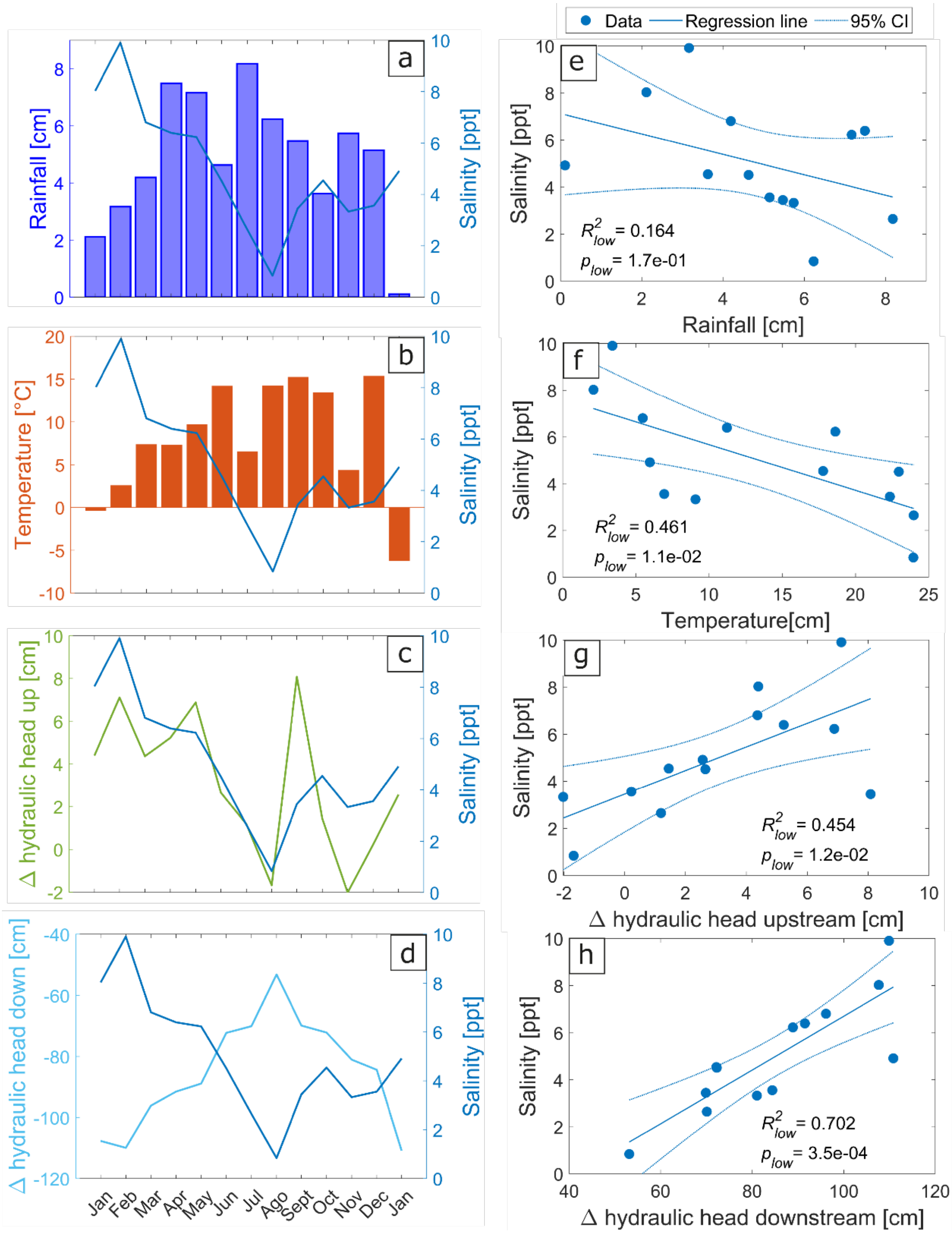
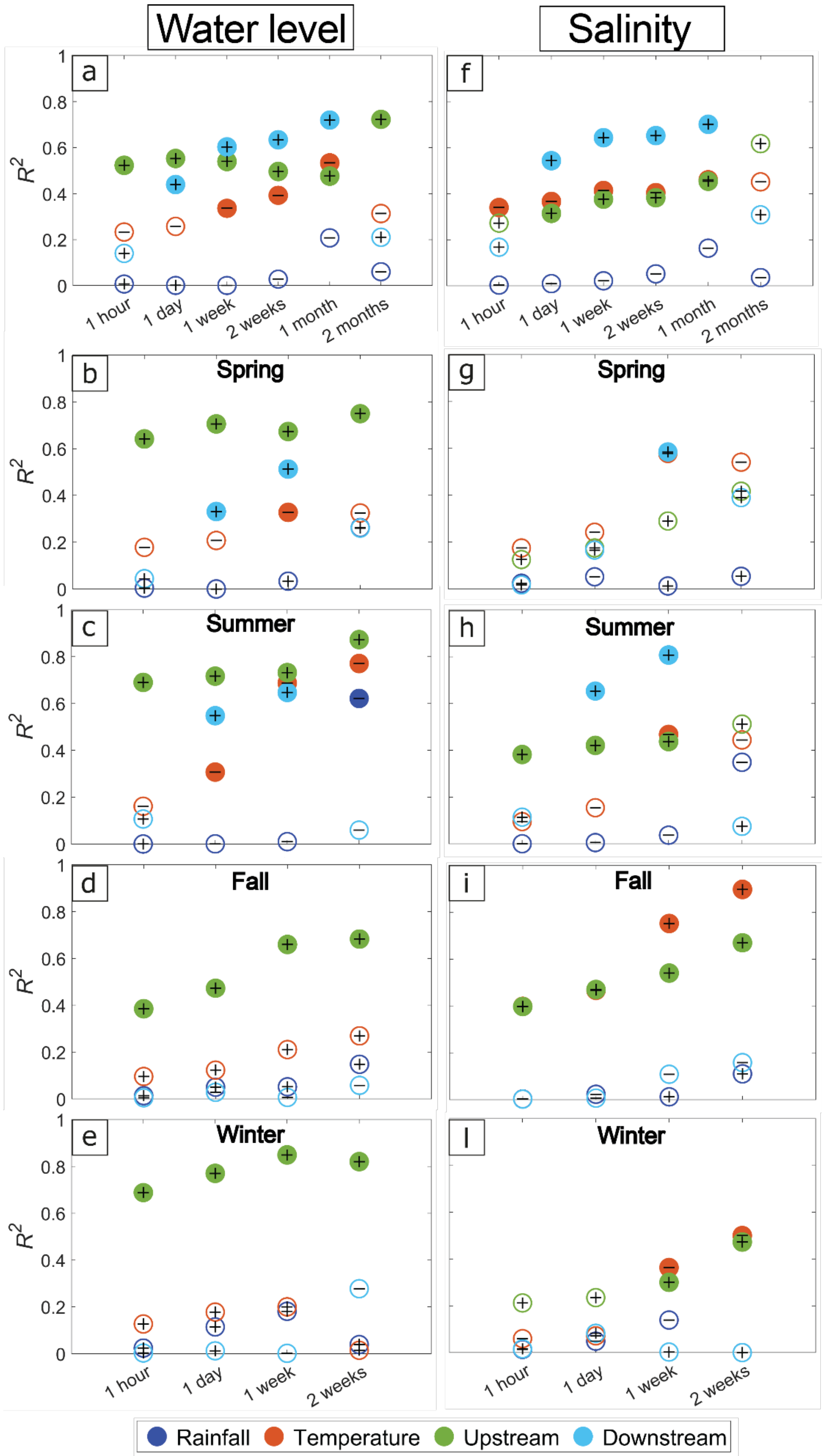

Data
Regression line
95% CI
a
Rainfall [cm]
Salinity [ppt]
b
Temperature [°C]
Salinity [ppt]
c
Δ hydraulic head up [cm]
Salinity [ppt]
d
Δ hydraulic head down [cm]
Salinity [ppt]
Jan Feb Mar Apr May Jun Jul Ago Sept Oct Nov Dec Jan
e
Salinity [ppt]
R^2_{low} = 0.164
p_{low} = 1.7e-01
Rainfall [cm]
f
Salinity [ppt]
R^2_{low} = 0.461
p_{low} = 1.1e-02
Temperature[cm]
g
Salinity [ppt]
R^2_{low} = 0.454
p_{low} = 1.2e-02
Δ hydraulic head upstream [cm]
h
Salinity [ppt]
R^2_{low} = 0.702
p_{low} = 3.5e-04
Δ hydraulic head downstream [cm]

Figure 10: a) Monthly cumulative rainfall; b) averaged temperature; c) averaged upstream hydraulic gradient; and d) averaged downstream hydraulic gradient related to monthly averaged groundwater salinity. Linear regression analysis on monthly data are represented in e), f), g), h).


Water level
Salinity
a
f
b
g
c
h
d
i
e
l
Spring
Summer
Fall
Winter
R^2
0
0.2
0.4
0.6
0.8
1
1 hour
1 day
1 week
2 weeks
1 month
2 months
Rainfall
Temperature
Upstream
Downstream

323

Figure 11: Linear regression analysis for groundwater level (a, b, c, d, e) and salinity (f, g, h, i, l) as a function of rainfall, temperature, upstream and downstream hydraulic gradients for different temporal windows. a), f) from 1 hour to 2 months over the year. From 1 hour to 2 weeks over spring b), g), summer c), h) fall d), i) and winter d), l). Empty circles represent not significant R^2($p>0.05$). The sign inside the circles indicates whether the correlation is positive or negative.

Table 1: Multiple regression analysis results. Groundwater level is correlated to upstream hydraulic gradient, downstream hydraulic gradient and temperature.

h= water level, Δh_{up}= upstream discharge, Δh_{low} = downstream discharge, t= temperature				
**P-value >0.05, *P-value <0.05, **P-value<0.01, ***P-value<0.001*				
Dependent variable	**Independent variable**	**Time window**	**Model coefficients**	**Adjusted R^2**
Groundwater level	• Upstream discharge • Downstream discharge • Temperature	1 hour	78.661(***)+1.881 Δh_{up} (***)+0.022 Δh_{low} (***)-0.622 t (***)	0.714 (***)
		1day	73.922(***)+1.898 Δh_{up} (***)+0.071 Δh_{low} (**)-0.580 t (***)	0.761 (***)
		1 week	70.464(***)+1.823 Δh_{up} (***)+0.108 Δh_{low} (*)-0.540 t (***)	0.806 (***)
		2 weeks	72.552(***)+1.750 Δh_{up} (***)+0.087 Δh_{low} (*)-0.557 t (*)	0.806 (***)
		1 month	78.999(**)+1.734 Δh_{up} (**)+0.034 Δh_{low} (*)-0.688 t	0.860 (***)
		2 months	55.010(*)+2.840 Δh_{up} (*)+0.183 Δh_{low} (*)-0.194 t (*)	0.886 ( )
	• Upstream discharge • Downstream discharge	1 hour	65.555(***)+1.858 Δh_{up} (***)+0.074 Δh_{low} (***)	0.561 (***)
		1day	51.246(***)+1.591 Δh_{up} (***)+0.257 Δh_{low} (***)	0.680 (***)
		1 week	44.707(***)+1.382 Δh_{up} (***)+0.342 Δh_{low} (***)	0.761 (***)
		2 weeks	44.057(***)+1.276 Δh_{up} (***)+0.352 Δh_{low} (***)	0.773 (***)
		1 month	43.271(***)+1.147 Δh_{up} (*)+0.366 Δh_{low} (***)	0.807 (***)
		2 months	45.421(**)+2.907 Δh_{up} (**)+0.260 Δh_{low} (*)	0.920 (**)
	• Upstream discharge • Temperature	1 hour	80.748(***)+1.919 Δh_{up} (***)-0.651 t (***)	0.711 (***)
		1day	80.803(***)+2.033 Δh_{up} (***)-0.680 t (***)	0.757 (***)
		1 week	81.190(***)+2.039 Δh_{up} (***)-0.713 t (***)	0.802 (***)
		2 weeks	81.407(***)+1.911 Δh_{up} (***)-0.707 t (***)	0.810 (***)
		1 month	82.446(***)+1.797 Δh_{up} (*)-0.747 t (***)	0.874 (***)
		2 months	77.256(***)+2.694 Δh_{up} (**)-0.610 t (*)	0.905 (**)

Table 2: Multiple regression analysis results. Groundwater salinity is correlated to groundwater level, upstream hydraulic gradient, downstream hydraulic gradient and temperature.

h= water level, Δh_{up}= upstream discharge, Δh_{low} = downstream discharge, t= temperature				
**P-value >0.05, *P-value <0.05, **P-value<0.01, ***P-value<0.001*				
Dependent variable	**Independent variable**	**Time window**	**Model coefficients**	**Adjusted R^2**
Groundwater salinity	• Upstream discharge • Downstream discharge • Temperature • Water level	1 hour	1.941(***)+0.046 h (***)+0.160 Δh_{up} (***)+0.008 Δh_{low} (***)-0.121 t (***)	0.601 (***)
		1day	0.156(*)+0.030 h (*)+0.160 Δh_{up} (***)+0.039 Δh_{low} (***)-0.093 t (***)	0.682 (***)
		1 week	-1.278(*)+0.049 h (*)+0.185 Δh_{up} (*)+0.035 Δh_{low} (*)-0.083 t (*)	0.741 (***)
		2 weeks	-4.977(*)+0.078 h (*)+0.147 Δh_{up} (*)+0.046 Δh_{low} (*)-0.033 t (*)	0.732 (***)
		1 month	-2.527(*)+0.043 h (*)+0.277 Δh_{up} (*)+0.048 Δh_{low} (*)-0.058 t (*)	0.745 (**)
		2 months	13.949(*)-0.188 h (*)+1.098 Δh_{up} (*)+0.053 Δh_{low} (*)-0.168 t (*)	0.996 (*)
	• Upstream discharge • Downstream discharge	1 hour	-2.411(***)+0.241 Δh_{up} (***)+0.021 Δh_{low} (***)	0.353 (***)
		1day	-1.916(***)+0.159 Δh_{up} (***)+0.076 Δh_{low} (***)	0.603 (***)
		1 week	-3.009(**)+0.185 Δh_{up} (***)+0.088 Δh_{low} (***)	0.698 (***)
		2 weeks	-3.241(**)+0.218 Δh_{up} (***)+0.089 Δh_{low} (***)	0.718 (***)
		1 month	-3.645(*)+0.278 Δh_{up} (*)+0.091 Δh_{low} (***)	0.775 (***)
		2 months	-2.938(*)+0.609 Δh_{up} (**)+0.070 Δh_{low} (*)	0.912 (**)
	• Upstream discharge • Temperature	1 hour	6.383(***)+0.262 Δh_{up} (***)-0.161 t (***)	0.574 (***)
		1day	6.391(***)+0.295 Δh_{up} (***)-0.168 t (***)	0.632 (***)
		1 week	6.2543(***)+0.356 Δh_{up} (***)-0.175 t (***)	0.719 (***)
		2 weeks	6.035(***)+0.381 Δh_{up} (***)-0.167 t (***)	0.708 (***)
		1 month	5.948(***)+0.444 Δh_{up} (*)-0.173 t (***)	0.773 (***)
		2 months	5.803(***)+0.550 Δh_{up} (**)-0.173 t (*)	0.942 (**)

4. Discussion

The data collected at the two wells shed light on the groundwater dynamics in the forested area of the Eastern Shore of Virginia National Wildlife Refuge in 2014. In particular, the four temporal windows and the correlation analysis among hydrological variables enable to draw important conclusions about the effects of external drivers on water table elevation and groundwater salinity, which in turn control vegetation cover.

4.1 Water Levels

Rainfall events, evapotranspiration, groundwater fluxes from the uphill and toward the marsh control groundwater level in different ways across short and long temporal scales (Fig. 12a). Rainfall causes instantaneous increases in the groundwater level. The larger is the cumulative rainfall in a single event, the higher is the increment in groundwater level. This occurs at both wells suggesting a significant positive correlation between the two variables at the event scale (Fig. 6a). After every water level peak due to rainfall, the water level values decrease, approaching the mean water level, as consequence of the deep-water recharge process. Cumulative rainfall does not have a direct effect on the groundwater level in the lower well on a long timescale (Fig. 9a,e ,11a, b, c, d, R^2 values are not significant). The inter-storm periods are on average around 2 days for all seasons (Fig. 3a). During spring and summer, the precipitation events are more intense, on average around 0.4 cm, while during winter and fall precipitation is around 0.2 cm for each event. The longer the inter-storm periods are, the more likely is the groundwater level to decrease. Under the same inter-storm conditions, if the precipitation event is conspicuous, ponding and surface runoff will likely occur (Assouline et al. 2007). During summer, mainly in July and August, precipitation is abundant, but the water level is decreasing due to evapotranspiration.

In the four temporal windows, it is possible to see how in correspondence of particular precipitation events, groundwater levels reach values higher than the ground surface at both wells. This happens in window A (Fig. 4d) and C (Fig. 5d) in the lower well, and in windows C in the upper well (Fig. 5d). During these events the soil can be considered saturated, and water in excess accumulates over the ground level in correspondence of the wells. Additional water might flow along the slope as runoff. According to the data reported in the four windows, it takes between 7 hours (Fig. 4d) to 2 days (Fig. 5d) to terminate water ponding and resume water infiltration, depending on quantity and frequency of external precipitation inputs.

Flooding events are dangerous for *Pinus taeda* survival. Reduced oxygen availability and a significant decrease in soil redox potential directly affect water uptake from the soil (Anderson and Pezeshki, 1999, Pezeshki 1991). Intermittent flooding can cause different results on stomatal conductance and net photosynthetic activity in seedling of different species, reaching the worst scenario when the reduction is so large that plants cannot recover any more (Anderson and Pezeshki, 1999). Pezeshki, (1991) indicates that a reduction in soil redox potential of 100 mV occurs in less than 10 days of flooding. Over a treatment period of 30 days, flooding resulted in a substantial reduction of soil redox potential, stomatal conductance and biomass (Pezeshki, 1991).

Evapotranspiration is one of the most significant drivers of groundwater level at longer temporal scales. Evapotranspiration mostly occurs during summer (Fig. 4i) when air temperature in the daylight hours is high and photosynthesis takes place. During this period, trees, fully foliated, transpire to maintain their inner temperature. This results in a decrease of mean water level of about 30 cm in both wells over the summer period. Evapotranspiration dominates over the other hydrological fluxes. The role of evapotranspiration is confirmed in the single regression analysis for the lower well (Fig. 11a, b, c, d, e). Over the year, the maximum correlation between groundwater level and temperature is reached on a temporal window of one month (Fig. 9b, 11a).

The hydraulic gradient between the lower well and sea level is the other chief variable controlling groundwater levels. The higher is the groundwater level, the more abundant is the downhill flux of water (Fig. 11a). During spring and summer, the groundwater level is positively correlated to discharge toward the marsh (Fig. 11b, c). This suggests that low groundwater levels are more affected by the discharge to the marsh. During winter and fall, high groundwater levels are not significantly affected by the discharge to the marsh. The existence of groundwater discharge to the sea has been already investigated in coastal regions (Li, 1999; Werner, 2013; Robinson, 2006;

Taniguchi 2002, Michael et al. 2005). Both fresh and salt groundwater discharges are present. The saline flow involves the deeper zone, while the fresh groundwater flow moves closer to the ground. On the basis of our analysis we can suppose the presence of a fresh groundwater flow to the marsh affecting the groundwater level at our site.

Storm surges are not significantly correlated to increments in groundwater level. Although in windows A, C and D (Fig. 4b, d, 5b, d, g, i) storm surge events do increase mean groundwater values. The storm surge events occur in correspondence to significant rainfalls that usually saturate the soil (Fig. 4a, Fig. 5a,f). They do not lead to an instantaneous change in water level, but they likely magnify the water level increase. Note that during the study period there was not a major storm surge able to flood the entire forest.

The hydraulic gradient from uphill to the lower well significantly affects groundwater levels. Over the year the correlation between the two variables is significantly positive, reaching R^2 values higher than 0.4 (Fig. 11a). The homogenous and sandy soil justifies this relation, favoring groundwater flow downhill. A multiple regression analysis yields adjusted R^2 values higher than 0.56 considering a model where upstream and downstream hydraulic gradients are dependent variables, and higher than 0.71 considering a model where upstream hydraulic discharge and temperature are dependent variables. An analysis on their correlation confirm they are negative linked. A model considering all dependent variables suggest that temperature and downstream discharge carry a redundant information, making multiple regression parameters not significant. (Table 1). Overall, the multiple regression provides better results in comparison to single regression.

4.2 Salinity

Groundwater salinity is not significantly correlated to precipitation events, even if it is possible to recognize an instantaneous decrease in salinity as the rainfall amount increases (Fig. 6b). As soon as the rainfall stops the salinity increases to values similar to the pre-event conditions.

As temperature increases, evapotranspiration increases and salinity decreases (Fig. 11). During fall the correlation between salinity and temperature is significantly positive (Fig. 11i). In September, an intense rainfall event occurred along with a large storm surge, and groundwater levels increased until reaching the soil (Fig. 3a, b, d, 5a, b, d). A water table near the surface leads to higher evaporation. When this occurs, salt ions are likely to accumulate near the ground surface, moving upwards along with water in the unsaturated zone and leaving the original depth (Mohamed, 2000). This could justify lower salinity values collected by CTD at a fixed deeper position.

The groundwater flux to the sea is positively correlated to salinity in the lower well (Fig. 11f). This occurs mainly during spring and summer (Fig. 11g, h). A net freshwater discharge can justify this trend. When groundwater is high in the lower well, water from the top fresh layer flows toward the marsh, and it is replenished by saltier water coming from below (Fig. 12b). A release of freshwater from the ground decreases the dilution of salt water, and salinity increases. The maximum increase of salinity is reached in September when sea level was around 85 cm on NADV88 (Fig. 6b). In that month, a significant storm surge event (Fig. 5b) acted along with high temperatures and groundwater discharge from uphill to increase salinity. The conspicuous amount of rainfall that occurred during the storm was unable to infiltrate the saturated soil, and moved away as runoff. A similar event occurred in Window A (Fig. 4b). In this period, most of the rainfall infiltrated. A storm surge occurred after some hours from the rainfall event. Salinity first rapidly decreased as a consequence of rainfall, and then increased because of mixing with the saline water. Salinity kept increasing until it surpassed the value before the event due to storm surge effects.

Storm surge events can be recognized as a slow increase in salinity in comparison to the steep increase after rainfall dilution. When no precipitation events occur, salinity increases are positively correlated to storm surge duration, if storm surges are higher than 40 cm (Fig. 7b).

The hydraulic gradient between the upper and lower well is positively correlated to salinity over the year and in each season (Fig. 11f, g, h, i, l). Therefore, a large groundwater discharge from uphill augments groundwater salinity. We suppose that the discharge from uphill becomes more saline during its infiltration path, reaching deeper saline areas, and recharging the lower well from below.

Groundwater salinity is strongly correlated to groundwater level in the lower well, for all temporal windows ranging from 1 hour to 2 months (Fig. 8a, c, d). As the groundwater level increases, the salinity increases and vice versa. The groundwater level is directly linked to the recharge from uphill, the discharge toward the marsh, and evapotranspiration.

A multiple regression analysis yields adjusted R^2 values higher than 0.35 considering a model where upstream and downstream hydraulic gradients are independent variables, and higher than 0.57 considering a model where upstream hydraulic discharge and temperature are independent variables. A model considering all independent variables suggest that groundwater level, temperature and downstream discharge carry redundant information, making multiple regression parameters not significant (Table 2). The models proposed are those leading to the best results in terms of significance as a whole and for each parameter. Overall, the multiple regression provides better results in comparison to single regressions.

We put forward the hypothesis that the discharge toward the marsh and evapotranspiration are depleting the surficial freshwater layer, while the uphill groundwater flux brings saltier water. An increase in water table elevation would therefore expose the freshwater layer to more evapotranspiration and fluxes to the marsh, reducing salinity. When the water table is low, more freshwater can be safely stored in the ground and in the root zone.

The sharp geotechnical boundary between forest and the marsh can also accentuate these dynamics. The impermeable marsh soils rich in silt and clay might prevent deep groundwater fluxes, forcing the water to move superficially from the forest to the marsh as return flow or runoff (Fig. 12b). This surficial flux would deplete the freshwater stored in shallow layers, increasing salinity. In the sandy hillslope, water from uphill can infiltrate and move in deeper layers, mixing with saltier water and thus bringing salt to the downhill location. Our results indicate that higher groundwater levels would trigger evapotranspiration and fluxes to the marsh, removing freshwater and increasing salinity at the roots depth. This negative effect can be magnified by sea level rise, which would further increase the water table elevation, and deplete freshwater in the roots area, encouraging salt water intrusion from deeper layers on long timescale.

The maximum correlation among all variables is reached using monthly averages, we therefore conclude that drivers of groundwater hydrology act at temporal scale of weeks and not instantaneously. For example, the average sea level in a month has more effect on the water table elevation than the instantaneous water level.

Sandy soils can faster drain water infiltrating from the unsaturated zone to recharge the groundwater systems (Kutilek and Nielsen 1994). In clay soils, water movement is slower and the effect of rainfall inputs on groundwater level is likely felt in a weaker way (Cao et al. 2012). In low-lying areas, dominated by shallow water, an upward discharge from below tend to pond the ground surface. In clay soils the evaporation rate is higher, and water tends to pond easily (Kutilek and Nielsen 1994). Moreover, sandy soils are less prone to salinization than clay soils because salts attach to small particles while they are easily leached in sand. When flow is faster (high hydraulic conductivity), advection dominates (Batany et al. 2019), so that groundwater flow from the upper to the lower sites can bring salts leached in deeper zones.

Plants that tolerate osmotic stress can adapt to new salinity conditions. These plants exclude Na^+ from leaf blades and roots or compartmentalize Na^+ and Cl^- at the cellular and intracellular level (Munns and Tester, 2008). The latter method is less efficient because the accumulation space is limited (Hasegawa, 2000). *Pinus taeda* is unable to use one of these approaches (Pezeshki, 1991), and salt water disturbs its roots environment undermining photosynthetic activity (Nawaz, 2010). In the lower zone of the forest, new salt-tolerant plant species can encroach where *Pinus taeda* trees die because of salinization, ultimately expanding the marsh environment. First, invasive species like *Phragmites australis* (Chambers et al. 1999) tend to expand finding better light condition in the gaps of the dying forest. This species can tolerate low salinities (~5 ppt) (Lissner et al. 1997; Hellings et al. 1992) butcan be soon replaced by extremely salt-tolerant marsh species like *Spartina patens*, *Juncus gerardi* and *Spartina alterniflora,* very common in the lower area of Chesapeake Bay (Rice et al. 2000; Hester et al. 2001). In the regenerative zone, we did not detect a significant increase in salinity. Here freshwater enables the forest to regenerate with saplings.

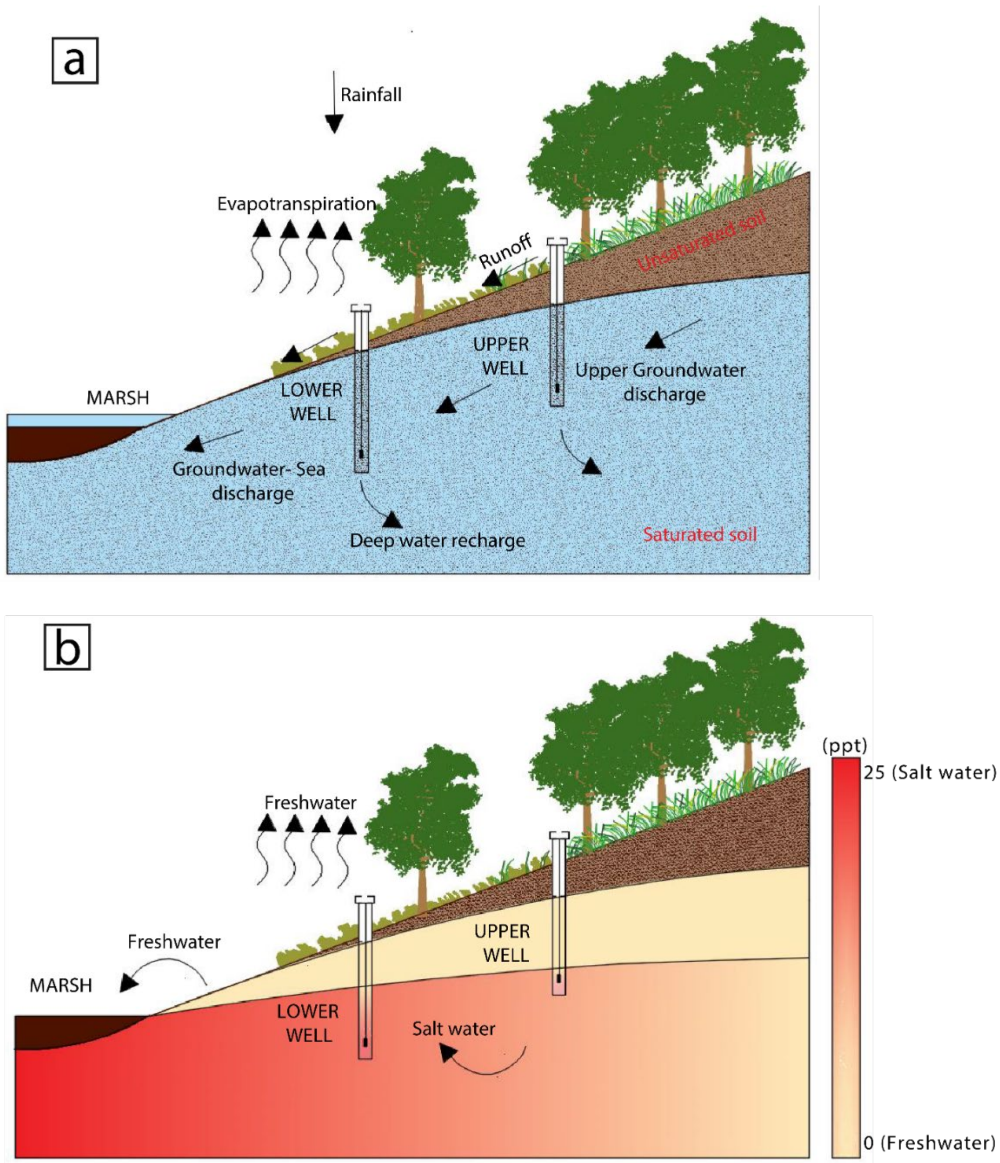


Figure 12: a) Hydrological processes affecting groundwater levels at the forest boundary. b) chief hydrological fluxes affecting groundwater salinity at the roots elevation. The color indicates salinity levels

5. Implications for sea-level rise and coastal forests

Our results can provide critical insight on the effect of sea level rise on coastal forests. Our data indicate that an increase in groundwater levels at the marsh boundary might trigger an increase in salinity in the root zone. Sea level rise is likely to increase water levels in coastal aquifers; in some coastal locations the percentage of flooded area by groundwater has already expanded due to climate change (Rotzoll and Fletcher 2012). The percentage could be higher in topography-limited systems like North Atlantic coast (Gleeson et al. 2011), where sea level rise is accelerating (Church et al. 2006; Sallenger et al. 2012). This increase in groundwater levels will likely trigger an increase in salinity. Similar results were presented by Michael et al. (2013) using numerical simulations. In low-lying areas where groundwater recharge is topographically limited, an increase in sea level results in the intersection of the groundwater table with the ground surface, favoring runoff and reducing the amount of freshwater that can be stored in the soil. As a result, the freshwater hydraulic head landward cannot balance SLR seaward, causing salinization of the aquifer. Moreover, Michael et al. (2013) simulations show that the salinization rate is higher in isotropic soils with high permeability, like those present at our study site. Our measurements confirm this hypothesis, and provide a quantitative relationship between water level and salinity that can be used to forecast the effect of sea level rise on forest ecosystems.

6. Conclusions

High resolution hydrological measurements in a coastal forest bordering a salt marsh indicate that the groundwater is fresh in the higher regenerative zone, where tree saplings are present, while it is brackish in the lower persistence zone, where only mature trees survive. In the short term (timescale of hours), groundwater levels significantly increase after a rainfall while salinity decreases. Storm surges are felt in the salinity trend as slow increments, as compared to the instantaneous steep decrease caused by rainfall and subsequent increase due to mixing with saline water.

In the medium term (timescales of weeks and months), temperature (a proxy for evapotranspiration), uphill and downhill hydraulic gradients (a proxy for lateral groundwater fluxes) significantly influence groundwater levels and salinity. Statistical analysis suggests that rainfall is not a direct driver of water level and salinity at the monthly timescale. Surprisingly, salinity at the roots depth is high when the water table is high. We ascribe this counterintuitive result to depletion of the top freshwater layer caused by surficial and sub-surficial fluxes to the marsh and increased evapotranspiration when water levels are high. We hypnotize that the lost freshwater is replaced by more saline water flowing at depth from uphill. Sea level rise, by increasing the water table, could therefore augment the salinity of the groundwater at the roots depth, triggering forest dieback.

Acknowledgments

This research was funded by the USA National Science Foundation awards 1832221 (VCR LTER), 1637630 (PIE LTER), and 2012322 (CZN Coastal Critical Zone). We thank William S. Kearney for help with the fieldwork and the Eastern Shore of Virginia National Wildlife Refuge for logistical support.

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