Climate Change’s Impact on Sea Level Rise in a Coastal Marsh Over 20 Years

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ENVS 603: Environmental Research Methods, Spring 2024

Virginia Commonwealth University

Learning Objectives

Goals:

- To understand coastal marsh importance and the effect of tidal fluctuations
- To utilize RStudio and R to recreate figure 7 from the focal paper and interpret results to understand sea level rise over time in a coastal marsh
- To understand ANCOVA with categorical and continuous variables

Prerequisites:

- Students should have RStudio and R installed on their computers as well as basic R programming knowledge, including how to load in datasets, packages, etc.
- Students should have read the introduction of the focal paper: “Climate and Vegetation Change in a Coastal Marsh: Two Snapshots of groundwater dynamics and Tidal Flooding at Piermont Marsh, NY Spanning 20 Years” by Sofi Courtney, Franco Montalto, and Elizabeth Burke Watson

Purpose of Lesson

The purpose of this lesson is to learn about the importance of coastal marshes and the increasing tide levels that are impacting them. Additionally, it aims to help understand how sea level rise has impacted the fluctuations of tides. This lesson will teach students how to use and interpret an analysis of a covariance test, or ANCOVA. Specifically, it will determine how the tidal range is increasing with the rate of sea level rise over a 20 year period. This will be observed by looking at how water elevation is changing as you move away from the water body.
Coastal Marshes

Coastal marshes exist on marine, estuarine, and freshwater coastlines and are highly impacted by the movement of water (NRC Solution). This movement of water consists of tides or waves and by freshwater that comes from runoff, rivers, or groundwater (NRC Solution). These areas experience inundation regularly which has caused their vegetation, soils, and water conditions to be adapted to aquatic conditions (NRC Solution). They are essential to the environment as they provide many ecosystem services such as flood regulation, erosion prevention, pollution control, and carbon storage. These systems are critical environmental areas for wildlife habitat and biodiversity as they support coastal fish and birds. These marshes have the ability to absorb and reduce the energy of waves limiting erosion (NRC Solution). They reduce flooding by slowing down the movement of water and allowing vegetation to take the water up (Climate Central, 2022).

Unfortunately, due to climate change, these coastal marshes are being reduced at an alarming rate. Sea level rise has threatened to turn coastal marsh areas into open water as tides rise and drown vegetation (Climate Central, 2022). The increasing rate of sea level rise could decline coastal marsh areas by 97% by 2100 if the pace exceeds the growth of the wetlands (Climate Central, 2022).

Tides

Coastal marshes are heavily influenced by the water that moves just below the earth’s surface, referred to as the hydrology. The hydrology in the area is influenced by diurnal tides, groundwater flow from terrestrial uplands, precipitation, and evapotranspiration (National Geographic). These all have a significant impact on the groundwater table elevation as a result. Similarly, temporal dynamics such as sea level rise and climate change impact marsh groundwater. Groundwater hydrology has many important roles in coastal marsh biogeochemical and ecological functions. An alteration in the groundwater hydrological functions of a marsh can alter the defined boundaries of a coastal marsh (National Geographic).

Tides bring seawater in and out of these systems through tidal creeks (Salt Marsh Guide, 2024). This results in a variability of water levels in the area throughout the day (Salt Marsh Guide, 2024). These ecosystems experience two high tides and two low tides a day which last 6 hours (Salt Marsh Guide, 2024). Tides are heavily influenced by the gravitational pull from the sun and moon onto the earth’s surface (Salt Marsh Guide, 2024). They create fluctuations of the water table and can impact what areas are underwater or dry depending on the time of day (Salt Marsh Guide, 2024). When areas are experiencing high tide the marsh is underwater while during low tide these areas are dry (Salt Marsh Guide, 2024). Twice a month tidal areas will experience the influence of the new moon and full moon
where they will experience **spring tides**, where tides will reach their maximum height (Salt Marsh Guide, 2024). While when the moon is at first quarter or third quarter the marsh will see **neap tides**, where the tides reach their minimum height (Salt Marsh Guide, 2024).

Tides are known to move salt water in and out of a marsh causing a change in the biogeochemistry of the marsh (Salt Marsh Guide, 2024). High tides can increase the salinity of the water impacting the vegetation and organisms that can thrive in the marsh (Salt Marsh Guide, 2024). While during low tides all the suspended fine sediment that was in the water falls away to the bottom and edge of the marsh where vegetation can then trap the sediment (Salt Marsh Guide, 2024).

![Image 1](image.jpg)

**Image 1.** Low and High tide in Salt Marsh in Southeastern United States. Guide to the Salt Marshes and Tidal Creeks of the Southeastern United States from the Salt Marsh Guide found [here](#).

Climate change has changed these tides by increasing the rate of sea level rise and ultimately increasing the range of the tides. This can alter how water is moving through the system and the overall connectivity in these habitats (Salt Marsh Guide, 2024). Ecosystems that have a bigger tidal range and more sediments with high connectivity experience water that flows faster and further through the system (Salt Marsh Guide, 2024). A high rate of sea level rise can lead to erosion as the tidal flat deepens and water movement increases against the marsh boundary (Salt Marsh Guide, 2024). High sea level rise can drown areas and transform the coastal marsh into a tidal flat.

This lesson will evaluate sea level rise in relation to coastal marshes and tides. Specifically, it will look at the changes in the neap and spring tides over a 20 year study period.
Focal Paper

The Focal Paper: Climate and Vegetation Change in a Coastal Marsh: Two Snapshots of Groundwater Dynamic and Tidal Flooding at Piermont Marsh, NY Spanning 20 Years

Authors: Sofi Courtney, Franco Montalto, Elizabeth Burke Watson

Study Goals

In the focal paper, the goal of the study was to measure the changes in water table levels at Piermont Marsh, New York, over a 20-year period from 1999 to 2019. Specifically, they examined how groundwater hydrology in the marsh may be affected by sea level rise.

In 1999, they first measured a variety of variables including water table elevation, marsh elevation, topography, and hydroperiod to help map the overall hydrology of the brackish tidal marsh within the Hudson River estuary. Twenty years later, in 2019, they revisited the study and replicated the original methods to evaluate the change in marsh hydrology over time due to sea level rise. The analysis in this lesson will focus on examining changes in water elevation as distance from the creek increases throughout the 20 years.
Methods

Methods from the original study in 1999 were replicated over the summer of 2019, with a goal to compare groundwater table levels. They installed 7 water level loggers, or wells, along a gradient in the marsh perpendicular to the tidal channel to monitor water levels. Well locations were established by georeferencing the maps created in the original 1999 study.

At each well, they measured water and marsh elevation to determine water distance from the surface. The NAVD88 datum was used as a national reference point for each measurement and served as a benchmark. Each time water elevation data was collected, it was related back to this datum that served as a fixed point.

![Image 3. Figure 2C from the focal paper. Location of stream gauges (denoted as circles) as well as groundwater wells along a transect perpendicular to a tidal channel](image-url)
Results

Compared to 1999, in 2019 high tide water levels measured in wells were 12-cm higher, and 13-cm greater during neap tides. Neap tides were also 4-cm higher relative to the marsh surface in 2019 compared to 1999, while spring tides remained at a similar elevation. Neap high tide water levels had a greater standard deviation of 7-cm in 2019, while there was no significant difference for spring tides. Tidal efficiency, a metric that integrates changes in both low and high tide water levels, also showed an increase between the 20 year timeframe. This was greater adjacent to the tidal channel and at the more inland sights.

Findings suggest that tidal range has increased in the marsh, and tidal influence extended further into the marsh in 2019 than in 1999. In reference to the NAVD88 datum, low tide water measurements in the wells were 7-cm greater in 2019 than in 1999, and high tide water levels were 12-cm greater in 2019 than in 1999.

Now, considering these results, we want to break it down further to analyze the interaction among the dataset. We can perform an ANCOVA test to look at the significance of distance from the creek on water elevation. First, let’s take a look at what an ANCOVA is.

Test your Understanding

1) What is the difference between neap and spring tides?

2) Why is sea level rise a threat to coastal marshes?

3) Why is the NAVD88 datum used in this study?

4) In the focal paper, from 1999 to 2019, they found that tidal influence has ________________ in 2019 than in 1999.
**ANCOVA**

ANCOVA, or analysis of covariance, will help us analyze an interaction between different variables. Essentially, we can extend a basic linear model to include combinations of continuous and categorical explanatory variables. This analysis estimates the group mean of the continuous variable across the explanatory variable. This helps by taking into consideration the effect the continuous variable has and can make the difference between the groups more apparent so the comparison can be more powerful.

The image below shows the difference between an ANOVA versus an ANCOVA. As seen below you can see that the ANOVA indicates that group A is similar to group B but is nothing like group C. While when you look at the ANCOVA you can see what is actually happening within the dataset. As you can see in the ANCOVA group A is similar to both groups B and C which is not shown in the ANOVA.

![ANOVA vs ANCOVA](image-url)

**Figure 1.** ANOVA vs ANCOVA. Image provided by Biostatistics on Youtube.

In this lesson, we will use an ANCOVA to determine if there is an interaction between water elevation (meters) and distance from the creek (meters) for the two years 1999 and 2019. But first, let’s visualize the data in the following R tutorial.

For further information on ANCOVA, visit chapter 7 of *The New Statistics with R: An Introduction for Biologists* by Andy Hector and watch ANCOVA - How to do it in R, Interpretation by Biostatistics on Youtube. [https://www.youtube.com/watch?v=3ZY9OSXmOrU](https://www.youtube.com/watch?v=3ZY9OSXmOrU)

**Test your Understanding**

1) What does an ANCOVA analyze?

*It will look at an interaction and effect of continuous and categorical variables*
2) What effect is it taking into account?

3) What makes it different from ANOVA?

**R Tutorial**

An R markdown with all necessary code for this tutorial has been provided. You can follow along in this paper or in RStudio to do the analysis yourself.

The two datasets that will be used in this analysis were collected from a coastal marsh in Piermont Marsh, New York, in 1999 and 2019, and look at minimum water levels during neap and spring tides. The dataset includes the following variables: distance, year, water elevation (one dataset has neap tide water elevation, while the other has spring), marsh elevation, and distance to surface. We will be using the data set titled "MinNeap_MarshSurface" and “MinSpring_MarshSurface from the study for this part of the lesson. This dataset was acquired from Dryad titled “Climate and Vegetation Change in a Coastal Marsh: Two Snapshots of Groundwater Dynamics and Tidal Flooding at Piermont Marsh, NY Spanning 20 Years” which can be found at the link [here](#).

| **Distance:** distance from tidal channel, in meters. | **Year:** the year the data was collected, 1999 and 2019 |
| *Measured as distances of each well* | |

| **Marsh elevation:** height of the marsh at that location, relative to the NAVD88 datum | **Water elevation:** height of the water at low tide, relative to the NAVD88 datum |
| |

Please note that although we are using the data from this study, we may quantify the variables differently than the paper intends. This lesson is only intended to allow students to practice creating and understanding both a figure from the paper and an ANCOVA analysis utilizing R and Rstudio.}
Figures for Minimum Neap Tide Water Elevation

First, we can recreate figure 7C from the focal paper to look at minimum water surface elevation measurements compared to distance from creek for both 1999 and 2019. For this we will be using the author’s R code given here.

Figure 2. Figure 7C. from the focal paper. Box plots depicting median, lower and upper quartiles, distribution, and outliers of the minimum water surface elevation at low tide relative to NAVD88 during neap tides in 1999 and 2019.
Figure 2 looks at minimum water elevation in 1999 and 2019 and distance from the creek. We can conclude that there has been an increase in minimum neap tide water elevation levels in 2019 compared to 1999. This shows that as you go away from the creek the water elevation is increasing. Is this what you expected to see? The paper addresses this phenomenon referring to it as vertical forcing, below is a passage from the paper that explains why this is happening.

Due to the restricted length of a tidal period and the low permeability of marsh sediments, water exchange through the marsh platform decreases with distance from tidal creeks (Harvey and Odum 1990; Williams et al. 2002; Wilson et al. 2011; Watson et al. 2022). Generally, the marsh platform at the creek edge is flooded and drained during each tidal cycle, resulting in fluctuations in water table elevation and tidal–groundwater exchange (Montalto et al. 2006; Watson et al. 2022). The water table elevation in the marsh interior is primarily driven by terrestrial groundwater inputs, precipitation, evapotranspiration, and neap and spring tides. Freshwater flows into the marsh from the terrestrial uplands and converges with saltwater inputs tidally forced from ocean systems. This flow convergence results in an upward flow, i.e. vertical forcing (Wilson et al. 2015b). This results in a relatively high water table in the marsh interior which rarely drains, so salts produced during evaporation and biological processes are not flushed out of the sediment. Consequently, the groundwater in the high marsh is higher in elevation and relatively saline compared to the creek edges (Xin et al. 2022).

Figure 3. Passage from the focal paper regarding “vertical forcing” phenomenon.
Scatterplots allow us to see the mean of the data and to see if there is a relationship between water elevation and distance from the tidal channel. In this case it also allows us to visualize the difference between the years 1999 and 2019. In this scatterplot, you can see there is a positive relationship in both the 1999 and 2019 data. As well as it shows that both years have a similar trend. As expected, besides a few outliers due to the size of the dataset, we can see that 2019 has a higher minimum water elevation than 1999.

**Figure 4.** Scatterplot depicting neap tide water elevation compared to distance from creek for each year, 1999 and 2019

Now, let’s take this analysis a step further. We have several variables that we can analyze through an ancova test including distance from creek, water elevation, and year. The ancova will be used to determine if there is an interaction between water elevation and distance from the creek for the two years, 1999 and 2019.

**ANCOVA for Minimum Neap Tide Water Elevation**

**The code for the ancova:**

```r
lm(water_elevation ~ distance * year)
```

Here, we are looking at the effect of distance from the creek on minimum water elevation. Our hypothesis is that the intercept for 2019 will be higher than 1999. As well as there will be a strong
interaction between distance from creek and water elevation. We will later compare outcomes from Neap and Spring to see if rates had increased between 1999 and 2019.

**Plotting the Ancova:**

These four plots allow us to understand our ANCOVA test by looking at linearity, normality of errors, scale location, and leverage. The first plot looks at linearity and expects the red line to fall along the dashed gray line. The second plot tests for normality of errors which is asking if errors of residuals fall along a normal distributed error. The third plot is looking at scale location to see if there are equal variances. The last plot above is looking at leverage which is asking if any data points lay outside the designated danger zones. In this particular plot you notice that there are no zones being indicated on the plot; this is due to the plot being too zoomed in to show these danger zones.

With that said these plots show that the ancova model decently fits the data. There are points where the data strays away from the model but overall is a decent match for the ANCOVA.
Summary Statistics:

Call: lm(formula = water_elevation ~ log(distance + 1) * min_neap_yeardata, 
      data = min_neap_df)

Residuals: 
           Min       1Q     Median       3Q      Max 
-0.216851 -0.022831  0.002101  0.028522  0.115101

Coefficients:                      Estimate Std. Error t value Pr(>|t|) 
(Intercept)               0.428899    0.005605  76.516  <2e-16 ***
log(distance + 1)          0.067387    0.001958  34.410  <2e-16 ***
min_neap_yeardata2019      0.074953    0.007941   9.439  <2e-16 ***
log(distance + 1):min_neap_yeardata2019 -0.003976    0.002784  -1.428     0.154
---
Signif. codes:  
  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Residual standard error: 0.04629 on 760 degrees of freedom 
Multiple R-squared: 0.7709, Adjusted R-squared: 0.77 
F-statistic: 852.5 on 3 and 760 DF, p-value: < 2.2e-16

First, let’s discuss how to interpret the output above. The first column shows the coefficients in the model. The one listed as “(Intercept)” is the average of the response variable, water elevation, when the other predictor variables are set to zero. Below the intercept are the predictor variables which show a specific increase or decrease of the value stated for every one unit of the intercept. The variable “log(distance+1)” is distance from creek, “min_neap_yeardata2019” is the year 2019, and “log(distance+1):min_neap_yeardata2019” is looking at the interaction between distance from creek and year.

In the summary above, the first column states the y-intercept of the response variable with the first line being the year 1999. Therefore the y-intercept of the year 1999 is .428899. The term min_neap_yeardata2019 is the effect size for the intercept for 2019. So, to get the y intercept for 2019 you would take the (Intercept) for 2019, which is .428899, and add the min_neap_yeardata2019 value of .074953. This sums to 0.503852, which matches the blue line in figure 4. The term log(distance +1):min_neap_yeardata2019 is the estimate of how different the slope for 2019 is compared to 1999. The parameter estimate, -0.003976, suggests that the slope for 2019 might be slightly shallower. The slope for 1999, labeled as log(distance+1), is .067387. To get the slope for 2019, you would take the slope for 1999, .067387, and add -0.003976, which would sum to about 0.063411. So, our best
estimate for the slope for 1999 is .067387 and the best estimate for the slope for 2019 is 0.063411. These numbers are fairly close, so is it really a statistically significant difference, or could the slope for these two lines actually be the same and this small difference is just due to chance?

To answer that question we have to take a look at the rest of the output for log(distance +1):min_neap_yeardata2019 in you ANCOVA table - SE = .002, t-stats is very small, only -1.4 and the probability is .154 = i.e., >> .05. Also, keep in mind that this is a large sample size of 762. Therefore you have lots of statistical power to detect even minuscule effects. So in conclusion there is no interaction and so we can assume that the slope for both lines are the same ( ex .067387).

In this assessment, we have confirmed that while the water elevation is higher in 2019 (intercept has shifted upwards) the relationship between distance and water elevation is the same in 1999 and 2019.

**Test your Understanding**

1) What is the estimated slope for 2019?

2) Does this analysis show a significant relationship of distance from creek and year on water elevation? How can you tell?
Figures for Minimum Spring Tide Water Elevation

Now, let’s switch to look at minimum spring tide water elevation measurements. We can start again by examining Figure 7G in the focal paper, which shows spring minimum water surface elevation measurements compared to the distance from the creek for both 1999 and 2019.

![Box plots depicting median, lower and upper quartiles, and outliers of the minimum water surface elevation at low tide relative to NAVD88 during neap tides in 1999 and 2019.](image)

**Figure 5.** Figure 7G. From the focal paper. Box plots depicting median, lower and upper quartiles, and outliers of the minimum water surface elevation at low tide relative to NAVD88 during neap tides in 1999 and 2019.

Figure 5 looks at water elevation in 1999 and 2019 and distance from the creek. This shows that as you go away from the creek the water elevation is increasing. On the other hand it also indicates that the water elevation has increased from 1999.

Now we will create another scatterplot looking at minimum spring tide levels. We can see that 2019 has, on average, a higher minimum water elevation than 1999.
Figure 6. Scatterplot depicting spring tide water elevation compared to distance from creek for each year, 1999 and 2019

**ANCOVA for Minimum Spring Tide Water Elevation**

Because this new dataset looks at minimum spring water elevation measurements, we can use the same variables in our new ancova, including distance from creek, water elevation, and year.

**The code for the ancova:**

```r
lm(water_elevation ~ distance * year)
```

Here, we are looking at the effect of distance from the creek on spring minimum water elevation. Again, here we expect the intercept for 2019 to be higher than 1999. As well as there will be a strong interaction between distance from creek and water elevation. Then we will compare outcomes from Neap and Spring to see if rates had increased between 1999 and 2019.
Plotting the Ancova:

Once again, these four plots allow us to understand our ANCOVA test by looking at linearity, normality of errors, scale location, and leverage. For further descriptions of each plot, refer back to the minimum water elevation data.

These plots show that the ancova model decently fits the data. There are points where the data strays away from the model but overall is a decent match for the ANCOVA.
Summary Statistics:

Call:  
\text{lm(formula = water\_elevation ~ log(distance + 1) \* min\_spring\_yeardata,}  
data = min\_spring\_df)  

Residuals:  
Min 1Q Median 3Q Max  
-0.279476 -0.015942 0.006675 0.023968 0.085524  

Coefficients:  
\begin{tabular}{lrrrrr}  
 & Estimate & Std. Error & t value & Pr(>|t|) \\
(Intercept) & 0.484158 & 0.005764 & 84.002 & < 2e-16 ***
log(distance + 1) & 0.054048 & 0.002012 & 26.869 & < 2e-16 ***
min\_spring\_yeardata2019 & 0.055318 & 0.007710 & 7.174 & 2.05e-12 ***
log(distance + 1):min\_spring\_yeardata2019 & 0.005040 & 0.002690 & 1.874 & 0.0614 .
\end{tabular}  

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Signif. codes: 0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1  

Residual standard error: 0.04069 on 630 degrees of freedom  
Multiple R-squared: 0.7817 ,  Adjusted R-squared: 0.7807  
F-statistic: 752.1 on 3 and 630 DF,  p-value: < 2.2e-16  

In this analysis, we are once again looking at the same variables. Refer back to the first ANCOVA test looking at neap tides for further descriptions on the output.

In the summary above, like the first ANCOVA test, the first column states the y-intercept of the response variable with the first line being the year 1999. Therefore the y-intercept of the year 1999 is .485158. The term min\_spring\_yeardata2019 is the effect size for the intercept for 2019. So, to get the y intercept for 2019 you would take the (Intercept) for 2019, which is .485158, and add the min\_spring\_yeardata2019 value of .055318. This sums to 0.540476, which matches the blue line in figure 6. The term log(distance +1):min\_spring\_yeardata2019 is the estimate of how different the slope for 2019 is compared to 1999. The parameter estimate, 0.005040, suggests that the slope for 2019 might be slightly steeper. The slope for 1999, labeled as log(distance+1), is .055318. To get the slope for 2019, you would take the slope for 1999, .055318, and add 0.005040, which would sum to about 0.060358. So, our best estimate for the slope for 1999 is .055318 and the best estimate for the slope for 2019 is 0.060358. These numbers are fairly close, so is it really a statistically significant difference, or could the slope for these two lines actually be the same and this small difference is just due to chance?

To answer that question we have to take a look at the rest of the output for log(distance +1):min\_spring\_yeardata2019 in you ANCOVA table - SE = .002, t-stats is small, only 1.874 and the probability is .0614 = i.e., >> .05. Also, keep in mind that this is a large sample size of 634. Therefore
you have lots of statistical power to detect even minuscule effects. So, in conclusion, there is no interaction and so we can assume that the slope for both lines are the same.

In this assessment, we have confirmed that while the water elevation is higher in 2019 (intercept has shifted upwards) the relationship between distance and water elevation is the same in 1999 and 2019.

**Test your Understanding**

1) What is the question being asked?

2) What is the categorical variable being observed?

3) What is the continuous explanatory variable?

4) What is the interaction we want to observe?

**Conclusions**

Although we may be quantifying the variables in the focal paper differently, our figures do show a difference between 1999 and 2019 for minimum water elevation measurements for spring and neap tides at each well. Additionally, in the ANCOVA tests, we can see significant effects of distance from the creek and year on water elevation.

More and more coastal marshes are being lost to climate change and sea level rise as the years go by. As sea level rises it poses a threat to turn coastal marshes into tidal flats and drown aquatic vegetation. We see this threat being shown in this study as the data shows that the range of tides have increased from 1999 to 2019. Studies like this are important in understanding the changes occurring in a marsh so that mitigation techniques can be implemented to slow down the impacts.
Sources


