

Supporting Coastal Resiliency by Investigating Tidal Reach and Inter-Connected Factors in Coastal Georgia

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ABSTRACT. Increasing our understanding of the tidal dynamics, the extent of tidal reach, and storm surge impacts on near-coastal areas of Georgia and South Carolina rivers is a significant research opportunity. It has the potential to have positive impacts for regulators and state agencies, local municipalities, coastal residents, and other regional stakeholders. This study leveraged existing United States Geological Survey (USGS) water level data for the Savannah River, added additional water level gauges in key areas for less than one year, and analyzed these combined large data sets with modified wavelet analysis and Fourier analysis. Results include identifying head of tide under various conditions including confirmation of river mile 45, historically referred to as Ebenezer Landing, as head of tide. We also provide information on the dynamics of wave propagation through the near-coastal area of the Savannah River, give indication of critical areas of concern for flooding resulting from interactions between elevated upstream flows and storm surge, and discuss relevance of study results for various stakeholders.

INTRODUCTION

The Georgia Department of National Resources (GADNR) has already identified a need to determine the reach of tide in major riverine systems. This need extends to the five major river systems in Georgia and is a high priority from the Protection of Tidewaters Act (O.C.G.A. 52-1-1 et seq.). In addition, Georgia Environmental Protection Division (GAEPD) could benefit from information on the boundary location and conditional interactions between tidal and river-influenced hydrology to inform water quality models.

Improved understanding of the interaction between water levels in the Savannah River, tidal conditions, storm surge conditions, winds, and local rainfall would lead to improvements in understanding the local estuarine and near-coastal river hydrology. This, in turn, could lead to improvements in predictive modeling for regulation, environmental protection, and emergency preparedness for local and regional state government agencies.

While the application of this project beyond our community has broad relevance for many end users, it also has direct relevance for preparation, response, and mitigation of future coastal hazards from tropical cyclones and meteotsunamis. Flooding during hurricanes and tropical storms is not limited to the immediate coastal area but could extend well upriver due to interactions between abnormally high estuary water level caused by storm surge and/or synergies of tidal forcing during spring tides. Higher rainfall intensity storms such as Hurricane Harvey (2017) and Florence (2018) are setting new precedents for inland flooding impacts. It may become increasingly critical to evacuate low-lying, near-river areas 10-20 miles inland. Moreover, while the spatial relationships of peak rainfall flooding, coastal storm surge, and estuary tidal fluctuations are important, the timing of these events is also important. This importance extends to pre- and post-peak conditions, when combined impacts may be most critical for emergency management agencies to focus resources toward preparation. Thus, another key deliverable of this project will be identification of scenarios and specific locations where coalescing factors may cause up-river flooding not currently predicted by storm surge inundation models. Recent storms that impacted Savannah, GA such as Matthew (2017) and Irma (2018) with differing approach vectors, wind fields, storm surge prediction, and highly-localized coastal inland flooding are creating a more complex scenario for evacuation versus shelter-in-place decisions. Further, efficient timing of evacuations must balance the necessary time for populations to prepare and travel away from the coast while avoiding gridlock with larger areas and populations involved. Current storm surge inundation models and predictions (SLOSH) do not incorporate river level or inland rainfall into risk assessments and inundation maps (NHC, 2018). Development and other human impacts also play a role. For the Savannah River in particular, recent Savannah Harbor Expansion Project (SHEP) work has made significant alterations to river bathymetry, which likely impacts upstream tides and storm surge extent.

PROJECT DESCRIPTION

Near-Coastal Hydrology

Near-coastal river hydrology is known to be complex involving multiple interconnecting tributaries and distributaries with complex hydrology. From Wolanski et al. (2013), “An estuary is never at steady state.” Like rivers, estuaries can be responsive to precipitation and water levels that can vary greatly due to upstream flow. This flow can also have impacts on salinity and water quality. Beyond rainfall, a regulated river, such as the Savannah, can experience unusual changes in water flow in the estuary due to releases from upstream reservoirs. Of course, near-coastal areas are also impacted by downstream tides. And tides have multiple predictive drivers, primarily lunar and solar gravitational forcings, but also less predictive, more stochastic transient influences related to weather, wind speed, and wind direction.

These systems are also subject to alterations based on anthropogenic activities. In the Savannah River, historic modifications to facilitate navigation on the river have shortened and deepened the channel. According to Hale and Jackson (2003) the practice of cutting off oxbows in the river removed 26.5 miles of the lower Savannah River. Channel maintenance kept the river at a minimum of 9 feet deep and 90 feet wide throughout the lower basin, much of this in areas that do not naturally have that shape. Dredging and channeling activities, among other modifications, can impact the relative “age” of the estuary and the way that it behaves in regards to the interaction of tide and river stage (Wolanski et al., 2013). In an important study to this work, Sassi and Hoitink (2013) indicate that the impact of upstream tidal forces on stage in the near-coastal area is dependent on bottom friction and upstream discharge. These modifications can affect the timing and magnitude of both of these elements. Dredging can reduce friction and shortening can reduce the opportunity for longitudinal dispersion of precipitation-driven waveforms.

While understanding near-coastal hydrology may be difficult, it is also critically important. Wei et al. (2013) details the various reasons why accurate prediction of hydrology in this portion of rivers is so important including, “monitoring pollutant load, calculating sediment transport, controlling flood and drought, determining environmental flows, power generation reservoir operation and agricultural irrigation, as well as water supply to industry and households.” Near-coastal areas are heavily subject to the effects of tropical cyclones, face heavy pressure from development and industrial water uses, and are an accumulation point for upstream pollution that may have increased residence time and/or deposit in near-coastal areas.

Time Series Analysis and Hydrologic Modeling

River hydrology, particular in near-coastal areas has been studied with time-series methods in many instances. Sassi and Hoitink (2013) used wavelet analysis with a distributed network of pressure sensors to investigate the effect of tidal and upstream stage on near-coastal water levels through an estimate of sub-tidal friction. Wei et al. (2013) use wavelet analysis and artificial neural network modeling in order to predict river discharge in a subsequent year. Moftakhari et al. (2013) estimated Sacramento River discharge with wavelet data and regression and were able to hind cast annual freshwater discharge to the estuary. Moftakhari et al. (2016) used stage data over approximately 200km of the lower Columbia and Frasier rivers, along with wavelet analysis and then regression to determine the relationship between river discharge and tidal factors. Then they used this relationship to estimate discharge where tidal information is known but discharge is absent. Kisi (2011) utilized a combination of wavelet analysis and regression to forecast daily river stage in the Schuylkill River. This study also indicated that the regression analysis performed in a superior way to artificial neural networks for this system.

The EDFC hydrodynamic model used in preparation for the Savannah Harbor Expansion Project covered the same area as this study, including the use of water level data from river mile 45 (RM45) near the mouth of Ebenezer Creek. It collected data as far upriver as Clyo, GA at RM61 and downstream to the mouth of the river. This modeling effort initially overestimated the tidal range at that location relative to observed data (approximately 0.5 ft of tidal range), before adding marsh areas and bottom roughness to the model to compensate (USACE, 2006). The same study described the Savannah River Estuary system in the following way. “As a result of the complexity of marshes and multiple channels in the Savannah River Estuary, the tidal wave on the Front River can neither be classified as a pure progressive wave nor a pure standing wave. The system’s resultant wave is a combination of multiple components of reflected and standing waves, and in some cases exhibiting resonance characterized by multiple velocity peaks in the same flood or ebb tide.”

Mendelsohn et al. (1999) describes the Savannah as being a partially mixed estuary, but at the low end of partially mixed, indicating that that river flows have a significant effect relative to tides. In contrast to these previous methods, tidal prediction has historically been by Fourier analysis identifying scores to hundreds of harmonics that influence timing and amplitude of these low frequency waves (Knauss, 1997). The key factor that separates these predictive models is regular, physically-predictable driving forces versus stochastic events that are generally predictable but transient and difficult to couple

with currently available models, covering different regions of the estuary and lower reaches of the river.

Critical to all of these models and predictions is analysis of very long time-series data. While identification of transients and the impact of events like rainfall flooding, storm surge, syzygy tidal events (i.e., king tides) is critical to future prediction, coastal resiliency, emergency management, and sustainable land-use development, fully understanding the “normal” or “baseline” responses within the highly dynamic and interconnected system in our estuary is paramount so that the transients can be actually identified beyond the normal conditions. However, changes to the system including the SHEP now limit the utility of long-established historical river gauge data. The impacts of these changes are being observed immediately and the lack of predictive knowledge associated in how the river system behaves reduces our coastal resiliency and disaster preparation. Alternatively, the installation of multiple temporary river stage gauges provides additional concurrent data for analysis. Although these data are fundamentally different, they provide insights in both normal and transient behavior within the river basin.

Head of Tide

The Protection of Tidewaters Act (2010) stipulates that the state has ownership of waters that are “affected by the tide, where the tide rises and falls.” This has been further defined by GADNR as the upstream extent of the river where the tidal range is at least 0.2 ft. We refer here to this definition for the term “head of tide”. While this legislation has existed for almost a decade, GADNR is still in need of data to verify the correct location for head of tide by this definition for the five major river systems in Georgia. It is imperative to their mission of implementing this law that they have this information. Historic reference placed the head of tide at or around the mouth of Ebenezer Creek at RM45 (USACE, 1994; USDOC, 1965). The USACE document also references average tidal ranges of 6.8 ft at the mouth of the river and 7.9 ft at the upper limit of the harbor.

Hydrology and Coastal Resiliency

Flooding associated with tropical cyclones is a major threat to life and property in coastal areas of the United States. Tropical cyclones can create flooding through winds pushing ocean water toward shore as what we know as storm surge, and can also deliver torrential rains. Thus, in areas further upstream where these impacts are known to be more significant, there may be a potential for water levels that are higher than SLOSH alone might predict if a storm surge were to occur with an already high river level or be accompanied by significant upstream rainfall.

In recent years, storms such as Harvey (2017) in Texas and Florence (2018) in the Carolinas have

challenged the conventional wisdom of the impacts of tropical storms being strongly correlated to their wind speed. While Harvey did make landfall as a major hurricane, it quickly weakened and spent much of its time impacting near-coastal areas of Texas with torrential rains as a tropical storm. Florence, which made landfall as a category 1 hurricane, nevertheless caused significant near-coastal impacts due to precipitation-driven flooding. This type of storm could potentially have flooding impacts in near-coastal rivers that are not well captured by either precipitation-driven river level modeling or coastal storm-surge-inundation modeling alone.

METHODS

Study Area and Data Collection

The primary focus of this study was the area between the extent of the SLOSH model upriver past historically-placed head of tide (USDOC, 1965; USCOE, 1994). This was roughly between RM27 and RM51. The larger area of study, included to investigate forcing from upstream flows and tidal range, was from RM1, the Fort Pulaski NOAA gauge, to RM61, the Clyo, GA, USGS gauge. The primary focus area included 6 temporary gauge stations set up through this study and 3 USGS gauges (Figure 1). The larger area includes two additional USGS gauges at RM61 and RM1 (not pictured). The gauge at RM51 was originally located at RM31 and moved to the top midway through the study to extend coverage. Neither RM31 nor RM51 proved to add significant additional information to the study and were not included in the analysis.

Water Level Logger Stations

Each temporary station consisted of a 30-ft range Hobo water level logger (Onset Computer Corporation, Cape Cod, MA) suspended within a 6-10 ft section of 3-inch polyvinyl chloride pipe that served as a stilling well. They were set to collect temperature and absolute pressure at 15-minute intervals continuously, synchronized to the hour, half-hour, and quarter-hour. The water level loggers were suspended in the pipe with stainless steel cable. The pipe sections were securely fastened with twisted metal wire to sturdy structures such as relict wing dams, trees, or in a few cases steel posts driven deep into the river bed. None of these temporary installations gave any evidence of having measurably moved during the study period.

Data Post-Processing

As the water level loggers measure absolute pressure and not water level directly, it was necessary to perform a correction to the data to account for atmospheric pressure changes. Atmospheric pressure data were collected from the RM29 USGS gauge and applied to all of the temporary stations. Temperature data from the stations were also used for the correction and an assumption of 0‰ salinity

spectral peaks are only identified as significant if their amplitude was 3 standard deviation above the variability produced by all frequencies. Additional refinement could improve this approach to Fourier analysis, but that was beyond the scope of this initial assessment of the rapid, multiple, temporary river gauge analysis technique.

Waveform Matching

The term waveform analysis is used instead of wavelet analysis because of key differences between what is done here and what is normally meant by wavelet analysis. Wavelet analysis has been well described elsewhere and will not be described completely here, but some comparisons are made. For example, while this method and wavelet analysis convolve functions or sets of functions through a time series to describe and deconstruct it into components, traditional wavelets are meant to integrate to zero (Vidakovic and Mueller, 1994), while the waveforms that are convolved in this analysis do not. While we will leave it to others to decide if the methods used here qualify to be called wavelet analysis, the method used is described as follows.

The waveform analysis used in this study was based largely on the method originally described by Rosenquist et al. (2010). However, further enhancements were made to increase the utility and performance of the method. Like the previous method, waveforms of equation 1 are convolved through the time series and a quality of fit parameter is calculated. The equation represents a sine wave in the domain 0 to 2π .

$$H = \sin \left[\left(\frac{k + \frac{j}{2} - 1}{j} \right) \pi \right] i + TS_k - i \quad (1)$$

where:

- H is waveform height,
- TS_k is the river stage at that time,
- j is the current wave period,
- i is the current wave height,
- k is the current location in the time series representing the peak of the wave,
- and l is the measurement location in the waveform being tested.

This equation differs from the previous method based on the inclusion of the last term, which binds the peak waveform being tested to the current value of the time series being tested instead of the previous method which bound the base of the waveform to zero. The determination of fit quality (Figure 2), which for this study was based on misfit/fit is also different from the originally method, which was based on the ratio of fit to misfit. In the current method, a perfect fit would be zero. Fits are only recorded below a value of 0.5 for efficiency of the

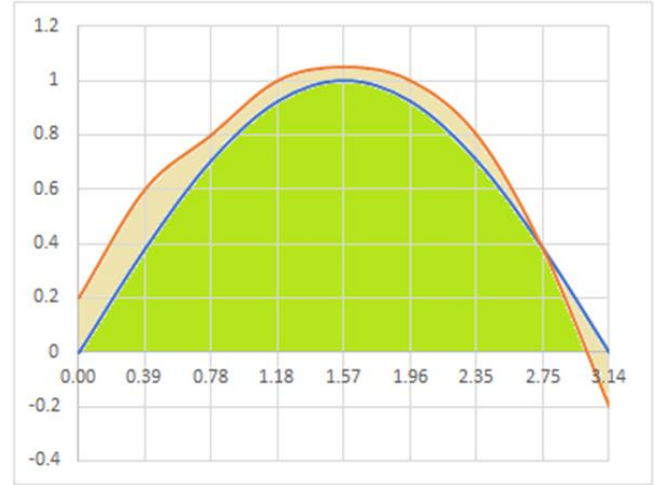


Figure 2. The blue line represents the test waveform while the red line represents the actual time series data. The green area represents fit, while the tan area represents misfit

program, but some of the higher ones are eliminated later in post processing.

Both methods then select the best quality fit in the resulting dataset and eliminated that section of the time series from further selection. This process is continued until the entire dataset is eliminated or until no more matches of a certain quality can be found. Deconstruction of the time series into various signals is done by running the method with different sets of wave periods so that both tidal and river waveforms can be found simultaneously. The first run is done with wave periods of 6hr to 24hrs for tide-driven waves from downstream and the second set from 48hrs to 1680hrs for precipitation or dam discharge-driven waves from upstream. Dam discharge-driven waves are included based on the presence of Thurmond dam at approximately RM215 and the effect that it can have on stage downstream during releases that are not based on precipitation.

In the process of selecting the waveform matches the method also records the following for each “match”:

1. Match quality (misfit/fit, 0-0.5)
2. Match wavelength
3. Match wave height
4. Time of peak
5. Actual stage at the match peak
6. Actual stage at the waveform minimums

The following additional parameters can then be calculated or searched for each match:

1. Actual height of rising limb
2. Actual height of falling limb
3. Averaged actual wave height (average of rising and falling limb heights)
4. RM61 stage at peak time
5. Most recent RM1 wave height
6. Time-matched wind speed/direction at NOAA Fripp Island Buoy

Determining the head of tide with waveform analysis involved considering the distribution of waveforms found at each location and some attempt at interpolation between river miles and interpretation of the variation at each location. Boxplots are used to compare these distributions to the established criteria of 0.2 ft to define head of tide. Interpolation methods assume linearity between adjacent river miles and included explanatory factors such as upstream flow and tidal range.

Post-Analysis Quality Assessment

To assess the quality and interpretation of the Fourier analysis, an alternative, simple low-pass filter was applied to the corrected river gauge data as a moving 24-h average. This 24-h average with a 0.2 ft ‘minimum tidal height’ was compared to the unprocessed river gauge data. If the river gauge data exceed the moving average with 0.2 ft head of tide criterion, this was an indication of tidal influence at the station.

A second quality assessment was the reconstruction of the single significant tidal harmonic identified by the Fourier analysis and compare the amplitude of this isolated waveform to the 0.2 ft wave height head of tide criterion. If the wave amplitude exceeded the head of tide criterion this also indicated significant tidal influence at the station.

To address the quality of the waveform analysis, several steps were completed to determine the best cut-off point for match quality. The first was a histogram distribution of the match quality values for all the chosen matches (Figure 3). A bimodal distribution did exist of the 3315 total matches with a minimum value between the modes of about 0.33. Next, a visual assessment was done of the some of the matches above and below this threshold which confirmed that the matches above where often not an accurate assessment of the time series data while the ones below were. Lastly, many of the matches above 0.33 were duplicates of the same time periods in the data from the higher set of wavelengths and the lower set of wavelengths. Therefore, 0.33 was chosen for this data as the cut-off for quality matches to be included. Furthermore, a test was done for any waveform match that was attempting to qualify the same waveform in the data

and the worse match was excluded. This is not to say that two matches could not occur at the same time, for instance a 12-hr match that sits within a larger 240-hr match did not require eliminating one, but matches of waveforms with the same actual peak and actual width could not have two different descriptions.

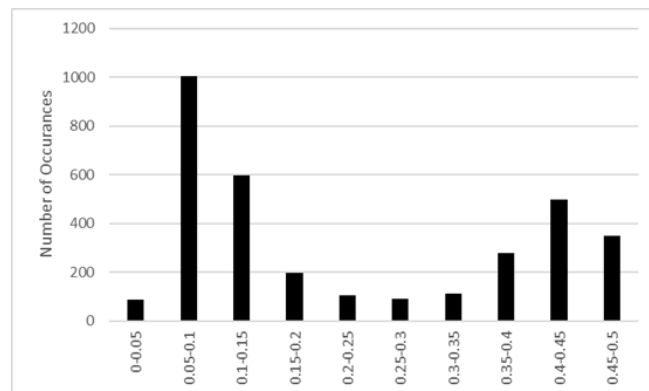


Figure 3. Histogram of waveform match quality parameters for all the matched waveforms.

Evaluating Potential Effects of River Stage, Tidal Phase, Wind, and Local Precipitation on Waveforms

To test for the effects of the above factors on 12-hr waveforms, the values for each group were categorized as follows. The upstream river stage was divided into three categories, Low (L), High (H), and Flood (F). The cut-off between L and H was the mean stage at RM61, Clyo, GA reported by USGS averaged over all available years, which is 6 ft. The cut-off between H and F was the National Weather Service minor flood stage of 11 ft, also at Clyo. During the study period water levels were in the L range 64% of the time, in the H range 20% of the time, and in the F range 16% of the time. Therefore, this sample data had lower water levels than average. Tidal range was divided into two groups, neap (N) and spring (S), based on the median value at RM1 during the study period of 7 ft. Local precipitation was estimated based on the stage of Ebenezer Creek, divided into Low (L) and High (H) values based on the mean value during the study period of 5.85 ft. Wind effect was divided into three categories Downriver (D), Moderate (M), and Upriver (U) based on the upper and lower quartiles of the vector quantity of wind observed in the 300° upstream direction. All these parameters were tested for significance based on a bootstrapped 95% confidence interval for the mean of the averaged actual wave height.

Towards Predictive Modeling

Based on the results of the above evaluation for the relative effects of the influencing factors on waveforms, we evaluated the potential to create a predictive model of water level through the study region based on a RM1 wave height or storm surge and the river level upstream at RM61. Methods including regression and artificial neural network methods have been considered. Prior work in these areas including the sources cited in this paper have been reviewed and the data available evaluated for suitability for use with these methods. While these methods were not completely implemented in this study, there are ongoing efforts to do so. However, toward this effort, a calculation was done of a tidal reach ratio, defined as the ratio of the height of each matched 12-hr wave (H_x) to the previous wave height most nearly matched in time and occurring at RM1 (H_1). RM1 is meant to represent a tidal forcing not impacted by river level, and the ratio is meant to indicate the amount of that wave that is propagated upstream to various stations, under various conditions. Results are presented as a boxplot.

Improvement of these predictive analyses may be found in cross correlation of the data produced by all river gauges in the study area. This method does need additional data to be successful, but preliminary analysis (not presented here) is promising. This approach will yield specific temporal relationships to improve and further inform our current spatial data. As previously noted though, this was beyond the scope of our initial question whether short-term, rapidly-deployed, inexpensive temporary river gauges could assess the influence of rainfall flooding, storm surge, and tidal reach on an estuary system.

RESULTS

Data Overview

Data were collected starting in mid-February of 2018 and data collection is ongoing. For the purposes of this study, data are included up to 8/2/2018. The full time period is available at RM35, RM43, and RM48, in addition to USGS stations 1, 2, 3, and 4. RM41 is not included in waveform analysis due to access issues at high river stage and data quality issues. RM45 had about 20 days of omitted data during this period due to low quality data but is included otherwise for the entire period. There were two notable high-water events during this period with one (late May through June) significantly higher than the other (early May). The larger event exceeded the National Weather Service 11-ft minor flood stage for almost a month and almost exceeded the 15-ft moderate flood stage. There were no storm surge events observed during the study.

Fourier Results

Fourier analysis of the river gauge data was confounded by the multiple flooding events experienced during the analysis period. Two specific analyses, identifying a period over 60 days when the river stage was less than 6 ft, before the month-long flooding in late May through mid-June when the river stage was over 11 ft, isolated a 'normal' river stage from an 'abnormal' or 'flood' stage for Fourier Analysis.

Under normal river stage conditions, RM45 at Ebenezer Landing was clearly influenced by the tide with a 12.42-hr lunar semidiurnal tidal harmonic in the river stage data. This was confirmed by both the raw data fluctuation about the 24-hour moving average and the isolated 12.42 harmonic amplitude exceeding the 0.2 ft head of tide criterion (Figure 4 A and B).

Moving upstream to the next station at RM48, just below Berry Landing, the 12.42-hr M_2 harmonic is observed in the river gauge data, however it does not meet the 3-standard-deviation threshold above the noise to be significant. Further, the raw data does not consistently exceed the 0.2 ft height about the 24-h moving average and the isolated harmonic amplitude is also less than 0.2 ft (Figure 4 C and D).

However, the head of tide determination was significantly impacted by the river stage. Considering the month-long flood stage during late May to mid-June, Fourier analysis did not positively identify any tidal influence above RM35 at Puryburgh Landing (Figure 5).

These data suggest under normal conditions that the head of tide is upriver from Ebenezer Landing but located before reaching Berry Landing between RM45 and RM48. The head of tide moves substantially down river when it is flooding and is located above RM35, but before RM41. This points to a distinct need to consider river stage when discussing head of tide (Figures 4 and 5). More data would significantly improve this analysis, but these results do demonstrate the relative utility of Fourier analysis for positively identifying tidal influences with a relatively short 30-60 days of data. Moreover, the method of placing inexpensive, rapidly-deployed, temporary river gauges could be improved by intermediate analyses and altering river gauge location to refine measurements during the determination process. Without significant cost and perhaps in as little as 120 days the head of tide could be identified to less than one river mile if actively analyzed throughout the period instead of leaving all the river gauges in place for the entire study duration.

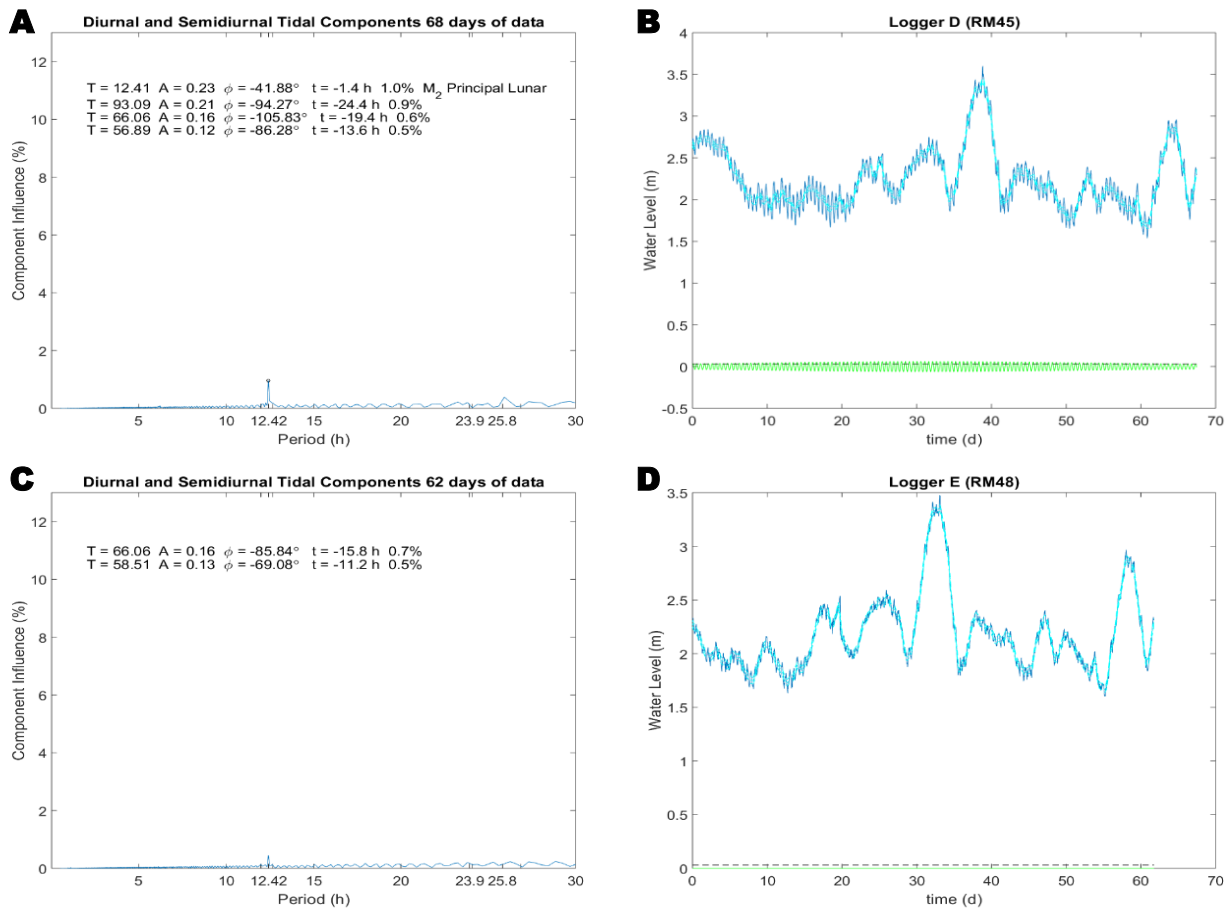


Figure 4. Fourier analysis and quality assurance data for temporary river gauge stations at RM 45 Ebenezer Landing and upstream at RM48 just downstream from Berry Landing. **A** - RM45 shows clear 12.42 h tidal harmonics that are 3 standard deviation above the spectral noise. **B** - This is corroborated by raw data (solid blue lines) exceeding the 24-h moving average with ± 0.1 ft boundaries (dashed light blue lines) and isolated 12.42 h harmonic amplitude (green waveform) exceeding 0.2 feet (black dashed line). **C** - Although the 12.42 h tidal harmonic is identified at RM 48, it did not exceed our 3-standard-deviation threshold above the noise and only analysis artifacts were isolated. **D** - These data are consistent with the raw river gauge data rarely exceeding the 24-h moving average ± 0.1 ft or the isolated 12.42 h spectral harmonic amplitude being less than 0.2 ft. This suggests the head of tide lies between RM45 and 48, but more data and further analysis is required to identify the specific location with Fourier analysis.

Match Overview –Waveform Analysis

Table 1 provides all of the high-quality (match value < 0.33) matches from the analysis. From RM1 to RM35 the same number of 12-hr matches were found, with decreasing wave height. Below RM35 the only matches were 12-hr and the only other match at RM35 was a 1200-hr wave period corresponding to the larger upstream-driven flood event. From RM35 to RM48 there were a decreasing number of 12-hr events with decreasing wave height. From RM39 to RM61 both of the noted upstream-driven flood events were matched at each station as were an increasing number of smaller events that were still greater than 12-hr wave period.

Head of Tide –Waveform Analysis

Figure 6 provides a summary of the distribution of all the 12-hr waveforms at each station. Of note, there appears to be a trend with two distinct linear or near-linear sections of different slopes. Starting at RM1 there is a decrease of wave height with a gentle slope followed by a “breakpoint” between RM29 and RM35 and then a rapid decrease to RM48. Also, note that the variability in wave height is highest from RM35-RM43. Regarding head of tide, RM45 is the last station where the median value is higher than the threshold of 0.2 ft, RM43 is the last station where the entire interquartile range is about 0.2 ft, and at RM48 even the extreme values are below 0.2 ft. Clearly

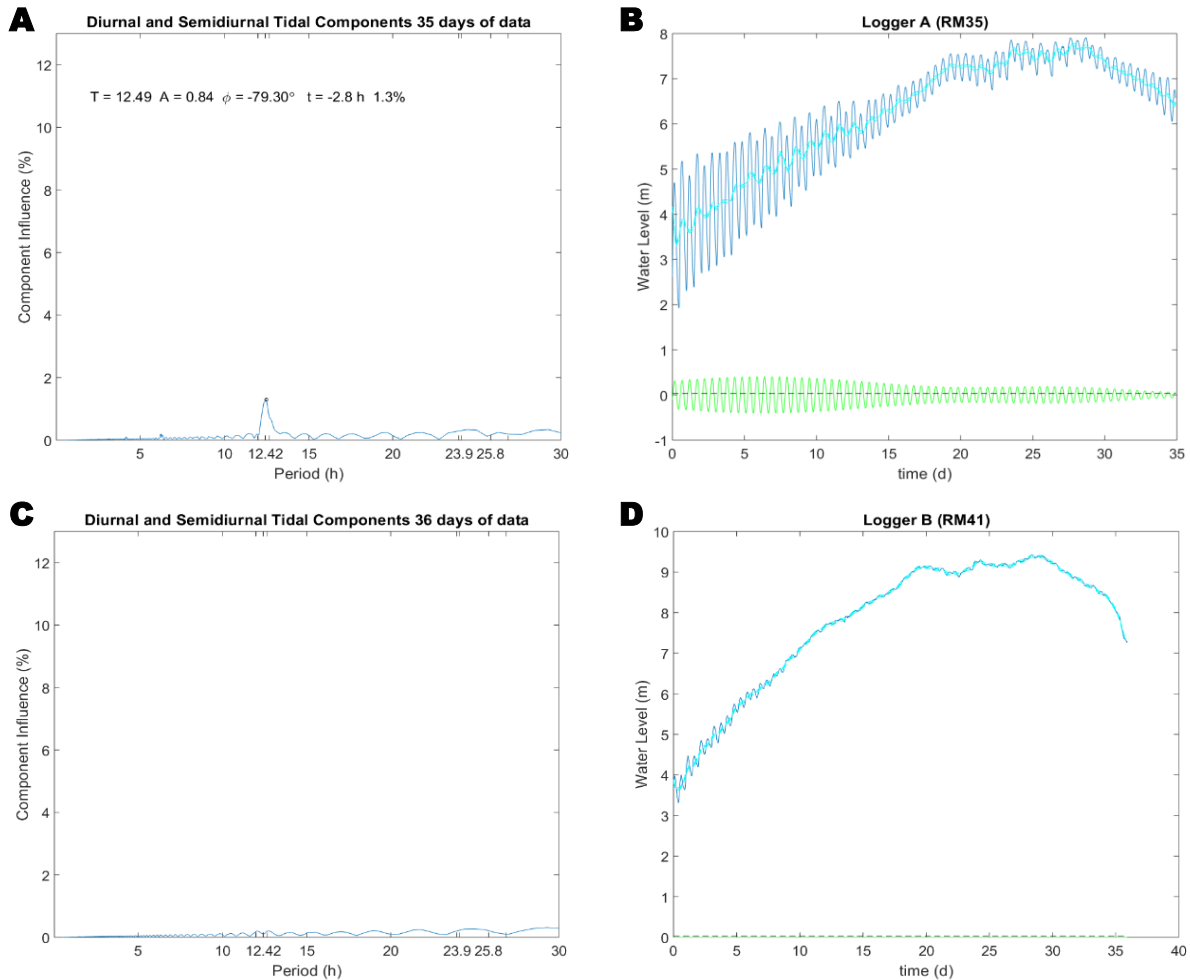


Figure 5. Under flood stage (> 11 ft) conditions, head of tide moves downstream. **A** - RM35 near Purysburgh Landing shows lunar semidiurnal tidal harmonics that are 3 standard deviation above the spectral noise, even though the limited data has split spectral energy across harmonic periods. **B** – The tidal influence is clearly observed in raw data (solid blue lines) exceeding the 24-h moving average with ± 0.1 ft boundaries (dashed light blue lines) and isolated 12.42 h harmonic amplitude (green waveform) exceeding 0.2 feet (black dashed line). **C** – No tidal harmonics are observed upriver at RM41 at cut-off #3 during flood stage. **D** – These data are consistent with the raw river gauge data rarely exceeding the 24-h moving average ± 0.1 ft. This suggests the head of tide lies between RM35 and 41 when the river stage is higher than normal, but as before, more data and further analysis is required to identify the specific location with Fourier analysis.

the head of tide exists in this region but is subject to some variability depending on conditions to be discussed below.

Effects of River Stage, Tidal Phase, Wind, and Local Precipitation on Waveforms

Bootstrap confidence intervals for the mean value of wave height revealed that wind and local precipitation were not significant explanatory factors for variability in 12-hr wave height. 95% confidence intervals overlapped for the various subgroups of data defined by the 3 wind categories and the 2 precipitation categories. However, bootstrap confidence intervals for river stage and tidal phase indicate significance in explaining this variability as

confidence intervals for the mean did not overlap. Figure 7 breaks out 12-hr wave height based on neap or spring tide. This factor is most powerful in explaining variability in the downstream (below RM35) and upstream (above RM39) regions and less powerful in the middle portion. Regarding head of tide, RM45 is above 0.2 ft for the entire interquartile range during spring tide and below during neap tide.

Figure 8 breaks out 12-hr wave height based on river level. This distinction is powerful in explaining variability throughout, but especially in the middle portion (RM35-RM39) where the tidal regime distinction is weaker. Note that during “Flood” conditions, head of tide drops down

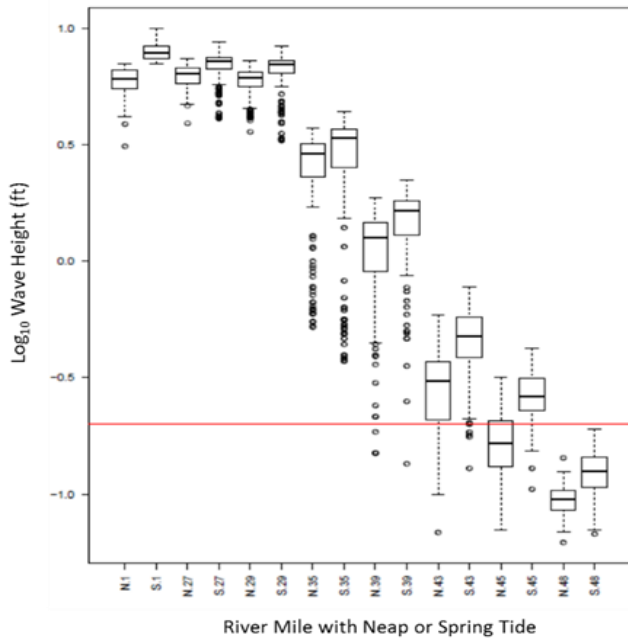


Figure 7. Boxplot of 12-hr waveform log-transformed height broken out by tidal phase and depicting median, interquartile range, maximum, and minimum values.

be as little as 0.5 ft, but under ideal conditions of spring tide and low flows it can have a tidal range of over 3 ft. Similarly, RM39 can have a tidal range of less than 0.2 ft to almost 2 ft, depending on circumstances.

Interpolation –Waveform Analysis

Linear interpolations between stations yield the following additional results. At low flows and/or spring tides, a median wave height of 0.2 ft probably reaches RM46. Under “Flood” conditions a median wave height of 0.2 ft probably occurs near RM38, with limited effect from spring versus neap tide.

Towards Predictive Modeling - Combined Effects of River Level and Tide/Storm Surge in Critical Areas

A goal of this study was to evaluate the flooding risk of areas that might be affected by both storm surge and upriver, precipitation-driven flooding that is not being captured by current SLOSH model predictions. In particular, we would like to be able to predict river levels throughout the study reach based on tidal range, or storm surge, and upriver (RM61) river levels. While the data in this study provided very promising results toward this goal, such a predictive model is not presented here for the following reasons: 1) the study period did not include a storm surge event that could be used to verify the trends seen at lower wave heights at storm surge and extrapolation would be occurring beyond reasonable

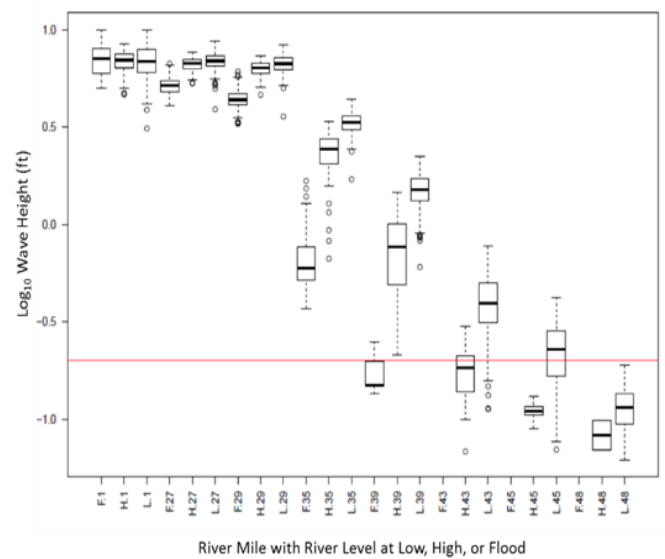


Figure 8. Boxplot of 12-hr waveform log-transformed height broken out by river level and depicting median, interquartile range, maximum, and minimum values. Note that the boxplot for H.48 is based on 2 values and H.45 is based on 6 values, so conclusions for these distributions are limited.

limits; and 2) modeling efforts to create robust validated predictions while verifying that the necessary assumptions for the methods have been met are still underway. Notwithstanding, some results are presented here, specifically tidal reach ratio (Figure 10). Note that the ratio is only presented from RM27 to RM43 because the ratio at RM1 would be 1 by definition, and the ratio beyond RM43 becomes negligible under all conditions. Also note that as in previous results, “Flood” conditions in the river cause the ratios to be negligible above RM35, at least under the range of 12-hr wave heights observed in this period at RM1. It is theoretically possible that higher (super-spring) storm surge might create non-negligible ratios further upstream. Also, recall that based on results presented above, precipitation-driven waves were not observed below RM35. Therefore, based on the range of forcing (tidal and upriver flow) available in this analysis, it is likely that area most likely to be affected by a combination of storm surge and upstream discharge would be some portion of the river above RM29 and below RM39. This includes Puryburgh, SC, and some of the areas around Hardeeville, SC. On the Georgia side, most of this area is relatively undeveloped as part of the Savannah National Wildlife Refuge. Based on a possible worst-case scenario of high water level in the river and storm surge, it is possible that 40% or more of the height of this storm surge wave could be propagated this far upstream. These ratios, and/or the predictive modeling of river elevation suggested, could be combined with current

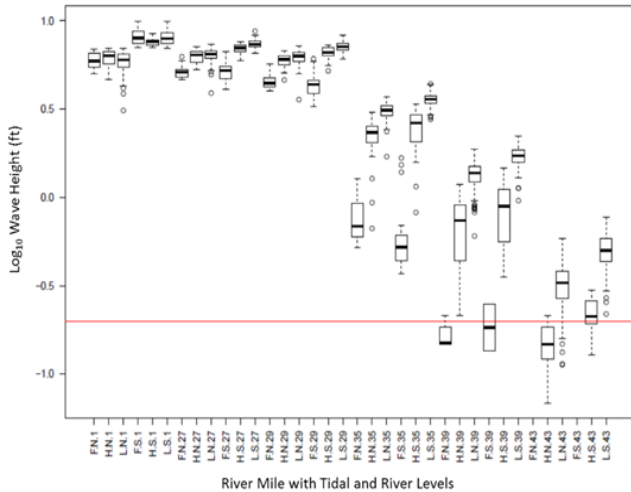


Figure 9. Boxplot of 12-hr waveform log-transformed height broken out by tidal phase and river level, depicting median, interquartile range, maximum, and minimum values.

SLOSH model results and GIS tools to inform potential inundation areas under predicted conditions. It should also be noted that the impact of elevated water level in the river has a significant effect on wave propagation all the way down to RM27 and potentially beyond.

DISCUSSION

Relevance for Natural Resource Management - Head of tide determination

Based on the significant impact of river level, and to a lesser extent, tidal cycle, the Fourier and waveform analysis results indicate that a definitive determination of head of tide to a specific river mile based solely on a 0.2 ft wave height requirement is not possible. Rather, it is necessary to define the tidal conditions and flow conditions that are to accompany that level. Also, it is necessary to define how frequently the wave heights must exceed this level under those conditions. For the purposes of this study, we are defining this as the presence of 12-hr waveforms for the majority of the time that river levels are less than the historic mean flow (6ft in this case) and inclusive of both spring and neap tide, but not storm surge. Based on this definition both methods of analysis converged on RM45, in agreement with the USDOC information from 1965 and the USACE information from 1994. Interpolation under the waveform analysis method may support RM46 under this definition, but with less confidence. Extrapolation of Fourier analysis also suggests RM46. However, this analysis also provided a basis for which GADNR can determine the regulatory head of tide for the purposes of the Protection of Tidewaters Act based on different conditions they feel to

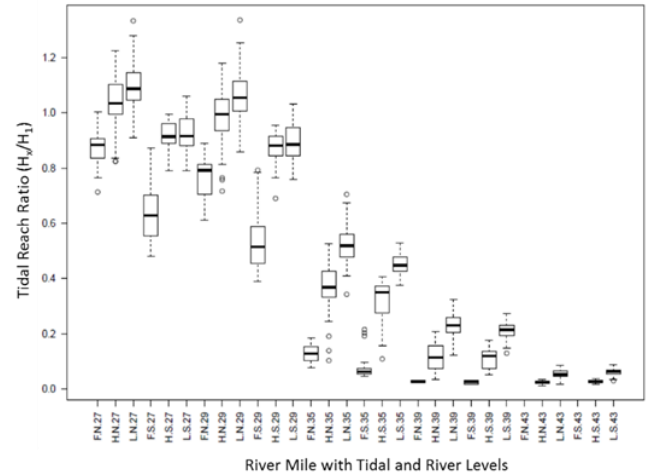


Figure 10. Boxplot of tidal reach ratio broken out by tidal phase and river level, depicting median, interquartile range, maximum and minimum values.

be most relevant for this purpose. For instance, the highest upstream extent of 12-hr waveforms of an amplitude of equal to or greater than 0.2 ft occurred anywhere between RM38 and RM46, depending on the tidal phase and the river level and river level was the dominant factor. In future work, it is likely that this method could be equally effective in providing head of tide information for other near-coastal rivers.

Relevance to Short-term response and Emergency Management

Limited resources during life-threatening events require their efficient deployment and use to ensure the most-effective response to protect life and property. This study revealed a need for developing predictive tools to analyze complex hydraulic river systems impacted by multiple deterministic, predictable, and stochastic inputs. However, this study provides some evidence for the potential to model river stage in the near-coastal region using 12-hr wave heights and Fourier analysis. Moreover, continued use of inexpensive, temporary, rapidly-deployed river gauges provides the necessary data to describe hydraulic linkages between fully river-influenced river gauge stations (USGS, Clio, GA) to tidal, but river-influenced stations (USGS, Abercorn Creek, GA), to fully tidal stations (NOAA, Ft. Pulaski, GA) near the mouth of the river.

Literature on the subject and preliminary work with regression models by the authors indicate the strong potential for such a model that may have very accurate prediction capabilities for this region without the need to deploy water level monitoring in this region permanently. The limitation of this approach is lack of a timing component, even if amplitude of the river stage at any

given location can be determined. In the future, Fourier analysis and cross correlation of the combined tidal and river stage data across the region may provide this critical timing of tide wave or storm surge propagation up the river and flood water downstream. What cannot be overstated though, is the importance of relating all these results to river stage at the time as a highly sensitive factor to river flood and tidal/surge interaction. This study clearly identifies a region of the river between RM35 to just above RM45 that is simultaneously sensitive to both upstream discharge and downstream tidal effects for the local water level. Ultimately with continued development of these analytical techniques, improving our understanding of the individual contributions of storm surge, tidal influences, and upriver flooding to overall river stage, will provide informed decisions on management and development in this section of river potentially impacted more by critical timing rather than solely magnitude of these events. For the future, this region of the river should be developed with care as it may be especially vulnerable to changes in long-term river flow impacted by stochastic precipitation and tropical cyclone events.

Relevance for Long-term Resiliency and Coastal Development

An interesting outcome of this study that warrants additional consideration is the observation of a breakpoint location around RM29 where the wave heights started diminishing more quickly moving upstream (Figure 6). The propagation of these 12-hr waves seems to be impeded in a different way around this region than previously, potentially by differences in storage or friction. A question for future study is whether that breakpoint is more dependent on sea level or on local geomorphology. If sea level, then perhaps future sea level rise could shift that breakpoint upstream resulting in significant changes to daily water levels in that upstream area. For instance, the area around Purysburgh, which may now be getting only 40-50% of the wave height seen at RM1, might get closer to 80-90% of that wave height. However, if based on geomorphology, the breakpoint may be more static, potentially resulting in erosive pressure on the geomorphology. The modeling effort conducted by Tetra Tech in conjunction with the Army Corp of Engineers (2006) indicated that additional floodplain wetlands and bed friction had to be modeled into the system in order to achieve the wave heights observed at RM45. If sea level rise or development affected the behavior of these wetlands, it could alter the head of tide significantly based on their model. Another long-term consideration for resiliency is the proposed reconnecting of the oxbows that were cut off in the latter half of the last century. This potential modification also has the potential to significantly impact the hydrology of this area. Reconnection will likely increase overall bed friction,

potentially resulting in less wave propagation upstream or a change in the breakpoint area. It may also allow for more longitudinal dispersion of precipitation-driven waveforms, reducing wave heights of this type in the more downstream area.

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