Spring 2021

Coastal windstorms create unsteady, unpredictable storm surges in a fluvial Maine estuary

Preston Spicer

Pascal Matte

Kimberly Huguenard

Laura N. Rickard

Coastal windstorms create unsteady, unpredictable storm surges in a fluvial Maine estuary

By

Preston Spicer,[1] Pascal Matte,[2] Kimberly Huguenard,[1] and Laura N. Rickard[3]

1) Department of Civil and Environmental Engineering, University of Maine, Orono, ME, USA.
2) Meteorological Research Division, Environment and Climate Change Canada, Québec City, Québec, Canada
3) Department of Communication and Journalism, University of Maine, Orono, ME, USA.
Corresponding author: P. Spicer (preston.spicer@maine.edu)

ABSTRACT

Storm surges create coastal flooding that can be damaging to life and property. In estuaries with significant river influence (fluvial), it is possible for tides, storm surge, and river discharge to interact and enhance surges relative to the immediate coast. These tide-surge-river interactions were previously identified in a fluvial Maine estuary as higher frequency (>four cycles per day) oscillations to storm surge which were proposed to be incited by enhanced friction and resonance during certain windstorm events (Spicer *et al.* 2019). The relative contributions to tide-surge-river interaction from atmospheric forcing variables (wind, barometric pressure, and externally generated surge) remains unclear. This work seeks to decompose and analyze a recent windstorm surge event to better isolate the effects of atmospheric forcing on tide-surge-river interaction. Results show total storm surges in the fluvial estuary to be two times larger than at the estuary mouth because of tide-surge-river interaction. Analysis indicated at least 50% of the magnitude of tide-surge-river interactions are created by non-tidal forcing, in the form of wind, enhancing frictional energy in the estuary. The remaining tide-surge-river interaction is likely a result of changes in tidal wave propagation speed due to surge deepening the mean estuary water level.

KEYWORDS: tide-surge-river interaction, fluvial estuaries, river tides.

Manuscript submitted 2 February 2021; revised & accepted 30 April 2021.

Storm surges are often the most threatening consequence of tropical and mid-latitude storms, particularly on the frequently impacted East Coast of the United States. In 2005, Hurricane Katrina hit Louisiana, producing a maximum surge topping 8 m and resulting in nearly $81 billion in damage (Blake *et al.* 2011). Of the more than 1,500 deaths that resulted from Katrina, the majority were considered a result of storm surge (Knabb *et al.*2006). Further north, more recent events like Hurricane Sandy in 2012 and the Patriot's Day nor'easter of 2007 produced significant, damaging storm surges in the New York City area and Boston, respectively (Drews and Galarneau 2015; Perrie *et al.* 2018). As coastal development, sea level rise, and storm frequency increase in the future, damaging surge events will occur more regularly, resulting in increasingly dangerous and costly impacts (Condon and Sheng 2012; Jongman *et al.* 2012). A better understanding and improved prediction of storm surge events is therefore imperative for mitigating damage and creating resilient coastal communities.

On the northern tip of the U.S. East Coast, the State of Maine is prone to storm surges resulting from mid-latitude winter storms. Typically called "nor'easters," due to the primary wind direction originating from the northeast, these storms tend to form between October and April and track over the coastal ocean. Nor'easters are intensified by large atmospheric temperature gradients between land and ocean, resulting in hurricane force winds and surge (Perrie *et al.* 2018). When these storms track inland, particularly west of Maine, winds become enhanced and directed from the south or southeast over coastal Maine due to the counterclockwise rotation of mid-latitude storms in the northern hemisphere. These strong coastal "windstorms" experience significant southerly winds which are enhanced due to large fetches over open ocean. Storm surge records from several windstorms show enhanced surges upstream in the Penobscot Estuary relative to the immediate coast (Morrill *et al.* 1979; Spicer *et al.* 2019). Morrill *et al.* (1979) suggested that the southerly wind direction was responsible for pushing water into estuaries (which are primarily north-south oriented in Maine) and explained enhanced surges there, but more recent observations point to nonlinear tide-surge-river interactions as the dominant mechanism contributing to upstream surge amplification (Spicer *et al.* 2019 [hereby referred to as SP19]). Although novel, the analysis of SP19 does not distinguish the relative importance of varying atmospheric forcing on surge and tide-surge-river interaction, and also fails to take river discharge into account in predicting water levels. In this paper, we present observations from another recent windstorm which created inland storm surges in Maine. We improve on the analysis of SP19 by including riverine effects in water level calculations and better decomposing the mechanisms contributing to tide-surge-river interaction during that storm.

ESTUARINE AND FLUVIAL STORM SURGES

In strongly tidal regions, storm surge can be considered a superposition of low-frequency surge (surge without tidal influence) and tide-surge interaction (oscillations to total surge level due to the interaction between tides and low-frequency surge) (Horsburgh and Wilson 2007; Rossiter 1961). Tide-surge interactions are nonlinear in nature, and generally a result of bottom friction and/or shallow water effects modulating tidal wave propagation speeds during surge events (Wolf 1978). Often, this results in peak total storm surge magnitudes and timing which differ from predictions. Recently, research has indicated that tide-surge interactions can be significantly larger within estuaries than on the immediate coast because of enhanced effects from shallow water and friction, and can

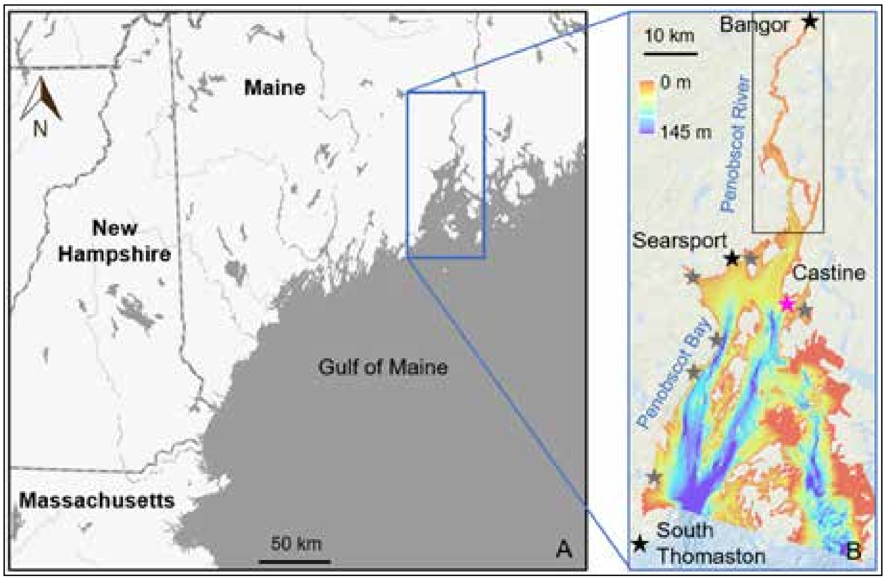

Figure 1. (A) Study area on the coast of Maine. (B) Zoom-in of the Penobscot estuary system, with the fluvial Penobscot River in the boxed region. Depths from NOAA estuarine bathymetry surveys (NOAA 2020) are shown as colored contours, gray and black starred locations denote water level collection sites (with black denoting locations utilized in this study), and magenta starred locations denote meteorological data collection sites.

Figure 2. High-water (A) and low-water (B) scenarios at the confluence of the Penobscot River and Kenduskeag Stream in Bangor during spring tides. Images courtesy of the United States Geological Survey (USGS 2021).

therefore result in total water levels that deviate substantially from predictions (Thomas *et al.* 2019; SP19).

Estuaries that extend far enough inland often turn fluvial in nature: that is, river forcing may become strong enough to modulate tidal energy. Fluvial estuaries can exhibit strong nonlinearities between tides and river flow which add an extra layer of complexity to predicting water levels (Kukulka and Jay 2003; Matte *et al.* 2013). Some unique estuaries, like the Penobscot River in Maine (Figure 1), have reaches that experience both substantial storm surges and river influences that collectively create tide-surge-river interactions (SP19). Tide-surge-river interactions can be manifested as rapid (>four cycles per day [cpd]) oscillations to water level sometimes exceeding 1 m in amplitude and are believed to be created by storm-generated currents enhancing frictional energy relative to non-storm conditions. Tide-surge-river interactions were responsible for doubling the total predicted storm surge in the Penobscot for one windstorm in 2017 (SP19) and are suspected to be the cause of an even larger windstorm flooding event recorded in 1976 (Morrill *et al.* 1979). A comprehensive water level monitoring network established in 2017 has allowed for further observation and analysis of these tide-surge-river interaction events (Spicer *et al.* 2020).

"SENSING STORM SURGE" IN THE PENOBSCOT BAY AND RIVER

The Penobscot Bay and River estuary system is a long, converging, and deep estuary extending approximately 100 km from the Gulf of Maine to the tidal limit at Eddington, 6 km north of Bangor (Figure 1). The estuary varies in width from roughly 30 km at the mouth to 240 m in the riverine section approaching Bangor. Depths at the mouth are deep (120 m maximum) relative to the confluence with the riverine section (30 m). Depths continue to decrease moving upstream to a minimum of 5.5 m at Bangor. The Penobscot River and Kenduskeag Stream converge in Bangor and are the primary sources of freshwater. The combined rivers have a mean annual discharge of 400 m^3/s and 100-year flood of 3400 m^3/s (Hodgkins 1999). Highest annual discharge rates occur in April and May during the spring thaw (averaged mean monthly discharges of 1100 m^3/s) and lowest rates are typically in September (140 m^3/s) (Dudley 2004). Tides are predominantly semi-diurnal, with amplitudes ranging from 1.5 m during neap tides to 2.5 m on spring tides (Geyer and Ralston 2018; SP19). During low to moderate river discharges, tidal ranges amplify moving up-estuary due to the convergent nature of the bay and river, resulting in greater maximum water levels in Bangor relative to the rest of the estuary (SP19). Figure 2 shows a typical spring tide high water scenario (Figure 2A) and spring low water scenario (Figure 2B) in Bangor. During astronomically high waters, a 1 m increase in water level can lead to minor flooding of local infrastructure and businesses, with increasing water levels leading to more widespread flooding in the downtown Bangor area.

The Penobscot estuary has a significant land border exceeding 300 km, on which lie many cities and towns with active working waterfronts. Towns on the estuary such as Belfast, Rockland, Rockport, and Stonington are nationally recognized as ship-building and lobstering hubs, contributing to the more than $100 million of gross state product that stems from Maine's working waterfronts (Colgan 2004). Many other towns on the estuary rely heavily on tourism connected to the bay, and so have extensive waterfront development which enhances the tourist experience and allows for easy boat access and travel between regions. Collectively, these communities are making larger efforts to establish more resilient waterfronts to adapt to climate change driven variations in tide, sea level, and storm surges (Birthisel *et al.* 2020; Bricknell *et al.* 2020).

The Sensing Storm Surge Project (SSSP) (http://sensingstormsurge.acg.maine.edu/) was established in 2017 as an interdisciplinary project utilizing citizen scientist volunteers to collect water level data at multiple locations in the Penobscot estuary and surrounding systems (Spicer *et al.* 2020). The SSSP was partly formed as a data collection mechanism, with the goal of better informing coastal communities in the Penobscot estuary region about extreme water levels. The water level data can also be used to answer more complex questions related to estuarine storm surge behavior (SP19) as well as provide local citizen volunteers a direct role in the environmental science on which to select climate adaptation strategies for their communities. Data has been collected in eight communities in the Penobscot estuary (see Figure 1b) over varying time periods since the inception of the project (Spicer *et al.* 2020). Those observations allowed for analysis of tide-surge-river interactions during the October windstorm of 2017 and more recently, the 01 December 2020 windstorm.

During the December 2020 windstorm, water level data were utilized in South Thomaston, Searsport, and Bangor while meteorological data were recorded at weather stations in Castine and Bangor (Figure 1b and Table 1). The South Thomaston and Searsport data were collected by citizen scientists using a HOBO water level logger sampling absolute pressure at a 2-minute interval with 0.1% measurement uncertainty. Water levels were then calculated from the absolute pressure using barometric pressure data (sampled at 1-minute intervals) taken in Castine.

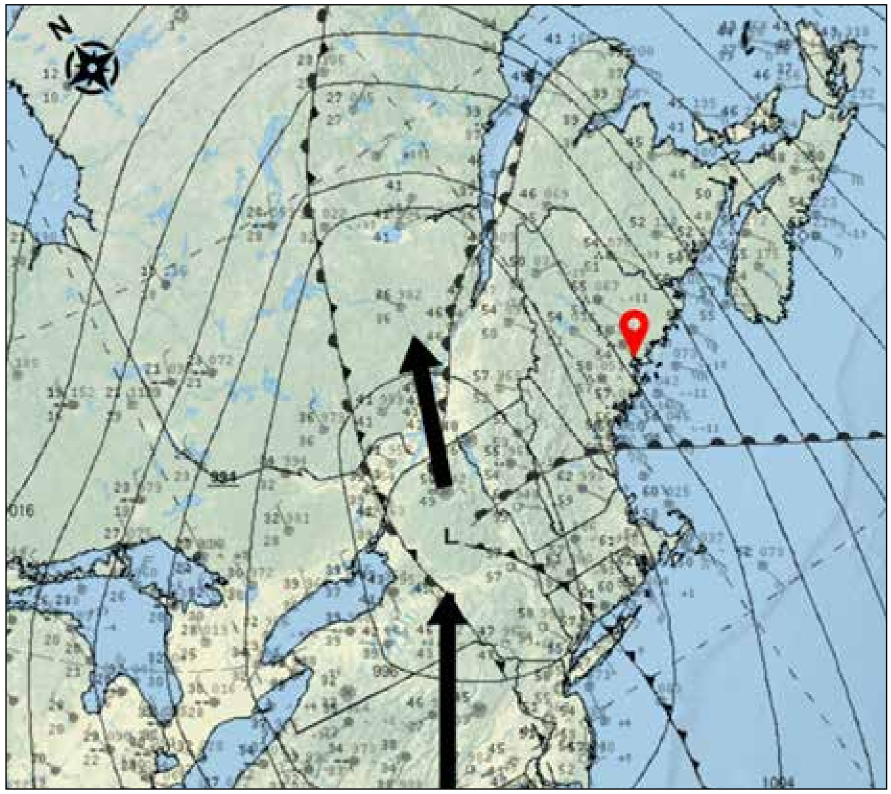

Figure 3. Storm track (arrows) and barometric pressure isobars for the December 01, 2020 windstorm relative to the Penobscot estuary, shown as a red marker. Map courtesy of the National Weather Service (NWS 2020).

Windspeed and direction were also taken at Castine at the same rate. Water levels in Bangor were recorded at a USGS river gauge (station #01037050) every 6 minutes, and supplemental wind data was also taken at the Bangor International Airport, sampling every 5 minutes.

01 December 2020 windstorm

The 01 December 2020 windstorm was a strong low-pressure system which tracked over New York from the mid-Atlantic states (Figure 3). Although far from the storm center, the barometric pressure in Castine reached a minimum near 1,000 mb during peak storm conditions (Figure 4a). Similar to past windstorms, Maine and the Penobscot Bay region were located on the eastern side of the storm which allowed for significant winds from the south to affect the region. Maximum sustained winds approached 15 m/s in Castine (Figure 4b) while gusts in Bangor approached 26 m/s (not shown) near the time of minimum barometric pressure.

River discharge was measured at a USGS gauge (#01034500) in West Enfield, ME, approximately 54 km north of Bangor. Discharge prior to the windstorm (~560 m^3/s) was above average for November/December (~480 m^3/s),

Table 1.

Summary of data collection including locations, data type, and sampling intervals.

Location	Data	Sampling intervals
West Enfield	River discharge	15 min.
Bangor	Water level	6 min.
Bangor Airport	Wind speed, wind direction	5 min.
Searsport	Absolute pressure	2 min.
Castine	Barometric pressure, wind speed, wind direction	1 min.
South Thomaston	Absolute pressure	2 min.

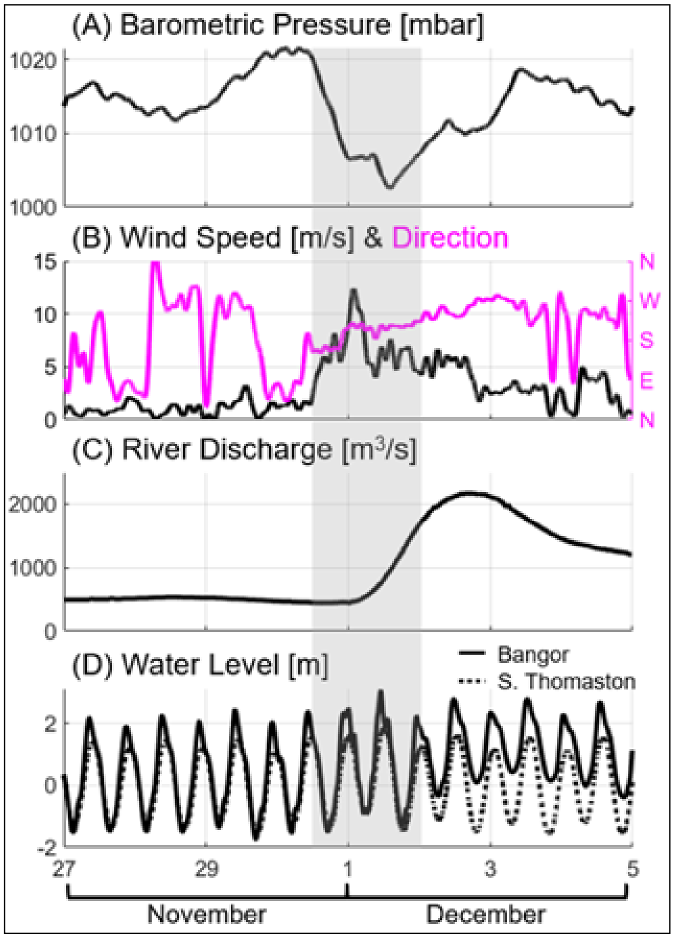

Figure 4. (A) Barometric pressure at Castine and (B) wind speed (black) and direction (magenta) measured at Castine (low-pass filtered), (C) river discharge measured at West Enfield, and (D) water level (in reference to mean sea level) measured in Bangor (solid line) and South Thomaston (dotted line). *X*-axis is the day of November or December 2020. The time at which the 01 December windstorm affected the region is shaded in gray.

increased during the roughly 36-hour event, and peaked at 2,300 m^3/s after the storm passed (Figure 4c).

The Penobscot estuary experienced spring tides when the 01 December windstorm passed, resulting in a 3.2 m tidal range at the mouth (South Thomaston, Figure 4d) and 4 m at the head in Bangor (Figure 4d). During the storm, high tides in both Bangor and South Thomaston were notably larger than preceding and succeeding high tides (day 1.5 of December, Figure 4d) indicative of a surge event. After the storm passed, tidal ranges in Bangor decreased while the total water levels increased relative to South Thomaston, coinciding with increases in river discharge (days 2 through 5 of December, Figure 4d).

ANALYSIS

This study aims to decompose the relative influences of atmospheric forcing variables (wind, barometric pressure, and externally generated surge) on observed water levels and tide-surge-river interaction in Bangor during the 01 December 2020 storm event. First, storm surges at each station are calculated and decomposed, then the more complicated surge signal in Bangor is analyzed in greater detail.

Water level decomposition

Water levels at each station were analyzed in a 2-month period starting 24 October 2020 and ending 23 December 2020. The citizen scientist data in Searsport and South Thomaston were collected in monthly segments, which were concatenated and interpolated onto a uniform, continuous time grid spanning the two-month duration. The sensor-collected water levels were pressure-corrected using barometric pressure at the Castine meteorological station, which is assumed to be representative of conditions over each location. They were then demeaned, and spikes removed to provide smooth data in reference to a mean sea level (0 m elevation).

Predicted water levels (*PWL*) were determined at Searsport and Castine using the *T_Tide* MATLAB toolbox (Pawlowicz *et al.* 2002), a harmonic analysis tool which can be utilized to predict oceanic tides by taking demeaned observed total water levels (*TWL*) as input. *T_Tide* is functionally simple and calculates the amplitude and phases of all tidal constituents present in the *TWL* signal without additional input. The *T_Tide* calculated tidal information is then used to create a *PWL* that represents the collective influence of the constituents. Any portion of *TWL* that is not resolved by *PWL* is therefore considered a nontidal variation to water level. At Bangor, where fluvial influences can have a noted effect on water levels (Figure 4d), the *NS_Tide* toolbox (Matte *et al.* 2013) was used to determine *PWL*. *NS_Tide* is a tidal harmonic analysis program which can be applied to nonstationary signals, i.e. river tides, by taking river discharge as input to the program in addition to *TWL* and the oceanic tidal range. *NS_Tide* has been found to reproduce riverine tidal water levels far better than traditional harmonic analysis (Guo *et al.* 2015; Matte *et al.* 2013; Matte *et al.* 2014; Pan *et al.* 2018), making it the appropriate choice for the fluvial Penobscot. By applying *NS_Tide* to Bangor water levels, we improve upon the analysis of SP19 which did not account for river influence in *PWL*.

Total storm surge (*TS*) at each station was calculated by subtracting *PWL* from *TWL*. *TS* represents set-up in water level relative to *PWL* and can be further decomposed into tidal and nontidal components. The nontidal surge, called low-frequency surge (*LFS*), is determined by using a Fourier low-pass filter with a 30-hour cutoff period (Walters and Heston 1982) on *TS*, therefore removing any tidal signal at the diurnal frequency or higher. *LFS* is physically the demeaned, nontidal water level and includes the classic wind and pressure-driven storm surge which propagates into the estuary. The component to *TS* that oscillates at tidal frequencies is tide-surge-river interaction (*I*) and is calculated by subtracting *LFS* from *TS*. Tide-surge-river interaction physically represents how either the tide changes an externally generated, propagating storm surge or how excess water levels due to storm surge modify the tides. Further, *I* can also represent nonlinear interactions between river discharge, tides, and surge (SP19).

Tide-surge-river interaction decomposition

Recent improvements to *NS_Tide* allow for other atmospheric forcing conditions to be considered in calculating *PWL* (Pan *et al.* 2018). Local winds, local barometric pressure, and/or coastal sea level setup (external atmospheric forcing) can be taken as input to *NS_Tide* which then determines correlations between observed water levels and each forcing variable with regression models, essentially fitting *PWL* to *TWL* based on those correlations. Basically a multiple linear regression is utilized, with the additional inputs beyond *TWL* being the additional predictors within the regression that improve *PWL*. During the 01 December windstorm, data were available to test the importance of barometric pressure, winds, and coastal sea levels on the fluvial water levels in Bangor. Wind and barometric pressure were taken at the Bangor and Castine weather station, respectively, while coastal sea level setup was taken as the low-frequency surge at South Thomaston. By testing different combinations of internal (atmospheric influence measured in the estuary) and external (product of atmospheric influence outside the estuary) forcing variables, it becomes possible to partly resolve some of the previously unknown contributions to tide-surge-river interaction by comparing each reconstructed *PWL* to cases without atmospheric forcing input.

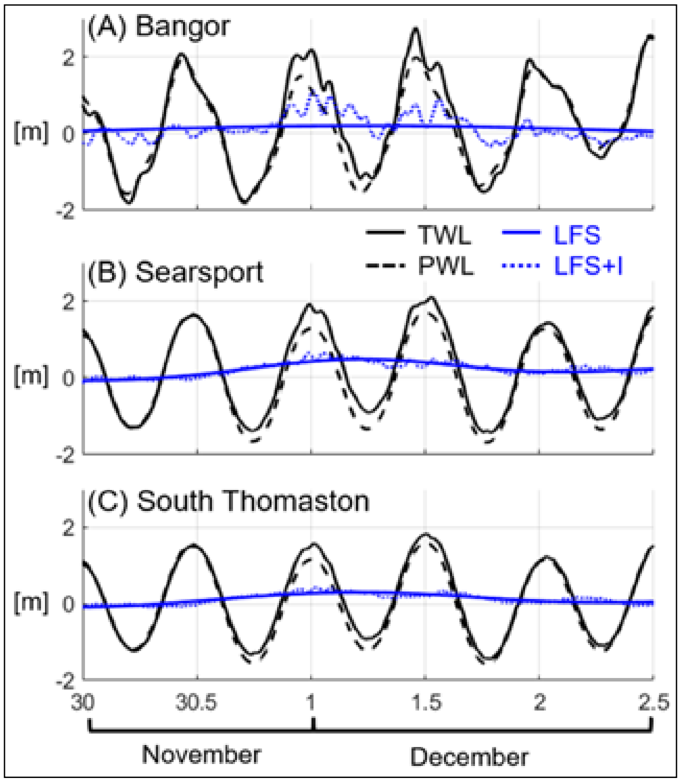

Figure 5. Observed total water levels (*TWL*, solid black), predicted water levels (*PWL*, dashed black), low-frequency surge (*LFS*, solid blue), and total surge (*LFS+I*, dotted blue) in Bangor (A), Searsport (B), and South Thomaston (C), during the 01 December 2020 windstorm. *Y*-axis is elevation in reference to mean sea level and the *x*-axis is the date of November or December 2020.

NS_Tide pre-processing notes

A number of pre-processing steps were taken prior to applying the various data sets to *NS_Tide*. River discharge taken in West Enfield was smoothed using a nine-hour moving average to remove high frequency oscillations. Ocean tidal ranges were computed from *TWL* at South Thomaston, using a "range-filter" which applies a high-pass filter followed by a diurnal minimum-maximum filter (Kukulka and Jay 2003; Matte *et al.* 2014). The step-like signal was then smoothed over 27 hours to attenuate sharp variations. Coastal sea-level setup was obtained by low pass filtering *TWL* at South Thomaston using Godin's filter (Godin 1972) to remove tides, consisting of consecutive moving averages of 24, 25, and 25 hours (see Walters and Heston 1982 for more information on "tidal eliminator" filters). Winds at Bangor were smoothed using a 24-hour moving average and barometric pressure at Castine was demeaned and smoothed using a six-hour moving average. All data was interpolated onto a common six-minute time grid. The discharge and coastal tidal range time series were lagged by 10.2 h and -3.5 h, respectively, to account for differences in location and timing relative to Bangor. Twenty-two tidal harmonics were used to predict Bangor water levels, with four extra high frequency (>4 cpd) tides applied to better resolve higher frequency oscillations.

The use of different moving average windows are used because each original time series (discharge, coastal sea level, wind, atmospheric pressure) is sampled at different frequencies (see Table 1) and present high-frequency variabilities associated to the measured phenomenon or to the noise level that differ from one another. In order to prevent contamination by spurious signals in both the stage and tidal-fluvial models of *NS_Tide* (see Matte *et al.* 2013), each time series was low-pass filtered using a smoothing window defined so as to keep as much variability as possible while removing high-frequency noise. It should also be noted that different filtering windows were tested for each series, with minimal impact on the results (not shown) as long as the high-frequency oscillations were effectively removed. In contrast, using the data in its original (non-filtered) form generated spurious oscillations in the analyzed water levels and time-varying tidal properties.

RESULTS

Storm surge in the Penobscot estuary on 01 December 2020

Storm surge from the 01 December windstorm began influencing the Penobscot estuary on 30 November and ended on 02 December 2020 (Nov. 30.5 through Dec. 2 in Figure 5). *LFS* amplified moving from the mouth at South Thomaston (0.3 m on Dec. 1.25, Figure 5c) to near the head of the bay at Searsport (0.5 m, Figure 5b). In the fluvial section of the Penobscot estuary, *LFS* then decreased with a maximum of only 0.2 m occurring in Bangor (Figure 5a).

Alternatively, *TS* (or *LFS+I*) was notably larger in Bangor relative to the bay, indicating enhanced tide-surge-river interactions there. At the bay locations (S. Thomaston and Searsport), *TS* peaked prior to *LFS* roughly at high water (Dec. 1, Figure 5) and was slightly larger than peak *LFS* (0.42 m in South Thomaston and 0.65 m in Searsport, Figure 5b, c). The roughly 0.15 m difference between *LFS* and *TS* in the bay indicates *I* is relatively unimportant there. In the river section, *TS* diverges more significantly from *LFS* and peaks twice around the high waters surrounding maximum *LFS* (1 m and 0.9 m on Dec. 1 and 1.6, respectively, Figure 5a). Further, higher frequency oscillations (>4 cpd) are evident in the *TS* signal during the surge event (Figure 5a), similar to observations from past tide-surge-river interaction events (SP19). Collectively, these observations of *TS* being nearly four times larger than *LFS*, multiple peaks in *TS*, and higher frequency oscillations to surge in Bangor during the December 01 windstorm indicate another significant tide-surge-river interaction event took place, increasing water levels enough to possibly flood low-lying infrastructure.

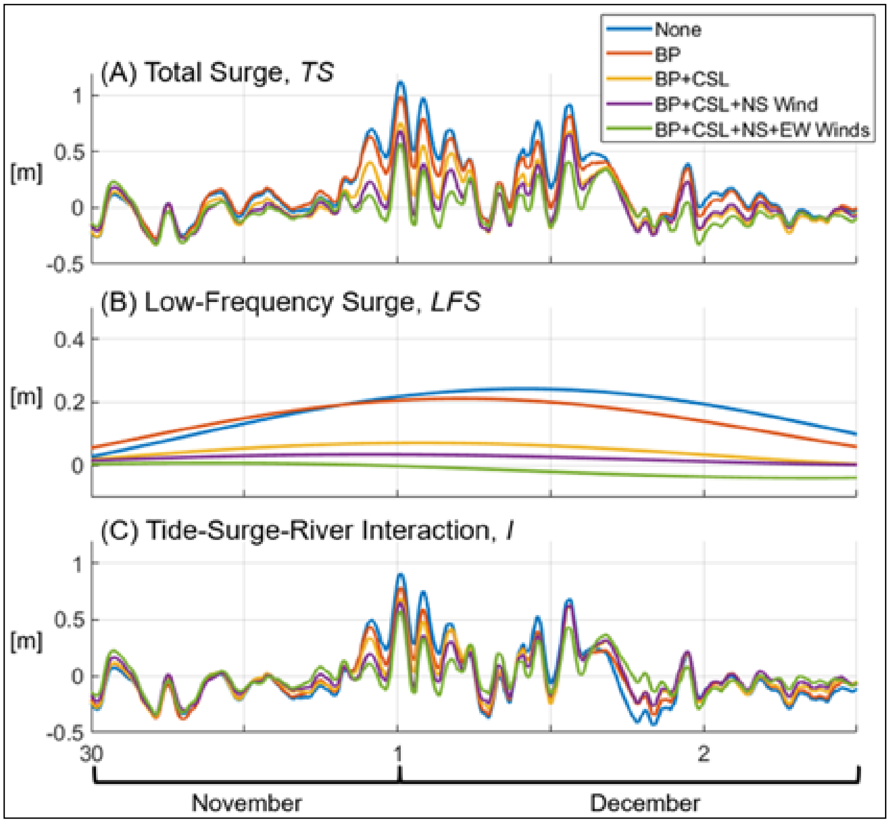

Figure 6. Total surge (A), low-frequency surge (B), and tide-surge-river interaction (C) in Bangor, calculated by fitting different external forcings. No external influence (blue), only barometric pressure (BP, red), BP & mean coastal sea level (BP + CSL, gold), BP & CSL & north-south winds (BP+CSL+NS wind, purple), and BP & CSL & NS & east-west winds (BP+CSL+NS+EW wind, green). *Y*-axis is elevation in reference to mean sea level and the *x*-axis is the date of November or December 2020.

Tide-surge-river interactions in Bangor

To better grasp the mechanisms contributing to the observed low frequency surge and higher frequency tide-surge-river interactions, *TS*, *LFS,* and *I* were quantified in Bangor for five different atmospheric forcing tests with *NS_Tide*: no atmospheric forcing, barometric pressure only (BP), adding coastal sea level set-up from low frequency surge (BP+CSL), adding the north-south component of wind (BP+CSL+NS Wind), and adding the east-west component of wind (BP+CSL+NS+EW Winds) (Figure 6). In Figure 6, the difference between the "none" (observed) signal and those calculated with external forcing quantifies the contribution of each mechanism (or combination of mechanisms) to the observed signal, while the difference between each line and zero is the remaining, unexplained residual. All the atmospheric forcing variables tested at least partly resolve some of the observed water levels in Bangor, evident by decreases in *TS* with the addition of each term (Figure 6a). CSL is the most strongly correlated to Bangor water levels relative to other terms, as peak *TS* decreased by roughly 0.2 m with the addition of CSL relative to more negligible decreases (<0.05 m) for other terms (Figure 6a). Ultimately, when all atmospheric forcing variables are included, *TS* still peaks at roughly 0.5 m, indicating nearly half the total surge observed during the 01 December storm is from forcing that is not directly related to atmospheric or river conditions or is not fully captured by the model when using atmospheric or river forcing.

When *TS* is split into tidal and non-tidal components, it is clear that the atmospheric forcing tested here mainly influences water levels in Bangor through *LFS*. *LFS* decreases notably (0.2-0.25 m) with the addition of each external forcing to be nearly equal to mean sea level (elevation of 0 m) for the final combined case (BP+CSL+NS+EW Winds, Figure 6b). Although noteworthy, this result is unsurprising as *LFS* is theoretically the combined effects of atmospheric forcing. By fitting the influence of *LFS* at the immediate coast (externally generated atmospheric surge) with local, internal atmospheric forcing into the fluvial water level calculation, we would expect the low-frequency surge in Bangor to nearly disappear, as is the case here. As a check, this shows reliability in the *NS_Tide* calculations of *PWL*.

The more marked result outlined in Figure 6 is the relatively significant *I* magnitude which still exists after linearly adding all atmospheric forcing. Maximum *I* values decrease by up to 0.4 m with the addition of the external forcing terms, but still end with a maximum near 0.5 m for the final combined case (BP+CSL+NS+EW Winds, Dec. 1, Figure 6b) which indicates nearly all *TS* for that case is from *I*. Perhaps more importantly, *I* still retains higher frequency oscillations after all the external forcing terms are considered (Figure 6b), which implies excess energy exists which is not resolved by the *NS_Tide* analysis, and it seems to exist in tidal frequencies greater than 4 cpd. These results verify that the nonlinear frictional mechanism outlined in SP19 likely accounts for the majority of tidally influenced storm surge during the December windstorm.

Frictional mechanism

Tides can be considered a superposition of different amplitude waves oscillating at varying, constant frequencies (called harmonics). In Maine, the primary harmonic is the semi-diurnal (two tides per day, denoted as D_2). The amount of frictional energy that effects a propagating, semi-diurnal tidal wave is often associated with the sixth-diurnal (six tides per day, denoted as D_6) harmonic, meaning increases in the D_6 amplitude imply increases in current velocities and friction (Parker 1991). In the Penobscot estuary, high frequency tide-surge-river interactions can be created from enhanced frictional energy from storm-induced currents which manifests in the D_6 harmonic band of *I*. Further, the D_8 harmonic, which generally scales with the D_6, has been shown to also amplify during storm events in the Penobscot because it resonates in the fluvial portion of the estuary (SP19). The oscillatory behavior of (normalized) *I* during the 01 December windstorm was quantified with a wavelet analysis to prove those frequency bands were present (Figure 7). Wavelets identify significant frequencies in a given time series and how the amplitudes at those frequencies change with time, and so are a useful tool to diagnose how *I* is formed. Results indicate significant frequencies in the 0.5- to 1-day period band (D_2 to D_1) and 0.125- to 0.25-day band (D_8 to D_4) (Figure 7b). The significant higher frequency band (8 to 4 cpd) which includes the D_6 and D_8 indicates that the frictional mechanism is in fact contributing to *I* during the 01 December windstorm. The energy evident in the semi-diurnal to diurnal band is typical of tide-surge interaction events (Feng *et al.* 2016), and so will not be elaborated on here.

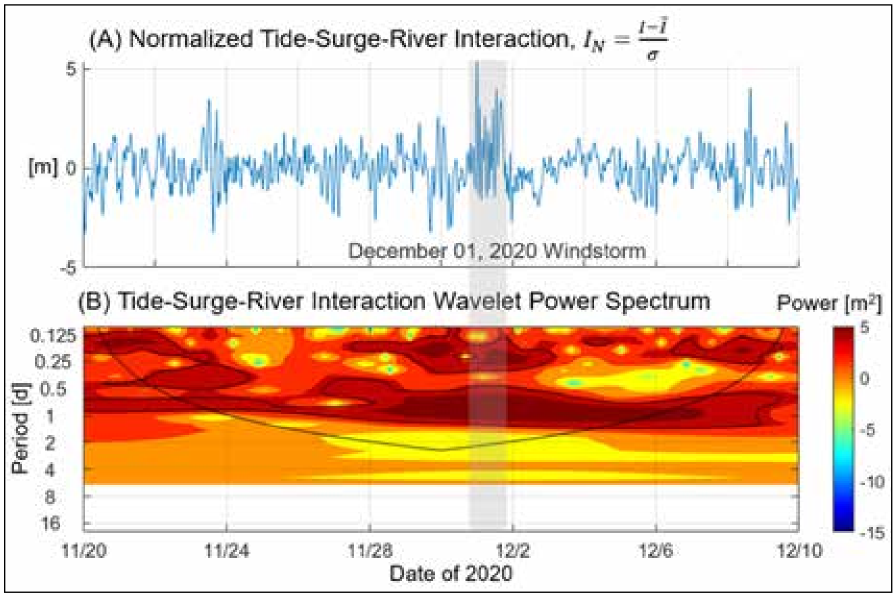

Figure 7. Normalized tide-surge-river interaction term, I_N, for 20 days around the 01 December windstorm (A) and corresponding wavelet power spectrum (B) from the BP+CSL+NS+EW winds case. *Y*-axis of panel B is the signal period in days. The December 01, 2020 windstorm is identified in the record with gray shading. σ represents the standard deviation of *I*. Solid black lines in panel B denote statistically significant frequencies.

DISCUSSION

The results partly reinforce SP19: tide-surge-river interaction is mainly a result of highly nonlinear interactions between tides, surge, and river discharge created by increased friction from storm-induced currents. Additionally, these results indicate tide-surge-river interaction is not strongly connected to any one of the atmospheric forcing variables tested here. Although low frequency surge can be resolved quite completely via the atmospheric variables, excess tide-surge-river interaction still exists. To put it simply, some tide-surge-river interaction is associated with atmospheric forcing and therefore low frequency surge, while some is not. The tide-surge-river interaction which is resolved with the addition of atmospheric forcing (Figure 6), is likely a result of the atmospherically generated low frequency surge modifying mean water levels that would have a corresponding modification to the tides. For example, with an increase in mean water level, tidal ranges and velocities can increase from less friction slowing the primary semi-diurnal tidal wave. Ironically, this would then present itself in tide-surge-river interaction as an increase in the frictional D_6 amplitude, as it directly scales with currents in the estuary, and therefore would be resolved by this analysis. The excess, non-resolved tide-surge-river interaction, must therefore be due to further increases in current magnitudes from nontidal influences, which in this case can only be wind. The predicated water level calculated in this paper can only account for variations to water level from mechanisms which directly influence water level (wind, barometric pressure, river discharge, surge) and the corresponding effect of those modified water levels on the tidal wave. Water level modifications through indirect mechanisms (wind-induced currents increasing friction) cannot be captured in predicted water levels without further modification of *NS_Tide*.

Lastly, it is also important to note that a portion of the excess tide-surge-river interaction described above could be a result of other errors in the *NS_Tide* model itself. For example, total surge is the residual water level after *NS_Tide* analysis and thus can contain unresolved, non-stationary tides, unresolved physical processes not represented by the model (other tide-surge-river interactions, resonance, etc.), and background noise (including instrumentation or pre-processing errors, like pressure corrections). Further model refinement in the future will allow a better understanding of those errors, though they are assumed to be quite small relative to the processes described in this paper.

CONCLUSIONS

The results of this study show the 01 December 2020 windstorm created significant tide-surge-river interaction in the fluvial Penobscot River estuary which was more than double the observed low frequency surge created by local and external atmospheric forcing (Figure 6). The tide-surge-river interaction was primarily caused by increased mean flow and frictional energy from the combined storm forcing enhancing tidal harmonics between the D_4 and D_8 frequency bands (Figure 7). Collectively, total water levels at the river location (Bangor) were roughly 1 m higher than predictions and 0.5 m higher than locations in the non-fluvial Penobscot Bay. Application of the river tide prediction program, *NS_Tide*, allowed for a more accurate analysis of water levels at Bangor relative to past analyses there (SP19), and was utilized to identify the role of atmospheric forcing on the Bangor water levels. Ultimately, internal, and external atmospheric forcing were determined to contribute primarily to low-frequency surge. The highly nonlinear, oscillatory nature of tide-surge-river interaction was not completely resolved by *NS_Tide*, likely because energy input into mean currents from wind, which indirectly modifies water levels through friction, is not considered.

The observations presented in this study, and in past work, are important to understand in order to create resilient, appropriately planned infrastructure along the Penobscot estuary in the future. Although flooding did not occur in Bangor during the December 2020 storm, it is very likely that nuisance flooding of low-lying infrastructure would occur for a larger spring tide or larger storm event with similar atmospheric conditions. Further, tide-surge-river interaction events could transition from nuisance scale flooding (as they generally are now) to more widespread, disruptive events as sea levels rise in the future. Thus, producing accurate predictions of surge will continue to be critical for this region. Further, although these observations encompass just one system in Maine, the findings should be broadly applicable to any fluvial estuary exposed to storm surges.

ACKNOWLEDGEMENTS

Funding for this project was provided by National Science Foundation Awards IIA-1644691 and IIA-1355457. The authors would also like to thank the citizen scientists who have made this work possible, and two anonymous reviewers who helped improve the original manuscript.

REFERENCES

Birthisel, S.K., Eastman, B.A., Soucy, A.R., Paul, M., Clements, R.S., White, A., Acquafredda, M.P., Errickson, W., Zhu, L.H., Allen, M.C., Mills, S.A., Dimmig, G., and K.M. Dittmer, 2020. "Convergence, continuity, and community: a framework for enabling emerging leaders to build climate solutions in agriculture, forestry, and aquaculture." *Climatic Change* 162(4), 2181-95. https://doi.org/10.1007/s10584-020-02844-w.

Blake, E.S., Landsea, C.W., and E.J. Gibney, 2011. *The Deadliest, Costliest, and Most Intense United States Tropical Cyclones from 1851 to 2010*, NOAA Technical Memorandum.

Bricknell, I.R., Birkel, S.D., Brawley, S.H., Van Kirk, T., Hamlin, H., Capistrant-Fossa, K., Huguenard, K., Van Walsum, G.P., Liu, Z.L., Zhu, L.H., Grebe, G., Taccardi, E., Miller, M., Preziosi, B.M., Duffy, K., Byron, C.J., Quigley, C.TC., Bowden, T.J., Brady, D., Beal, B.F., Sappati, P.K., Johnson, T.R., and S. Moeykens, 2020. "Resilience of cold water aquaculture: a review of likely scenarios as climate changes in the Gulf of Maine." *Reviews in Aquaculture* 13(1), 460-503. https://doi.org/10.1111/raq.12483.

Colgan, C., 2004. *The Contribution of Working Waterfronts to the Maine Economy.* https://www.maine.gov/dmr/mcp/downloads/workingwaterfront/workingwaterfronteconomy_feb04.pdf.

Condon, A.J., and Y.P. Sheng, 2012. "Evaluation of coastal inundation hazard for present and future climates." *Natural Hazards* 62, 345–73. https://doi.org/10.1007/s11069-011-9996-0.

Drews, C., and T.J. Galarneau, 2015. "Directional analysis of the storm surge from Hurricane Sandy 2012, with applications to Charleston, New Orleans, and the Philippines." *PLoS ONE* 10(3). https://doi.org/10.1371/journal.pone.0122113.

Dudley, R., 2004. *Estimating Monthly, Annual, and Low 7-Day, 10-Year Streamflows for Ungauged Rivers in Maine*, U.S. Geological Survey Scientific Investigations Report, 22p.

Feng, X., Olabarrieta, M., and A. Valle-Levinson. 2016, "Storm-induced semidiurnal perturbations to surges on the U.S. Eastern Seaboard." *Continental Shelf Research* 114, 54-71. https://doi.org/10.1016/j.csr.2015.12.006.

Geyer, W., and D.K. Ralston, 2018. "A mobile pool of contaminated sediment in the Penobscot Estuary, Maine, USA." *Science of the Total Environment* 612, 694-707. https://doi.org/10.1016/j.scitotenv.2017.07.195.

Godin, G. 1972. *The Analysis of Tides*. University of Toronto Press.

Guo, L., Van Der Wegen, M., Jay, D.A., Matte, P., Wang, Z.B., Roelvink, D., and Q. He, 2015. "River-tide dynamics: exploration of nonstationary and nonlinear tidal behavior in the Yangtze River estuary." *J. Geophysical Research: Oceans* 120(5), 3499-3521. https://doi.org/10.1002/2014JC010491.

Hodgkins, G., 1999. *Estimating the Magnitude of Peak Flows for Streams in Maine for Selected Recurrence Intervals*, U.S. Geological Survey Water-Resources Investigations Report, 45p.

Horsburgh, K.J., and C. Wilson, 2007. "Tide-surge interaction and its role in the distribution of surge residuals in the North Sea." *J. Geophysical Research: Oceans* 112(C8). https://doi.org/10.1029/2006JC004033.

Jongman, B., Ward, P.J., and J.C.J.H. Aerts, 2012. "Global exposure to river and coastal flooding: long term trends and changes." *Global Environmental Change* 22(4), 823-35. https://doi.org/10.1016/j.gloenvcha.2012.07.004.

Knabb, R.D., Rhome, J.R., and D.P. Brown, 2006. *Tropical Cyclone Report: Hurricane Katrina, August 23-30, 2005*. National Hurricane Center Report.

Kukulka, T., and D.A. Jay, 2003. "Impacts of Columbia River discharge on salmonid habitat: 1. a nonstationary fluvial tide model." *J. Geophysical Research: Oceans* 108(C9). https://doi.org/10.1029/2002jc001382.

Matte, P., Jay, D.A., and E.D. Zaron. 2013. "Adaptation of classical tidal harmonic analysis to nonstationary tides, with application to river tides." *J. Atmospheric and Oceanic Technology* 30(3), 569-89. https://doi.org/10.1175/JTECH-D-12-00016.1.

Matte, P., Secretan, Y., and J. Morin. 2014. "Temporal and spatial variability of tidal-fluvial dynamics in the St. Lawrence fluvial estuary: an application of nonstationary tidal harmonic analysis." *J. Geophysical Research C: Oceans* 119(9), 5724-44. https://doi.org/10.1002/2014JC009791.

Morrill, R.A., Chin, E.H., and W.S. Richardson, 1979. *Maine Coastal Storm and Flood of February 2, 1976.* U.S. Geological Survey Professional Paper.

National Oceanographic and Atmospheric Administration (NOAA), 2020. Bathymetric Data Viewer, https://maps.ngdc.noaa.gov/viewers/bathymetry/ (Accessed 20 January 2021).

National Weather Service (NWS), 2020. Weather Prediction Center, https://www.wpc.ncep.noaa.gov/archives/web_pages/sfc/sfc_archive.php (Accessed 20 January 2021).

Pan, H., Lv, X., Wang, Y., Matte, P., Chen, H., and G. Jin, 2018. "Exploration of tidal-fluvial interaction in the Columbia River estuary using S_TIDE." *J. Geophysical Research: Oceans* 123(9), 6598-6619. https://doi.org/10.1029/2018JC014146.

Parker, B.B., 1991. "The relative importance of the various nonlinear mechanisms in a wide range of tidal interactions (review)." In *Tidal hydrodynamics*, ed. Parker, B.B., 79-108. New York, New York: John Wiley and Sons.

Pawlowicz, R., Beardsley, B., and S. Lentz, 2002. "Classical tidal harmonic analysis including error estimates in MATLAB using TDE." *Computers and Geosciences* 28(8), 929-37. https://doi.org/10.1016/S0098-3004(02)00013-4.

Perrie, W., Toulany, B., Roland, A., Dutour-Sikiric, M., Chen, C., Beardsley, R.C., Qi, J., Hu, Y., Casey, M.P., and H. Shen, 2018. "Modeling North Atlantic nor'easters with modern wave forecast models." *J. Geophysical Research: Oceans* 123(1), 533-57. https://doi.org/10.1002/2017JC012868.

Rossiter, J.R., 1961. "Interaction between tide and surge in the Thames." *Geophysical Journal International* 6(1), 29-53. https://doi.org/10.1111/j.1365-246X.1961.tb02960.x.

Spicer, P., Huguenard, K, Ross, L., and L.N. Rickard. 2019. "High-frequency tide-surge-river interaction in estuaries: causes and implications for coastal flooding." *J. Geophysical Research: Oceans* 124(12), 9517-30. https://doi.org/10.1029/2019JC015466.

Spicer, P., Schlichting, D., Huguenard, K., Roche, A., and L.N. Rickard, 2020. "Sensing storm surge: methods for establishing a citizen science storm surge monitoring network." *Ocean and Coastal Management*, (submitted).

Thomas, A., Dietrich, J.C., Asher, T.G., Bell, M., Blanton, B.O., Copeland, J.H., Cox, A.T., Dawson, C.N., Fleming, J.G., and R.A. Luettich, 2019. "Influence of storm timing and forward speed on tides and storm surge during Hurricane Matthew." *Ocean Modelling* 137, 1-19. https://doi.org/10.1016/j.ocemod.2019.03.004.

United States Geological Survey (USGS), 2021. SGS 01037050 Penobscot River at Bangor, Maine. https://waterdata.usgs.gov/nwis/uv?site_no=01037050 (Accessed 20 January 2021).

Walters, R.A., and C. Heston, 1982. "Removing tidal-period variations from time-series data using low-pass digital filters." *J. Physical Oceanography* 12(1), 112-15.

Wolf, J. 1978. "Interaction of tide and surge in a semi-infinite uniform channel, with application to surge propagation down the East Coast of Britain." *Applied Mathematical Modelling* 2(4), 245-53.