Bank Erosion by Wind-Generated Waves II: Application of a Wind-Wave Sub-Model in BSTEM-Dynamic

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Abstract

In response to the need to provide reliable analysis of the causes of bank-retreat and effective mitigation strategies in wide, impounded rivers and embayments, both a wind-prediction algorithm (WPA) and a wind-wave erosion module were developed and added to the BSTEM-Dynamic code (v. 2.4). The enhanced model was applied to two studies where at least one of the objectives was to evaluate the relative roles of various bank-erosion processes on rates of erosion and bank retreat: a 29-km reach of the Tennessee River between Pickwick Dam and Savannah, TN and a 1-km reach of the Fox River at De Pere, WI, in backwater from Lake Michigan. BSTEM-Dynamic was calibrated at 21 sites along the Tennessee River over the 1985 to 2016 period using the retreat measured from the aerial imagery. One cross-section was used for calibration on the Fox River for the period of 1990 to 2020.

At least two runs were conducted initially at each site, with and without waves, to determine the role of wind-generated waves on erosion. Results from the two studies provided very different outcomes. In the reach of the Fox River which can be characterized as a "drowned channel" with a beach-like bank toe and low bank heights, wind-generated waves accounted for 77% to ~100% of the modeled bank erosion. Water-surface elevations (wse) vary only within a ~2-m range, thereby concentrating wave action at the base of the bank face above the beach. In contrast, on the study reach of the Tennessee River where wse varied over a much larger, 13 m range, wind-generated waves accounted for <1% of the bank erosion at the vast majority of sites, notwithstanding longitudinal zones of turbid water that were observed along bank toes on windy days. It is hypothesized that because of fluctuating water levels and the relatively resistant nature of the surficial bank materials, the cumulative impacts of waves were minimized. Average-annual rates of bank erosion were ~5.2 $m^3/m/yr$ and were largely attributed to high flows in this incised channel.

The BSTEM-Dynamic model that includes the wind-wave sub-model has proven effective in evaluating the roles of a range of processes that impact streambanks. Application to real-world issues has also shown its utility in determining effectiveness of mitigation alternatives.

Background and Objectives

The USDA-ARS Bank-Stability and Toe-Erosion model (BSTEM) has become a widely used tool since its initial development over 20 years ago (Simon et al 2000; 2011). A somewhat simplified version of the Static model (v. 5.4) has been incorporated into HEC-RAS. The Dynamic version, which handles a varying-flow series has been continually developed and enhanced to include new features such as variable roughness (and effective stress) by layer, choice of a variable energy slope by time-step and accounting for shear stress from boat-generated waves. Some or all of these features have been successfully deployed by the authors in recent studies in the US, Australia and New Zealand to evaluate the relative impacts on bank erosion from dam operations and releases, high flows, roughness from established vegetation and boat-generated waves.

In response to the need to provide reliable analysis of the causes of bank-retreat and effective mitigation strategies in wide, impounded rivers and embayments, both a wind-prediction algorithm (WPA) and a wind-wave erosion module were developed and added to the BSTEM-Dynamic code (v. 2.4). This work is detailed in Ozeren et al. (2023, this volume). The enhanced model was applied to two studies where at least one of the objectives was to evaluate the relative roles of various bank-erosion processes on rates of erosion and bank retreat. One of the project areas was a 29-km reach of the Tennessee River between Pickwick Dam and Savannah, TN (Figure 1, Left). The other was a 1-km reach of the Fox River at De Pere, WI that is in backwater from Lake Michigan (Figure 1, Right).

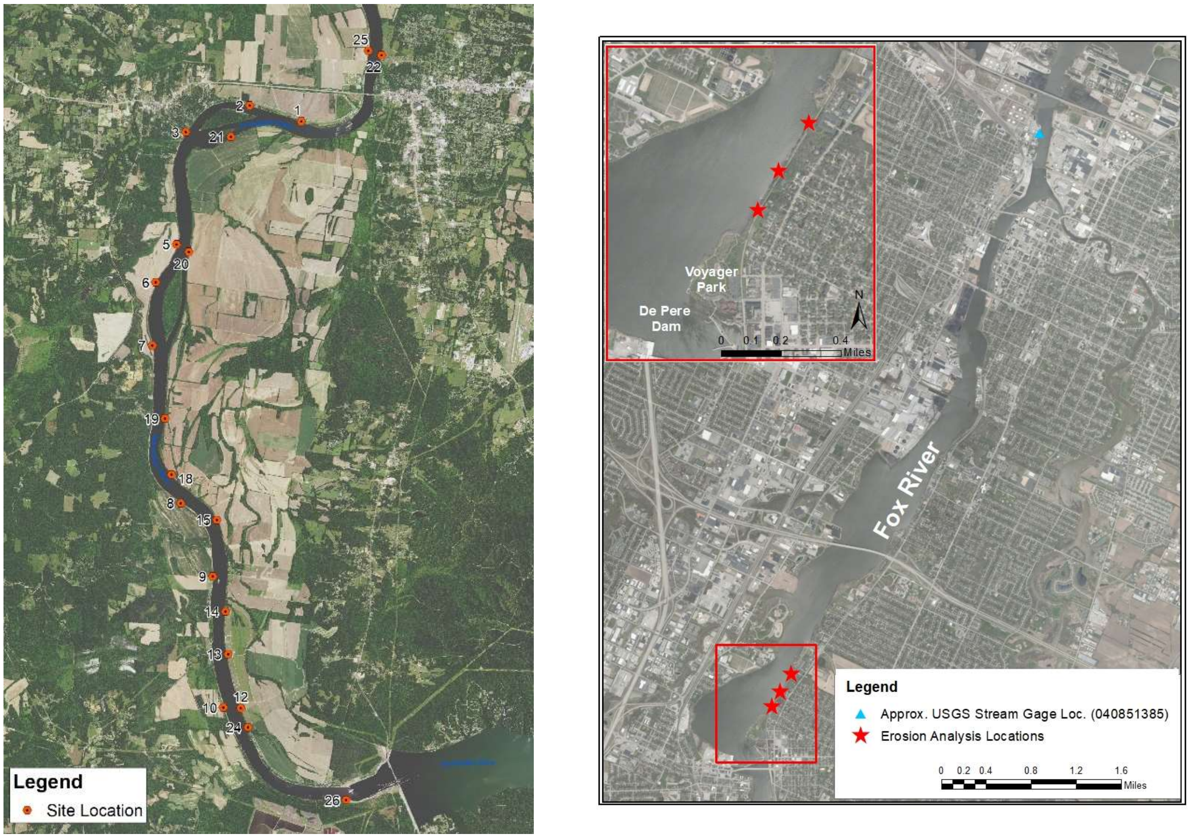

Figure 1. Study reaches and detailed-study sites for the Tennessee River, TN (Left) and the Fox, River, WI (Right)

Study Approach

Bank erosion, instability and retreat along rivers are generally the result of the hydraulic and/or geotechnical (gravitational) forces acting on the banks that exceed the resistance of the bank materials. Waves can play an important role in bank erosion under conditions where water levels do not vary greatly such as in lakes, bays or estuaries. These conditions permit wave action to be focused and have longer durations on specific sections of bank which can accentuate undercutting and subsequent upper-bank collapse. To predict erosion and, therefore, effective stabilization, it is crucial to quantify the driving and resisting forces at work. This analysis was to be done using the dynamic version of the USDA-ARS Bank-Stability and Toe-Erosion model (BSTEM-Dynamic). Supported by data on water levels, bank geometry and bank resistance, it was deemed the most effective tool to determine rates of bank erosion and retreat, and differentiate the role of various controlling processes on erosion rates.

Bank Resistance

A number of sites were selected along each of the study reaches where *in situ* measurements were conducted to quantify bank resistance, 21 along the Tennessee River and three along the Fox River. For hydraulic resistance, critical shear stress and erodibility coefficients were measured with a submerged mini-jet test device on the bank toe and bank face. Where the bank surface could not be tested because it was covered with gravel or larger materials, a particle count was conducted to determine the median size (d_{50}) and representative resistance of the materials. Geotechnical resistance (effective cohesion and friction angle) was calculated for at least two layers from measurements made with a Borehole Shear Tester (BST). Required input data on bulk unit weight and ambient pore-water pressure were derived from samples taken at the time and location of testing with the BST.

Tennessee River: The median critical shear stress of bank face and bank toe materials was 22.1 Pa, with the interquartile range spanning 4.1 Pa to 91.5 Pa. Although the hydraulic resistance of the 83 tested materials was highly variable, at least 80% of the tests were as resistant as gravel-sized materials, thereby providing moderate resistance to the flow. Roughly 35% of the tested materials were as resistant as cobble-sized material, about 64 mm. The relative frequency of tests within each equivalent-diameter class is shown in Figure 2.

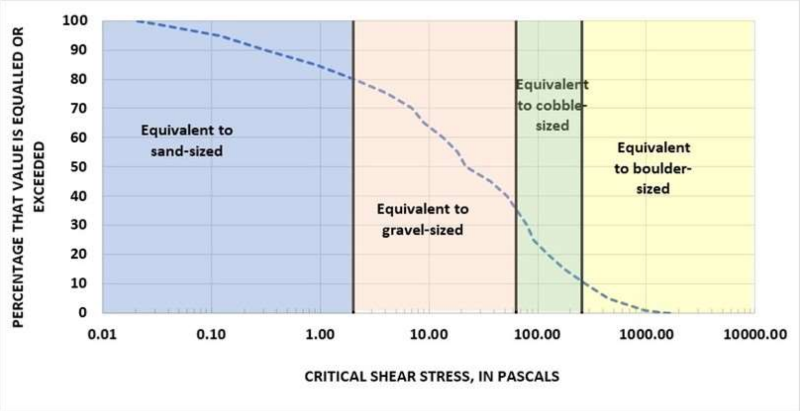

Figure 2. Critical shear stress and equivalent diameter of surficial bank materials as determined by mini-jet tests along the Tennessee River between Pickwick Dam and Savannah, TN

Internal bank-materials tested along the river ranged from cohesionless sands to moderately cohesive mixtures of silt and clay. The median value of effective cohesion for all tests (c’) was 7.7 kPa, with a range from 0.0 to ~80 kPa. As is typical, friction angles varied within a more-narrow spread with the inter-quartile range being 26.9 to 32.0°. The median value was 30.1°. These data show substantial variability in cohesive strength between sites and the benefit of testing. Distributions of effective cohesion and friction angle for the 44 tests are presented graphically in Figure 3.

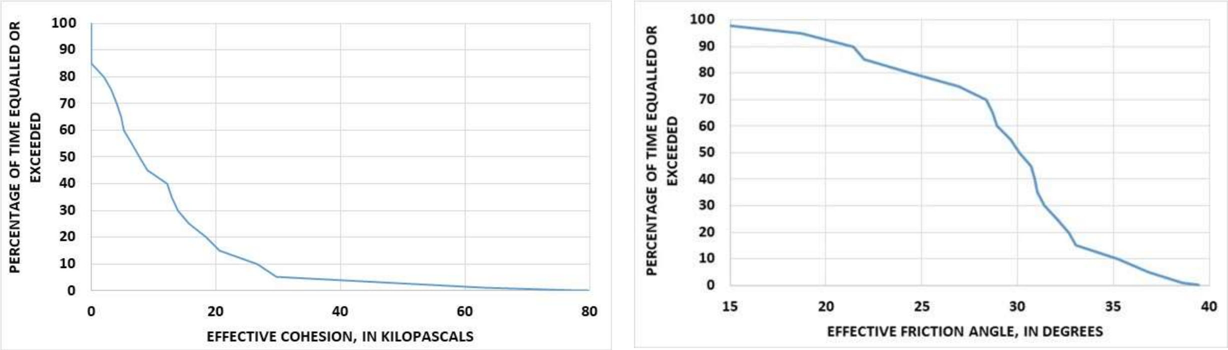

Figure 3. Borehole shear tester (BST) (Top) and mini-jet tester (Bottom) used to quantify bank resistance at sites along the Tennessee River study reach

Fox River: In all cases, erosion resistance to hydraulic forces (flow) was equivalent to sand-sized materials. Materials below elevation 175.4 m (extreme low water) were assumed to be composed of fine gravels and assigned a d_{50} of 3 mm. Particle counts were conducted along the bank face at two sites along the Fox River where d_{50} was determined to be 140 and 60 mm, respectively. “Internal” bank materials were composed predominantly of sand, silt, and clay with gravels at depth. Six BST tests were conducted within the upper meter of the profile and disclosed moderately cohesive materials with effective cohesion (*c’*) ranging from 4.6 to 21.7 kPa. Below the top 1 m were cohesionless fine gravels.

Bank Geometry, Flows and Model-Calibration Periods

BSTEM-Dynamic was calibrated at 21 sites along the Tennessee River by comparing model results to top-bank retreat measured from aerial imagery over the period 1985 to 2016. One cross-section was used for a similar calibration for the three sites on the Fox River for the period of 1990 to 2022.

Tennessee River: To inform this study, initial bank geometry was generated using a combination of sources including the 1985 HEC-RAS cross-sections, approximate “tape and Brunton” surveys conducted at the time of data collection, and 2016 LiDAR. The more recent physical bank survey was used primarily to obtain proper shaping of the bank while the other surveys were used for bed and floodplain elevations.

A historical record of hourly discharge from Pickwick Dam was provided by TVA for the 1985-2019 period. How this period compares to the long term mean-daily flow record (from 1930 at Savannah, TN) is shown in Figure 4. The 1985-2016 data formed the basis for flow inputs to a HEC-RAS hydraulic model that in turn established the time series of water-surface elevations used as inputs at all of the test sites for modeling with BSTEM-Dynamic. An example from one of the sites is shown in Figure 5. Note the large (~13 m) range of water-surface elevations for the modeling period. This is in distinct contrast to that for the Fox River which is ~ 2 m.

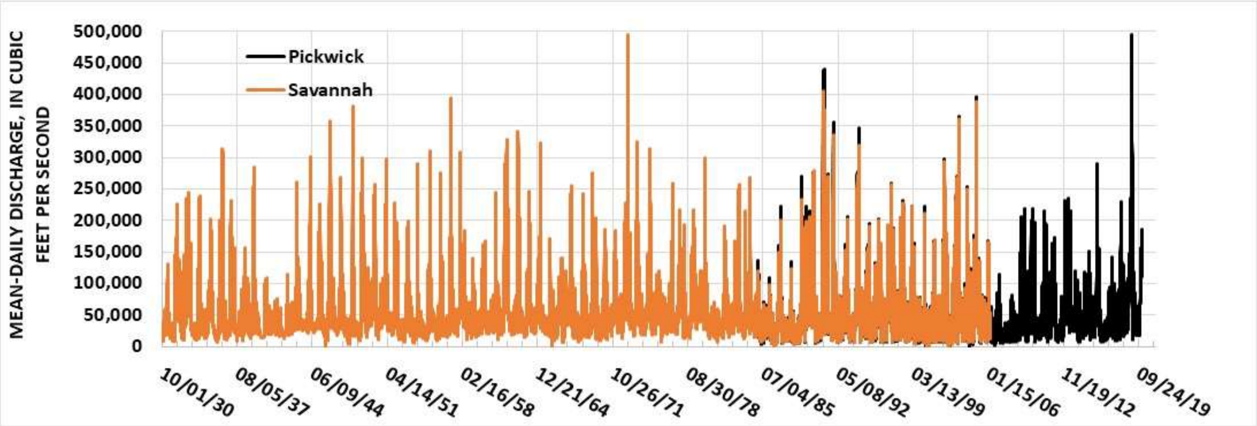

Figure 4. Mean-daily discharge for the Tennessee River at Savannah, Tennessee 1930-2006

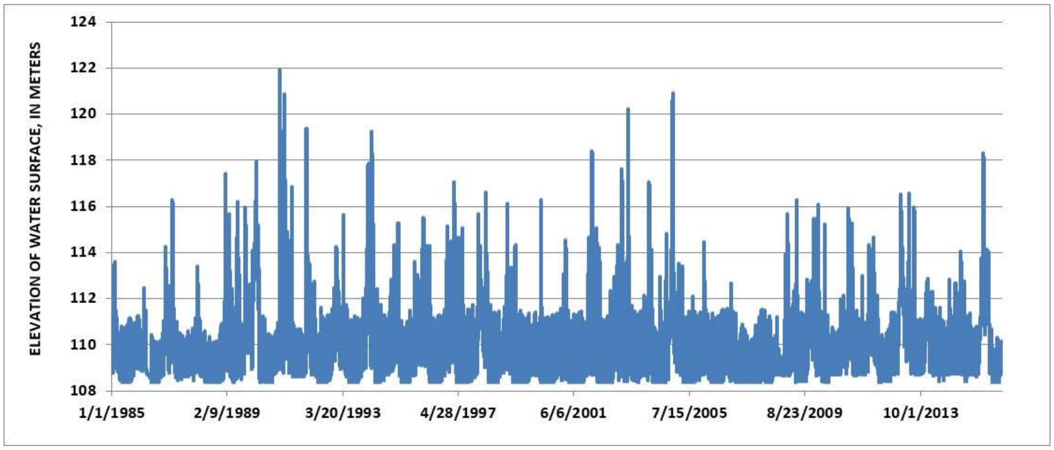

Figure 5. Example of the hourly-flow series from Site 18, Tennessee River used as input into BSTEM-Dynamic for the period January 1, 1985 to August 31, 2016

Fox River: To coincide with the period represented by the aerial imagery and current observations, a calibration period of January 1, 1990 through May 23, 2022 was selected. Water-surface elevations for the 1990-2022 modeling period are displayed in Figure 6 where several features stand out to aid in interpretation of bank processes over the period. The long-term (1918-Present) average lake level of 578.9 ft. is shown for context and provides evidence of:

1. A prolonged period of low water levels between 1999 and 2014 where flows generally did not impact the steeper sections of the bank but were confined to the flatter "beach-like" areas of the slope (Figure 6); and
2. A dramatic increase in water levels coming to a peak in 2020 and corresponding to the highest lake levels in Lake Michigan over the last 100 years. It is during this period that water levels and their associated forces were sufficient to impact the steeper section of the banks (Figures 6 and 7).

The bank section used in Figure 7 represents conditions in 1990 and was obtained from a HEC-RAS model of the reach: RS 34534.3 (FEMA, 2014).

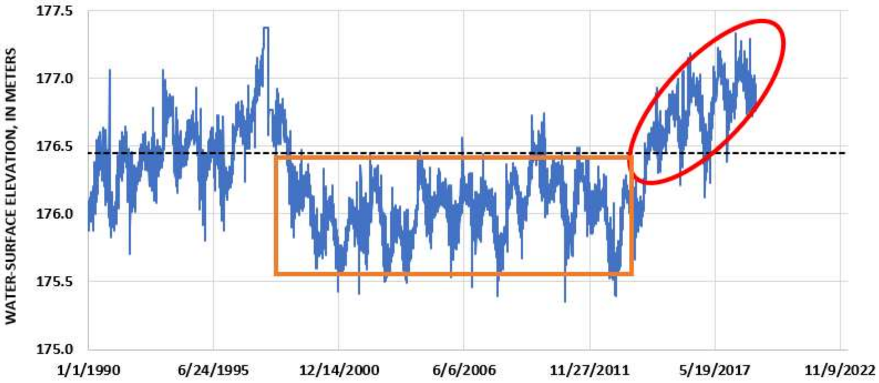

Figure 6. Water-surface elevations in the Fox River reach (1990-2022) obtained from USGS gauge 040851385. Dotted line is long-term average

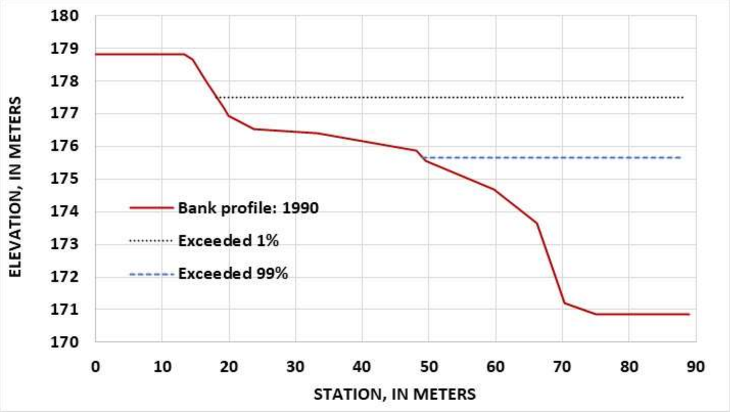

Figure 7. Typical bank section in the Fox River reach showing approximate locations where the water surface is for 99% of the time. See Figure 5 for variation in levels over the 1990 – 2022 period

Wind Waves and Data

The physical processes involved in the generation of waves by wind are complex. The net force created by the higher pressure on the windward face of the wave results in wave growth. The heights and periods of the waves depend on the speed of the wind, the duration of the wind and the fetch length.

Many wind-wave prediction models have been developed since 1950s to describe the complex behavior of wave generation, propagation and dissipation. The prediction model employed in BSTEM-Dynamic and described in Ozeren et al. (this volume) is based on the JONSWAP experiment (Hasselmann, 1973). The Shore Protection Manual (SPM) prediction model is based on the JONSWAP prediction graphs given in the 1984 version of the SPM. In these equations, an adjusted wind speed is used to account for the relation between stress and wind speed. The JONSWAP wind wave-prediction model requires wind speed and fetch length as input to estimate the significant wave height and peak wave period.

Tennessee River: Before using the JONSWAP procedure to estimate wind-generated waves for BSTEM simulations, the method was first verified with the measured data at two data collection sites. Wind data from the nearby Muscle Shoals Airport between 1985 -2019 was then used to calculate wave heights and periods for BSTEM simulations. To calculate fetch length, straight line fetch was first extracted for each site along the riverbank for every direction at 1-degree increments. This is defined as the straight-line distance from the site to the opposite shore in the direction of the wind.

Fox River: The working hypothesis here, is that wind-generated waves play an important role in bank erosion along the reach in part due to the narrow range of water-surface elevations. To account for the role of wind-generated waves, a data set of wind direction and wind speed was obtained from the NOAA weather station at Green Bay Austin Straubel International Airport. Based on the wind direction, a fetch length was then assigned for each day according to a look-up table developed for that parameter at each site (Figure 8). As can be seen, some of the greatest fetch lengths occur with winds from the N to NE and the W and SSW. The distribution of wind directions and speeds over the modeling period are also shown in Figure 8.

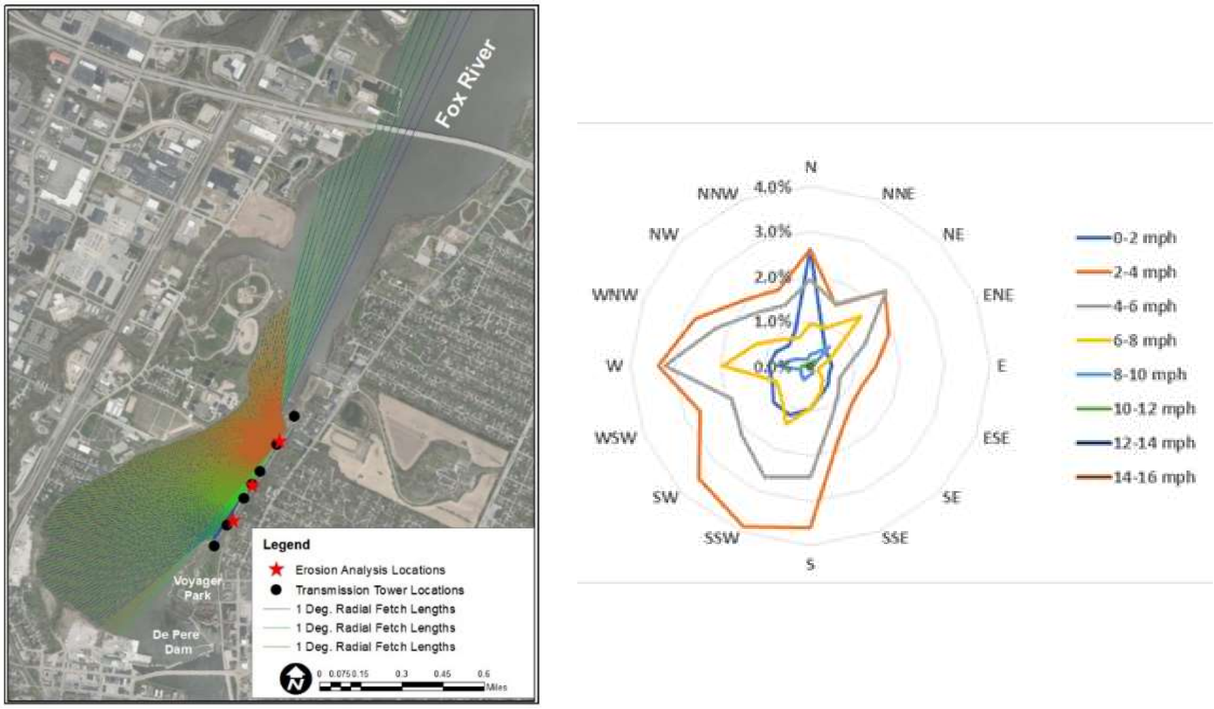

Figure 8. Schematic of how fetch lengths were calculated at the three sites for wind direction at 1-degree intervals (Left) and wind speed and direction for the modeling period (Right)

Results of Bank-Stability Modeling with BSTEM-Dynamic

Tennessee River: BSTEM-Dynamic was calibrated at all 21 detailed sites for the 1985 to 2016 period using the retreat measured from the aerial imagery as the metric to be compared with the retreat derived from the simulations (Figure 9). Hourly data of flow releases plus the wave contributions were used for a 31.7-year simulation period. The calibration results showed that the average difference between observed and modeled retreat was -0.3 m, or -2.8%. Maximum overprediction by the model was 4.3 m while the greatest under prediction was about 3.0 m. Nevertheless, these calibration results are considered very good, and indicate that BSTEM-Dynamic was suitable to simulate observed retreat and erosion.

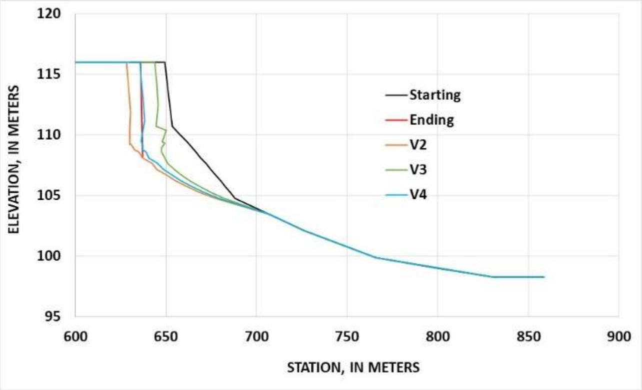

Figure 9. Example of calibration runs conducted at Site 6, Tennessee River to refine model results by adjusting values of surface roughness on the individual layers. "Ending" trace is based on retreat measured from aerial imagery over the period

Average-annual rates of bank erosion and top-bank retreat as determined by the calibrated model were ~5.2 m^3/m/yr and 0.4 m/yr, respectively. There was significant variation in erosion rates for the 21 detailed-study sites, with minimums of 0 m^3/m/yr and 0 m/year for the one modeled, rock-protected site and maximums of 14.5 m^3/m/yr and 0.85 m/yr. The median erosion rates were 3.7 m^3/m/year and 0.3 m/year, both lower than the average erosion rates, suggesting some high- erosion sites are skewing the averages higher.

To determine the impacts of both boat waves and wind waves on bank erosion, a series of wave-model scenarios were simulated at all 21 detailed-study sites using BSTEM-Dynamic. The results showed that for the vast majority of sites, neither boat or wind waves have a significant impact (<1%) on erosion along the study reach. This outcome was somewhat surprising as it was suspected that with the high boat traffic and the frequency of large boats and barges, that waves would have a significant contribution to bank erosion and failure. Apparently, however, this is not the case due to fluctuating water levels and the relatively resistant nature of the bank materials.

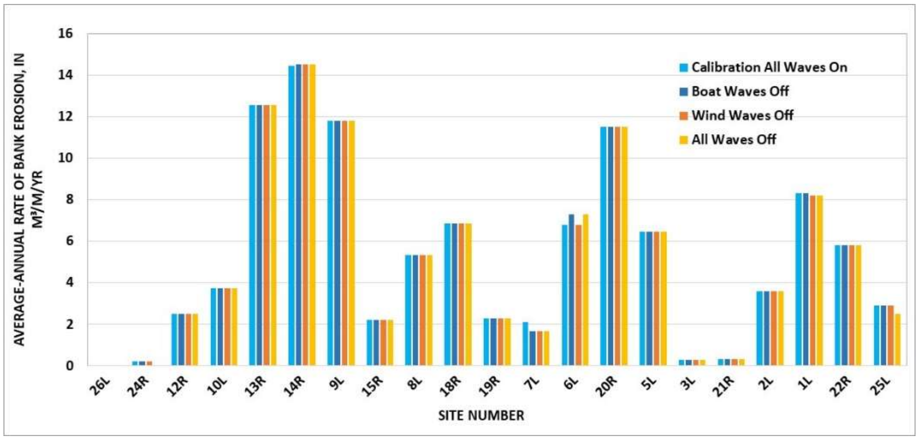

Figure 10. Results of model runs with BSTEM-Dynamic along the study reach of the Tennessee River. Note the lack of any difference between erosion rates with and without waves

Fox River: Simulations of bank erosion and top-bank retreat were conducted at the three sites for the period 1990-2022 using the water-level series shown in Figure 6 and by assuming that rock had not been placed on the bank face. Two runs for the period were conducted at each site, one without waves and the other with waves to determine the relative role of wind-generated waves on erosion (Figure 11).

Bank erosion was predicted at all sites with erosion due to wind-generated waves accounting for 77% at Site 2, 82% at Site 1 and ~100% at Site 3 (Table 1). Total-erosion volumes range from 2.2 to 21.7 m^3/m of bank. Most importantly though, top-bank retreat as defined as the landward retreat at the top-bank elevation was simulated only at Site 1. At the other two sites, erosion was confined to areas below the top-bank elevation and, therefore, no top-bank retreat was simulated (Figure 11). These results seemed surprising given the concern about the potential threat posed by bank erosion.

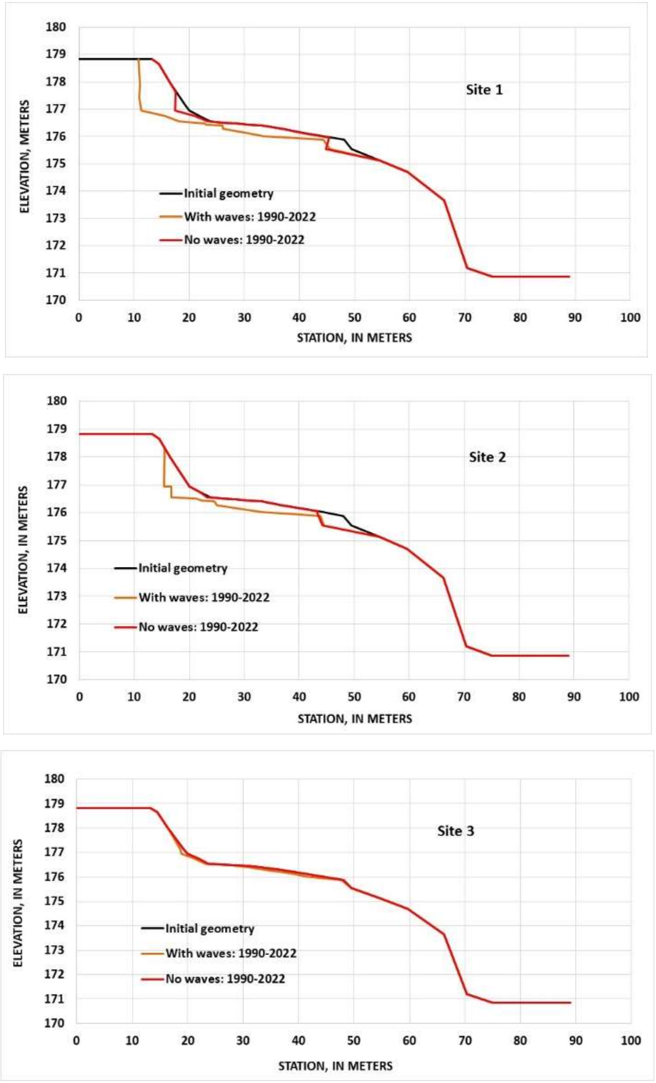

Figure 11. Model runs with BSTEM-Dynamic showing erosion with and without wind-generated waves for the three sites along the Fox River, WI

Table 1 – Simulated erosion and top-bank retreat for the 1990-2022 period assuming no rock on the bank face. Note the important role of wind-generated waves on total erosion

Site	Period	Wind waves	Erosion (m^3/m)	Retreat (m)	Erosion by waves
1	1990-2022	No	3.95	0.00	
	1990-2022	**Yes**	**21.7**	**2.54**	82%
2	1990-2022	No	3.25	0.00	
	1990-2022	**Yes**	**14.1**	**0.00**	77%
3	1990-2022	No	0.00	0.00	
	1990-2022	**Yes**	**2.15**	**0.00**	100%

GIS-based analysis of bank retreat that was conducted as part of this study using aerial imagery from 1990, 2000, 2010, 2014, 2017 and 2020, similarly indicated moderate retreat rates along the reach. Given the uncertainties that can be associated with these types of assessments from images with poor resolution and described above, these results are not considered precise, but perhaps could be useful as order-of-magnitude type estimates. Thus, the inference is that perhaps up to ~6.1 to 9.1 m of retreat could have occurred at some locations over this 31-year period. This could also occur over the next 31 years under similar conditions and without sufficient protection. On average, based on the results, it would be reasonable to estimate approximately 2.4 to 4.3 m of retreat over a similar period with similar water levels. About 2.4 m of retreat was also the value obtained with BSTEM-Dynamic at Site 1.

Conclusions

Results from the two studies provided very different outcomes. In the reach of the Fox River which can be characterized as a "drowned channel" with a beach-like bank toe and low bank heights, wind-generated waves accounted for 77% to ~100% of the modeled bank erosion. Here, water-surface elevations varied only within a 2 m range, thereby concentrating wave action at these elevations. In contrast, on the study reach of the Tennessee River where water=surface elevation varied over a much larger 13 m range, wind-generated waves accounted for <1% of the bank erosion at the vast majority of sites, notwithstanding longitudinal zones of turbid water that were observed along bank toes on windy days. It is hypothesized that because of fluctuating water levels and the relatively resistant nature of the surficial bank materials, the cumulative impacts of waves were minimized. The BSTEM-Dynamic model that includes the wind-wave sub-model has proven effective in evaluating the roles of a range of processes that impact streambanks. Application to real-world issues has also shown its utility in determining effectiveness of mitigation alternatives.

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