Review of boat wake wave impacts on shoreline erosion and potential solutions for the Chesapeake Bay

STAC Review Report

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Executive Summary

The goal of this technical review was to evaluate 1) the potential impacts of boat generated waves on shoreline stability and attendant ecosystem properties, and 2) policy options to minimize any adverse effects. We reviewed available literature, examined relevant data and information from Chesapeake Bay, discussed modeling approaches and highlighted data gaps to further quantify effects on shorelines and ecosystems, and detailed available management and policy actions to minimize potential boat wake impacts. The major findings are:

1) The literature review indicates an unequivocal connection between boat wake energy and shoreline erosion, sediment resuspension and nearshore turbidity.
2) There is not currently enough data to determine the extent (spatially and in magnitude) to which boat wakes are contributing to erosion or turbidity of the Chesapeake Bay.
3) Recommended next steps are to identify highly vulnerable waterways and implement management or policy actions to minimize adverse effects.

The Chesapeake Bay Commission (CBC) requested that the Scientific and Technical Advisory Committee (STAC) of the Chesapeake Bay Program (CBP) conduct a technical review that addresses five focal areas: (i) State of the science of known effects of boat generated waves on shoreline stability and ecosystem structure and function; (ii) Specific implications and concerns for Chesapeake Bay restoration and shoreline management, including an analysis of continuous turbidity data in relation to boating activity; (iii) Modeling approaches and data requirements for assessing boat wake wave effects on shorelines; (iv) Data gaps and research needs to quantify effects on shorelines and ecosystems; and (v) Relevant management and policy actions in Chesapeake Bay that could be adopted to minimize potential boat wake impacts to shorelines and Bay resources.

Boat wakes have been shown to have erosive effects on shorelines (e.g., Castillo et al. 2000, Bauer et al. 2002), scour the bottom of the shoreface, and temporarily decrease water clarity (e.g., U.S. Army Corps of Engineers (USACE) 1994, Asplund 1996). In addition to shoreline erosion, boat wake impacts include vegetative damage and disruption of faunal communities (Parnell and Koefoed-Hansen 2001). Boat wake energy is event-dependent and is influenced by the vessel length, water depth, channel shape, and boat speed (Sorensen 1973, Glamore 2008). Wakes are most destructive in shallow and narrow waterways because wake energy does not have the opportunity to dissipate over distance (FitzGerald et al. 2011). Although boat wakes are periodic disturbances, in comparison to wind waves, they can be a significant source of erosive wave force due to their longer wave period and greater wave height, even when they represent

only a small portion of the total wave energy (Houser 2010). Our review of the literature demonstrated that even small recreational vessels within 150 m (~500 ft.) of the shoreline are capable of producing wakes that can cause shoreline erosion and increased turbidity (e.g., Zabawa and Ostrom 1980). Vegetated shorelines can effectively attenuate waves in certain settings; however, there is a limit to this capacity particularly if there is frequent exposure to boat wakes.

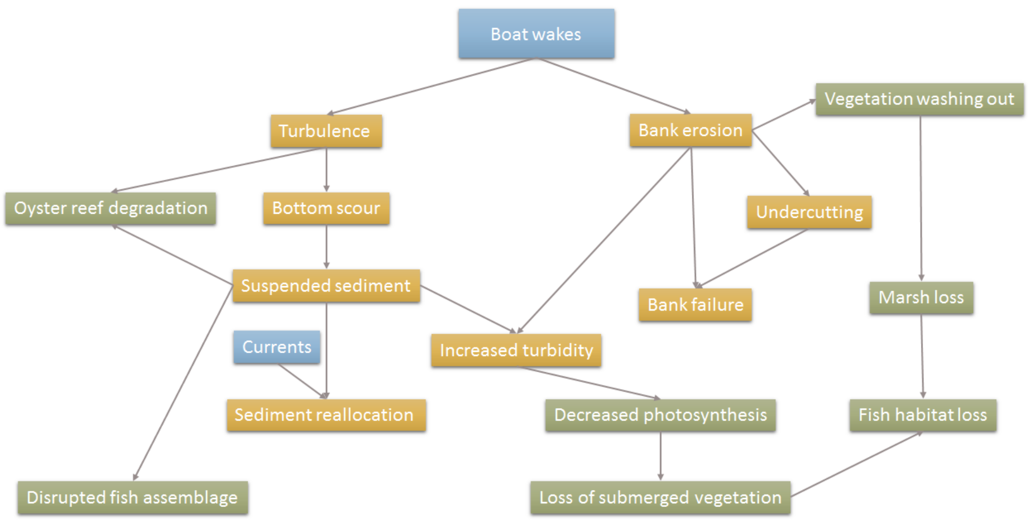

Figure 1. Diagram showing potential impacts from boat wakes to some different aquatic resources. Adapted from Liddle and Scorgie 1980. Blue boxes are drivers of change. Yellow boxes are changes in ecosystem structures and functions. Green boxes are impacts on living resources.

In the Chesapeake Bay, our analysis of long-term (~3 year) turbidity data indicate that there is a likely nexus between turbidity of small waterways, shoreline erosion, and boating activity. However, the relationships between these factors were weak due the lack of direct information and the need to use proxy measures of boating (i.e., number of piers in an area), past erosion experience (i.e., shoreline armoring) and boat wake experience (i.e., distance to the 1-m contour). These results, in combination with past studies that controlled for boat wake activity, are an indication that boat wake activity could significantly contribute to shoreline erosion and poor water clarity in some Bay creeks and tributaries.

In addition, boating activity likely contributes to the desire to armor shorelines (CCRM 2017), reducing and fragmenting the natural Bay habitats. In each of the three tidal creek systems with relatively high boating activity that were examined for this review (Lafayette River, Sarah Creek, and Lynnhaven River), approximately 25% of the low energy shoreline (i.e., shoreline not expected to have active erosion from wind-waves) has been armored, suggesting another source of erosion - possibly boating. In turn, armored shorelines can also contribute to erosion of adjacent downdrift shorelines. Living shorelines, more beneficial from a habitat perspective than armor (Bilkovic et al. 2016), could be considered a more palatable alternative than hard shoreline armor in cases in which no degree of erosion can be tolerated. Management strategies to minimize adverse impacts by addressing boating behavior (e.g., speed limits) rather than shoreline modifications are preferred to be most protective of the environment.

Policy makers who are concerned about boat wakes may want to use existing models of boat wake erosive potential (e.g., BoMo, Decision Support Tool) to inform decisions on where to put no-wake zones or other boat policies. However, at this time, we do not have sufficient data to run either model for the Chesapeake Bay. Concerns about the impacts of boat wakes on Bay shorelines have been voiced for at least 30 years (e.g., Zabawa and Ostrum 1980), leading to some regulation of boat wakes through reduced speed requirements in certain water bodies. Virginia, Maryland and Delaware localities have demonstrated authority and willingness to establish wake restrictions, but have not done so comprehensively nor with Bay-wide coordination. Evidence suggests that boat wake erosion impacts achievement of three of the CBP Restoration Goals: preservation/restoration of tidal marshes (through enhanced shoreline erosion), preservation/restoration of seagrass beds (through enhanced bottom erosion and increased local turbidity), and water clarity improvements (through increased local turbidity).

We recommend that this issue be addressed by two means:

1) First, because we have enough evidence to suggest an impact of boat wakes, protective policy measures should be adopted in highly vulnerable systems to reduce current boat wake energy.
2) Second, data should be collected that allow a more thorough analysis of the extent of the problem throughout the Bay.

These two processes need not be consecutive, but may need to occur concurrently. In locations where shoreline erosion has been attributed to boating activity with a resultant significant adverse effect on resources and property, policy actions need not wait on new data.

Recommended science, management, and policy actions include:

- Develop predictive models to quantify the relative contribution of boat wake induced erosion to overall shoreline erosion to inform water quality, habitat restoration, and shoreline protection management strategies.

- Collect needed data to identify shores vulnerable to erosion from boating (specific data needs defined below), and to calibrate and validate predictive models. Then, develop a definition for, and classification scheme of, small tidal waterways with the greatest likelihood for significant boat wake wave shoreline erosion.

- Incorporate boat wake induced turbidity and erosion when siting Bay Restoration activities (e.g., wetland/submerged aquatic vegetation (SAV) restoration).

- Investigate the opportunities within the Bay states to implement no-wake zones or other wake reduction strategies (navigation buffers from shore, speed limits, boat size restrictions, boat bans) for addressing shoreline erosion where public safety is not also a concern. In Virginia, current implementation of no-wake zone requires a finding of public safety concern and erosion is a second consideration. Empanel an expert group from the appropriate Bay jurisdictions to develop and recommend a uniform boat wake policy in the Chesapeake Bay.

Recommended data needs include:

- High resolution recreational boating intensity information (the number of vessels that pass by on an average day, vessel types, vessel speeds, vessel traffic patterns).

- Information on recreational boating trends in small waterways.

- Information on the location, extent and level of enforcement of no-wake zones throughout the Bay.

- Data on grain size of bottom sediments in all the Bay tributaries and small creeks; even a simple categorization of sand and fines would be useful.

- Data on wave height (measure for wave energy) and suspended sediment concentration (a measure for potential erosion).

- High resolution shallow water bathymetry is needed throughout the Bay. If data even exist, most are 50-100 years old in these areas.

This review found that boat generated waves, particularly in shallow and narrow waterways, can increase turbidity, erode shorelines, compromise coastal habitats, and disrupt ecosystems. This has the potential to impede progress towards several Bay restoration goals, particularly habitat restoration and water quality improvement. Not accounting for potential boat wake effects during the planning and implementation of Bay restoration activities may compromise the attainment of Bay Program goals. Further, incorporating the boating effects into the Bay Model may help to reduce uncertainty and ensure that restoration projects are sited in the most favorable settings.

Background and scope of the review

The Chesapeake Bay Commission (CBC) requested that the Scientific and Technical Advisory Committee (STAC) of the Chesapeake Bay Program (CBP) conduct a technical review of the relevant information on the potential impacts of boat generated waves on shoreline stability and attendant ecosystem properties, and provide advice on available policy actions to minimize any adverse effects. This request was made in January 2016; the request was approved by the STAC in March 2016, and the review was initiated in June 2016. The request to the STAC (see Appendix I) from the CBC was that the review be focused on the following topics:

1. Evaluate the state of the science of known effects of boat generated waves on shoreline stability and other ecosystem components (e.g., vegetative habitat, faunal community composition),
2. Identify data requirements to effectively model the potential effect of boat wake waves on shorelines,
3. Identify data gaps and research needs, and
4. Determine existing and potential policy actions to reduce adverse effects of boat wake waves on shorelines. Describe political and legal challenges for designating no-wake zones in Chesapeake Bay. Are there case studies of no-wake zone designation and/or evaluation of response from management action in the Bay that can be learned from?

STAC was also asked to address several questions related to (*i*) erosion and sediment inputs caused by boat wake waves, (*ii*) existing and needed data to develop best management practices to minimize shoreline erosion from boat wake waves, and (*iii*) political and legal challenges associated with policy actions to reduce boat wakes.

Questions of Interest:

1. What is the relative contribution of sediment inputs from boat wake-induced shoreline erosion in Chesapeake Bay?
2. Are these types of sediment inputs currently represented in the Bay Watershed Model?
3. Would expanding no-wake zones be beneficial to the Bay?
4. Are there other policy options besides no-wake zones to consider?

To be responsive to the CBC request, the STAC assembled a team of 9 professionals with backgrounds in sediment dynamics, shoreline erosion, coastal management and policy, environmental engineering, coastal engineering, estuarine shoreline systems, and estuarine ecology to assimilate relevant information in the form of a technical white paper. The document was then reviewed by additional external reviewers for further input to ensure critical areas of expertise were well-represented.

The body of the review is organized into the following 6 sections:

1. Evaluation of the state of the science of known effects of boat generated waves on shoreline stability and other ecosystem components
2. Specific Chesapeake Bay implications and concerns
    a. Examination of continuous data for evidence of elevated turbidity from boating activity
    b. Case study that describes boat-wake induced erosion implications for city-managed property in the Lafayette River, VA
3. Modeling approaches and data requirements to assess the potential effect of boat wake waves on shorelines
4. Data gaps and research needs
5. Management and policy in Chesapeake Bay
6. Summary and Recommendations

Section 1: State of the Science

Shoreline erosion is a natural process that can be exacerbated by human activities. Natural drivers of shoreline erosion include wind waves, currents, and sea level rise (SLR). Human activities that exacerbate erosion include shoreline hardening (armoring) and boat wake impacts. It is not possible to visually distinguish between the natural and human-induced components of erosion; these must be deduced from measure of human use of an area combined with wind wave erosion models.

This report focused on boat wake-induced erosion, but this should not be interpreted to mean that the other drivers of erosion are unimportant in the Chesapeake Bay. Historic Virginia shoreline erosion rates can be found at the Shoreline Studies, VIMS website (http://vims-wm.maps.arcgis.com/apps/webappviewer/index.html?id=cd5cf9b788d0407fb9ba5ffb494e9bae). Historic Maryland shoreline erosion rates can be found at Maryland Department of Natural Resources (http://www.mgs.md.gov/publications/maps.html).

Boat wake dynamics

As a boat travels through the water, it displaces water, effectively pushing it to the side and creating a pressure gradient that radiates outward in a wave form. Forward movement of the bow creates a series of symmetrical waves that propagate away from the bow at oblique angles, while the stern generates a single transverse wave that travels in the same direction as the vessel (Sorenson 1973). The point at which bow and stern waves interact (known as the cusp), is the region of maximum wave height (Maynord 2001, Figure 2). Waves that fall between the cusp points are smaller than the maximum height. The cumulative result is that each boat passage generates a complex series of waves known as a wave train, which propagate away from the sailing line at an angle that is dictated by hull shape and vessel speed. The specific characteristics of the waves generated by each passage are dependent on a multitude of factors including water depth, vessel length and speed, displacement (loading), hull shape, and the presence of natural waves and currents, among others (Maynord 2001). Given the complexity of predicting waves in a natural system, it is valuable to understand the basic traits of idealized waves.

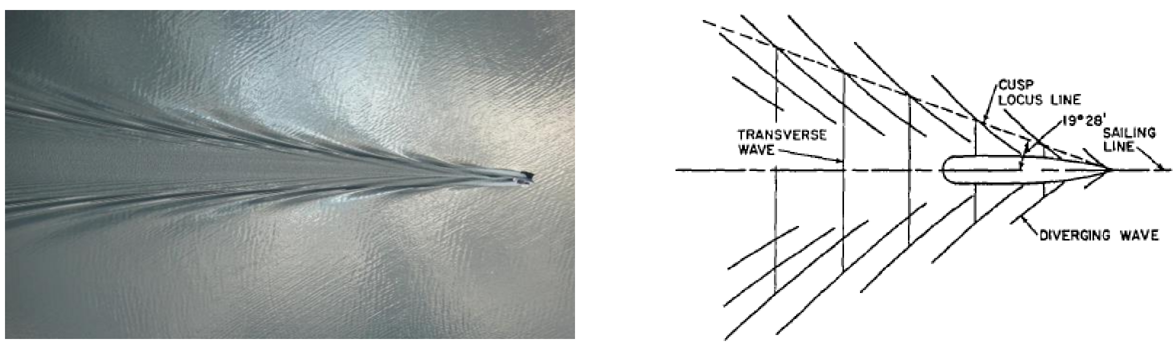

Figure 2. Pattern of vessel-generated waves in deep water. Diagram from Sorenson 1973. Photo by Edmont - Own work, CC BY-SA 3.0, https://commons.wikimedia.org/w/index.php?curid=6920796

Waves that travel in water that is deeper than 1/2 of their wavelength (the distance between two successive wave crests) are referred to as deep water waves. The motion of deep water waves do not penetrate the full depth of the water column, thus these waves have little impact on the bottom sediments (Sorenson 1997, Hill et al. 2002). As a deep water wave travels away from the sailing line, wave height will decrease with distance traveled as wave energy spreads out along the wave crest. Given a long enough transit in deep water, much of the wave energy will distribute over a wide area before reaching a shoreline. In deep water, the speed at which a wave moves away from its point of generation is largely a function of wavelength; waves with longer wavelengths travel faster than those with shorter wavelengths. As faster waves overtake slower ones, waves produced by one boat may merge with those produced by a different boat (Figure 3), or with wind waves. Merging of waves from different sources can be constructive (resulting in higher wave heights) or destructive (resulting in decreased wave heights) depending on whether they merge crest to crest, or crest to trough. In most cases, the interaction of waves from a variety of sources results in a water surface that appears highly disordered.

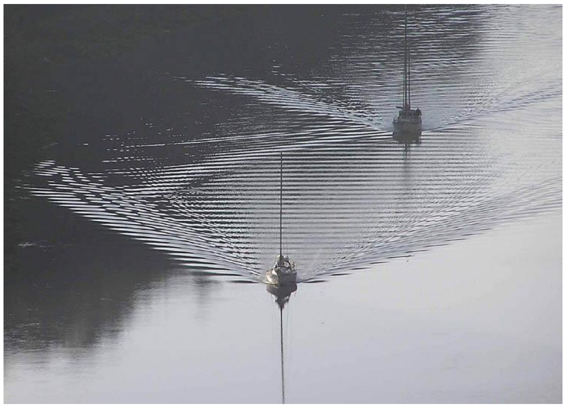

Figure 3. Boat wakes from different boats interact, changing wake patterns. Photo by Arpingstone, https://commons.wikimedia.org/w/index.php?curid=5957943

Waves that travel through water depths that are less than 1/20 of their wavelength are referred to as 'shallow water waves'. Waves that fall between deep and shallow water wave categories (when water depth is greater than 1/20 but less than 1/2 of wavelength) fall into the "transitional" category. The movement of both transitional and shallow water waves is influenced by water column depth because the energy associated with both types reaches all the way to the sea floor. Deep water waves traveling toward a shoreline will therefore eventually become transitional and shallow water waves due to changes in water column depth. Shallow water waves can influence the seafloor by causing sediment resuspension and, conversely, the friction created by wave motion interacting with the seafloor can influence waveform. As a wave travels into shallow water, interaction with the seafloor causes a decrease in the forward speed of the wave train and a concomitant increase in wave height (shoaling) until the wave eventually breaks (Parnell and Kofoed-Hansen 2001). As a result, waves of low amplitude and long wave-length that seem trivial in deep water, may result in large plunging breakers when they reach the shoreline.

The size and shape of boat wakes are strongly influenced by hull type and speed. Planing hulls are designed to ride on top of the water. Displacement hulls (e.g., sailboats, trawlers and large ships) are not capable of planing but rather, ride in the water, pushing it to the side as they move forward. The amount of water displaced is equivalent to the weight of the vessel, thus very large displacement hulls like tanker ships displace large volumes of water, resulting in the creation of wakes with large wave heights. The shape of a hull further influences its wake characteristics. A catamaran, a single-hulled vessel, and a jet ski will all produce different wakes. Previous investigators have shown that a boat towing a water skier will produce a wake with greater wave energy than the same boat when not towing (Baldwin 2008). All other factors being equal, a positive correlation exists between the size of a vessel and the size of its wake (Hill et al. 2002, Fonseca and Malhotra 2012).

The single best predictor of the size of the wake that any given boat will produce is the speed at which the vessel is traveling (Sorenson 1973, Zabawa and Ostrom 1980, Fonseca and Malhotra 2012), although this relationship is not linear for planing hulls. When planing vessels are operating in displacement mode (such that the bow of the boat is fully supported by the water), wake size increases with speed. The maximum wake is produced at the point just before a vessel transitions to planing mode (this range of speeds is commonly referred to as transition mode). When speed is increased enough that the vessel is fully “on plane”, wake sizes begin to decrease as less of the boat is in the water. This relationship between speed and wake size is illustrated in Figure 4. It is important to note that while all planing vessels will produce a curve with this same general pattern, the curve is slightly different for each boat and each set of operating conditions (Stumbo et al. 1999).

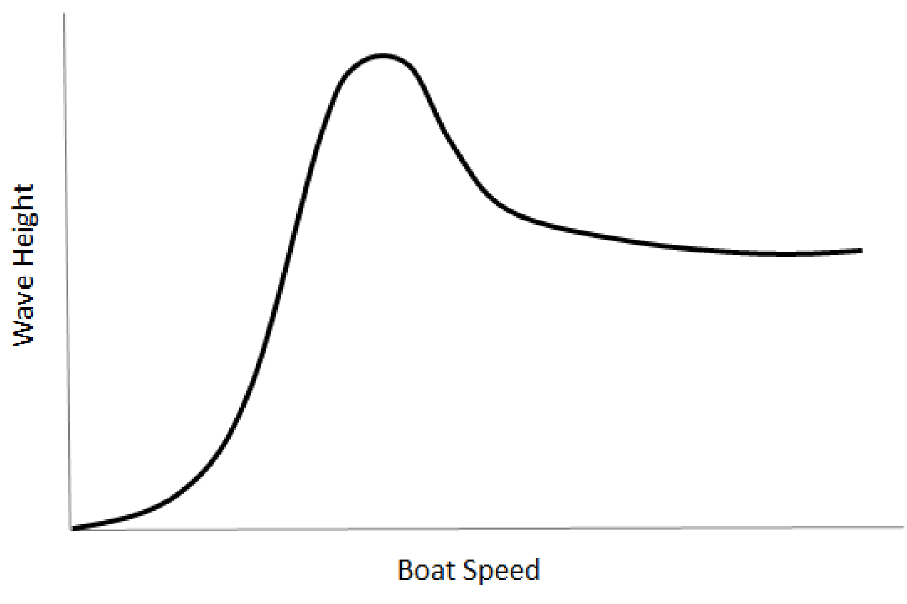

Figure 4. Wave height as a function of speed in planing hull vessels. Adapted from Maynord 2001.

Efforts to quantify the impacts of boat wakes on shorelines are complicated by the fact that each boat passage produces waves with a unique set of characteristics (McConchie and Toleman 2003). As a result, many previous efforts to establish wake management strategies have used wave height, or wave energy based criteria (Stumbo et al. 1999, Glamore 2008).
Wave energy, given as:

$$E = 1/8 \; p \; g \; H^2 \; L$$

(where p = water density, g = gravity, H = wave height, and L = wavelength) is proportional to both the height and length of a wave. As wave energy increases with wave height squared, wave height provides a reasonable proxy for erosive force. Wave height is also more easily estimated by the casual observer than wave energy (Nanson et al. 1994). Wave energy dissipates with distance from the boat thus, the smaller a wave is at the onset, and the farther from the shoreline it is generated, the less energy it will contain when it reaches the shoreline and the less likely it is to cause erosion.

Site specific factors that control impact of boat wakes on shoreline erosion

Local vessel usage

The amount of boat wake energy impacting a given shoreline is a function of not only the size and speed of vessels passing that shoreline, but also the frequency of vessels (Zabawa and Ostrom 1980, Glamore 2008). Highly traveled waterways are more likely to experience boat wake-induced shoreline erosion than less frequently travelled waterways. Further, because wave energy decays with distance from the boat, narrow waterways in which boats must pass closer to shore are more likely to experience wake-induced erosion from both direct wave impact, and wave energy reflected from the opposite shoreline, than wider channels (Nanson et al. 1994, FitzGerald et al. 2011; Table 1).

It should be noted that shallow draft vessels (like personal watercraft) with the ability to run at high speed in shallow nearshore water may play a disproportionate role in shoreline erosion simply by virtue of their ability to operate close to shore where waves have little chance to dissipate. However, when run in a manner similar to that of a small boat (i.e., in a straight line) personal watercraft were found to generate smaller lower energy waves than boats (McConchie and Toleman 2003).

Table 1. Published values of measured wave heights vs. vessel speed at varying distances from the sailing line: * indicates planing hull, ** indicates displacement hull. These data are excerpts from the larger data sets published by a) Zabawa and Ostrum 1980, Chesapeake Bay and b) Sorenson 1973. For context, waves as small as 10 cm result in erosion of sediments from vegetated shorelines (Coops et al. 1996), and marsh survival is compromised when waves exceed 30 cm, even 5% of the time (Schafer et al. 2003, Roland and Douglas 2005).

Boat	Distance From Sailing Line (m)	Speed of Boat Travel (knots ((km hr^{-1}))	Max wave height (m)
26' (8 m) Uniflight*	100	10 (19)	0.41
	100	26 (48)	0.29
	150	10 (19)	0.37
	150	27 (50)	0.21
16' (5 m) Boston Whaler*	50	10 (19)	0.22
	50	24 (44)	0.13
	150	12 (22)	0.14
	150	27 (50)	0.07
45' (14 m) Tugboat**	30	6 (11)	0.2
	30	10 (19)	0.5
	150	6 (11)	0.1
	150	10 (19)	0.3
263' (80 m) Barge**	150	10 (19)	0.2
	300	10 (19)	0.1

Wave energy at site

In many instances, the cumulative impact of boat wakes is often small relative to that of wind waves (Laderoute and Bauer 2013). In a study of boat wake versus wind-wave energy at multiple sites within Chesapeake Bay, Zabawa and Ostrom (1980) determined that <5% of total annual shoreline wave energy was attributable to boats. The sites included in this study were along either the mainstem of the South and Severn Rivers, or on smaller creeks and coves near each river. All sites were selected based on being popular areas for boating/water skiing and being relatively sheltered from wind. Several more recent studies have found similar results with respect to the total amount of wave energy attributable to wind vs. boating activity (Knutson et al. 1990, Houser 2010, Fonseca and Malhotra 2012).

While total cumulative wave energy associated with boating impacts is often less than that of wind waves, the height of the largest boat generated waves can substantially exceed that of the largest wind waves. Winds represent an almost constant source of low to moderate wave energy while large boat wakes represent a comparatively rare but high energy event that may be responsible for significant damage to some shorelines. Houser (2010) estimated that while cumulative boat wake energy accounts for less than 5% of total wave energy on the Savannah River, they account for more than 30% of total wave force acting on shorelines. The disproportionately high wave force relative to total wave energy associated with boat wakes in this study was attributed to the fact that the Savannah River is heavily trafficked by large displacement hull vessels that generate large amplitude, long period waves. Further, the relative amount of wave energy attributable to boats vs. wind has been shown to change throughout the year due to seasonal changes in boat usage (Zabawa and Ostrom 1980, Maynord et al. 2008).

Shoreline characteristics

Shoreline profiles influence erosion rates with ramped (gently sloping) and scarped (vertical shore profile) marsh shorelines experiencing greater wave thrust and consequently higher erosion than terraced shorelines (characterized by a step-like profile) under the same wave conditions (Tonelli et al. 2010). In Boston Harbor, the highest rates of shoreline retreat were shown to occur along high elevation shorelines (bluffs of >10 m; FitzGerald et al. 2011). In this case, the high erosion was attributed to wave-induced undercutting of the shoreline that eventually led to slumping of large sections of the bank.

As waves come into contact with a shoreline they may either shoal and break, or be refracted, thus further contributing to the wave energy of nearshore waters. The amount of wave energy that is reflected along a given stretch is heavily influenced by the amount of shoreline modification. Hard, vertical structures like bulkheads and seawalls are purported to reflect much of the incoming wave energy, thus resulting in an overall increase in nearshore energy (NRC 2007). Shoreline geometry further influences wave energy as headlands are impacted by wave energy from a variety of directions while embayed shorelines may experience greater influences from refracted wave energy (Priestas et al. 2015).

Water Levels

The impact of waves is even more challenging to predict along tidally influenced shores, as water levels and tidal flow interact to determine the effect of incoming wave energy on a shoreline (Tonelli et al. 2010). Along shorelines that are fronted by extensive tidal flats, much of the incoming wave energy will be dissipated over the tidal flats, effectively buffering the shoreline from wave attack. The lower the water level, the more influence a tidal flat exerts on water column dynamics. River stage plays a similar role. In the Kenai River, Alaska, Maynord et al. (2008) demonstrated higher shoreline erosion rates when peak boating conditions corresponded to times of high river flow and decreased erosion, despite high boat activity, during lower flow conditions. They noted that during low flow conditions, much of the wave energy was lost due to contact with gravel sediments near the river margins. Tonelli et al. (2010) have modeled the impacts of waves along salt marsh shorelines and showed that wave thrust on a shoreline increases with rising tide levels until the tide is just above the marsh surface elevation, at which point, wave thrust on the shoreline decreases sharply. Houser (2010) demonstrated this effect with wave sensors in the Savannah River. The importance of tidal stage is further supported by Marani et al. (2011) who demonstrated a strong relationship between wind wave energy and measured marsh edge retreat by considering wind data only from periods when marsh was not flooded.

Tidal flows may further influence the ultimate fate of eroded sediments by providing a mechanism for their dispersal. Bauer et al. (2002) used back-scatter sensors to measure the concentration of suspended solids in the water column after individual boat passages. Their data indicated that suspended solid concentrations (SSC) returned to background values within a few minutes of each boat passage, despite much longer calculated settling times. These data suggest that once suspended, the particles are carried downflow by currents, thus representing a net loss of sediment from the site.

Vegetation

Figure 5. Marsh vegetation helps attenuate wave energy and binds the sediment, reducing erosion. Photo from NOAA/NCCOS.

Whether waves of a given size will result in significant levels of sediment resuspension and/or shoreline erosion is further influenced by sediment characteristics and the presence or absence of shoreline vegetation. Soils with a high sand content have been shown to be more easily eroded than finer-grained sediments (Feagin et al. 2009). Shorelines that are vegetated tend to have finer-grained sediments than non-vegetated shorelines due to the incorporation of decaying organic matter (Craft et al. 2002). As a result, the presence of living root material in shoreline soils results in a stronger soil that is less easily eroded (van Eerdt 1985, Francalanci et al. 2013). Additionally, shoreline vegetation like marsh plants combats erosion by attenuating wave energy (Yang et al. 2012, Möller et al. 2014; Figure 5) and this response is proportional to both the height and density of the vegetation (Möller 2006). The presence of even a narrow band (on the order of 1 m wide) of marsh vegetation in front of the shoreline has been shown to result in decreased rates of shoreline erosion (Currin et al. 2015). Vegetated shorelines and marshes in particular are limited to regions of relatively low wave energy, thus their geographic extent limits the opportunity to minimize the impacts of incoming wave energy. Recent wave tank modeling results show that marsh vegetation is adapted to short period, high frequency wind waves, but may not be as resilient to long-period ship-generated waves (Silinksi et al. 2015).

Boat wakes and shoreline stability

Shoreline change may include shoreline erosion and resuspension in the foreshore environment, although sediment can be transported landward as well. The balance of transport (whether the shoreline erodes or accretes) depends on the size of the wake (Osborne and Boak 1999, Houser 2011). Most studies found the effects of boat wakes on the shoreline are dependent on many factors. Site-specific conditions such as water depth, bank profile, type, size and supply of sediment and bank resistance can control suspended-sediment concentrations (McConchie and Toleman 2003, Hughes et al. 2007). In coastal areas subject to significant wave action, boat wakes may have a negligible effect on shoreline stability. However, in sheltered coastal, estuarine, and river environments, boat wakes may be the leading cause of shoreline erosion

(Gourlay 2011; Figure 6).

Shoreline erosion

There are many anecdotal accounts of boating activity leading to shoreline erosion; however, documenting the role that boat wakes play in the rate of shoreline change is complicated by the fact that any single boat passage (aside from the case of very large displacement vessels) will not produce a measureable change in shoreline position. It is, rather, the cumulative effect of many boat passages that result in shoreline change and these effects can be difficult to discern from those of wind waves. To further complicate matters, in narrow channels boat wakes may reflect off one shore, cross the channel, hit the opposite shore and return to the original shore for a second impact. In suspected cases of boat-wake induced shoreline erosion, often few data exist regarding the shoreline position and natural rate of shoreline change before the impact of boats was suspected. This lack of "control" data makes it challenging to quantify the amount of shoreline change that is attributable to boat wakes alone.

Many studies of boat wake-induced shoreline erosion have focused on the effects of large shipping vessels and high-speed passenger ferries (Kirkegaard et al. 1998, Parnell and Kofoed-Hansen 2001, Soomere et al. 2005, Schroevers et al. 2011). While fewer efforts have focused on the cumulative impacts of recreational boating (Cox and Macfarlane 2004), there is a developing body of literature that demonstrates the negative impacts of small boats on shoreline stability. Among the current published literature relating recreational boat traffic to shoreline erosion, most take the approach of relating boat passages to changes in water column turbidity (Bauer et al. 2002, Cox and Macfarlane 2004, Baldwin 2008, Laderoute and Bauer 2013). While increased turbidity is not a direct measure of erosion (i.e., it is possible for suspended sediments to settle back into their original location) most water bodies experience some level of flow, and settling times for small particles are long, making it likely for suspended sediments to be carried away from their original location. In the Sacramento River, a series of current meters and backscatter profilers were installed on a shallow bank on the river margin in a shoreline-perpendicular transect (Bauer et al. 2002). This instrumentation allowed researchers to evaluate the wave characteristics and amount of sediment suspension associated with individual boat passages. The data were used to model erosion rates on a per-boat basis. The results indicated that each boat passage resulted in 0.01 - 0.22 mm of erosion at a given location on the shoreline. These rates were well-supported by measured rates of cumulative shoreline erosion after multiple (hundreds of) boat passages. The variability in erosion potential of shorelines makes it unlikely that these specific rates will apply to shorelines in other regions; however, they demonstrate that the additive effect of multiple boat passages can lead to measurable erosion.

When boat frequency and/or speed are reduced, measured rates of bank retreat have been shown to decline dramatically (Nanson et al. 1994). On the Gordon River, Tasmania, Nanson et al. (1994) documented an average erosion rate of 1 m yr^{-1} on a stretch of the river without speed restrictions. Erosion rates along that same stretch decreased to 0.3 m yr^{-1} when boat speeds were restricted to 17 km h^{-1}. Erosion rates decreased further (to 0.06 myr^{-1}) when boat passages along that same stretch were limited to 1 per day.

Figure 6. Marsh erosion reportedly induced by boat generated waves on Lynnhaven River, Virginia. Photo by Bill Fleming.

Resuspension

Observation and research regarding the effects of boat wakes on sediment movement have been ongoing for decades (e.g., Nanson et al. 1994, Osborne and Boak 1999, Gourlay, 2011). Resuspension of bottom sediments in shallow water may occur in the foreshore, in shallow waters, and adjacent to channels after boat passage (Figure 7). Increased turbidity varies in its persistence. In river systems, suspension events may be short-lived, even with very fine sediments, because the suspension plumes are carried downstream (Bauer et al. 2002). In other settings, such as Venice Lagoon, Italy, elevated concentrations persisted for nearly an hour (Rapaglia et al. 2011). The popularization of personal watercraft, with their exceptionally shallow drafts, has brought boating activity to regions of water bodies which have historically seen little boating traffic. Turbulent prop or jet wash have the ability to resuspend bottom sediments. In field studies, boat speed, size, and water depth were the critical factors affecting resuspension on an unnamed lake bed (Beachler and Hill 2003).

Figure 7. Imagery capture of boating-induced resuspended sediment along shoreline (upper left of image).

Boat wake impacts to specific resources

Commercial and recreational boating can have a wide-array of adverse effects on aquatic resources, including direct physical impacts from boat contact with the bottom, noise disturbance, as well as those effects resulting from physical disturbances to the bottom sediments, nearshore habitats and shorelines from boat generated waves. The latter is often understudied and thus less well-understood. Though other boating impacts on a resource may be significant, the primary focus of this report is on boat generated wave impacts.

Oyster reefs

The distribution of intertidal oyster reefs is strongly shaped by wave energy, such that natural intertidal reefs do not occur in high wave energy settings. In Pamlico and Core sounds, North Carolina, Theuerkauf et al. (2016) found that the distribution of intertidal oyster reefs was limited to a fairly narrow range of wave energies, but that wave energy did not limit the occurrence of oysters on hard substrates like rock jetties and seawalls. In Chesapeake Bay, intertidal reefs were once prevalent; for over 100 years oysters supported one of the Bay's most valuable fisheries with tens of millions of bushels of oysters removed each year. This massive shell removal led to the flattening of reefs, with oyster reefs now largely subtidal in the Bay (Hargis and Haven 1999). While there have been many anecdotal accounts of boating-related impacts on oyster reefs, empirical data are limited. In the Indian River Lagoon, Florida, Grizzle et al. (2002) described a pattern of dead margins (evidenced by piles of shells that had apparently originated as living oysters dislodged off of the reef, pushed above high tide line by subsequent wakes, and then perished due to exposure) on the seaward side of oyster reefs that faced navigation channels and hypothesized that boat wakes were responsible. Survival of oyster spat on these same reefs was later found to be significantly lower than on reefs that were not impacted by boat traffic (Wall et al. 2005). Experimental evidence from this same system indicates that waves as small as 2 cm can result in the movement of both individual oysters and small clusters of oysters (Campbell 2015).

Salt marshes and beaches

As previously described, salt marsh vegetation can help to stabilize sediments and dissipate wave energy. Both of these functions can result in decreased erosion rates relative to those of unvegetated shorelines. The benefit of shoreline vegetation does have limits however, as marsh vegetation only exists along relatively low energy shorelines. Efforts to establish the wave energy threshold for marsh survival suggest that marshes will not exist naturally along a coast line where incident wind-generated waves exceed 0.3 m, even 5% of the time (Schafer et al. 2003, Roland and Douglas 2005). Previous efforts to quantify the impact of boat wakes on shorelines suggest that waves of 0.3 m are likely when navigation channels are within 150 m of the shoreline (Table 1, Figure 8). As 0.3 m may represent the threshold of survival, there is likely to be a gradient of wave heights beneath this threshold which span the range from conditions where marshes thrive, to those where chronic erosion occurs. Evidence from wave tank experiments suggests that waves as small as 10 cm result in erosion of sediments from vegetated shorelines (Coops et al. 1996). Furthermore, several researchers have demonstrated positive correlations between wind-wave power along a shoreline and measured rates of shoreline retreat (Schwimmer 2001, Marani et al. 2011).

Studies have shown a direct impact of boat wakes on tidal marsh stability (e.g., Castillo et al. 2001, Allison 2005, Houser 2010) although not all of the studies concluded that boat wakes were the primary source of annual erosion. Boat wakes seem to contribute significantly to shoreline change where boat activity is regular, concentrated, close to the shore and in small tidal creeks, but may be less important than wind waves in other systems. Although the impacts are generally framed as tidal marsh loss, a study of vegetative community change in San Francisco marshes attributes a shift from intertidal *Schoenoplectus californicus* to submerged aquatic vegetation to shoreline erosion caused by recreational boating (Watson and Byrne 2012). Personal watercraft (Jet skis) have the ability to operate in very shallow water including marsh channels. Within three National Estuarine Research Reserve (NERR) marshes (North Carolina, South Carolina, and New Hampshire), a significant change in turbidity from personal watercraft passages was demonstrated; in addition, the speed and the weight of passengers created higher waves and more turbidity (Anderson 2002). Much less research has been directed to the question of the effects of boat wakes on non-vegetated shores (beaches), but sand entrainment and movement offshore was attributed to jet boat wakes in a controlled experiment on the Snake River (Mussetter et al. 2007).

Figure 8. Waves generated by boat passages along the Atlantic Intracoastal Waterway, NC. Photo from NOAA/NCCOS.

Submerged Aquatic Vegetation

Boat wakes and wash can cause erosion of submerged aquatic plant roots in freshwater and marine waters. The susceptibility of freshwater aquatic plants to erosion can be variable and may be related to the petiole cross-sectional area (Liddle and Scorgie 1980). Direct damage to seagrasses from contact with propellers, anchors, and moorings has been well-documented (e.g., Williams 1988, Walker et al. 1989, Dawes et al. 1997, Hallac et al. 2012). However, boat wake wave impacts are less understood for seagrasses. Boat generated waves can have indirect impacts on seagrasses through increased suspended sediments that lead to reduced light availability and elevated nutrients (Koch 2002, Koch et al. 2006). Seagrasses have relatively high minimum light requirements (11-20% of surface light) in order to thrive (Durante 1991, Dennison et al. 1993); therefore, wave-induced increases in water turbidity can be detrimental to seagrasses. Unfortunately, there is limited quantitative information regarding this impact. Research from a shallow sandy bay in Massachusetts suggests that turbidity may be sufficiently elevated (reducing light by more than 60%) in areas with heavy boating, particularly at low tide, to be detrimental to eelgrass; however, the sandy sediment resuspended from boating resettled within 1-2 hours, much quicker than wind-driven events (Crawford 2002). A single study from Chesapeake Bay observed a minimal negative impact of boat generated waves on seagrass light availability likely because at the study site (Hopkins Cove, MD) boat waves were very small compared with naturally occurring waves (Koch 2002). Additional study is needed on seagrasses in other systems to more fully estimate the potential effect of boat generated waves.

Estuarine fauna

Boat generated waves can have direct and indirect effects on fish. Direct effects may include temporary increases in water turbidity or wave energy that physically disrupt fish assemblages (Whitfield and Becker 2014). Indirect effects may result because of physical disturbances to the bottom sediments (resuspension) and nearshore habitats (seagrasses, wetlands) from boat generated waves. Frequent and intense boating activity may enhance seagrass blade movement (‘flapping’) that can cause reduction in the abundance and diversity of invertebrate prey resources (Bishop 2008). Experimental studies in the littoral zone of freshwater have demonstrated that wave velocities corresponding to waves generated by small recreational boats caused ~10% of benthic invertebrates (e.g., amphipods) to dislodge and become more vulnerable to predation as well as a reduction in foraging success for certain littoral fish species (Gabel et al. 2011). Beyond immediate habitat and prey disruptions, long term damage and fragmentation to structural habitat such as seagrasses and salt marshes from regular exposure to elevated turbidity and/or physical stress from waves has the potential to change fish assemblages and productivity (Fagherazzi et al. 2013). Boat generated waves may erode the essential habitats of diamondback terrapin (*Malaclemys terrapin*) – marshes and nesting beaches (Schwimmer 2001).

Birds

There are few studies on the effect of boating on birds and little effort to tease the effect of boat wakes from the suite of possible disturbances (noise, visual, proximity, etc.). Exposure to rapid and repeated movement of personal watercraft significantly increased flushing of least terns (*Sternula antillarum*) on a marsh island in New Jersey. Motorboats prompted a similar, though significantly smaller, response. Terns relocated nesting sites opposite the boating channel and experienced greater rates of nest loss due to flooding (Burger 2003). Of 6 wading birds species (great egret (*Ardea alba*), tri-colored heron (*Egretta tricolor*), snowy egret (*Egretta thula*), great-blue heron (*Ardea herodias*), yellow-crowned night heron (*Nyctanassa violacea*), and green heron (*Butorides virescens*), all but the snowy egret displayed boat-induced flushing response and lower numbers of birds post-disturbance. Environmental factors (weather, wind speed, time of day, air temperature) and prey availability have documented effects of avian habitat use and behavior, potentially masking disturbance effects (Peters and Otis 2006). Colonial nesting grebes construct over-water nests which are subject to both wind and boat generated wave-induced failure (Allen et al 2008). Nests with adequate vegetative protection are three times more likely to hatch eggs than unprotected nests. A loss of endangered California light-footed clapper rail nesting habitat (*Spartina foliosa*, low marsh) is attributed to personal watercraft and boat wake erosion (Dayton and Levin 1996). Anecdotal linkages between boat wakes and a decline in common tern and black skimmer populations have been made by the Maryland Coastal Bays Program and the Program has initiated a "no-wake" sign program (Holloway 2015).

Section 2: Specific Chesapeake Bay implications and concerns

Recreational boating

Recreational boating is a highly prevalent and an economically important water-related activity in Chesapeake Bay (Lipton 2007, Murray et al. 2009). In Virginia, there are nearly 250,000 registered boats (Virginia Department of Game and Inland Fisheries, data from 1997-2012). In Maryland, there are nearly 200,000 registered boats, and an additional 57,000 non-registered vessels (Environmental Finance Center, University of Maryland 2013). The majority of the boats are small, trailered vessels, the trend however is for boat owners to 'trade up' for larger boats (Maryland's Recreational Boating and Infrastructure Plan 2004). According to the US Coast Guard National Recreational Boating Survey (2012), the annual number of days spent boating is 2,547,000 for Marylanders and 5,600,000 for Virginians; these numbers include boat days spent on non-power boats. The economic downturn from 2008 to about 2013 showed a decrease in boat registrations in Maryland while the last several years have shown an uptick in sales and registrations. Moreover, as coastal populations grow, more development is occurring along shallow tidal creeks which has increased boating traffic from shallow creeks to main water bodies (CCRM 2010). From 2002 to 2009 in Virginia, increases in pier construction were highest in new residential areas (increased housing density and low-intensity development) near small creeks (Isdell 2014). These low energy tidal creeks with relatively little wind-driven waves are sheltered environments that tend to allow for the proliferation of marsh and seagrasses. Furthermore, these shallow creek habitats may be particularly sensitive to sediment resuspension and shoreline erosion from boat wake waves.

The Chesapeake Watershed Agreement (2014) designates a goal to "Expand public access to the Bay and its tributaries through existing and new local, state and federal parks, refuges, reserves, trails and partner sites". To accomplish that goal, a defined outcome is to *add 300 new public access sites, by 2025, with a strong emphasis on providing opportunities for boating, swimming and fishing, where feasible*. The intent of the goal is to, in part, increase stewardship and local economies; however, this goal may be in conflict with other water quality and habitat restoration Bay goals in some areas.

Is there evidence of elevated turbidity induced by recreational boating in Chesapeake Bay?

Recreational boating has been shown to induce an elevation in turbidity above ambient conditions in lake systems because of shore erosion and/or resuspension of sediments from boat wave wakes, resulting in temporally low water clarity on weekends and holidays (e.g., USACE 1994, Asplund 1996). We hypothesized that this trend might be seen in the Chesapeake Bay because there are generally higher levels of recreational boating intensity during the weekend and during major warm-weather holidays (i.e., Memorial Day, July 4th, Labor Day) than during the week. Water quality monitoring in the Chesapeake Bay includes programs that capture continuous measurements of water quality (e.g., dissolved oxygen, turbidity) taken from fixed, shallow water monitoring stations (www.vecos.org, www.eyesonthebay.net). We tested the hypothesis that turbidity was affected by recreational boating at 26 sites at which continuous monitoring data were available in the Chesapeake Bay (Virginia N=14; Maryland N=12 stations; Figure 9-map of stations, Table S1). These stations are typically affixed to a pier near the shore (most stations are within 50 meters of the shore).

To minimize the likelihood of commercial vessel traffic and the opportunity for wind waves as significant influencing factors on nearshore turbidity patterns, monitoring stations with moderate to high exposure to commercial vessel traffic and/or located on the mainstem of major tributaries were not considered for the analysis. Using data on ship traffic patterns collected by the U.S. Coast Guard through the Automatic Identification System (AIS) and summarized for Chesapeake Bay at 1 km x 1 km grid cells for the interval 2009 through 2014 (spatial data source: Bilkovic et al. 2016; and the Marine Cadastre http://marinecadastre.gov/ais), the total number of pings recorded in the vicinity of the monitoring station was determined (Figure 9). AIS is an onboard navigation safety device that transmits and monitors the location and characteristics of large vessels in U.S. and international waters in real time. The Marine Cadastre provides AIS data filtered and summarized into one-minute intervals, with each record representing a ship's location every minute. All monitoring stations used in the analysis were in reaches with low or no commercial traffic; half of the stations were in reaches with no pings, 11 stations had < 500 pings, and 2 sites had less than 2000 pings for the entire 6-year record.

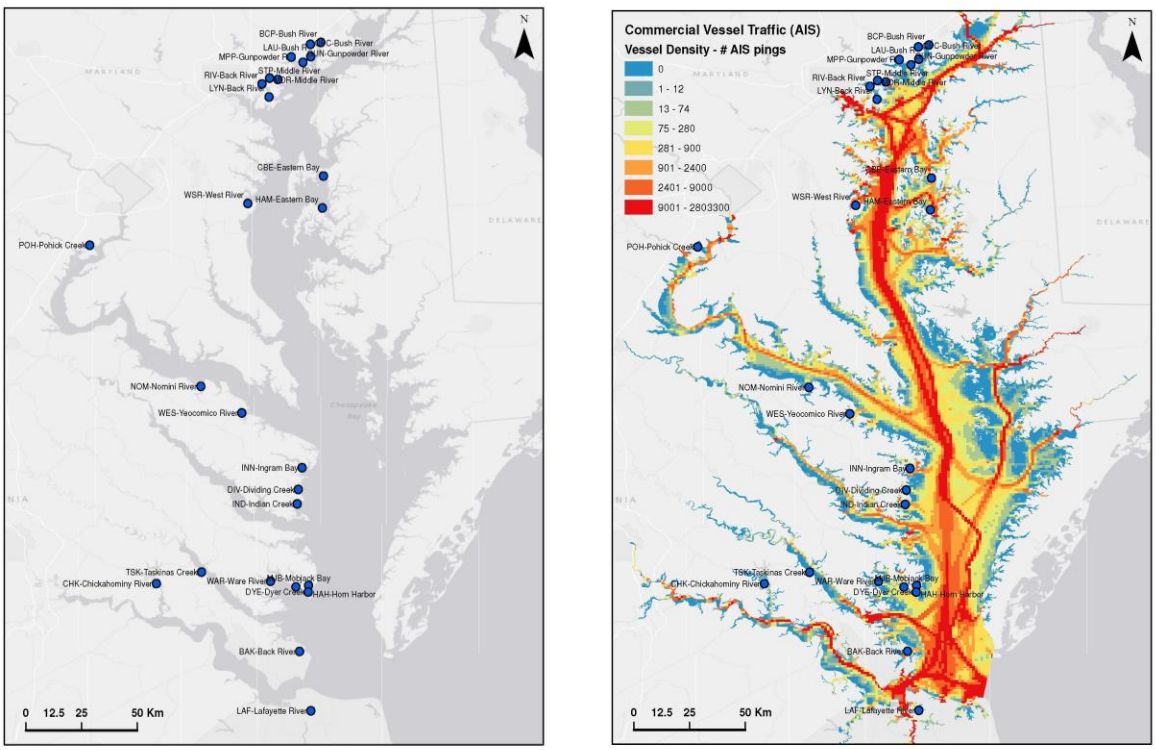

Figure 9. Distribution of long-term water quality monitoring stations in Chesapeake Bay used in analysis of turbidity patterns (L). Commercial vessel traffic density in relation to monitoring stations. All stations were in low or no commercial traffic reaches (R).

Turbidity data included in the analysis were from May through September when recreational boating is expected to be prevalent in certain periods (e.g., weekends and holidays) and allow for comparison with other periods in which boating is less prevalent (e.g., weekdays). Most stations had 3 years of data with the exception of 4 MD sites that had 2 years of available data. For stations with more than 3 years of data, we extracted the 3 most recent years. Raw turbidity data were nearly continuous over the 3-year time period (readings every hour). To summarize the information, weekend/holiday and weekday turbidity was averaged across each year from May-Sept, excluding data flagged as suspect when they were greater than 10% of the data. The three years of data were then averaged together for a single weekend/holiday and weekday measure for each site. Due to the fact that monitoring activities were not explicitly designed to evaluate boat wake impacts on shoreline erosion or elevated turbidity, we developed a turbidity index to capture relative change in turbidity between weekends and weekdays averaged over the entire time period examined. This approach was taken to remove all other environmental variables (sediment sources, storms, tidal flow, etc.) out of the measured response, as these variables were assumed to be the same for a station over weekend and weekdays (Figure 10).

Turbidity Index = (mean weekend turbidity - mean weekday turbidity) ÷ mean weekday turbidity

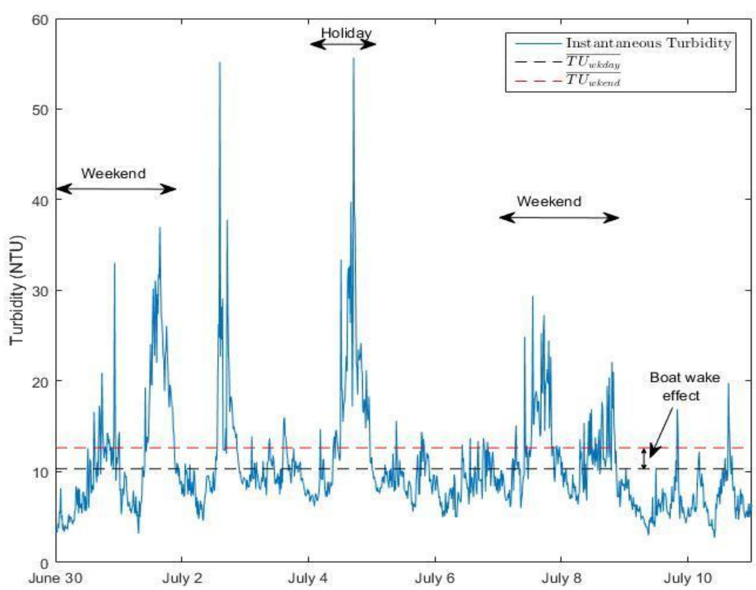

Figure 10. Elevated turbidity associated weekends and July 4th, 2007 in Pohick Creek, Virginia. TU_{wkday} shows the mean turbidity on weekdays in May through September of 2007-2009, and TU_{wkend} is the mean turbidity on weekends and holidays in the same time frame.

We considered four site-specific factors that may influence the magnitude of change in turbidity that recreational boating could elicit at each station, including: distance to navigational depth (m), maximum fetch (m), shoreline armoring (bulkhead, seawall, or riprap revetment), and boating intensity. Analyses of the effect on turbidity of the various factors for each station location were conducted in ArcGIS 10.1 as follows:

- Distance to navigational depth was estimated as the distance (m) from the station to the 1-m depth contour. The 1-m depth contour was chosen as the cut-off for navigable depth to be inclusive of small watercraft (e.g., jet-ski).
- Relative boating intensity was estimated by summing the number of piers and marinas upriver of the monitoring station on both sides of the tidal creek. The number of marinas was multiplied by a factor of 5 to account for the heavy boat use associated with these facilities relative to that of private piers. The Mobjack Bay station was an exception; the waterway was so wide that piers and marinas only on the northern shore (where the station is located) and those upriver tributaries on the northern shore were counted. Information on piers and marinas was extracted from Chesapeake Bay Shoreline Inventory: CCRM-VIMS; http://ccrm.vims.edu/gis_data_maps/shoreline_inventories/index.html).
- Fetch (distance over water that the wind blows in a single direction) was estimated for 16 directions (N, NNE, NE, ENE, E, ESE, SE, SSE, S, SSW, SW, WSW, W, WNW, NW, NNW) originating from each shoreline location and the maximum fetch value was extracted.
- The presence of shoreline armoring at the location of the monitoring station was determined using aerial imagery and the Chesapeake Bay Shoreline Inventory, noted above.
- The effect of the four site-specific factors (boating intensity, maximum fetch, distance to 1-m depth, and presence of armoring) on the relative difference in turbidity over weekends/holidays compared to weekdays was examined using a General Linear Model (GLM). Boating intensity, maximum fetch, and distance to 1-m depth were log-transformed prior to the analysis to meet test assumptions.

Water quality monitoring station characteristics used in the analysis are shown in Table S1. The majority of the stations examined (n=19; 73%) possessed elevated turbidity on the weekends in comparison to weekdays; however the percent difference was low for many of these stations (<5% turbidity difference, 42% of stations with a positive turbidity index). Of the 7 stations that possessed a negative turbidity index (higher turbidity during the week), only 2 stations were more than 5% higher during the week (Figure 11, Table S1). None of the site-specific factors examined were statistically significantly associated with the turbidity index (GLM: $X^2 = 3.14$; p=0.53). On unarmored shores, the turbidity index was higher on average during the weekend than weekday (TI=10.5% ± 15.1%) in comparison to armored shores (TI=4.5% ± 11.3), though this pattern was not significant likely due to high variability between stations.

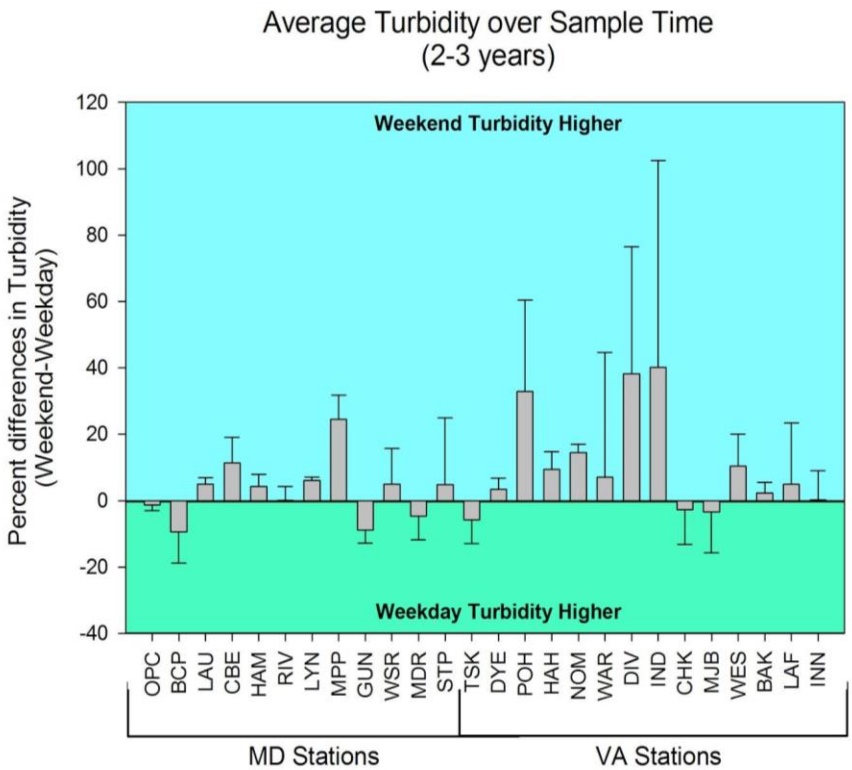

Figure 11. Comparison of weekend turbidity measures in comparison to weekday measures. Positive values indicate relatively higher turbidity during the weekend than the week possibly because of increased recreational boating intensity during the weekend. Negative values indicate relatively higher turbidity during the week than weekend.

The analysis provides support for the hypothesis (shown in previous studies) that boating activity is correlated with increased turbidity in local waterways. However, some waterways did not show an uptick in turbidity on the weekends and holidays. There are four potential explanations for this, and it is possible that more than one explanation is relevant to a given station. First, our measure of boating intensity was imprecise as we have no data on the actual number of boats and personal watercraft that pass by a given station. Some of the small creeks with few piers may actually experience heavy recreational traffic. Second, the turbidity sensor may be located too far offshore to be influenced by shoreline erosion and resuspension so it is missing the signal. Third, all data were not from the same set of years. Since there are many more weekdays than weekends, a storm is statistically more likely to occur on a weekday. In years with multiple storm events, the storm-induced turbidity may be dampening out a weekend-weekday signal. Last, effective shoreline armoring reduces shoreline erosion, dampening the turbidity signal (see Figures 12 and 13). It is likely that in areas with heavy boat traffic, at least a portion of the shoreline has been armored in response to boat wake erosion, creating a circular issue where heavy boat traffic is driving armoring which is dampening the erosion signal, making it appear that boat influence in the waterway is low.

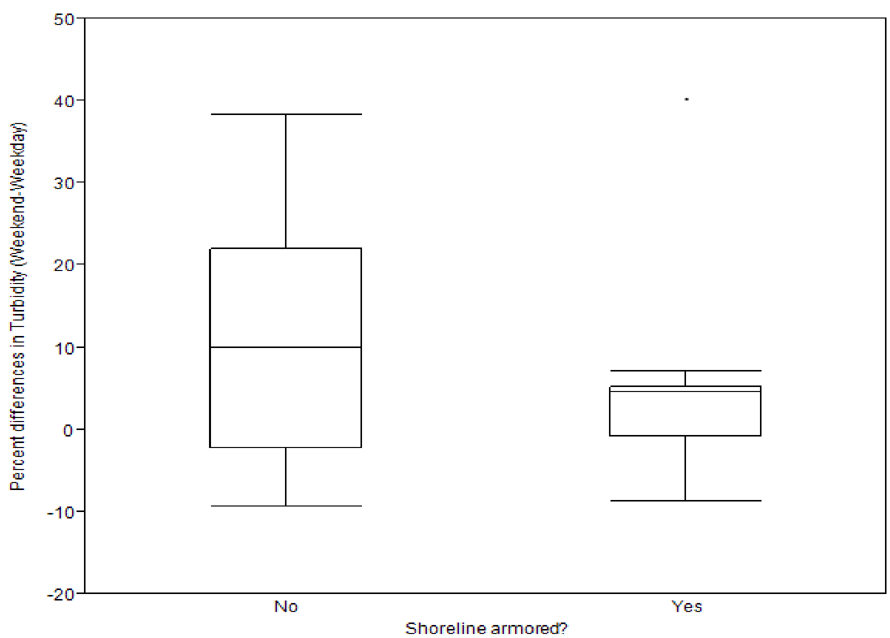

Figure 12. The presence of armoring may be influencing the variability in turbidity measures. Armoring prevents bank erosion, reducing the turbidity signal and is likely a result of a combination of high boat activity and long fetches (see Fig. 13). Armoring potentially can increase bottom resuspension through wave reflection, but this was not apparent in our analysis.

Resolution of the first three issues mentioned above would require intensely detailed data analysis or the collection of new data. However, we have attempted to address the fourth issue in a separate analysis, below.

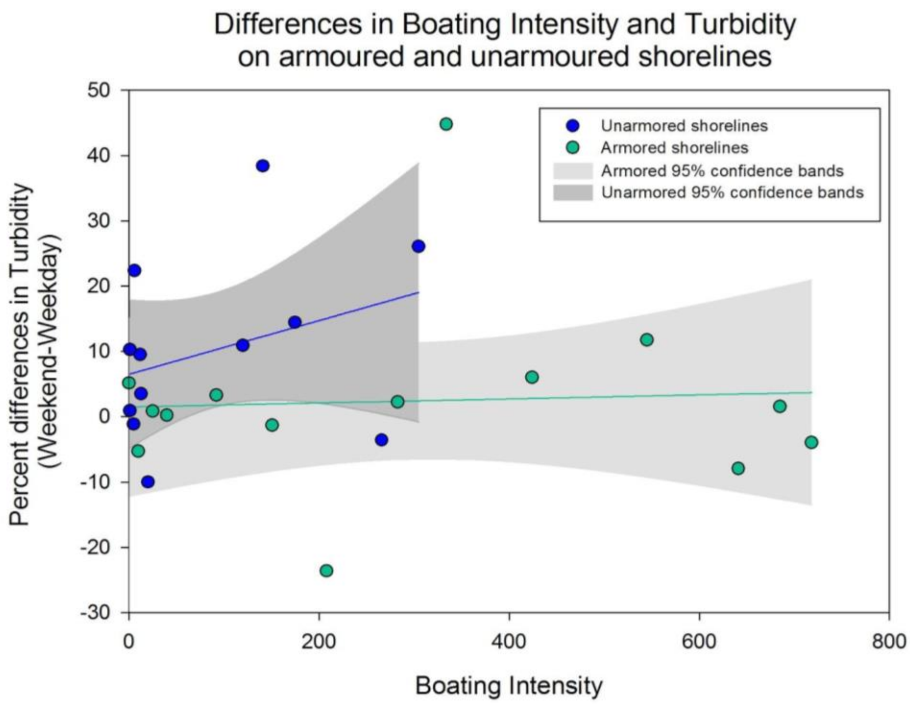

Figure 13. While boating intensity was not significantly related to observed differences in weekend-weekday turbidity, there is some suggestion along unarmored shores that boating may be elevating local turbidity within some waterways. There is uncertainty as to whether armoring is a response to boat wake-induced shoreline erosion, particularly in low wind-wave energy waterways.

Shoreline armoring in response to erosion from boat wakes

Anecdotally, people cite boat wake erosion as a reason for armoring their shorelines. However, it is very difficult to disentangle the effects of boat wakes versus wind waves on shoreline erosion; both shorelines with a long maximum fetch (potential for high wind-wave energy) and high boating intensity (potential for frequent boat wake energy) seem to be armored (Figure 14) which is one indication of active shoreline erosion. One-way ANOVAs of maximum fetch and high boating intensity by shoreline armoring were both significant ($p=0.05$ and 0.03, respectively). Maximum fetch and boating intensity are somewhat correlated with each other, likely because people build more piers on wide creeks and open shorelines. However, this correlation complicates the analysis and a different approach is necessary to try to apportion erosion causes.

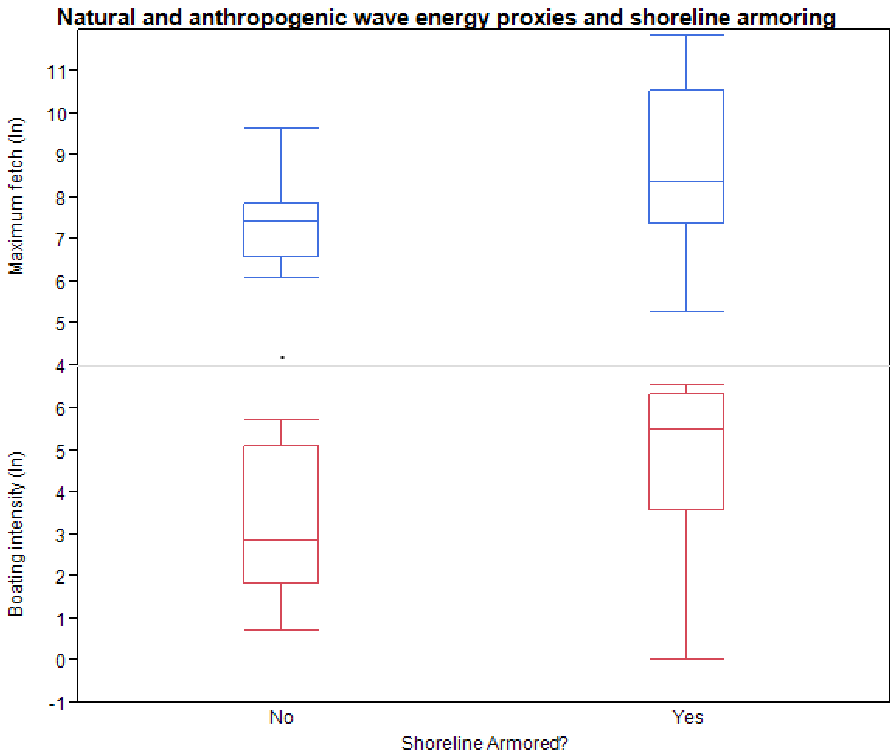

Figure 14. Shorelines with either high boating intensity or high maximum fetch are significantly more likely to be armored. This suggests that both sources of wave energy (one natural and one anthropogenic) are associated with shoreline erosion.

The comparison of recommended shoreline management options on the basis of physical conditions (e.g., fetch, bathymetry) with the 'actual' management approach applied (e.g., bulkhead, riprap, create marsh) can provide some insight into whether shores were armored in areas which are not anticipated to have active erosion. We used a Shoreline Management Model (SMM) that identifies appropriate shoreline management activities on the basis of local physical conditions including fetch, bathymetry, intertidal habitats (e.g., marsh, beach, etc.), riparian condition, and bank condition/height along Virginia's tidal shores (CCRM 2015). The model does not account for boat activity since it is difficult to quantify remotely. If areas that were anticipated to have low erosion are being heavily armored, this is a potential indication of heavy boating activity and boat wake energy. As an example, we compared the recommended shoreline management approaches to existing armoring (bulkhead, riprap revetment) for two tidal creek systems in Virginia known to have relatively high recreational boating (Figures 15 and 16). In both instances, armoring occurred along approximately a quarter of the shorelines with physical conditions conducive to using marsh enhancement/maintenance alone as a means to secure shorelines. This suggests another source of shore erosion, possibly boating, or some concern or interest other than erosion, has resulted in armoring of shores (along with the attendant adverse effects of armoring) in physical settings where it should not be necessary based on physical conditions.

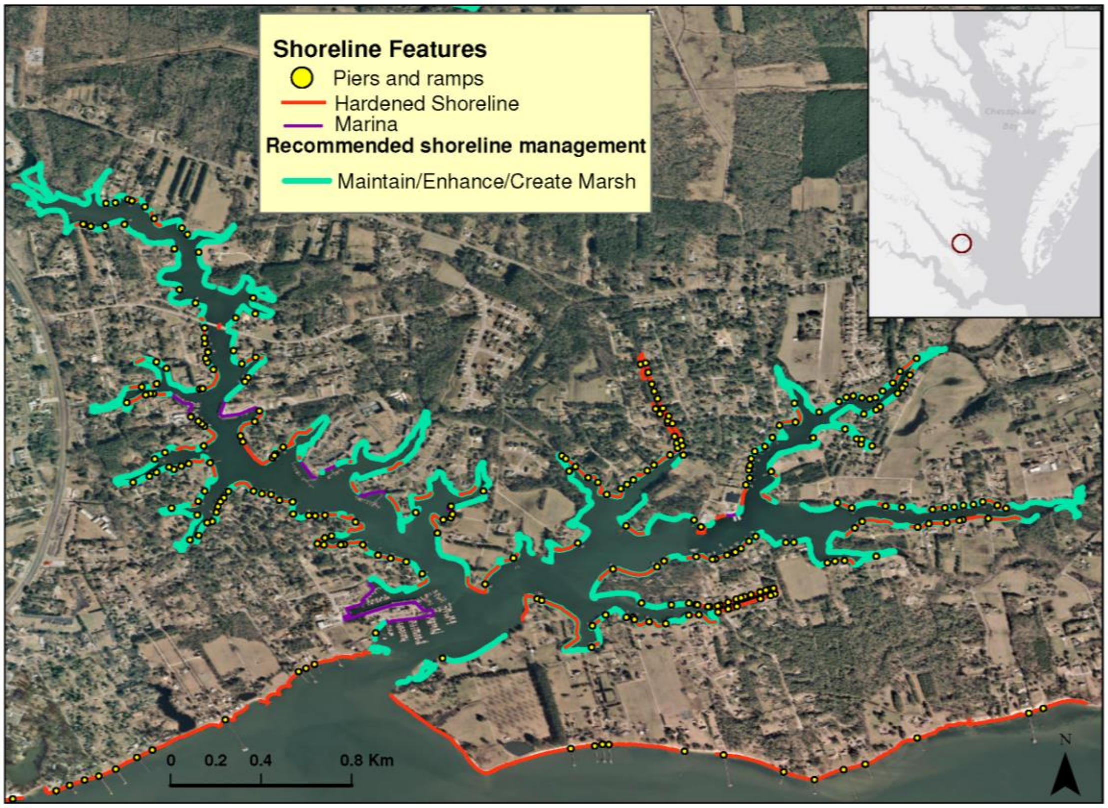

Figure 15. Sarah Creek, VA is a rapidly developing tidal creek with relatively low wind wave energy and relatively high boating pressure including the presence of several marinas. On the basis of physical conditions, the recommended shoreline protection approach is to maintain or enhance marsh for 83% of the shoreline. Of that shoreline, 28% has armoring (revetment, bulkhead) currently.

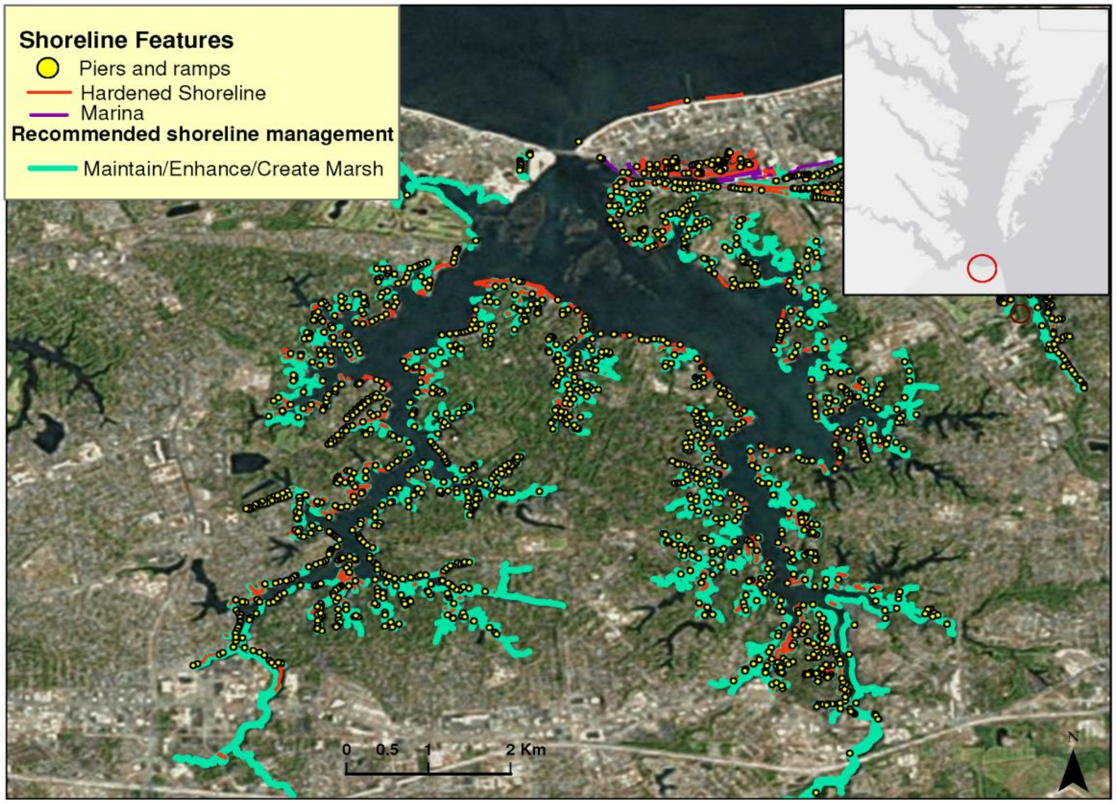

Figure 16. Lynnhaven River, Virginia Beach, Virginia is an example of a shallow-water tidal system under intense development pressure. In this system, very shallow creeks have been dredged to provide residential boat access and there continues to be pressure to dredge additional creeks (Bilkovic 2011). On the basis of physical conditions, the recommended shoreline protection approach is to maintain or enhance marsh for 74% of the shoreline. Of that shoreline, 22% has armoring (revetment, bulkhead) currently.

What is the relative contribution of sediment inputs from boat wake induced shoreline erosion in Chesapeake Bay?

Patterns of elevated weekend turbidity compared to weekday turbidity may be evidence of boat wake wave-induced elevated turbidity. However, there are two potential sources of sediment that may influence nearshore turbidity measures. New sediment may be added to a system from shoreline (bank) erosion or existing sediment may be temporarily resuspended. It can be very challenging to precisely quantify the sediment inputs from shoreline erosion. For example, sand that is resuspended settles more quickly than fines (e.g., mud). Sites with elevated turbidity may be from nearby shoreline erosion of fines, or advection of fines from resuspension or shoreline erosion elsewhere. With sufficient data, the relative significance of each source may be inferred from the sediment composition (grain-size) on the shore and nearshore bottom, tidal excursion, and the presence of armoring. Periodic elevated turbidity along extensively armored shorelines is likely the result of resuspension.

Erosion effects from boat wakes

Case study of Lafayette River, VA

Tidal marsh extent in the Lafayette River, VA has declined over time, concurrent with population expansion. Tidal wetland loss from 1944-1977 was quantified as 588.76 acres (or a 55% loss) and was attributed to the urbanization of the watershed (Priest 1999; Figure 17). Most of the losses are attributed to direct human action (filling or dredging of wetlands, etc.); the Lafayette River was significantly altered during the study period for both residential and commercial purposes. However, the cause of other losses are harder to directly define, but in some instances anecdotal observations suggest that shore erosion and marsh loss can be attributed to boating.

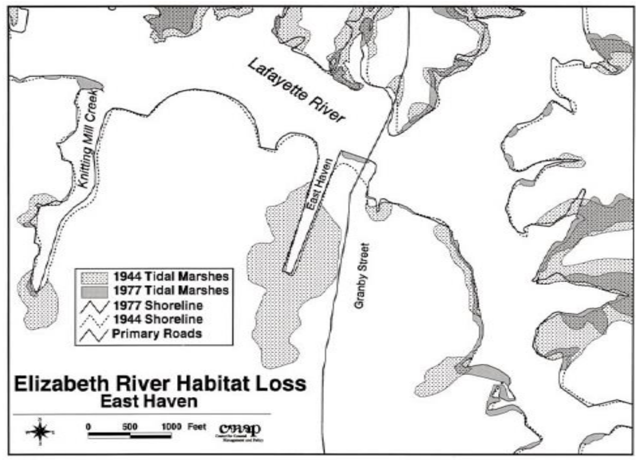

Figure 17. Changes in tidal marshes in the Lafayette River between 1944 and 1977. Map from Priest 1999.

As previously noted, *in situ* shoreline change due to boat wake induced erosion is difficult to assess and quantify. Nevertheless, coastal managers and shoreline property owners are reasonably certain that boat wakes play a role in shoreline erosion, in some cases significantly, especially in narrow, shallow waterways. As one example, Justin Schafer, a lifelong resident and employee of the City of Norfolk, has been observing the shoreline of the Lafayette River his whole life and has spent the last 20 years rowing on the river out of the Norfolk Rowing Center at Lakewood Park (northeast of the East Haven area shown in Figure 18). The club has boats on the water 7 days a week for 9 months of the year and 2-3 times a week in the winter. The club uses jon boats as chase boats and they frequently travel close to shore creating a wash on the fringing marsh and causing an increase in observable turbidity. Mr. Schafer has noticed that the fringe marsh that was about 15 feet wide in the 1990's is now about 2-3 feet wide. The boat operations, observed turbidity, and loss of marsh fringe has all led Mr. Schafer to question the role of boat wakes in shoreline erosion along this reach of the River. As the club is located near the head of navigable tidal waters and has a fetch less than 1/4 mile, there is little opportunity for the generation of wind-driven waves. While other factors including tidal (ebb/flood) erosion and sea level rise have a likely role in the changes that have been seen on the River, Mr. Schafer is convinced that erosion from power boat waves have contributed to the erosion of the shoreline (Justin Shafer, personal communication, September 2016). This observation is further supported in that 31% of the Lafayette River low-energy shoreline has been armored where physical conditions suggest that marsh vegetation alone would be protective (Figure 18).

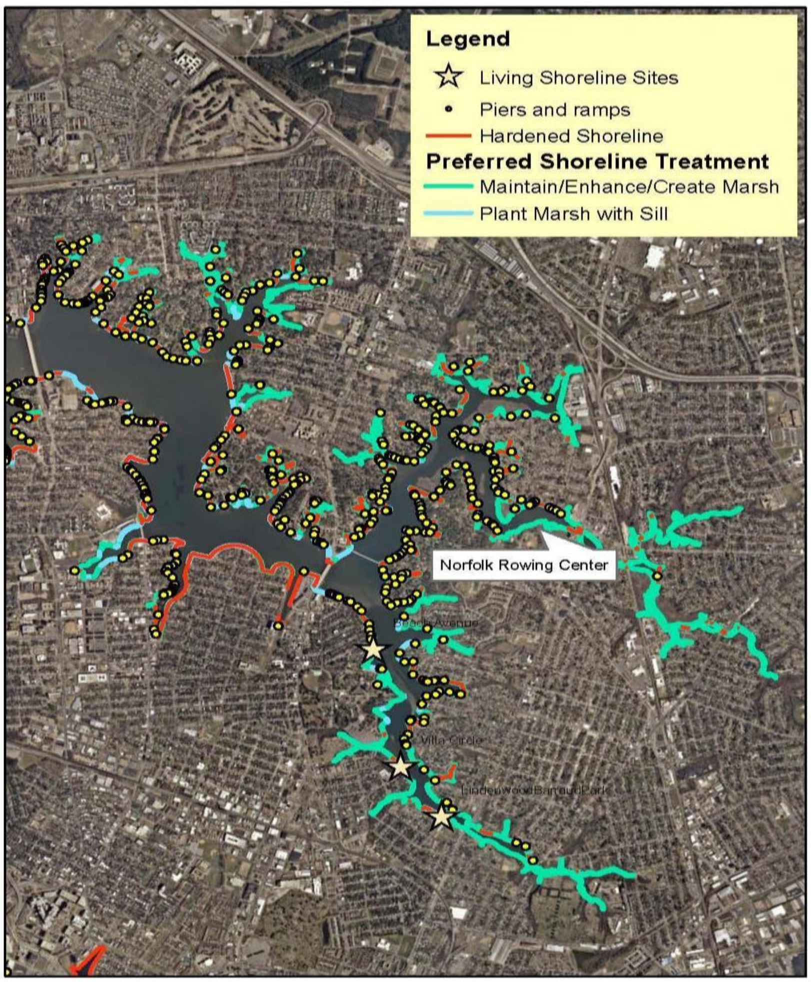

Figure 18. Lafayette River, Virginia. On the basis of physical conditions, the recommended shoreline protection approach is to maintain or enhance marsh for 78% of the shoreline. Of that shoreline, 31% has armoring (revetment, bulkhead) currently.

Section 3: Modeling approaches and data requirements to effectively model the potential effect of boat wake waves on shorelines

The first step in determining the impact of boat wakes on shoreline erosion is to evaluate the boat wake energy occurring along the shoreline and the stability of the shoreline. To determine the appropriate management action, it may be helpful to compare the boat wake energy to the background wind-wave energy (Glamore 2008). In areas where the wave energy attributable to boat wake waves is significantly less than that of wind waves, management actions directed at boat wakes may have limited utility. However, scale of the waves matters as much as the persistence of the impact; a few large boat wake waves can do a great deal of damage compared to persistent small wind generated waves.

There are a number of different measures which have been used for determining the erosive potential of boat wakes for management purposes. Some examples include: wave energy (e.g., Decision Support Tool, Glamore 2008), maximum wave height within the wave train (e.g., Nanson et al. 1994, Parnell and Kofoed-Hansen 2001), and wave speed (e.g., Australian Maritime College 2003). Deciding on an appropriate measure is complicated since every measure is, in some sense, a proxy for the actual impact of the boat wake on the shore. Total wave train energy is a cumulative combination of wave height and wave period for all waves generated by the wake, so it may be the best measure to use, even if it does not entirely capture the erosive force of the waves. Total wave train energy can be estimated from maximum wave height using a derived equation (Glamore 2008). The energy of the total wave train can be modeled for boats based on their size (using Froude Numbers for various boat types), speed and distance from the shore (both measured in areas of interest) following the methods of Glamore (2008) or Świerkowski et al. (2009).

One potential approach to understanding shoreline energetics is through the deployment of wave sensors. This results in an unambiguous determination of wave climate but the results are highly site-specific and it can be challenging to tease apart the impact of wind vs. boats. The most accurate predictive method to estimate shoreline erosion is the application of high-fidelity hydrodynamic models that account for waves, currents, and morphological changes under these effects. Site-specific wave, current, and bathymetric data, if available, can be used to initialize the models and erosion data can be used for calibration and validation. The validated model can then be applied to a large domain. Another approach, perhaps preferable (depending on available expertise), is to estimate values of wave energy based on empirically derived relationships between wind, boat activity and wave climate. Cumulative wind-wave energy can currently be calculated across the entire Chesapeake Bay using either a fetch-based model (such as Wave Exposure Model, or WEMo) or a hydrodynamic model (such as SLOSH, Sea, lake, and overland surges from hurricanes). These models are highly dependent on the quality of available bathymetric data and these data are currently limited for small creeks where the potential for boat-induced erosion is greatest. Such models also require high quality wind data. Sources for wind data include local airports, buoys, and other weather stations.

To estimate boat wake energy experienced at a given location, it is critical to know: 1) the number of boats that pass by on an average day; 2) how big the boats are; 3) how far they are from the shore; 4) how fast each boat is going; and 5) shoreline bathymetry. There is no repository of this information for the Chesapeake Bay; therefore, modeling shoreline boat wake energy over large spatial scales requires making broad assumptions.

Shoreline susceptibility to erosion is difficult to measure on a large scale. There are several proxies which can be used in combination, although this approach has its difficulties. Spatial analysis of shoreline type (hardened, forested, emergent wetland, sand bank, etc.) and shoreline topography can provide a general overview of susceptibility to erosion (Cowart et al. 2011, Currin et al. 2015). There are databases of shoreline armoring for the Chesapeake Bay in the CCRM inventories (http://ccrm.vims.edu/gis_data_maps/shoreline_inventories/index.html) and armored areas can be considered to be stable. Shoreline type is available through the USGS National Land Use Land Cover database but the spatial resolution (30 m) doesn't allow for determination of changes over small spatial scales (Chesapeake Bay Conservancy is currently working to produce a similar product with 1 m resolution). Lidar data resources for VA are available at http://virginialidar.com/index.html and for MD at http://imap.maryland.gov/Pages/lidar.aspx. By mapping areas of concern based on shoreline characteristics (unvegetated shores with high vertical relief would rank highest for erosion concern) against proximity to frequently travelled navigation channels, it may be possible to rank areas in terms of their general susceptibility to erosion.

In an effort to determine the relative importance of boat wakes to erosion on the Atlantic Intracoastal Waterway in NC, Fonseca and Malhotra (2012) applied a dual modeling approach using the freely available WEMo in conjunction with a prototype boat wake model (BoMo). The output of both models include representative wave energy, significant wave height, and shear stress at the seafloor. The value of this approach is that it allows for direct comparisons of wind and boat wake energy (assuming that one has the necessary data concerning number, size and speed of passing boats) and because it provides shear stress values, which can be used to estimate the degree of sediment movement (as a proxy of erosion). However, in order to make this estimation, it is necessary to know sediment grain size and that data is not available on a wide scale. At this time, BoMo is still in the prototype stage and not publicly available.

The most accurate predictive tools for shoreline erosion due to wind- or boat generated waves are hydrodynamic models that account for wave generation, currents, sediment transport, and bed level change (e.g., Delft 3D). Hydrodynamic models require detailed data on bathymetry, wind, tides, and sediment properties.

Section 4: Data gaps and research needs

The dearth of quantified information on the effects of boat wakes and wash on Chesapeake Bay shoreline erosion limits accounting within the Bay Model for contributions of boat-induced erosion to the sediment loads in the Bay. At the same time, any efforts to develop new policies, or enforce existing ones, are hampered by a lack of specific evidence of the extent and magnitude of the adverse effects of boating on shoreline erosion, private property, water quality, habitat or other ecosystem services.

Specific data needs include:

- High-resolution recreational boating intensity information (e.g., the number of vessels that pass by on an average day, vessels types, vessel speeds, vessel traffic patterns).
- Information on trends of recreational boating in small waterways.
- Information on the location, extent and level of enforcement of no-wake zones throughout the Bay.
- Measurements of waves and suspended sediment concentration (SSC); such data, acquired in representative shorelines with high boat activity, can provide insight into the dependency of erosion on wave climate.
- Data on grain size of bottom sediments in all the Bay tributaries and small creeks. Even a simple categorization of sand and fines would be useful.
- High resolution shallow water bathymetry is needed throughout the Bay. If data even exist, most are 50-100 years old in these areas.

Section 5: Management and Policy in Chesapeake Bay

Editor's Note: Citations for this section can be found at the end of this report in Endnote citations: Management and Policy in Chesapeake Bay [1]

Existing and Potential Policy Actions to Reduce Adverse Effects of Boat Wake Waves on Shorelines in the Chesapeake Bay

Cooperation of three states is required to successfully implement a Bay-wide boat wake policy. Virginia, Delaware, and Maryland border the Bay and have the authority to govern boating activity along their shorelines. Localities in each of these states have adopted policies regarding boat wake restrictions. Virginia, a state that follows the "Dillon Rule" of strict construction [2], has expressly delegated authority to the Virginia Department of Game and Inland Fisheries to administer the Commonwealth's boating laws and also has authorized localities to implement boat wake restrictions. Virginia has not established no-wake zones for specific water bodies in its code or regulations. Maryland has established boat speed limits for three water bodies in its state code and granted authority to the Maryland Department of Natural Resources to regulate the operation of vessels, which they did in agency regulations. Some localities also have enacted their own wake restrictions. The Delaware State Code delegates regulatory authority to the Department of Natural Resources and Environmental Control regarding the operating requirements of vessels, and some localities also have enacted their own restrictions. Like Virginia, Delaware has not established no-wake zones for specific water bodies in its code or regulations. In both Maryland and Delaware, localities are permitted to adopt local restrictions on the subject, but only if such restrictions conform to state law. Thus, within each of the three coastal states, some localities have implemented their own boat wake policy, with only Virginia broadly authorizing localities to adopt ordinances to establish no-wake zones based on public safety and erosion concerns. A uniform boat wake policy in the Chesapeake Bay therefore is achievable if each coastal locality were to agree to adopt the same requirements. Cooperation between the states via the Chesapeake Bay Program is an option for them to come to agreement to achieve that, even though the water quality model for the Chesapeake Bay total maximum daily load (TMDL) currently does not distinguish sediment erosion caused by boat wakes when it accounts for sediment from shoreline erosion.

The Regulatory Framework in Virginia, Maryland, Delaware, and Pennsylvania

In Virginia, "any county, city or town may, by ordinance, establish 'no-wake' zones along waterways within the locality in order to protect public safety and prevent erosion damage to adjacent property," with notice to the Virginia Department of Game and Inland Fisheries

(VDGIF) [3]. Although the term "property" is not defined, the context of "erosion damage" indicates that the statute is intended to prevent shoreline erosion, in addition to protecting public safety. However, the VDGIF requires that both public safety concerns and erosion damage concerns be met for a 'no-wake' zone to be established [4]. In other words, erosion concerns alone are not a sufficient basis to seek imposition of a 'no-wake' zone. Several localities have implemented such ordinances for specific areas within their jurisdiction [5]. In addition, the VDGIF's regulations require that motorboats must slacken their speed when approaching or passing vessels, piers, docks, boathouses, and persons in the water or using water skis or surfboards "to the extent necessary to avoid endangering persons or property by the effect of the motorboat's wake." [6]

Additionally, an individual or business in Virginia may apply to their local county board of supervisors to request the placement of a regulatory waterway marker such as a 'no-wake' zone using an application provided by VDGIF [7]. The process is that a county board of supervisors or city council hears the request at a public meeting and decides whether to approve, approve with modifications, or disapprove the request. Once the governing body makes a recommendation, the application is forwarded to VDGIF, which must reach the same decision in order for the 'no-wake' zone to be approved. A law enforcement officer will visually inspect the proposed location to determine whether the position is accurate and report back. The state then makes its final decision, which can be different than the county's decision but rarely is [8].

It is also of interest to note that in Virginia, the federal government has imposed a no-wake zone in Back Bay, just outside the Chesapeake Bay watershed. The no-wake zone is in effect within 150 yards (137 meters) of the shoreline within the Back Bay Wildlife Refuge. The regulation was promulgated by the US Army Corps of Engineers in an effort to protect the environment and increase boating safety (Glass 2006) [9].

Maryland has implemented boat wake and/or speed restrictions by statute (Maryland State Code), state-wide regulation (Maryland Department of Natural Resources' (DNR) regulations), and local regulation (municipal ordinances such as for the cities of Annapolis and Cambridge). The Maryland State Code itself sets speed limits for the Severn River, Seneca Creek, and Monocacy River [10]. The State Code also delegates the regulation of the operation of water vessels to the DNR [11], and clarifies that municipalities may not establish any local regulation which does not conform with DNR's regulations [12].

The DNR defines various speed limits in the Code of Maryland Regulations, including “[r]estricted 6 knots . . . ,” which prohibits a person from operating a vessel more than 17 feet in length “[a]t a boat speed in excess of 6 knots . . . ; or [t]o cause an objectionable or excessive wake” [13]. Additionally, a “[m]inimum wake zone” prohibits a person from “operat[ing] a vessel in excess of the slowest possible boat speed necessary to maintain steerage under prevailing wind and sea conditions not to exceed 3 knots . . .” [14]. The DNR regulations apply these definitions to various areas designated by the regulations, which include regions of the eastern and western shore of the Chesapeake Bay [15]. Some of the restrictions only apply to certain times of the year, such as during boating season, or only on Saturdays, Sundays, and state holidays [16]. DNR cites to provisions of the State Code as authority for adopting the various speed limits [17]. In addition to the Maryland state-imposed speed limits and the DNR’s definitions and restricted areas, municipalities such as Annapolis and Cambridge also have exercised authority to implement speed limits. The Cambridge municipal code states that “[a] person may not propel or navigate any motor-driven watercraft in any of the waters of the city, except the Choptank River, at a speed greater than six miles per hour, nor create a wash which endangers persons or property” [18]. Annapolis imposes broader language that merely requires vessel operators to proceed “in a safe manner with due regard for the safety of persons and property” and includes considerations of “traffic conditions, proximity to other vessels, weather, speed, wake size, size of vessel, condition of the vessel and its equipment, and presence or absence of required safety equipment” [19].

Similarly, the State Code of Delaware delegates regulatory authority to the Department of Natural Resources and Environmental Control (DNREC) with respect to, among other things, the operating requirements of vessels [20]. The DNREC regulations define “slow-no-wake” to “mean as slow as possible without losing steerage way and so as to make the least possible wakes” [21]. The DNREC regulations limit vessel speed to “slow-no-wake” within 100 feet of various structures such as docks and launching ramps, as well as swimmers [22]. Additionally, the City of Dover ordinance similarly restricts speeds under the Silver Lake Bridge and at specified hours [23]. For example, the Town of Smyrna ordinance states, “Power boats shall be operated on Lake Como at ‘no-wake’ speed which shall mean as slow as possible without losing steerage and so as to make the least possible wake [24]. This will almost always mean speeds of less than five miles per hour.” The City of Dover ordinances similarly restrict speeds around the Silver Lake Bridge and during specified hours [25].

While Pennsylvania territory does not front directly on the Bay itself, it is worth noting their policies on boat wakes on the Susquehanna River, since it runs into the upper Bay at the Susquehanna flats near Havre de Grace, Maryland. The Consolidated Statutes of Pennsylvania authorize the Fish and Boat Commission (FBC) to administer and enforce rules and regulations regarding the operation of boats [26]. Among other things [27], FBC regulations define "slow, no wake speed" as the "slowest possible speed of a motor boat required to maintain maneuverability so that wake . . . created . . . is minimal" [28] and establish special regulations by county [29]. The special regulations for Lancaster County establish slow, no-wake speeds for areas in Lake Aldred and the Susquehanna River [30].

In summary, Virginia specifically authorized the adoption of and delegated the implementation of boat speed restrictions to localities. Maryland and Delaware address boat speed restrictions in various authorities – state code, state agency regulations, and localities' ordinances, but specify that local ordinances must conform to state law. Virginia is the only state to expressly recognize shore erosion as a factor to consider in restricting wakes/boat speed, but localities in Maryland and Delaware presumably have the authority to implement restrictions to address both safety and shore erosion concerns since their laws reference "property". Since the Bay states take different approaches to regulating boat wakes and speeds, it would be beneficial to empanel an expert group with representation from the appropriate Bay jurisdictions to develop a recommended uniform boat wake policy for the Chesapeake Bay in order to achieve consistent shoreline protection.

Boat Wake Policies Established For Other Shallow Estuaries

Comparing the management strategy for other shallow water estuaries may be helpful when considering options for establishing a boat wake restriction policy in the Chesapeake Bay. Some examples of similar estuaries are Biloxi Bay in Mississippi, Narragansett Bay in Rhode Island, and Pamlico Sound in North Carolina.

Mississippi State Code designates that the Commission on Marine Resources, through the Department of Marine Resources, shall exercise the duties and responsibilities of the Mississippi Boat and Safety Commission with respect to marine waters [31]. DMR regulations under this authority include the designation of no wake zones generally [32], specific no wake zones [33], and temporary specific no wake zones [34]. Examples of coastal Mississippi localities with boat wake restrictions include the cities of Gautier [35] and Gulfport [36].

The General Laws of Rhode Island authorize the Department of Environmental Management (DEM) to "establish maximum speeds for boats in the public harbors in the state of Rhode Island at five (5) miles per hour, no-wake" [37]. Additionally, the General Laws specifically state that the adoption of an ordinance or local law identical to state laws and regulation is not prohibited

[38], and that subdivisions of the state may make formal application to DEM, after public notice, for special rules and regulations regarding the operation of vessels within the subdivision's territorial limits [39]. As a result, many coastal localities have adopted wake restrictions [40].

The North Carolina State Code authorizes the North Carolina Wildlife Resources Commission, a state agency, to implement wake zone policies [41]. This strategy is part of the Boating Safety Act, the purpose of which is "to promote safety for persons and property in and connected with the use, operation, and equipment of vessels, and to promote uniformity of laws relating thereto" [42]. The Commission is specifically authorized to adopt rules "to prohibit entry of vessels into public swimming areas and to establish speed zones at public vessel launching ramps, marinas, or vessel service areas and on other congested water areas where there are demonstrated water safety hazards" [43]. In addition, a locality can petition the Commission for wake rules for waters within the locality's territorial limits. [44]. The Commission may adopt rules applicable to local areas of water that it finds to be "heavily used for water recreation purposes by persons from other areas of the State and as to which there is not coordinated local interest in regulation" [45]. As a result, almost every coastal county of North Carolina has speed/wake restrictions for specified areas [46].

North Carolina utilizes a state agency to promote uniformity in coastal regulations. This strategy has resulted in boat wake restrictions, set forth in agency regulation, for almost all coastal counties. Capturing such restrictions within the agency's regulations ensures consistent language between the restrictions and increases the public's access to the information. With the goal of reaching similar uniformity across the Chesapeake Bay, oversight and coordination at the state agency level could be a useful tool. A panel of experts from the appropriate Bay jurisdictions could develop a recommended uniform policy for boat wake restrictions that could be used by all of the states surrounding the Bay. Another option would be to pursue an amendment to the Chesapeake Bay Watershed Agreement or an interstate compact between the three states to achieve uniform requirements throughout the Bay. These options are more difficult because there likely will be an unwillingness to undertake amendments to the Chesapeake Bay Watershed Agreement in the near future due to the difficult and time-consuming nature of the agreement process, and a formal interstate compact requires Congressional approval.

Alternative Strategies to Combat Wake-Induced Shoreline Erosion

One alternative strategy to regulating boat wakes and speeds is to impose a ban on motorboats altogether in the Bay. Motorboat bans have been successfully implemented in small lakes and ponds that are isolated waterbodies and are particularly environmentally sensitive. One example of this is Quimby Pond in Maine, where motorboats were banned after excess phosphorous from soil erosion was found to be partially responsible for the deteriorating water quality and algal bloom in the pond [47]. However, despite these successes in small, isolated lakes and ponds, imposing a Bay-wide ban on motorboats is likely not a feasible option, as it would present both a daunting and unpopular task that would be difficult to enforce. This strategy is unlikely to gain support across Virginia, Maryland, and Delaware because these coastal states' economies rely heavily on both recreational and commercial boating – two activities that would be greatly restricted by a motorboat ban.

In addition to motorboat bans and boat wake restrictions, various shoreline armoring strategies also may be used to combat erosion caused by boat wakes. Hard armoring is the use of physical barrier structures in a fixed location to stop wakes and contain the shoreline sediment [48]. These structures include bulkheads, riprap, seawalls, groins, and revetments. Although these structures effectively reduce erosion from boat wakes for that property protected, they also decrease natural habitat and water quality [49] and can lead to erosion of adjoining downdrift shorelines due to deflected wave energy or lack of sediment supplies to maintain the shorelines. Other forms of armoring utilize living shoreline strategies, which are preferred because they strengthen the endurance of the shoreline and build resilience to boat wakes by using natural sediment and vegetation [50].

The Code of Virginia encourages the use of living shorelines as a stabilization strategy and provides for a general permit for localities to use to authorize living shoreline projects [51]. Specifically, the Code designates living shorelines "as the preferred alternative for stabilizing tidal shorelines in the Commonwealth" [52]. The Code calls for the Virginia Marine Resources Commission, in cooperation with the Virginia Department of Conservation and Recreation, the Virginia Department of Environmental Quality, local wetlands boards, and the Virginia Institute of Marine Science to establish the authorization process and create guidance for the permit implementation [53]. Additionally, in 2016 the Virginia legislature provided an exemption from local taxation for approved living shoreline projects [54] and in 2015 they authorized the State Water Control Board to provide loans from the Virginia Water Facilities Revolving Fund to local governments to establish living shorelines or to provide low-interest loans or other incentives to individuals to assist in establishing living shorelines [55].

Similar to Virginia, Maryland also has designated nonstructural strategies as its primary form of shoreline stabilization [56]. Any structural shoreline stabilization measure will only be approved by the Department of the Environment with a showing that nonstructural strategies are not feasible [57]. As a result, Maryland mandates the use of nonstructural strategies such as living shorelines to prevent erosion over any other structural measure. To assist with erosion prevention projects, the state established the Shore Erosion Control Construction Loan Fund, which may be administered to persons, municipalities, or counties to design and construct beach protection projects [58]. Delaware delegated "authority to enhance, preserve, and protect public and private beaches" to the Department of Natural Resources and Environmental Control [59]. This authority includes the responsibility to "prevent and repair damages from erosion of public beaches," which includes constructing and repairing armoring structures [60]. The Department of Natural Resources and Environmental Control regulates all beach protection measures through a permit system [61]. Although the Delaware Code does not specifically address "living shorelines", the Department's regulations state that efforts must be made to use "shoreline erosion control methods that best provide for the conservation of aquatic nearshore habitat, maintain water quality, and avoid other adverse environmental effects," including but not limited to vegetation, revetments and gabions [62]. Structural erosion control measures are allowed where it can be shown that nonstructural measures would be ineffective in controlling erosion; and "[w]hen engineering feasibility and effectiveness considerations are equal" the shoreline erosion control method used must be the one with the least adverse environmental impact [63]. Nonstructural measures also are preferred for shoreline stabilization work in low wave energy areas with wetlands or no significant shoreline erosion, and eroding areas where combinations of structural and nonstructural measures would be a practicable and effective method to control erosion [64]. The regulations for siting and designing new marinas also discourage the installation of bulkheads by requiring evidence that no practicable alternative is available [65]. Furthermore, the regulation also states that any shoreline protection structure must be designed to have minimal adverse effects on the aquatic resources [66]. Discouraging the use of bulkheads and focusing on minimal adverse effects suggest that living shorelines are preferred. The Delaware Living Shoreline Committee has implemented several significant living shoreline projects in the state. The Living Shoreline Committee is a "voluntary group of state, private, and non-profit professionals coordinating research, funding and opportunities for living shoreline projects in Delaware" [67]. Furthermore, funding for shoreline preservation and protection is available through the state's Beach Preservation Fund, which provides bonds for shore stabilization projects [68]. Pennsylvania, by contrast to Virginia, Maryland, and Delaware, has no statute or regulations related to living shorelines.

Summary and Recommendations

Studies outside the Chesapeake Bay and anecdotal evidence along the Bay waterways indicate that boat wakes and wash can cause shoreline erosion and adverse impacts on aquatic fauna and their habitats. Published values generally indicate that recreational vessels within 150 m (~500 ft) of the shoreline can produce waves large enough to result in significant shoreline erosion. It should be noted that vessels traveling further offshore can still produce erosive boat wakes; the magnitude of a vessels' impact is a function of vessel size and speed. A 150 m setback may help to reduce erosion in a channel that is frequented by smaller recreational vessels while a much larger setback may be necessary to combat erosion along waterways used by large commercial vessels. It is also notable that whether, and to what extent, boat wakes will lead to shoreline erosion is dependent on site-specific bathymetry. Vegetated shorelines can effectively attenuate waves in certain settings; however, there is a limit to this capacity particularly if there is frequent exposure to boat wakes. For marsh shorelines, it has been shown that waves as small as 10 cm result in erosion of sediments (Coops et al. 1996), and marsh survival is compromised when waves exceed 30 cm, even 5% of the time (Schafer et al. 2003, Roland and Douglas 2005).

Virginia, Maryland, and Delaware localities have demonstrated authority and willingness to establish wake restrictions, but have not done so comprehensively nor with Bay-wide coordination. North Carolina has an effective approach that provides authority to a state agency to establish wake restrictions and that has resulted in wake restriction policies for almost all of its coastal localities set forth in state regulations. Coordination of wake restrictions between the Chesapeake Bay states, based on the assessment of wake damage in this STAC review, could be achieved via a multi-state agreement or program, and would result in greater policy consistency Bay-wide.

- **Are boat wake induced sediment inputs currently represented in the Bay Watershed Model?**

No, the water quality model for the Chesapeake Bay total maximum daily load (TMDL) currently does not distinguish sediment erosion caused by boat wakes when it accounts for sediment from shoreline erosion. Although it could be an important factor, because we do not have comprehensive data throughout the Bay to accurately distinguish boat wake induced erosion, it is premature to include this factor in the model.

- **Would expanding no-wake zones directed at reducing boat wake impacts be beneficial to the Bay?**

It is likely that in narrow, low energy waterways or along extremely sensitive shorelines with relatively high boating activity, establishing additional no-wake zones would reduce shoreline erosion and related ecosystem impacts. However, there may be challenges to enforcement of additional areas and/or expanded existing no-wake zones. This strategy also involves tradeoffs as no-wake zones result in increased travel times (Fonseca and Malhotra, 2012). An alternative approach to no-wake zones could involve establishing a minimum distance that navigation channels must pass from the shoreline where possible.

- **What other management options might mitigate shoreline erosion from recreational boating?**

In addition to the establishment of no-wake zones, other management options to ameliorate boat wake impacts fall into two categories: 1) shoreline management and 2) management of recreational boating activities.

Shoreline erosion is a natural and necessary process supporting the persistence and resilience of coastal wetlands and in many cases, the best and most ecologically appropriate shoreline management solution is to maintain natural shorelines. In areas where shoreline management treatments become necessary, for instance to decrease erosion and the resulting landward migration of the shoreline and reduce adverse impacts to infrastructure, treatments to protect the shoreline from boat wakes are no different than protection of the shoreline from wind waves. Both Maryland and Virginia encourage 'living shorelines' or nonstructural shoreline stabilization measures as the preferable method for shoreline erosion control, with Maryland requiring them unless they can be proved to be infeasible, and both states providing loan assistance to support their installation. Virginia has a streamlined General Permit process to encourage living shoreline use. In Delaware structural erosion control measures are allowed where it can be shown that nonstructural measures would be ineffective in controlling erosion.

Management of boating activities could include the placement of restrictions on boat size in small bays, creeks, and estuaries (an approach recommended by Glamore (2008), speed limits, navigation buffers from the shore, or motorboat bans. Historically, many narrow creeks have been dredged to allow larger boats into the waterway. Since boat wake energy is positively correlated with boat size, this increases the boat wake energy in these narrow systems. In addition, in narrow waterways boats are passing very close to the shoreline by default.

Minimizing boat size in small waterways would help minimize boat wake exposure. However, anecdotally, small waterway wake-induced erosion is frequently blamed on personal watercraft. There are no data to verify this claim, but if true, limiting boat size in small waterways may not successfully prevent erosion and turbidity. Speed limits have been implemented in Maryland and Delaware primarily due to safety concerns, but the limits functionally reduce boat wake energy and thereby associated erosion. In areas of great environmental sensitivity, motorboat bans, or limits on motor size, have been implemented to eliminate adverse impacts on natural resources.

Primary Recommendations

- Develop predictive models to quantify the relative contribution of boat wake induced erosion to overall shoreline erosion to inform water quality, habitat restoration, and shoreline protection management strategies.

- Collect data necessary to identify shores vulnerable to erosion from boating, and to calibrate and validate predictive models. Data needs identified in this report include recreational boating usage patterns, boat generated wave energy and currents, shallow-water bathymetry, shoreline slope and vegetation characteristics, suspended sediment concentration as a measure of potential erosion, and shoreline erosion rates. Then, develop a definition for, and classification scheme of, small tidal waterways with the greatest likelihood for significant boat wave shoreline erosion.

- Incorporate boat wake induced turbidity and erosion when siting Bay Restoration activities (e.g., wetland/submerged aquatic vegetation (SAV) restoration).

- Investigate the opportunities within the Bay states to implement no-wake zones or other wake reduction strategies (navigation buffers from shore, speed limits, boat size restrictions, boat bans) for addressing shoreline erosion where public safety is not also a concern. In Virginia, current implementation of a no-wake zone requires a finding of a public safety concern and erosion is a second consideration. Empanel an expert group from the appropriate Bay jurisdictions to develop and recommend a uniform boat wake policy in the Chesapeake Bay.

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Endnote citations: *Management and Policy in Chesapeake Bay*

[1] The Virginia Coastal Policy Center wishes to thank W&M Law School students Sarah Edwards, Kristin McCarthy and Emily Messer for their assistance with this section.
[2] In a "Dillon Rule" state, local government authority is limited to those powers that are conferred expressly or by necessary implication by the state legislature. *Board of Supvrs. v. Horne*, 216 Va. 113 (1975); *Commonwealth v. County Bd. of Arlington*, 217 Va. 558 (1977); BLACK'S LAW DICTIONARY, 523 (9th ed. 2009).
[3] Va. Code Ann. § 29.1-744(D) (2001). "No wake zone" is defined in the Code as "operation of a motor boat at the slowest possible speed required to maintain steerage and headway." Va. Code Ann. § 29.1-700.
[4] Based on discussions with VDGIF boating and policy staff, Oct. 2016.
[5] *See, e.g.*, Alexandria, Va., Code § 6-3-9(c) (1986); Bedford County, Va., Code § 10-21 (1999); Chesapeake, Va., Code § 86-9 (1970); Gloucester County, Va., Code § 21-2 (1995); Hampton, Va. Code § 7-26 (2006); Norfolk, Va., Code § 25.2-177 (2007); Virginia Beach, Va., Code §§ 6-111, 6-112.1 (1989).
[6] 4 Va. Admin. Code § 15-390-80. In addition, Virginia Code requires that motorboats slacken speed and control wakes near certain structures and swimmers. Va. Code Ann. § 29.1-744.3.
[7] Va. Code Ann. § 29.1-744(E) (2001).
[8] Based on discussions with VDGIF boating and policy staff, Oct. 2016.
[9] Jon W. Glass, *No-Wake Zone Imposed for Parts of Back Bay*, The Virginian-Pilot Online (June 28, 2006), http://pilotonline.com/news/local/environment/no-wake-zone-imposed-for-parts-of- back-bay/article_ef4a5523-7ffa-54ff-8245-4a5c4dc3ae59.html.
[10] Md. Code Ann., Nat. Res. § 8-725.2, 725.5-6 (2002).
[11] Md. Code Ann., Nat. Res. § 8-704(c) (2007).
[12] Md. Code Ann., Nat. Res. § 8-704(f) (2007).
[13] Md. Code Regs. 08.18.01.03 (2004).
[14] *Id.*

[15] Md. Code Regs. 08.18.07.01-02 (2016).
[16] *Id.*
[17] Md. Code Regs. 08.18.01.00 (1992).
[18] Cambridge, Maryland Code of Ordinances Sec. 19-30(C) (2012).
[19] Annapolis, Maryland Code of Ordinances Sec. 15.10.070 (2016).
[20] Del. Code Ann. tit. 23 § 2114(b)(4).
[21] 7 Del. Admin. Code § 3100-2.1.
[22] 7 Del. Admin. Code § 3100-6.1.2.
[23] Del. Code Ann. tit. 23 § 2121.
[24] Smyrna, Delaware Code of Ordinances Sec. 46-58(h) (1995).
[25] Dover, Delaware Code of Ordinances Sec. 74-122 (2012).
[26] 30 Pa. Cons. Stat. § 5100, 5121.
[27] *See, e.g.*, 58 Pa. Code § 103.3(a) (establishing a "slow, no wake speed" for special areas such as within 100 feet of docks, swimmers, etc.); 58 Pa. Code § 103.16 (mandating a general rule to operate watercraft at a safe speed, establishing that the FBC may set forth specific restrictions of slow, no wake speed by general or special boating regulations, and establishing that the FBC may set numerical (mile per hour) speed limits by general or special boating regulations); and 58 Pa. Code § 107.5(a) (establishing that a slow, no wake speed restriction exists for streams less than 200 feet across, unless FBC special regulations state otherwise).
[28] 58 Pa. Code § 103.2.
[29] 58 Pa. Code §§ 111.1 - .72.
[30] 58 Pa. Code § 111.36.
[31] Miss. Code Ann. § 59-21-111.
[32] 22 Miss. Admin. Code, Pt. 16, Ch. 7.
[33] 22 Miss. Admin. Code, Pt. 16, Ch. 8.
[34] 22 Miss. Admin. Code, Pt. 16, Ch. 9.
[35] Gautier, Mississippi Code of Ordinances Sec. 15-2 ("All bayous and canals within the municipal boundaries…shall be a 'minimum wake' zone.").
[36] Gulfport, Mississippi Code of Ordinances Sec. 2-106 (2015) ("No personnel shall operate any boat or watercraft in the yacht basin at a speed greater than five (5) miles per hour or a speed leaving a noticeable wake, whichever is the lesser.").
[37] 46 R.I. Gen. Laws § 22-9(c) (1977).
[38] 46-22 R.I. Gen. Laws § 14(a) (1977).
[39] 46-22 R.I. Gen. Laws § 14(b) (1977).
[40] Bristol, Rhode Island Code of Ordinances Sec. 8-41; Cranston, Rhode Island Code of Ordinances Sec. 12.24.020; East Providence, Rhode Island Code of Ordinances Sec. 13-86;

Jamestown, Rhode Island Code of Ordinances Sec. 78-27; Narragansett, Rhode Island Code of Ordinances Sec. 82-161; New Shoreham, Rhode Island Code of Ordinances Sec. 9-91; Newport, Rhode Island Code of Ordinances Sec. 12.28.051; North Kingston, Rhode Island Code of Ordinances Sec. 7-80; Providence, Rhode Island Code of Ordinances Sec. 11-9; South Kingstown, Rhode Island Code of Ordinances Sec. 4-23; Tiverton, Rhode Island Code of Ordinances Sec. 14-229; Warren, Rhode Island Code of Ordinances Sec. 10.21; Warwick, Rhode Island Code of Ordinances Sec. 24-6.

[41] N.C. Gen. Stat. § 75A-15 (2006).

[42] N.C. Gen. Stat. § 75A-1 (1959).

[43] N.C. Gen. Stat. § 75A-15 (2006).

[44] *Id.*

[45] *Id.*

[46] *See, e.g.*, 15A N.C. Admin. Code 10F.0302 - .0376. Counties subject to the rules and policies of the Coastal Resources Commission include: Beaufort, Bertie, Brunswick, Camden, Carteret, Chowan, Craven, Currituck, Dare, Gates, Hertford, Hyde, New Hanover, Onslow, Pamlico, Pasquotank, Pender, Perquimans, Tyrrell, and Washington. All of these counties, except Bertie and Gates, have boat speed/wake restrictions.

[47] Me. Rev. Stat. Ann. tit. 12 § 13068-A(16) (2003).

[48] C.S. Hardway, Jr. & R.J. Byrne, *Shoreline Management in Chesapeake Bay*, Virginia Inst. of Marine Sci. (Oct. 1999).

[49] *Id.*

[50] *Id.*

[51] Va. Code Ann. § 28.2-104.1 (2014).

[52] *Id.*

[53] *Id.*

[54] Va. Code Ann. § 58.1-3666, Ch. 610, 2016 Va. Acts of Assembly.

[55] Va. Code Ann. § 62.1-229.5, Ch. 474, 2015 Va. Acts of Assembly.

[56] Md. Code Ann., Nat. Res. § 8-1808.11 (2008).

[57] *Id.*

[58] Md. Code Ann., Nat. Res. § 8-1005 (2004).

[59] Del. Code Ann. Tit. 7 § 6803(b) (2005).

[60] *Id.*

[61] 7 Del. Admin. Code § 5102(1983).

[62] 7 Del. Admin. Code § 7504-4.10.1.2 (2006). "Shoreline erosion control structure or measure" is defined in the regulation as "any activity or structure which provides for stabilization of the shore or bank of a watercourse including, but not limited to, a bulkhead, breakwater,

gabion, groin, jetty, rip-rap revetments, seawall, vegetation, and/or grading of banks." 7 Del. Admin. Code § 7504-§ 1.0 (2006).

[63] 7 Del. Admin. Code § 7504-4.10.1.2 (2006).

[64] 7 Del. Admin. Code § 7504-§ 4.10.1.3.

[65] 7 Del. Admin. Code§ 7501-1.0, -11.4.3 (2006).

[66] *Id.*

[67] Delaware Living Shoreline Committee, http://dnrec.maps.arcgis.com/apps/MapJournal/index.html?appid=371a244682084370a78d0a54c5edb27a#detail (last visited Sept. 23, 2016).

[68] Del. Code Ann. tit. 7, § 6808 (1953).

Table S1. Chesapeake Bay Monitoring station characteristics for analysis of weekend-weekday turbidity changes.

State	Site	Station Name	Turbidity Index	Max Fetch (m)	Number of docks & piers	Number of marinas	Boating intensity	Distance to 1-m depth	Armoring on site	Years of data
VA	BAK	Back River	2.3	35068	278	1	283	3	Yes	2010-2012
VA	CHK	Chickahominy Haven	-2.7	1563	256	2	266	0	No	2006-2008
VA	DIV	Dividing Creek	38.2	1223	141	0	141	46	No	2013-2015
VA	DYE	Dyer Creek	3.5	1326	13	0	13	25	No	2010-2012
VA	HAH	Horn Harbor	9.4	608	12	0	12	38	No	2010-2012
VA	IND	Indian Creek	40.2	63393	289	9	334	129	Yes	2013-2015
VA	INN	Ingram Bay	0.2	45262	665	4	685	150	Yes	2013-2015
VA	LAF	Ashland Circle	4.9	436	25	0	25	13	Yes	2012-2014
VA	MJB	Mobjack Bay	-3.4	23571	703	3	718	170	Yes	2010-2012
VA	NOM	Nomini Bay	14.4	2761	170	1	175	197	No	2007-2009
VA	POH	Pohick Creek	32.8	1895	6	0	6	9	No	2007-2009
VA	TSK	Taskinas Creek	-5.8	66	1	0	1	0	No	2013-2015
VA	WAR	Ware River	7.1	138671	208	0	208	136	Yes	2010-2012
VA	WES	Yeocomico River	10.4	2012	105	3	120	194	No	2007-2009
MD	LYN	Back River - Lynch Point	6.0	4032	621	8	424	40	Yes	2014-2015
MD	RIV	Back River - Riverside	0.0	2571	621	8	40	31	Yes	2014-2015
MD	BCP	Bush River - Church Point	-9.4	4551	165	6	20	15	No	2008-2010
MD	LAU	Bush River - Lauderick Creek	4.9	4147	165	6	0	130	Yes	2005-2007
MD	OPC	Bush River - Otter Point Creek	-1.3	1835	165	6	5	697	No	2013-2015
MD	CBE	Eastern Bay - CBEC	11.4	15269	461	17	1	0	No	2006-2008
MD	HAM	Eastern Bay - Hambleton Point	4.3	13825	564	11	545	136	Yes	2005-2007
MD	GUN	Gunpowder River - APG at Edgewood	-8.8	4548	649	5	641	45	Yes	2003-2005
MD	MPP	Gunpowder River - Mariners Pt Park	24.4	428	649	5	305	0	No	2003, 2005
MD	MDR	Middle River - Cutter Marina	-4.6	197	1191	32	10	0	Yes	2003-2005
MD	STP	Middle River - Strawberry Point	4.9	1788	1191	32	151	31	Yes	2003, 2005
MD	WSR	West River - Shady Side	5.0	1118	683	25	92	5	Yes	2005-2007

Appendix I: STAC Technical Review Request

Evaluating boat wake wave impacts on shoreline erosion and potential policy solutions

The Chesapeake Bay Commission (CBC) requested that STAC conduct a technical review of the relevant information on the potential impacts of boat generated waves on shoreline stability and attendant ecosystem properties, and provide advice on available policy actions to minimize any adverse effects.

STAC was also asked to address several questions related to (*i*) erosion and sediment inputs caused by boat wake waves, (*ii*) existing and needed data to develop best management practices to minimize shoreline erosion from boat wake waves, and (*iii*) political and legal challenges associated with policy actions to reduce boat wakes.

Background:
Salt marshes have weak resistance to wave action (Fagherazzi et al. 2013) and boat wakes have been shown to negatively impact shoreline stability in salt marshes (Castillo et al. 2001). Boat wake impacts include shoreline erosion, vegetative damage, and impacts to the faunal communities (Parnell and Koefoed-Hansen 2001). Although periodic disturbances (compared to wind waves) boat wakes can be a significant source of erosive energy. In one study, it was discovered that although boat wakes only accounted for about 5% of the wave energy at a site, due to their longer height and period, they accounted for 25% of the cumulative wave force (Houser 2010).

Shoreline erosion due to boat wakes is related to the number of boats passing (frequency of the disturbance) and the energy of the total wave disturbance (calculated by speed, vessel size and distance from channel; Glamore 2008). Wake effects are particularly significant in areas of restricted depth and width (FitzGerald et al 2011), such as tidal creeks. In these systems, they can undercut banks and have significant impact to marshes, especially in areas where synergistic impacts may have reduced marsh soil strength.

Review focus areas:

1. Evaluate the state of the science of known effects of boat generated waves on shoreline stability and other ecosystem components (e.g., vegetative habitat, faunal community composition, nearshore TSS concentration).
2. Identify data requirements to effectively model the potential effect of boat wake waves on shorelines
3. Identify data gaps and research needs
4. Determine existing and potential policy actions to reduce adverse effects of boat wake

waves on shorelines. Describe political and legal challenges for designating no-wake zones in Chesapeake Bay. Are there case studies that can be learned from in the bay of no-wake zone designation and/or evaluation of response from management action?

Questions of interest:

1. What is the relative contribution of sediment inputs from boat wake induced shoreline erosion in Chesapeake Bay?
2. Are these types of sediment inputs currently represented in the Bay Watershed Model?
3. Would expanding no-wake zones be beneficial to the Bay?
4. Are there other policy options besides no-wake zones to consider?

Overview of review approach:
To be responsive to the CBC request, we are proposing to form a core review panel to assimilate relevant information in the form of a white paper. Once a draft technical review is complete, the document will be disseminated to additional external reviewers for further input to ensure critical areas of expertise are well-represented.

Proposed Timeline

June 1 2016	Begin technical review
Sept 30 2016	Draft review document completed by core team
October 2016	External review
December 2016	Core Team synthesizes external reviewer comments into final document
January 2017	Internal document review by STAC
February 2017	Final Report released
Spring 2017	Report to Chesapeake Bay Commission