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Donna Marie Bilkovic
Virginia Institute of Marine Science, donnab@vims.edu

Molly Mitchell
Virginia Institute of Marine Science, molly@vims.edu

Jennifer Davis

Julie Herman
Virginia Institute of Marine Science, herman@vims.edu

Elizabeth Andrews

See next page for additional authors

Authors
Donna Marie Bilkovic, Molly Mitchell, Jennifer Davis, Julie Herman, Elizabeth Andrews, Angela King, Pamela Mason, Navid Tahvildari, Jana Davis, and Rachel L. Dixon

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Defining boat wake impacts on shoreline stability toward management and policy solutions

Donna Marie Bilkovic[a,*], Molly M. Mitchell[a], Jennifer Davis[b], Julie Herman[a], Elizabeth Andrews[c], Angela King[c], Pamela Mason[a], Navid Tahvildari[d], Jana Davis[e], Rachel L. Dixon[a,f]

[a] *Virginia Institute of Marine Science, William & Mary, PO Box 1346, Gloucester Pt, VA, 23062, USA*
[b] *NOAA - National Centers for Coastal Ocean Science, 101 Pivers Island Rd, Beaufort, NC, 28516, USA*
[c] *Virginia Coastal Policy Center, William & Mary Law School, PO Box 8795, Williamsburg, VA, 23187, USA*
[d] *Department of Civil and Environmental Engineering, Old Dominion University, Norfolk, VA, 23529, USA*
[e] *Chesapeake Bay Trust, 60 West Street, Annapolis, MD, 21401, USA*
[f] *Chesapeake Research Consortium, 645 Contees Wharf Road, Edgewater, MD, 21037, USA*

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ABSTRACT

Coastal economies are often supported by activities that rely on commercial or recreational vessels to move people or goods, such as shipping, transportation, cruising, and fishing. Unintentionally, frequent or intense vessel traffic can contribute to erosion of coastlines; this can be particularly evident in sheltered systems where shoreline erosion should be minimal in the absence of boat waves. We reviewed the state of the science of known effects of boat waves on shoreline stability, examined data on erosion, turbidity, and shoreline armoring patterns for evidence of a response to boat waves in Chesapeake Bay, and reviewed existing management and policy actions in Chesapeake Bay and nearby states to make recommendations for actions to minimize boat wake impacts. In the literature, as well as in our analyses, boat wake energy may be linked to elevated turbidity and shoreline erosion, particularly in narrow waterways. In Chesapeake Bay, three lines of evidence suggest boat waves are contributing to shoreline erosion and poor water clarity in some Bay creeks and tributaries: 1) nearshore turbidity was elevated in many waterways during periods of expected high boating activity, 2) armoring was placed along about a quarter of the low energy shorelines of three examined tidal creeks that are exposed to relatively high boating pressure, and 3) 15% of the shorelines we examined throughout the Bay (9000 km) are low energy shorelines that are experiencing high erosion (≥ 0.3 m/yr) that cannot be attributed to wind wave energy. Still, there remain significant data gaps that preclude the determination of the overall contribution of boat waves to shoreline erosion throughout the Bay, notably, shoreline erosion data in low energy waterways, recreational boating traffic patterns, and nearshore bathymetry. Interim protective measures can be (and have been) applied in high risk waterways, such as small, low energy waterways that have high recreational boating activity, to help reduce shoreline erosion. Policy options used in Bay states and elsewhere include setbacks from the shore, wake restrictions, and speed restrictions; other more restrictive policies may include prohibition on boats of a certain size or limiting the number of passages. Finally, a systems-approach to boat wake impact management using uniform boat wake policies is likely to be the most effective for consistent shoreline protection.

1. Introduction

Human pressures in coastal systems are extensive as a large proportion of the global population inhabits these areas and utilizes the natural resources they provide (McGranahan et al., 2007). The magnitude of some human impacts are well understood, such as those caused by land development and occupation along the coastline. The magnitude of other impacts are poorly quantified, such as the implications of the intensive vessel traffic that supports our maritime and recreational pursuits. Commercial and recreational boating activities

* Corresponding author.
E-mail addresses: donnab@vims.edu (D.M. Bilkovic), molly@vims.edu (M.M. Mitchell), jenny.davis@noaa.gov (J. Davis), herman@vims.edu (J. Herman), eaadrews@wm.edu (E. Andrews), amking02@wm.edu (A. King), mason@vims.edu (P. Mason), ntahvild@odu.edu (N. Tahvildari), jdavis@cbtrust.org (J. Davis), rldixon@vims.edu (R.L. Dixon).

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are often prominent contributors to a coastal economy, resulting in intensive and frequent vessel traffic. This is especially true when the region is a major route for shipping, transportation, and/or cruise industries. In 2013, the Ocean Economy for U.S. coastal states comprised about 2.2% of both U.S. GDP and employment, a larger share of the U.S. economy than other major natural resource industries, including farming, food products, oil and gas extraction, and forest products. Marine Transportation, the movement of people and goods across oceans and Great Lakes, generated $59 billion in annual total GDP (Kildow et al., 2016). As coastal communities continue to struggle to address rapidly eroding shorelines and increasing nearshore turbidity, more attention has been given to the contribution of boat-generated waves to these issues.

In general, boat wakes have been shown to erode shorelines (e.g., Castillo et al., 2000; Bauer et al., 2002), scour the bottom of the shoreface, and decrease water clarity through turbulence (e.g., U. S. Army Corps of Engineers (USACE) 1994; Asplund 1996). Boat wakes negatively affect coastal systems through two general processes – turbulence and bank erosion. Turbulence causes elevated suspended sediment concentrations which can lead to degraded oyster reefs, light-limitation of submerged aquatic vegetation, and can alter prey resources for fish (e.g., Liddle and Scorgie, 1980; Grizzle et al., 2002; Koch, 2002; Koch et al., 2006; Hallac et al., 2012; Whitfield and Becker, 2014; Campbell, 2015). Bank erosion can cause undercutting, marsh loss or degradation, and disturbance to faunal communities (Parnell and Koefoed-Hansen, 2001).

Boat wake energy is event-dependent and influenced by vessel length, water depth, and boat speed (Sorensen, 1973; Glamore, 2008). While each boat passage generates a complex series of waves with unique characteristics, wake wave height can be reasonably predicted by vessel speed (Sorenson, 1973; Zabawa and Ostrom, 1980; Fonseca and Malhotra, 2012). Wakes tend to be most harmful in shallow and narrow waterways where wake energy has limited ability to dissipate with distance from the vessel. Published values of wave decay after boat passage indicate that even small (16 ft) recreational vessels traveling within 150 m (~500 ft) of shore are capable of producing erosion – causing waves (Sorenson, 1973; Zabawa and Ostrum, 1980). Although periodic in comparison to wind waves, boat wakes may be the primary source of erosion in areas with low wind wave energy due to their greater heights and longer periods. For example, on the Savannah River, boat wake energy contributes less than 5% of the total wave energy, yet it accounts for 30% of the wave force impacting shorelines (Houser, 2010). Adding to the complexity, the relative amount of wave energy attributable to boats versus wind may vary temporally because the intensity of boating activity may vary throughout the year (Zabawa and Ostrom, 1980; Maynord et al., 2008). The frequency of vessel passage influences the overall amount of boat wake energy impacting a given shoreline, with highly traveled waterways more likely to experience boat wake-induced shoreline erosion than those that are less frequently traveled (Zabawa and Ostrom, 1980; Glamore, 2008).

Waves can be attenuated by shoreline vegetation in certain settings; however, frequent exposure to boat wakes may limit the capacity of these shorelines to mitigate erosion. Vegetated marsh shorelines can erode when regularly exposed to 10 cm waves (Coops et al., 1996); when waves are greater than 30 cm for as little of 5% of the time, marsh survival was shown to be compromised in the Gulf of Mexico (Schafer et al., 2003; Roland and Douglas, 2005). Therefore, even infrequent wake impacts may lead to erosion and habitat loss. Several studies in coastal systems have examined the relationship among wave heights, vessel speed, and distance offshore for a variety of typical vessel types and sizes. Generally, for speed ranges of 11–50 km/h within 150 m from shore, maximum wave heights between 10 and 50 cm occurred, suggesting erosion is likely in most cases (Table 1).

The Chesapeake Bay is a major maritime center along the Eastern Seaboard that supports a myriad of marine transportation sectors including military, cargo, transportation, cruise, fisheries, and recreational boating. There are several major ports, most notably, Baltimore and Port of Virginia (includes Norfolk, Portsmouth, Newport News) which handle significant cargo tonnage. There is a large military presence in the Chesapeake Bay, including the Navy, Coast Guard, and Marines Joint Forces, as well as major ship building industries that make use of Chesapeake Bay waterways. In addition to commercial traffic, there are at least 500,000 registered recreational vessels in the Chesapeake Bay (Virginia Department of Game and Inland Fisheries, data from 1997 to 2012; Environmental Finance Center, University of Maryland, 2013). Boating activity has intensified with increasing Bay populations and improved access to waterways from the growing number of private and public piers. Recreational boating can be most concerning for shoreline erosion because of the ability of these small (or shallow-draft) vessels to pass frequently near the shores, often at high speeds.

Table 1
Measured wave heights at varying vessel speeds and distances extracted from Zabawa and Ostrum (1980) for Chesapeake Bay and Sorenson, 1973 for Oakland Estuary, CA. Wave heights of 0.3 m or less have been shown to erode vegetated shores or compromise marsh survival (Coops et al., 1996; Schafer et al., 2003; Roland and Douglas, 2005). Table modified from Bilkovic et al., (2017). * indicates planing hull, ** indicates displacement hull.

Boat type	Distance from sailing line (m)	Speed of boat travel (knots ((km hr^{-1}))	Max wave height (m)
26’ (8 m) Recreational boat: Uniflight*	100	10 (19)	0.41
	100	26 (48)	0.29
	150	10 (19)	0.37
	150	27 (50)	0.21
16’ (5 m) Recreational boat: 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) Commercial boat: Tugboat**	30	6 (11)	0.2
	30	10 (19)	0.5
	150	6 (11)	0.1
	150	10 (19)	0.3
263’ (80 m) Commercial boat: Barge**	150	10 (19)	0.2
	300	10 (19)	0.1

The Chesapeake Bay region has experienced extensive development over the course of hundreds of years, currently supporting about 18 million inhabitants, which has caused eutrophication, hypoxia, and coastal habitat and species loss. In response to growing pollution issues, the Chesapeake Bay Program (CBP) - a partnership between the states of Maryland, Virginia, Pennsylvania, New York, West Virginia, Delaware, the District of Columbia, federal agencies (represented by the U.S. EPA), and the Chesapeake Bay Commission - was formed in 1983 to guide restoration of the Bay. The Chesapeake Watershed Agreement (2014) designates a series of goals including habitat (tidal marsh, submerged aquatic vegetation) and water quality restoration that could be adversely affected by boat wave-induced erosion. Other Bay Agreement goals may inadvertently exacerbate the issue, such as the goal to increase public access to the Bay waterways.

Here, we: (1) evaluate existing and new data for evidence of enhanced turbidity, high erosion, or enhanced shoreline armoring in response to boat-generated waves in Chesapeake Bay and identify data gaps, and (2) review existing management and policy actions in Chesapeake Bay states and make recommendations for actions to help minimize potential boat wake impacts.

2. Methods

Comprehensive information on boating activity and shore erosion driven by boat wakes is not available for Chesapeake Bay. However,

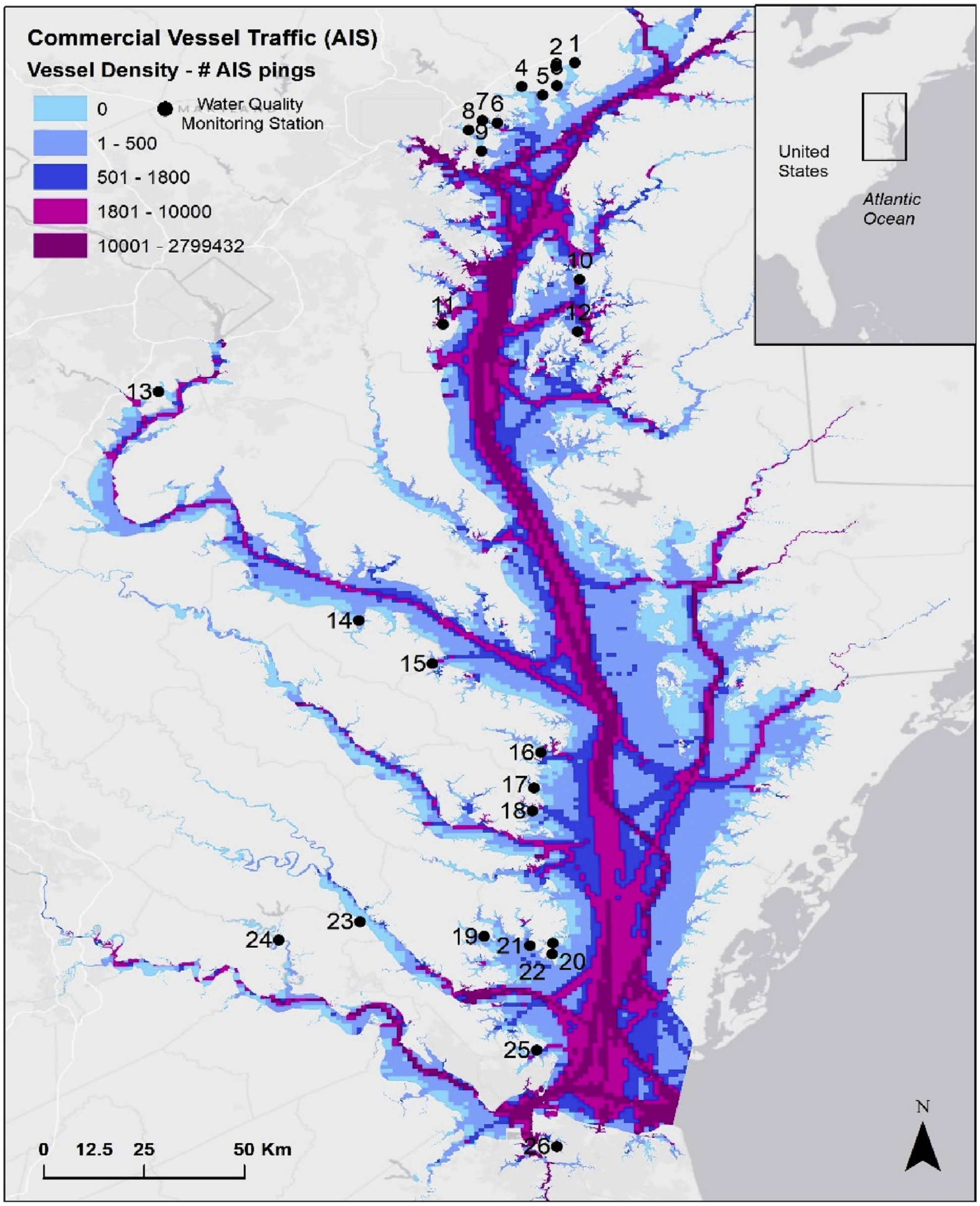

Fig. 1. Distribution of long-term water quality monitoring stations in relation to commercial vessel traffic patterns in Chesapeake Bay. Figure modified from Bilkovic et al., (2017).

surrogate measures can be useful as indicators of the potential for boating to be contributing to shore erosion. Using existing data from Chesapeake Bay, we examined *1)* the relationship between recreational boating activity and nearshore turbidity; *2)* the occurrence of high erosion along shorelines with low wind energy (small fetch), and; *3)* the occurrence of shoreline armoring along shorelines with low wind energy. We acknowledge the limitations in these analyses because the data used were not collected to specifically address boat wake impacts; however, our objectives were to use available data to explore potential trends and identify data gaps.

2.1. Elevated turbidity and recreational boating

We investigated the relationship between nearshore turbidity and recreational boating activity using data from 26 fixed, shallow water monitoring stations at which continuous water quality data, specifically turbidity, were available between the years 2003–2015 (www.vecos.org, www.eyesonthebay.net, Virginia N = 14; Maryland N = 12 stations; Fig. 1). The number and location of continuous water quality monitoring stations have varied as research needs and available resources have changed; stations are often located for a period of 3 years and then moved to another waterway. At each station, water quality parameters including depth, water temperature, salinity, pH, chlorophyll, turbidity, and dissolved oxygen are collected at 15-min intervals using YSI 6600 data sondes. In our analyses, we included monitoring stations with 2–3 years of consecutive data, near to shore (within ~50 m of shore and attached to a pier or dock), and on shore reaches with minimal exposure to commercial vessel traffic and/or wind waves to better isolate the effect of boat waves on nearshore turbidity patterns. We used ship traffic pattern data collected by the U.S. Coast Guard through the Automatic Identification System (AIS) to determine the level of commercial vessel traffic. The 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 1-min intervals, with each record (ping) representing a ship's location every minute. We determined the total number of pings recorded in the vicinity of the stations from 2009 to 2014 and identified stations 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 1800 pings during the 6-year record) to be used in the analysis (spatial data source: Bilkovic et al., 2016a; and the Marine Cadastre http://marinecadastre.gov/ais) (Fig. 1).

In the Chesapeake Bay there is generally higher recreational boating activity on weekends (Saturday, Sunday) and major warm-weather holidays (i.e., Memorial Day, July 4th, Labor Day) than during weekdays (Monday, Tuesday, Wednesday, Thursday, Friday). As a result, our analytical approach involved comparing levels of turbidity during the week with the weekend and holidays (henceforth referred to as "weekend"). We limited the analysis to include turbidity data from May through September, when recreational boating is most prevalent. We used the 3 most recent years of consecutive data recorded in 15 min intervals for each station (except 4 Maryland stations which had 2 years of data). For each site, we estimated mean turbidity for weekend and weekdays during the three years examined. To control for other environmental factors (sediment sources, storms, tidal flow, etc.) that may affect an individual station's turbidity measures, we developed a turbidity index to represent the relative change in turbidity between weekends and weekdays (Equation (1), Fig. 2).

$$\textit{Turbidity Index } (TI) = (\textit{mean weekend turbidity} - \textit{mean weekday turbidity}) \div \textit{mean weekday turbidity} \quad (1)$$

In addition to the primary factor of interest, boating intensity, we included three potential moderating factors on the relative change in turbidity in the analysis: distance to navigational depth (m) from station, maximum fetch (m), and presence of shoreline armoring (bulkhead or riprap revetment). We conducted all estimates of factors for station locations in ArcGIS v. 10.4. We used the total number of piers and marinas upriver of the stations as a proxy measure for relative boating intensity; marinas tend to concentrate boat activity compared to private piers, so these were weighted by a factor of 5 (data source: Chesapeake Bay Shoreline Inventory, CCRM-VIMS, 2016). We defined navigational depth as 1-m to be inclusive of small watercraft (e.g., jet-ski), and estimated the shortest linear distance (m) from the station to the 1-m depth contour. We used maximum fetch as a surrogate for relative wind wave energy. We determined maximum fetch by estimating fetch, the distance over water that the wind blows in a single direction, for 16 compass directions originating from each station location and taking the largest value (i.e., longest distance). Presence or absence of armoring along the shoreline near the station was determined using aerial imagery and the Chesapeake Bay Shoreline Inventory (CCRM-VIMS, 2016). We then examined the effect of the 4 factors on the turbidity index (TI) using generalized linear models (GLM) with a Gaussian distribution, coupled with Akaike information criterion (AIC) model selection. Boating intensity, maximum fetch, and distance to navigational depth were log-transformed prior to the analysis to meet test assumptions. All possible combinations of the variables were assessed using AICc, which ranks models based on the principle of parsimony (Johnson and Omland, 2004). The top models were based on ΔAICc values < 2, and ΔAICc values between 3 and 7 were considered to be models with moderate but less support (Burnham and Anderson, 2002).

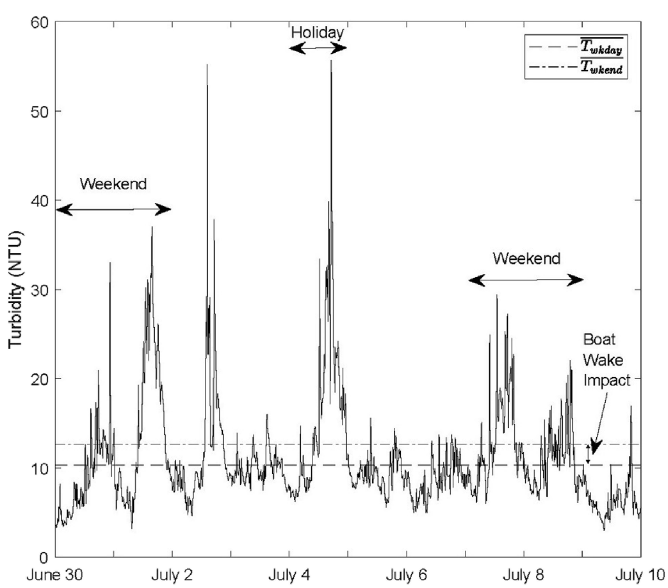

Fig. 2. Elevated turbidity associated with weekends and July 4th, 2007 in Pohick Creek, Virginia. T_{wkday} shows the mean turbidity during weekdays from June 30 to July 10, 2007. T_{wkend} is the mean turbidity during weekends and holidays in the same time frame. Figure modified from Bilkovic et al., (2017).

2.2. Occurrence of high erosion in low energy settings

Absent data on boating activity in relation to shoreline erosion rates, those shorelines that may be experiencing boat wake-induced erosion can be targeted for further study by comparing wind energy (fetch) with shoreline erosion rates. A shoreline with low fetch exposure would not typically have high erosion rates. If this does occur, another driver for the erosion - often boat wakes - is the likely cause. To evaluate the extent that this occurs in Chesapeake Bay, we identified shores potentially experiencing erosion from boating by selecting shorelines with low fetch (< 1000 m) and high erosion (≥0.3 m/yr) using GIS (ArcGIS v. 10.5). We determined maximum fetch for points every 50–100 m along all of the Virginia and Maryland tidal shorelines and used those values as the fetch along that reach of shoreline.

We transferred existing shoreline erosion rate data to the same shoreline as our estimated fetch data to facilitate spatial analyses. For both states, erosion rate data (distance/time) were previously developed using digital shoreline analysis system (DSAS) software 2.0 (Maryland) and 4.2 (Virginia) (Thieler et al., 2003; Thieler et al., 2010; https://woodshole.er.usgs.gov/project-pages//; DSAS). For Maryland, erosion rate data were calculated for transects spaced 20 m apart for a series of shorelines in varying time spans, with most occurring in some interval between 1942 and 1995 (MGS, 2003). For Virginia, erosion rate data were taken from the Shoreline Studies Program shoreline evolution database 1937–2009 (Hardaway et al., 2017), which calculated the erosion rate using the linear difference on transects between 1937 and 2009 shorelines. We then summarized the linear distances and percentages of Chesapeake Bay shorelines with low fetch exposure and high erosion rates.

2.3. Occurrence of shoreline armoring in low energy settings

Shoreline erosion can be caused by wind waves, boat wakes, or a combination of the two. Disentangling these effects is challenging, requiring site specific data on vessel traffic patterns combined with wind wave erosion models. Armoring on shorelines exposed to low wind wave energy can be indicative of erosion from other sources. In some instances, property owners have pointed specifically to boat wake erosion as a reason to armor their shorelines (Smith et al., 2017).

To evaluate the possibility that shorelines are being armored in areas not anticipated to have active erosion from wind waves, we compared a recommended shoreline management option for eroding shores on the basis of physical conditions with the actual management approach applied (e.g., bulkhead, riprap revetment, created or enhanced marsh) within three low wind wave energy tidal creeks in Virginia known to experience relatively high recreational boating pressure - Lynnhaven River, Virginia Beach; Lafayette River, Norfolk; Sarah Creek, Gloucester Point. Sarah Creek is a rapidly developing tidal creek with relatively low wind wave energy and relatively high boating pressure including the presence of several marinas. Lafayette River is an urban tidal creek in Norfolk, Virginia. Lynnhaven River is a highly developed shallow-water tidal river. 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). We used a geospatial Shoreline Management Model (SMM), Version 4.0 that identifies appropriate shoreline management approaches along Virginia's tidal shores using a suite of parameters that can be mapped and measured using GIS including fetch (a surrogate for wind wave energy), nearshore bathymetry, intertidal habitat (e.g., marsh), riparian features, bank height, and permanent structures within the riparian zone (CCRM, 2015). The SMM is based on decision tree logic and guidance that has been vetted through the Virginia Institute of Marine Science Wetlands Advisory Program and state locality shoreline management boards over many years (https://www.vims.edu/ccrm/ccrmp/bmp/decision_tools/index.php). The model extracts information from eleven spatial datasets containing attributes describing the shoreline. Using ESRI's ArcGIS ModelBuilder and scripts written in Python, a series of model pre-steps compiles the datasets into one linear shapefile. The model calls for specific data from the shapefile as a way to evaluate on-site condition, and follows the logic pathways of the decision tree to yield the final model output of shoreline best management approach recommendations for estuarine and tidal fresh shorelines, which is exported as a shapefile. All processing steps occur in ESRI's ArcMap, ArcGIS version 10.4 and 10.5 software.

Shoreline best management approach options in the SMM include three living shoreline treatments: 1) to create a new marsh or to maintain or enhance an existing marsh (maintain/enhance/create marsh), 2) create marsh with a stabilizing sill structure fronting the marsh, or 3) maintain beach or place offshore breakwaters with beach nourishment, and an armoring treatment: riprap revetment. Living shoreline approaches address erosion by providing protection, restoration, enhancement, or creation of vegetated shoreline habitats through strategic placement of plants, stone, sand fill and other structural or organic materials, while maintaining the connection between aquatic and terrestrial habitats (Bilkovic et al., 2016b). In Virginia, living shorelines are the preferred shoreline management option for tidal shorelines where appropriate (Code of Virginia §28.2–104.1). The SMM is a tool to help identify shoreline reaches that are appropriate for the preferred management approach of living shorelines. A recommendation to maintain/enhance/create marsh is applied to shorelines with low wind wave energy (low fetch, 0–0.8 km) where marshes can be established or maintained naturally without protection, no physical structures near the shoreline that would prohibit bank grading to achieve proper tidal elevations for marsh plants, and shallow water (no greater than 1 m deep up to 10 m from shore). A stabilization structure fronting the marsh (e.g., rock sill or oyster reef) may be required in shallow water, moderate wind wave energy environments (fetch between 0.8 and 3.2 km) to allow the marsh to become established. Armoring (riprap revetment) is recommended for moderate (fetch between 0.8 and 3.2 km) to high (fetch > 3.2 km) wind wave energy, where the nearshore is deep, and/or the shoreline has permanent physical structures that would prohibit bank grading. For each tidal creek, we documented the occurrence of shorelines that have been armored (bulkhead or riprap revetment) while having a recommended shoreline management approach to maintain/enhance/create marsh that is indicative of a low wind wave energy shoreline. In addition, we extracted information provided by property owners from the Virginia Shoreline Permit Database (1993–2010; CCRM, 2019) on their purpose for applying for a permit to armor their shoreline; listed reasons include erosion control, marina development, commercial construction, water access, yard improvement, aesthetics, and other.

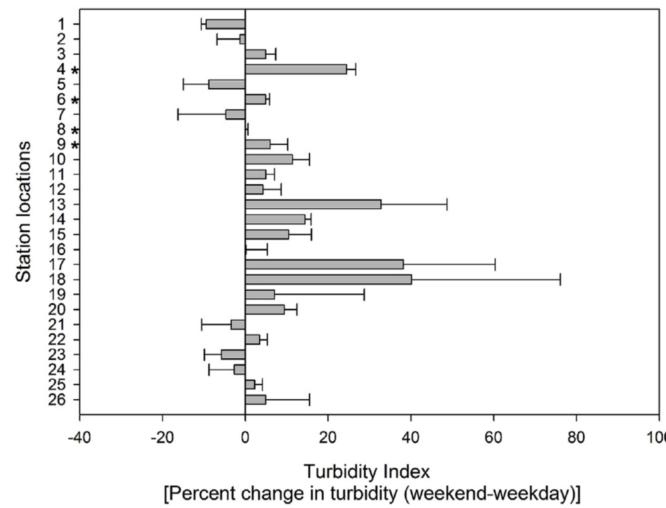

Fig. 3. Comparison of weekend turbidity measures to weekday measures. Positive TI values indicate relatively higher turbidity during the weekend than the week possibly because of increased recreational boating intensity during the weekend. Negative values indicate relatively higher turbidity during the week than weekend. Station location numbers correspond to those on Fig. 1. Stations with * had 2 years of data, all other stations had 3 years of data. Figure modified from Bilkovic et al., (2017).

3. Results

3.1. Elevated turbidity and recreational boating

Elevated turbidity was evident on the weekends in comparison to weekdays for the majority of the stations (n = 19; 73%); however, in many instances, the percent difference was low (< 5% turbidity difference for 35% of stations with elevated weekend turbidity). A negative turbidity index (higher turbidity during the week) occurred for 7 stations, but weekday turbidity at those sites was only slightly (> 10%) higher than the weekend turbidity (Fig. 3). None of the variables examined were significantly associated with the turbidity index (GLM: $X^2 = 3.14$, df = 21, p = 0.53). However, model selection based on AICc indicated marginal support ($\Delta AIC_c = 3.04$) for a best fit model that included boating intensity and armoring (Supporting table 1). This was likely because on unarmored shores, the turbidity index tended to be higher (TI = 10.5% ± 15.1%) in comparison to armored shores (TI = 4.5% ± 11.3) and along unarmored shores, boating intensity appeared to be associated with elevated local turbidity within some waterways.

3.2. Occurrence of high erosion in low energy settings

There are about 26,000 km of tidal shoreline in Chesapeake Bay, but only about a third of that shoreline has erosion data available (Table 2). Of the 8576 km of shoreline for which erosion data are available, 1310 km (15%) are potentially experiencing boat wake-induced erosion. This is likely an underestimate because a large proportion of low energy shorelines, the areas most at risk of experiencing boat wake-induced erosion (i.e., tidal creeks), were lacking erosion rate information (68%), which limited our ability to identify areas experiencing unusually high erosion (Fig. 4).

3.3. Occurrence of shoreline armoring in low energy settings

In all three creeks, armoring is present along approximately a quarter (Sarah Creek 28% (7.1 km), Lynnhaven River 22% (41.1 km), Lafayette River 31% (22.3 km)) of the shorelines where the SMM specifies that only marsh enhancement, maintenance, or creation should be

Table 2
Chesapeake Bay tidal shorelines with available data, approximately 15% (1310 km) are experiencing high erosion (≥0.3 m/yr) in low wind-wave energy settings (fetch < 1000 m), indicating potential boat wakewave induced erosion. Significant erosion data deficiencies exist for high risk areas, so these estimates are likely low.

Location	Total tidal shoreline (km)	Shoreline with erosion and fetch data (km)	Shoreline with erosion and fetch data (%)	Shorelines with low fetch and high erosion (km)	Shorelines with low fetch and high erosion (%)
Maryland	10,945	3302	30	569	17
Virginia	15,776	5274	34	741	14
Total	26,721	8576	32	1310	15

needed to stabilize shorelines (Fig. 5). In fact, on the basis of the physical setting, the vast majority of the shorelines in these low energy creeks could be managed simply by maintaining, enhancing, or creating marshes (Sarah Creek 83% (25.6 km), Lynnhaven River 74% (185.6 km), Lafayette River 78% (70.8 km)). This suggests another source (or perceived source) of shore erosion, possibly boating, has led to the armoring of shorelines (along with the attendant adverse effects of armoring) in low energy areas, where armoring should not be necessary. The vast majority of property owners stated erosion control was the purpose for armoring ((Sarah Creek 98% (62 projects), Lynnhaven River 97% (251 projects), and Lafayette River 92% (135 projects)).

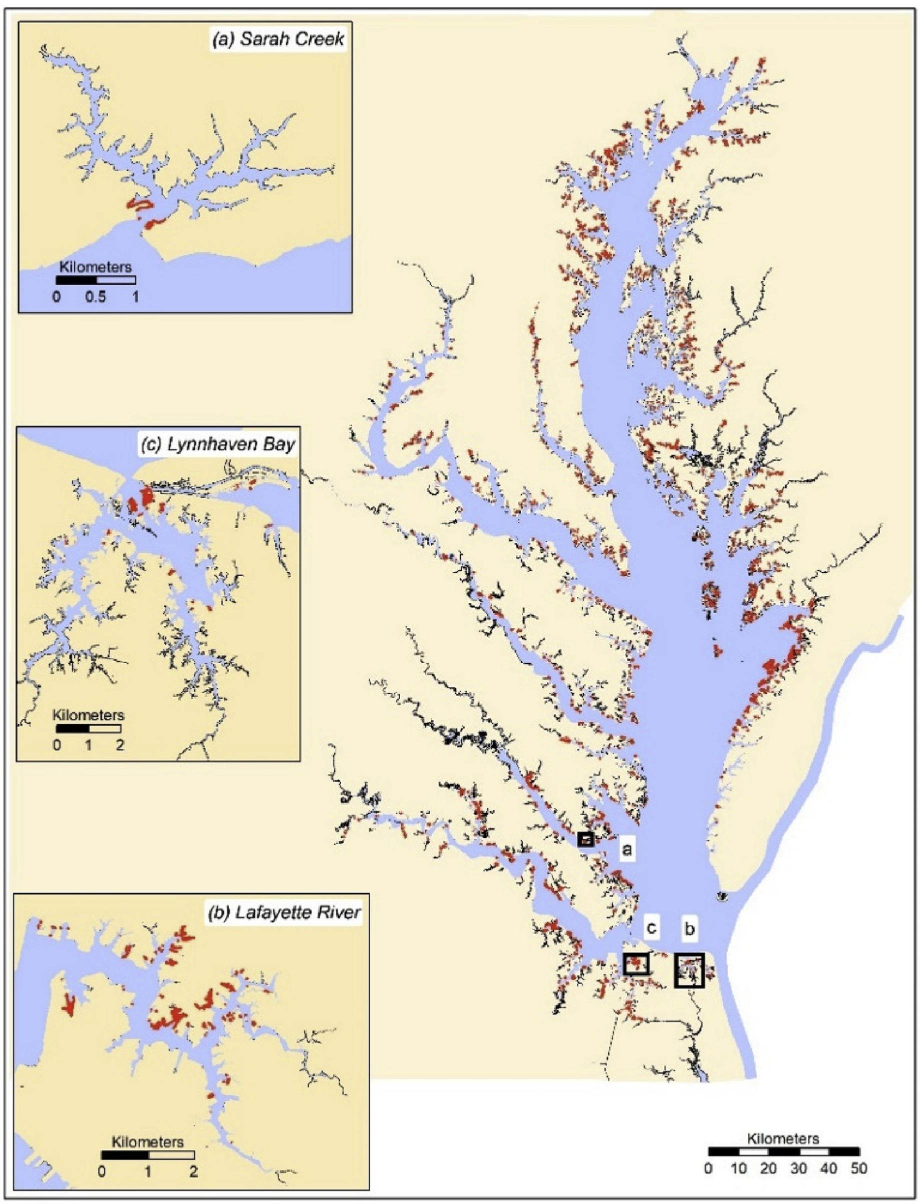

Fig. 4. Distribution of shorelines likely experiencing boat wave-induced erosion in Chesapeake Bay (shown in red); these are shorelines with low fetch (< 1000 m) and high erosion rates (≥0.3 m/yr). The black shorelines are areas lacking erosion data. The insets show example waterways with low wind wave energy where erosion should be low – Sarah Creek (a), Lafayette River (b), and Lynnhaven River (c). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

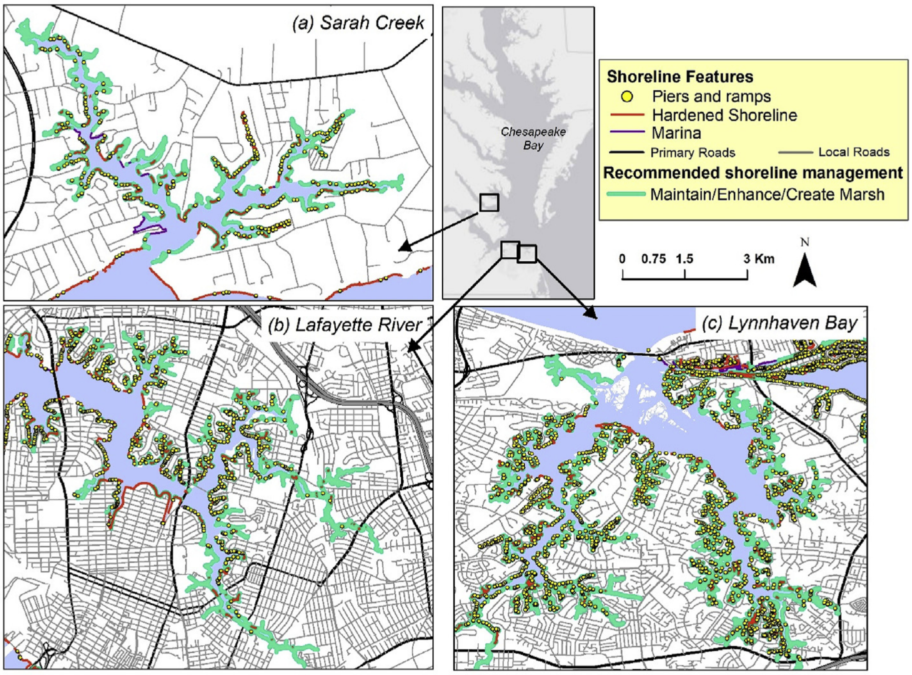

Fig. 5. On the basis of physical conditions, the recommended shoreline management approach is to create a new marsh or to maintain or enhance an existing marsh for the majority of the shoreline – **(a)** Sarah Creek, Virginia (83%), **(b)** Lafayette River, Virginia (78%), and **(c)** Lynnhaven River, Virginia Beach, Virginia (74%). Of those shoreline reaches where marsh is recommended, 28%, 31% and 22%, respectively, have armoring (revetment, bulkhead) currently. Figure modified from Bilkovic et al., (2017).

4. Discussion

There is evidence that links boat wake energy to elevated turbidity and shoreline erosion, particularly in narrow waterways (Ellis et al., 2002; Baldwin, 2008; Houser, 2010; Currin et al., 2017). Our findings suggest that boating may contribute to shoreline erosion and poor water clarity in some Chesapeake Bay creeks and tributaries. Turbidity was elevated in many waterways during periods of expected high boating activity. Armoring was placed along about a quarter of the low energy shorelines of all three examined tidal creeks that are exposed to relatively high boating pressure. Of the nearly 9000 km of shoreline examined throughout the Bay, 15% (1,310 km) are low energy shorelines that are experiencing high erosion (≥ 0.3 m/yr) that is not likely attributable to wind wave energy. Although our study cannot causally link boat traffic to high erosion along low fetch shorelines, the reaches we identified as potentially being vulnerable to boat traffic impacts are places to target for additional data collection on boating intensity and wave conditions, as well as potential candidate areas for management or policy action to mitigate boat wake impacts. A series of strategically targeted investigations of shorelines of particular concern (ideally shorelines that are experiencing significant erosion and that represent a range of conditions with respect to fetch and boating activity), would be a valuable first step to development of a Bay-wide understanding of the conditions under which boat wakes make a significant contribution to shoreline erosion. This type of data would provide the foundation for sound policy decisions regarding boat wake management strategies in the Chesapeake Bay and elsewhere.

Boat wake policies and the overarching regulatory framework in states with Bay frontage (Virginia, Maryland, and Delaware) vary from state to state. In Virginia, neither state code nor regulations establish wake or speed restrictions for any specific waterway. However, a state agency, the Virginia Department of Game and Inland Fisheries, has express authority to enforce and administer state boating laws (Va. Code Ann. § 29.1–701(A)) and has adopted regulations regarding boat speed near vessels, piers, docks, boathouses, and persons generally (4 Va. Admin. Code § 15-390-80). Additionally, localities have express authority to implement their own boat wake restrictions via a local ordinance (Va. Code Ann. § 29.1–744(D)), and individuals or businesses may apply to their local governing body for the establishment of a no-wake zone via a local ordinance (Va. Code Ann. § 29.1–744(E)). Although Maryland also delegates regulatory authority to a state agency, the Maryland Department of Natural Resources (DNR) (Md. Code Ann., Nat. Res. § 8-8-704(c)), and permits localities to establish local regulations that conform with DNR regulations (Md. Code Ann., Nat. Res. § 8-8-704(f)), Maryland has set forth speed limits for specific waterways within state code (*see,* e.g., Md. Code Ann., Nat. Res. § 8–725.2). Additionally, DNR's regulations define various speed limits (Md. Code Regs. 08.18.01.03) and apply these defined limits to specific designated areas, such as the eastern and western shores of the Chesapeake Bay (Md. Code Regs. 08.18.07.01–02). As with both Virginia and Maryland, Delaware also delegates regulatory authority to a state agency, the Delaware Department of Natural Resources and Environmental Control (DNREC) (Del. Code Ann. tit. 23 § 2114(b)(4)). DNREC regulations define "slow-no-wake" and limit speeds next to swimmers and certain structures (Del. Admin. Code § 3100–2.1 & −6.1.2). Additionally, localities have limited boat speeds near specific structures or on specific waterways (*See* e.g., Smyrna, Delaware Code of Ordinances Sec. 46-58(h)). While regulation of boat wake speed does occur in some manner within each of the three states with Bay frontage, this regulation has not been done comprehensively across the Bay or through coordination between the states.

Other shallow water estuaries have established boat wake policies following differing procedures. Examples include the Narragansett Bay in Rhode Island and the Pamlico Sound in North Carolina. Rhode Island authorizes 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" (46 R.I. Gen. Laws § 22–9(c)). Additionally, ordinances or local laws may be adopted that are identical to the state laws and regulation, and subdivisions of the state may apply to DEM for special rules and regulations regarding vessel operations within the subdivision's territorial limits (46-22 R.I. Gen. Laws §§ 14(a)&(b). This has resulted in many coastal localities adopting wake restrictions (*See* e.g., Bristol, Rhode Island Code of Ordinances Sec. 8-41)). North Carolina utilizes a state agency, the North Carolina Wildlife Resources Commission (NCWRC), to implement boat wake policies in a uniform manner across the state (N.C. Gen. Stat. § 75A-15). NCWRC is authorized to adopt its own rules to prohibit the entry of vessels and establish speed zones in certain areas (N.C. Gen.

Stat. § 75A-15). Additionally, localities may petition NCWRC for wake rules and the Commission is authorized to adopt rules for local areas that are "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" (N.C. Gen. Stat. § 75A-15). Under this management structure, boat wake restrictions have been established for almost all coastal counties through agency regulation. This results in consistent language between regulations and provides easier access to boat wake restriction rules because the information can be found in one place.

Management and policy strategies to address boat wake-induced shoreline erosion that are alternatives to boat speed/wake restrictions include motorboat bans and shoreline armoring. Banning motorized vessels is unlikely to be adopted in any major waterway, especially one whose economy relies heavily on both recreational and commercial boating and/or shipping; however, in smaller waterways this can be a viable option. With respect to armoring of the shoreline, living shorelines are preferred to armoring because these techniques strengthen the endurance of the shoreline and build resilience by using natural vegetation and sediment. By contrast, armoring may result in adverse effects, such as natural habitat degradation and erosion of downdrift shorelines due to deflected wave energy or lack of sediment supplies to maintain the shorelines. Other policy strategies targeting boating behavior that have a higher likelihood of being implemented include limiting the number of passages that a boat makes in a waterway, setting minimum distance of a navigation channel from the shore, and implementing boat size restrictions in small waterways.

Although concerns about the harm that boating activity may pose for shoreline stability, water quality, and ecosystem integrity have been voiced for decades, the development and implementation of management and policy actions to mitigate boat impacts has been hampered by lack of a proven approach for quantifying the role of boat waves in shoreline erosion. While there is currently no one-size-fits-all approach for evaluating boat wake impacts, there have been a few recent attempts to develop overarching strategies. Glamore (2008) developed a Decision Support Tool (DST) aimed at evaluating the relative impact of boat vs. wind waves along a given reach of shoreline. The tool calculates total wind wave energy, total boat wake energy and shoreline erosion potential. User inputs include data on the frequency of boat passage, local wind data, and 22 different shoreline characteristics that are used to determine erosion potential including: shoreline slope, sediment type, channel width and upland land use, among others. Output from the DST includes guidance regarding whether management of boat wakes is necessary based on the relative amount of shoreline wave energy contributed by boats compared to that of wind energy, and the calculated shoreline erosion potential. This tool represents a viable approach to analysis of boat wake impacts and has been successfully employed in the management of lake shorelines and limited river reaches, but the large number of required input variables make its application across a large and diverse system like Chesapeake Bay challenging.

Fonseca and Malhotra (2012) developed a similar approach that involved the use of two GIS-based modeling packages: WEMo (Wave Exposure Model) for quantifying wind-wave energy and its companion product BoMo (Boat wake Model) for quantifying boat wake energy. In their approach, these tools are used in tandem to estimate the relative contribution of boat wake energy along a given shoreline. WEMo (which is freely available, https://coastalscience.noaa.gov/research/coastal-change/wemo/) requires users to input local wind data, a GIS shoreline shapefile, and high quality bathymetry data; BoMo (not yet available) also requires shoreline and bathymetry data and allows a user to select hull type, size and speed. The models then calculate the total amount of wave energy impacting the shoreline from their respective sources. With this approach, both wind and boat wakes can be hindcast or forecast to determine which is the predominant driver of shoreline erosion. Like the DST, this dual model approach is limited by the availability of data. While wind data and shoreline shapefiles are relatively easy to obtain, much of the publicly available bathymetry data is either outdated, or not of sufficient spatial coverage, and data on the number of boat passages along a given shoreline do not exist. As a result, these approaches have not been broadly implemented.

Prior to development of a truly quantitative understanding of boat wake-induced erosion at a systems-level, interim protective measures can be applied on the basis of documented effects of boat wakes in the literature. Wave height- or wave energy-based criteria have been used to establish wake management strategies (Stumbo et al., 1999; Glamore, 2008). Wave decay studies indicate that, in general, even small ($<$ 9 m) power boats traveling within 150 m of the shore are capable of generating wave heights that can cause erosion of vegetated marsh shorelines (Zabawa and Ostrum, 1980; Coops et al., 1996; Coops et al. 1996, 1996; Schafer et al., 2003; Roland and Douglas, 2005). This distance is not without exceptions, for example, boats traveling further offshore can still produce erosive boat wakes, particularly those vessels that are large or moving at high speeds, which increases the wake energy. Still, setbacks can be a relatively easy solution to boat wake-induced shoreline erosion where the setting allows. With additional information on recreational and commercial boating traffic, varying setback distances could be established in vulnerable Bay waterways. A 150 m setback in small, low energy, waterways that have high recreational boating activity could help reduce shoreline erosion, while those waterways used by large commercial vessels may require larger setbacks to lessen the erosive effects of wakes. In restricted waterways where there is no space to move channels away from shore, no-wake zones provide an alternative strategy for managing erosion. A GIS-based investigation of regions where there IS high erosion that is likely caused by boat wakes and there IS NOT room to move navigation channels farther from shore might provide the first cut for sites to investigate for potential implementation of no-wake zones. Another important consideration for the implementation of no-wake zones is that maximum wave height can be produced as a boat transitions in and out of planing mode, often at the start and finish of designated no-wake zones. This should be factored into their placement.

Shoreline wave energy, whether generated by wind or boating activity, is a critical factor to consider in the implementation of shoreline management strategies. The design and use of more natural approaches to shoreline erosion (i.e., living shorelines) is strongly influenced by shoreline wave energy. A quantitative understanding of the relationship between boating activity and shoreline wave energy will help to inform the design of these sites and give property owners and design practitioners a greater level of confidence in their application. In addition, this information could be used when planning and siting Bay restoration activities (e.g., wetland or seagrass restoration) to evaluate the probability of long-term persistence. Conversely, and just as important, this information can help to identify areas where shoreline wave energy is too high to consider the use of "softer" living shoreline management strategies.

While our focus area is Chesapeake Bay, sheltered coasts around the world are struggling with these same issues and as coastal regions continue to become more densely populated, the role of boat wake-induced erosion will be increasingly significant. In general, there is a dearth of data on boating activity and its consequences, particularly that of small, recreational boats. While some of these data gaps can be effectively addressed through citizen science-led efforts (e.g., documenting the frequency of boat passages at a given location), others will require field and modeling studies. All efforts to increase our quantitative understanding of the amount of boat wake energy impacting a given shoreline, and the consequences of this impact, will be vital to the development of effective management strategies for mitigating boat wake-induced shoreline erosion. Such strategies should be implemented with a whole-system perspective, as uniform boat wake policies will likely be most effective for consistent shoreline protection.

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Appendix A. Supplementary data

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