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Considering Tidal Flooding to Provide a Holistic Approach to Nutrient Input Management

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Executive Summary

This report explores the integration of tidal flooding impacts into nutrient management frameworks for the Chesapeake Bay, a potentially large gap in current strategies. Coastal communities in the Chesapeake Bay, face an increasing threat from tidal flooding—also known as sunny-day flooding—which occurs without rainfall. In 2023, Norfolk, Virginia experienced 10 days of tidal flooding, but forecasts indicate that by 2075 the area could be experiencing tidal flooding every day. Recent research highlights that even a single tidal flooding event can introduce substantial nutrient loads into the Bay, sometimes exceeding the annual nutrient allocations. This significant increase in both the frequency and intensity of tidal flooding underscores the urgency of reevaluating its role in nutrient inputs across the Bay. Historically, traditional water quality management has not considered tidal flooding a significant contributor to nutrient loads. As a result, nutrient load allocations, water quality monitoring, and the design of best management practices (BMPs) currently do not account for these events, likely leading to an underestimation of nutrient inputs. This omission necessitates a thorough rethinking of our current approaches to nutrient management in the face of changing environmental conditions. An overview of recommendations outlined in this report are as follows:

- **Model Integration:** Update the Chesapeake Bay Program's water quality models to incorporate tidal flooding considerations, improving the accuracy of nutrient load predictions and management responses.
- **Enhanced Data Collection:** Expand empirical data collection on tidal flooding across different watershed areas to refine model inputs and understand the variable impacts of land use on nutrient contributions. Leverage community science initiatives and stakeholders to enhance data collection.
- **Best Management Practices (BMPs):** Review and adapt BMPs to address the unique challenges posed by tidal flooding, particularly in urban areas where nutrient loads during flooding can be substantial.

This report aims to serve as a foundation for policymakers, researchers, and coastal managers to reconsider and enhance nutrient management strategies by acknowledging the significant role of tidal flooding. It serves as a call to action to integrate these considerations into broader water quality management practices to better protect the Chesapeake Bay.

1 Introduction

Coastal ecosystems are facing unprecedented threats from various anthropogenic pressures, including alterations in land use, rising temperatures, and eutrophication (Nixon 1995; Lotze et al. 2006; He & Silliman 2019) Of particular concern are anthropogenic nutrient inputs, primarily dissolved inorganic nitrogen and phosphorus. These nutrients originate from various sources including point (e.g. factory outflow pipes, sewage, and wastewater treatment plants) and nonpoint origins (e.g. agricultural, commercial, residential, and urban runoff) (Nixon 1995; Pinckney et al. 2001; Nie et al. 2018; Sabo et al. 2022). Point sources typically have identifiable and regulated locations, making them comparatively easier to manage. In contrast, non-point sources are diffuse and dispersed, typically over large areas, rendering their management more complex and challenging (Carpenter et al. 1998; Pinckney et al. 2001; Nie et al. 2018; Zhang et al. 2021; Sabo et al. 2022). Despite years of targeted efforts to reduce nutrient pollution, particularly in the Chesapeake Bay, nonpoint sources persist in their difficulty to control. Excess nutrient inputs in the Chesapeake Bay have been directly linked to eutrophication, harmful algal blooms, and hypoxia (Kemp et al. 2005; Beyer et al. 2013; Nie et al. 2018). Effective management of these nonpoint sources is critical for maintaining the health and sustainability of the Chesapeake Bay.

1.1 History of Chesapeake Bay Nutrient Management

The Chesapeake Bay serves as a poignant example of the challenges in managing nutrient pollution, particularly from nonpoint sources. Concerns over the Bay's declining health in the late 1970s prompted the United States Congress to sponsor a comprehensive study. This research identified excess nutrient pollution as the primary culprit behind the Bay's degradation, leading to the formation of the Chesapeake Bay Program (CBP) in 1983 (Harbachewski et al. 1984; CBP). The Program emerged as a unique partnership encompassing all six states within the Bay's watershed—Virginia, Maryland, Pennsylvania, West Virginia, Delaware, and New York—plus the District of Columbia. This collaboration extends to federal, state, and local government agencies, academic institutions, and nonprofit groups, all united in their commitment to the Bay's health.

A pivotal achievement in the Bay's management was the establishment of the Chesapeake Bay Total Maximum Daily Load (TMDL) in 2010 (EPA 2010; CBP). This regulatory framework set stringent limits on the nutrients and sediment entering the Bay and its tidal rivers, essential for meeting water quality goals (EPA 2010). Subsequently, each of the seven jurisdictions within the Bay's watershed developed detailed Watershed Implementation Plans (WIPs) to achieve these pollution reductions by 2025 (CBP). The Chesapeake Bay Program (CBP) relies heavily on modeling outcomes to guide the management plans of individual jurisdictions and inform the overall strategy of the CBP Partnership. These models are instrumental in reducing both point and nonpoint pollution sources, including regulations aimed at curbing pollutant transport into the Bay (Linker et al. 2013; Shenk & Linker 2013). Over the past four decades, the CBP modeling system has significantly evolved as understanding of processes operating in the Bay and its watershed have advanced and management questions progressed (Hood et al. 2021). The current CBP modeling system, released in 2017, consists of multiple components, including airshed, land use, watershed, estuarine hydrodynamic, and water quality models (Hood et al. 2021). Prior to 2017, the Chesapeake Bay's management approach was more static, lacking a formalized system for incorporating new scientific findings and adjusting strategies accordingly. The introduction of the Strategy Review System (SRS) in 2017 marked a significant transformation in how the Bay's management was conducted (CBP). The SRS embodies the principles of adaptive management, enabling the Bay Program to systematically evaluate and refine strategies based on progress, emerging scientific insights, and evolving environmental conditions every two years (CBP). This iterative approach is critical because failing to account for all elements in management strategies can lead to skewed results and setbacks in achieving nutrient management goals. As our understanding of these complex systems deepens, the management of nutrient pollution in the Chesapeake Bay can continue to adapt and evolve.

1.2 Tidal Flooding and Nutrient Input

Tidal flooding exemplifies precisely why an iterative and adaptive management strategy is necessary. Tidal flooding, also known as high tide flooding or sunny day flooding, happens when rising sea levels interact with local conditions, pushing water levels beyond the usual high tide mark (NOAA). Variations in prevailing wind patterns, alterations in ocean currents, and intense tidal forces—often during full or new moons—can all contribute to this phenomenon, leading to the inundation of streets even on clear, sunny days (Moftakhari et al. 2018; Macías-Tapia et al. 2023; NOAA). Historically, water quality management has not fully accounted for tidal flooding as a significant contributor to nutrient loads, primarily because its impact was not recognized as substantial until recently. However, recent findings by Macías-Tapia et al. (2023) within a sub watershed of the Lower Chesapeake Bay have demonstrated the potentially critical implications of tidal flooding. During just one tidal flooding event, inputs of dissolved nutrients can exceed annual load allocations for total nitrogen (TN) and total phosphorus (TP) by more than 100%. This reveals that current tidal flooding is already delivering large concentrations of nutrients to the Lower Chesapeake Bay system, a trend that is projected to worsen as both the frequency and severity of tidal flooding increase due to accelerating rates of relative sea level rise (Spanger-

Siegfried et al. 2014; Dahl et al. 2017; Li et al. 2022). In the Lower Chesapeake Bay region, occurrences of high-tide flooding have already escalated because this area experiences some of the highest rates of relative sea level rise compared to the global average (Ezer et al. 2013; Mitchell 2013; Ezer 2018; Loftis et al. 2019).

Increasing occurrences of tidal flooding underscores the urgent need to improve the limited understanding of tidal flooding as a significant potential source of nutrient contributions across the Chesapeake Bay. While the impact of storm-related flooding and runoff in transporting pollutants to coastal waters has been extensively studied and managed, tidal flooding introduces distinct dynamics (Selbig 2016; Moftakhari et al. 2018; Lee et al. 2022). Unlike the one-way flow of stormwater runoff, tidal flooding encompasses a complex ebb and flow pattern, submerging the landscape during high tide and gradually receding (Pandey et al., 2014; Selbig 2016). This prolonged exposure allows floodwaters to mobilize and interact with the landscape's accumulated materials before flowing back into the estuary as the tide retreats (Weissman & Tully 2020; Macías-Tapia et al. 2021; Macías-Tapia et al. 2023). Current management practices, primarily designed to address stormwater runoff, may not be well-equipped to handle the unique challenges posed by tidal flooding. (Gold 2017; Macías-Tapia et al. 2023). For example, green infrastructure projects, often effective in managing stormwater runoff, may struggle to retain pollutants when consistently inundated by tidal flooding.

Tidal flooding has yet to be integrated into calculations of Total Maximum Daily Loads (TMDLs) for nutrient inputs (EPA 2010), likely underestimating the amount of nutrients entering the Chesapeake Bay and other coastal environments. If TMDL calculations are missing a substantial source of nutrient input, then we are likely not meeting our nutrient load goals even if the CBP modeling system suggests are on track. It is imperative that we begin to evaluate how much of a limitation the lack of tidal flooding inclusion represents within our current management framework and begin to explore innovative solutions that can adapt to the changing landscape of coastal nutrient pollution. This report aims to shed light on tidal flooding as a potential major gap in nutrient input management within the context of the Chesapeake Bay and provide recommendations on how to begin incorporating tidal flooding into existing water quality management frameworks.

2 Methods

The methods used in this report encompassed a multifaceted approach to investigate the integration of tidal flooding considerations into water quality management. I began with a thorough literature review aimed at exploring the existing discussions surrounding "tidal flooding" or "high tide flooding" in relation to "water quality". A subsequent literature review was conducted investigating the relationship between “tidal flooding” or “high tide flooding” and “best management practices” or “green stormwater infrastructure”. Following the literature review, thirteen informational interviews with various stakeholders involved in water quality management were conducted. This included experts from the Chesapeake Bay Program, US Geologic Survey, Environmental Protection Agency, Virginia Department of Environmental Quality, and various state and regional water quality and resilience planners. These interviews served as a key method for gathering insights on how tidal flooding is currently considered within the scope of water quality management and the challenges to its integration into existing frameworks. Additionally, a targeted survey was sent to a selected group of these stakeholders to rank and categorize the pressing needs associated with managing tidal flooding, such as data acquisition, model integration, and enhancing stakeholder engagement. The results of that survey are not published in this report due to low response rate, but still contributed to the understanding of current management practices regarding water quality and tidal flooding. This mixed-method approach provided a comprehensive understanding of the current management landscape and was instrumental in developing informed strategies and robust policy recommendations for future research directions and practical implementations.

3 Tidal Flooding: A Water Quality Problem

While previous research has suggested a connection between tidal flooding and water quality (Kiaghadi and Rifai 2019; Smith et al. 2021), the studies by Macías-Tapia et al. (2021) and Macías-Tapia et al. (2023) are the first to quantify the extent of nutrient input during tidal flooding events within a sub watershed of the Chesapeake Bay. Macías-Tapia et al. (2021) was an inaugural experiment leveraging community science to collect water samples during a single 2017 king tide event in the Chesapeake Bay. The study revealed significant loading of total nitrogen and total phosphorus to the Lafayette River sub-estuary. This single tidal flooding event contributed approximately 30% more nitrogen than the annual load allocation recommended by the Environmental Protection Agency (EPA 2010; Macías-Tapia et al. 2021).

A follow-up study, Macías-Tapia et al. (2023), then assessed the impact of multiple tidal flooding events on nutrient loads from 2017 to 2021 during annual autumn king tides in the Lafayette River. To determine the nutrient loads resulting from tidal flooding, nutrient concentrations were measured in floodwaters and compared with pre-flood estuarine water levels. These concentrations were then integrated with floodwater volumes, calculated using a hydrodynamic model that provided geospatial inundation depths. The findings of this investigation revealed dissolved nutrient concentrations in floodwaters were consistently higher than those in estuarine waters before flooding. However, there was variability in nutrient loadings between each flood event, likely influenced by baseline environmental conditions and specific timing of flood events (Morse et al. 2014; Macías-Tapia et al. 2023). Despite these variations, nutrient loads from tidal flooding over five years contributed significantly to the estuary's nutrient influx. These loads were compared against the Total Maximum Daily Load (TMDL) set by the EPA for the Lafayette River, which specify limits for nitrogen (7.95×10^4 kg $year^{-1}$) and phosphorus (5.37×10^3 kg $year^{-1}$) (EPA 2010). Concentrations of dissolved inorganic nitrogen (DIN) and dissolved organic nitrogen (DON) from tidal floods occasionally contributed to as much as 226% of the total annual permissible nutrient loads under scenarios of extreme flooding. Similarly, phosphorus loads during these events could surpass 200% of the allowed levels, underscoring the potential for tidal flooding to dramatically affect water quality.

This issue becomes even more pertinent as tidal flooding in Norfolk has increased 325% since 1960 and is only becoming more prominent (Burgos et al. 2018). The US Climate Resilience Toolkit indicates that if emissions remain high, Norfolk can expect to see 365 days of high-tide flooding per year by 2075. Even with lower emissions, 2075 is projected to see approximately 225 days of high-tide floods (Fig. 1). Tidal flooding is currently not recognized as a nutrient source in water quality management or modeling efforts throughout the Chesapeake Bay, including in the bay wide Total Maximum Daily Load. This lack of integration highlights a potential critical gap in the region's nutrient management strategies given that a single tidal flooding event can exceed the annual TMDL for nutrients. With approximately 10 tidal flooding events occurring each year (Burgos et al. 2018; US Climate Resilience Toolkit), this issue already poses a significant challenge. As the frequency of tidal flooding is expected to increase dramatically—potentially affecting the region on most days—tidal flooding could emerge as the primary source of nutrient pollution in the Bay, highlighting the urgent need to integrate it into our nutrient management strategies. The upcoming section will discuss recommendations aimed at addressing research gaps, proposing ways to incorporate tidal flooding into existing water quality management frameworks to enhance the efficacy of nutrient management across the Chesapeake Bay.

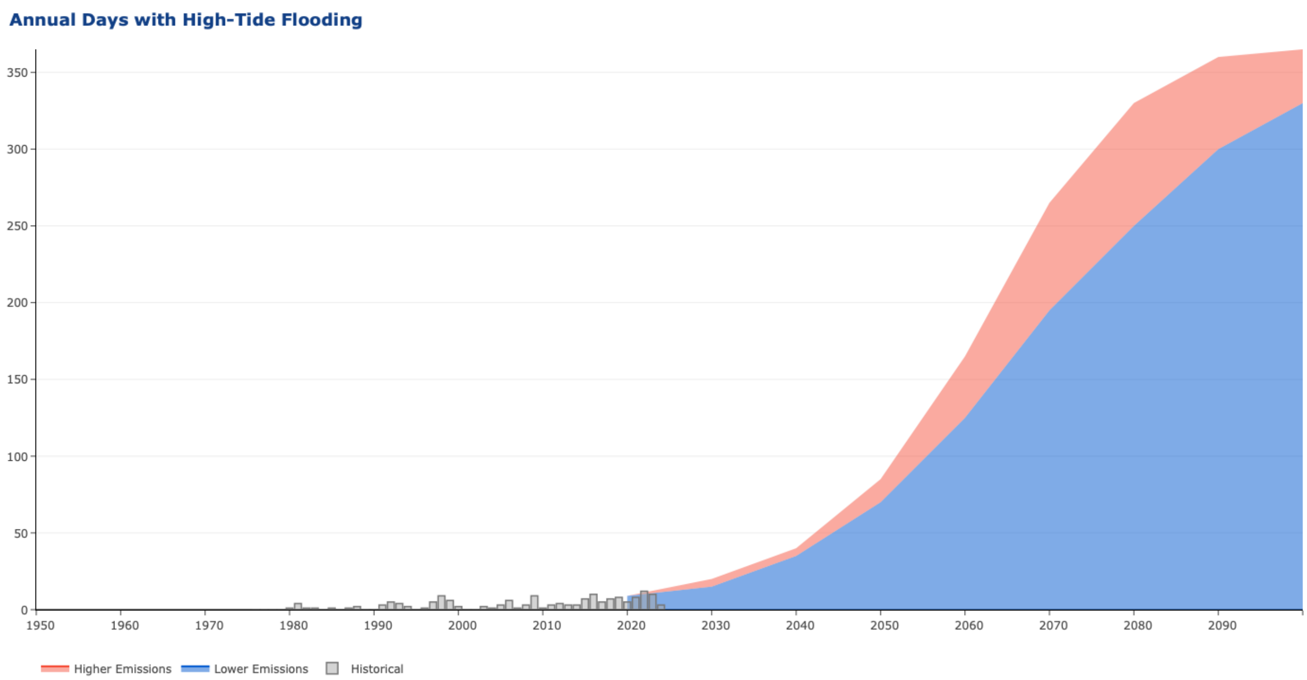

Figure 1: Demonstrates this projected increase in tidal flooding days for Norfolk, VA under both higher and lower emissions scenarios. (Source: US Climate Resilience Toolkit)

4 Recommendations

This section outlines a series of strategic recommendations that will be needed to effectively address the complex challenges posed by tidal flooding and its impact on nutrient management in the Chesapeake Bay. The recommendations are designed to enhance the current frameworks and approaches in three key areas: refining water quality modeling, expanding spatial data coverage, and optimizing nonpoint source BMPs.

4.1 Chesapeake Bay Program Water Quality Modeling

The Chesapeake Bay Program has made significant strides in understanding and managing the nutrient and sediment loads affecting the Bay through sophisticated modeling efforts (Linker et al. 2013; Shenk & Linker 2013; Hood et al. 2021). However, the dynamic and episodic nature of tidal flooding presents new challenges in predicting and managing its impact on nutrient loads. This section outlines recommendations for integrating tidal flooding considerations into the Bay's watershed and estuary models.

4.1.1 Current Model

The Chesapeake Bay Program water quality model is divided into two models, the Watershed and Estuary model. The Watershed model is an advanced system that incorporates a wide array of data to estimate the nutrients and sediments reaching the Chesapeake Bay, identifying the origins of these pollutants across a 64,000-square-mile watershed (CBP 2020). The model divides the watershed into over 2,000 segments, delineating political and physical boundaries for enhanced precision in data analysis. It integrates information about land use, fertilizer applications, wastewater plant discharges, septic systems, air deposition, farm animal populations, weather patterns, etc. to simulate the transportation and fate of nutrients and sediments across the Chesapeake Bay watershed (Linker et al. 2013; Shenk & Linker 2013). This extensive modeling effort allows for the estimation of freshwater, sediment, nitrogen, and phosphorus loads to the Bay and evaluates how various management actions could influence these loadings (Linker et al. 2013; Shenk & Linker 2013; Hood et al. 2021). The Estuary model complements the Watershed model by examining the effects of the estimated pollution loads on the Bay's water quality. This model is composed of 57,000 computational cells that represent the

Bay and its tidal tributaries through two critical sub-models; the hydrodynamic sub-model which simulates the physical mixing of waters and the water quality sub-model which calculates the biological, chemical, and physical changes occurring in the Bay (Linker et al. 2013; Shenk & Linker 2013; CBP 2020). These sub-models also determine Chesapeake Bay TMDLs by predicting changes in oxygen concentration, water clarity, and chlorophyll *a* concentration resulting from changes in nutrient and sediment loads (Linker et al. 2013; Shenk & Linker 2013; Hood et al. 2021).

Environmental managers across various watershed jurisdictions utilize the coupled modeling system to steer decisions related to water quality management in their areas. The primary function of the model is to establish defensible targets for nutrient and sediment loads across states and local jurisdictions and to facilitate the effective implementation of BMPs (Hood et al. 2021). The system helps managers to establish reduction targets, formulate plans to achieve these targets, and monitor progress toward meeting both local and broader Chesapeake Bay restoration goals. While the Watershed model handles typical stormwater runoff pollution effectively, it lacks specific mechanisms to incorporate the sporadic yet significant nutrient contributions from tidal flooding.

4.1.2 Integration of Tidal Flooding

To significantly enhance the Chesapeake Bay Program models' predictive capabilities regarding nutrient inputs, the forthcoming Phase 7 integration — expected to be completed by late 2025 — should begin to include tidal flooding considerations. The current modeling framework primarily focuses on simulating the one-way flow of stormwater runoff from the landscape into the Chesapeake Bay and its tributaries. While this approach effectively simulates the transport and fate of nutrients and sediments from various land uses into the estuary via runoff, it does not capture the intricate interactions associated with tidal flooding. Tidal flooding is characterized by a more complex ebb and flow pattern which involves water flowing from the estuary onto the landscape. It also entails a generally longer inundation period, which may result in more nutrients being collected during extended exposure compared to stormwater runoff (Macías-Tapia et al. 2023). Integrating tidal flooding necessitates developing a more dynamic linkage between the Watershed and Estuary models. Such development will likely require the implementation of new hydrodynamic modules capable of simulating the spatial and temporal extent of tidal flooding across the watershed's interface with the estuarine environment. Establishing a dynamic linkage between the Watershed and Estuary models would allow for a more sophisticated representation of this coastal process where the hydrodynamic movement of the water flows on to the land from the estuary and then carries nutrients with it in back into the estuary.

While the inclusion of tidal flooding in the Watershed model is necessary, we lack empirical data to properly model this process. Research is needed to understand the frequency, duration, intensity, and impact of tidal flooding events, which could vary across different parts of the Bay. By capturing these dynamics, the model could more accurately predict how these flooding events redistribute and potentially increase nutrient loads during tidal flooding events. This expanded modeling approach would better reflect the real-world interactions between terrestrial landscapes and aquatic systems, thereby providing a more robust tool for environmental planning and decision-making. However, this report recognizes that in order to successfully integrate tidal flooding dynamics into the Watershed and Estuary model, there must first be a substantial increase in comprehension and data collection efforts surrounding tidal flooding and nutrient dynamics across the Chesapeake Bay.

4.2 Enhancing Spatial Coverage

4.2.1 Extent of the Data Gap

While the Macías-Tapia et al. (2021) and (2023) studies provide the impetus for considering tidal flooding as a substantial source of nutrient input, they also highlight the need for further data collection and analysis to ascertain the full extent of this issue across the broader Chesapeake Bay watershed. While it is well-documented that land uses significantly impact nutrient runoff (Tu 2011; Cheng et al. 2022), our understanding of how land uses impact tidal flooding remains unclear. The Macías-Tapia et al. (2021) and (2023) studies indicate that nutrient levels during tidal flooding in density populated urban areas like the Lafayette River can significantly exceed the TMDL limits, suggesting a potential widespread issue. It is imperative to verify whether similar nutrient loading dynamics are present across various land uses, such as agricultural, forested, and industrial areas, as well as urban zones with different impervious surface levels. The nutrient loadings during tidal flooding events can vary across different land use types, as each type of land use determines the quantity and nature of nutrients present and their potential for mobilization during these events (Arnold & Gibbons 2007; Elrashidi et al. 2013). This complexity underscores the challenge of understanding nutrient loadings at a sub-watershed or catchment scale based on the available data. This gap in detailed, localized data prevents effective correlation between specific land use patterns and nutrient levels, highlighting a critical area for future research and modeling improvements. Such understanding is vital for developing more accurate predictive models.

Additionally, further research is needed to refine predictions about when and how significantly a tidal flooding event will impact nutrient input into a system. The study by Macías-Tapia et al. (2023) challenges assumptions that greater inundation volume during tidal floods corresponds directly with increased nutrient loads. Contrary to hypotheses, their multi-year analysis did not show a significant correlation between the volume of floodwaters and the nutrients delivered to the Lafayette River. This highlights a complex relationship where factors other than simple inundation volume—such as land use characteristics and the rate, duration, and frequency of inundation—may influence nutrient dynamics during tidal flooding events. Understanding the rate of inundation is essential as it can illuminate how quickly an area becomes submerged and the subsequent effects on surrounding sediment and nutrient dynamics. Rapid inundation could lead to significant disturbances in sediment layers, potentially mobilizing nutrients embedded within these sediments more effectively than slower inundation rates (Kiaghadi & Rifai 2019). This aspect of flood dynamics is critical in understanding the initial stages of nutrient release into floodwaters and, ultimately, how much nutrients are released during a tidal flood event. The duration of flood events may also play an integral role in determining the total nutrient load transported by floodwaters. Extended periods of inundation allow for more extensive interactions between water and land-based nutrients, leading to greater dissolution and transport of these nutrients into the aquatic system (Smith et al. 2021). This prolonged contact could significantly amplify the nutrient loads, particularly in areas with high organic matter or previously accumulated nutrient deposits. However, the frequency of inundation could represent a change in these dynamics. As tidal flooding becomes more frequent, it is possible that the nutrient load entering the estuary after each event could decrease, given the reduced availability of nutrients on the landscape that tidal flooding events interact with. Understanding the dynamics of tidal flooding helps in predicting where nutrients might accumulate or dilute, providing valuable insights for managing water quality post-flooding.

It is also necessary to explore the ecosystem responses observed following significant tidal flooding events. Tidal flooding can introduce large concentrations of nutrients within a short time frame, potentially leading to increased phytoplankton biomass. Understanding the inputs of nitrogen (N) and phosphorus (P) across different tidal areas of the Chesapeake Bay is crucial. The availability of these nutrients, which vary spatially and temporally across the estuary, affects the growth and health of phytoplankton communities (Buchanan 2020; Zhang et al. 2021). In many regions of the lower Chesapeake Bay, phytoplankton are primarily nitrogen-limited. However, the introduction of excessive nutrients through tidal flooding can disrupt this balance, potentially leading to eutrophication and harmful algal blooms (Kemp et al. 2005; Beyer et al. 2013; Nie et al. 2018). The variability in nutrient concentrations and their ratios significantly influences phytoplankton community dynamics, altering growth rates, species composition, and even the nutritional quality of the community (Arrigo 2005; Burson et al. 2016; Aranguren-Gassis et al. 2019). This variability presents challenges for efforts aiming to correlate ecosystem responses with nutrient pollution, yet these investigations are crucial to inform targeted management strategies. For example, in areas where phytoplankton growth is typically nitrogen-limited, an influx of nitrogen from tidal floods could stimulate an increase in algal biomass. Conversely, in regions where phosphorus is the limiting factor, increased loads of phosphorus could have a similar effect. The stoichiometric balance between nitrogen and phosphorus is crucial; deviations from the ideal N:P ratio can lead to changes in phytoplankton species dominance and overall ecosystem health (Redfield 1958). Excessive phosphorus, relative to nitrogen, as observed in some flood events, could favor the growth of certain algal species over others, potentially promoting blooms of species that are less favorable or even harmful, such as certain cyanobacteria known to produce toxins (Davis et al. 2010).

Addressing these identified data gaps is vital for refining the Chesapeake Bay Program's water quality model and enhancing its utility in managing nutrient pollution effectively. These gaps, if resolved, would provide a more nuanced understanding of how different land uses and inundation differences influence nutrient dynamics during tidal flooding. This data can be used to integrate tidal flooding into the Chesapeake Bay Program's water quality model and predict the movement and concentration of nutrients more accurately during tidal flooding events. Understanding these dynamics at a sub-watershed scale is essential for practical applications in water quality management. Without addressing these gaps, integrating tidal flooding into the Chesapeake Bay water quality model remains challenging and inaccurate, thus continuing to overlook a potentially key factor that influences nutrient loads in the Chesapeake Bay. Particularly concerning is the impact on the TMDL allocations, which are premised on model outputs. If the model does not account for significant sources of nutrients like those from tidal flooding, then the TMDL allocations and BMPs informed by the model may not effectively limit nutrient entry into the Bay, undermining efforts to improve water quality.

4.2.2 Addressing the Data Gap

To address this gap, future research should consider the following:

a. Expand data collection across multiple watersheds with diverse land uses to assess how variations in land use influence nutrient contributions during tidal flooding events. This includes agricultural areas whose main nutrient source is fertilizer application, industrial areas who introduce both nutrients and other pollutants, such as heavy metals, through runoff, and urban areas with varying degrees of impervious surfaces that affect the speed and volume of runoff entering water bodies (Arnold & Gibbons 2007; Elrashidi et al. 2013). Residential areas themselves could be further differentiated by factors such as the presence of green spaces, the density of development, and the types of sewage and stormwater management systems in place (Macías-Tapia et al. 2023).

b. Explore the relationship between the rates, durations, and frequency of tidal flooding with nutrient loading to enable a clearer understanding of how different inundation rates influence nutrient contributions during such events.

c. Explore the differential impacts of nutrient loading due to tidal flooding on phytoplankton dynamics across various regions of the Chesapeake Bay.

d. Leverage community science initiatives to collect the extensive data required for analyzing nutrient loads during tidal flood events across the Chesapeake Bay. The Macías-Tapia et al. (2021) and (2023) studies found success in using community scientists to collection water samples during tidal flooding events, providing a cost-effective method to gather a large quantity of water quality data across large areas impacted by tidal flooding. Engaging the community not only aids in comprehensive data gathering but also fosters environmental awareness and local stewardship.

4.3 Nonpoint Source Best Management Practices

A nonpoint source best management practice (BMP) refers to a strategy or technique designed to mitigate pollution originating from diffuse sources, such as stormwater runoff from agricultural lands, urban areas, or forestry operations. Traditionally, BMPs are selected based on site-specific conditions, their observed performance, and efficiency standards. BMPs can be implemented either independently or in series to mitigate the impacts of land use and other human activities on water quality (Johnson et al. 2018). Practices are typically designed based on existing problems (e.g. recurrent stormwater flooding) or in anticipation of potential problems based on experience with similar sites (e.g. expected impacts from new urban development) (Johnson et al. 2022). BMPs are broadly defined as nonstructural or structural. Nonstructural BMPs focus on prevention of pollutants through education, watershed planning, and restoration efforts. Structural BMPs, on the other hand, are engineered solutions that physically manage pollutants by preventing their entry into water bodies (Muthukrishnan et al. 2004). Structural BMPs can be broadly categorized into 'gray', 'green', and 'hybrid' infrastructure.

Gray infrastructure involves hard structures like detention basins and storm sewers, designed to quickly channel runoff away from urban areas. Although these structures are necessary to handle large precipitation events, they are generally inflexible and difficult to modify under changing conditions, such as increases in water volumes and the dynamic ebb and flow patterns of tidal flooding (Johnson et al. 2018; Johnson et al. 2022). Many gray infrastructures, often outdated, already struggle with capacity and efficiency, leading to the importance of integrating green infrastructure (Johnson et al. 2018; Johnson et al. 2022). Green infrastructure utilizes vegetation and soil to manage and treat stormwater at its source, leveraging physical retention or filtration of water, plant growth, biological uptake, and other mechanisms sensitive to changes in water volume and flow rates. This approach offers scalability and additional social, economic, and environmental benefits, referred to as co-benefits. Hybrid systems, such as wet ponds, combine gray and green infrastructure elements, integrating both detention capabilities and biological processes. While hybrid approaches do offer co-benefits through the employed biological processes, the incorporation of gray infrastructure components may also limit their flexibility and adaptability for modification if needed.

Flexibility and adaptability are crucial as increasing tidal flooding poses risks to the effectiveness of BMPs. Best management practices were designed under historical conditions and may not be equipped to handle the altered water dynamics brought on by increasing frequency and scale of tidal flooding events (Moftakhari et al, 2018). The complex ebb and flow pattern and prolonged inundation of tidal flooding, in contrast to the one-way flow of stormwater, flooding poses potential challenges to BMPs (Macías-Tapia et al. 2023). For example, the extended exposure to water and the cyclic movement may overwhelm infiltration based BMPs, leading to reduced pollutant removal efficiency over time (Strauch et al. 2013; Liu et al. 2016). Given the complexities and uncertainties associated with tidal flooding, managing its risk and future impacts requires proactive planning and adaptation strategies. Developing resilient BMPs that can withstand disturbances from tidal flooding is crucial. Resilient BMPs should either maintain functionality despite disturbances or have a strong capacity for recovery or adaptation. In the context of tidal flooding, resilient best management practices need to consider factors such as the potential for backward flow of water, accumulation of materials during inundation, the inundation of saltwater, and the need for modifications to handle varying tidal flood volumes and frequencies. Since gray infrastructure is harder to modify and potentially less effective at handling tidal flooding, this section will focus on the sensitivities of green and hybrid infrastructure to tidal flooding, as well as potential strategies for improvement, given their comparative adaptability.

Studies on the sensitivities of BMPs often focus on increased precipitation volume and intensity. While studies on the effects of tidal flooding on BMPs are limited, research on the effects of increased precipitation under changing climatic conditions may offer valuable insights as both involve an increase in water levels. Tidal flooding, however, possesses unique characteristics, such as a complex ebb and flow pattern and prolonged inundation (Macías-Tapia et al. 2023). These features may have unique effects on BMP performance that differ from those of increased precipitation alone. Nevertheless, due to limited research, this section focuses on the literature that that increases understanding of how tidal flooding could affect best management practices, including any reference to increased precipitation. The focus of this section also primarily regards urban BMPs because the quantification of nutrient inputs from tidal flooding has only been conducted in an urban area of the Chesapeake Bay watershed. However, if tidal flooding in agricultural and forested areas is also found to contribute significant nutrients, further research should be extended to those BMPs as well. It is likely that tidal flooding affects BMPs used in agricultural and forested settings in similar ways, even though it is not explicitly addressed in this paper.

Job et al. (2020), using a modeling approach, assessed the water quantity and quality performance of a range best management practices under current and future climate scenarios. Specifically, they modeled projected increases in precipitation intensity to assess effects on stormwater infrastructure. Job et al. (2020) found that across the board increased precipitation events can lead to decreased effectiveness of BMPs due to inadequate size structures to handle higher runoff velocities and an increased risk of biocomponents or control structures being washed out. Increased precipitation can also overwhelm BMPs designed for typical rainfall patterns, leading to increased runoff and reduced pollutant removal efficiency. These findings from Job et al. (2020) suggest that BMPs may face similar challenges when subjected to the increased volumes and flow rates associated with tidal flooding. The results from Job et al. (2020) did not highlight specific BMPs, but rather served as an evaluation of BMP performance wholistically. To aid in this understanding, a comprehensive table (Table 1) has been compiled, delineating each urban BMP's potential sensitivities to tidal influences alongside pertinent literature. The goal of this table is to systematically lay out the vulnerabilities of each specific BMP to tidal flooding, which can help to steer research efforts toward refining their design, aiming to bolster their effectiveness against the specific challenges introduced by increased tidal events. The following sections highlight specific BMPs and their sensitives to tidal flooding in more detail.

BMP Class	**Type** (Gray, Green, Hybrid)	**Tidal Flooding Sensitivity**	**Supporting Literature**
Biofiltration	Green	● Tidal flooding can introduce water volumes that exceed the design capacity of biofiltration systems. ● Tidal waters may be higher in salinity which can affect the vegetation negatively especially if the plants are not tolerant to salt. ● Tidal flooding encompasses different patterns of water flow, and could potentially bypass the biofiltration system all together.	Semadeni-Davies 2012; Strauch et al. 2013; Liu et al, 2016; Butcher et al. 2017; Fowdar et al. 2021; Tirpak et al. 2021; Johnson et al. 2022
Bioreactors	Hybrid	● Tidal flooding can introduce saline water into bioreactors, potentially inhibiting the microbial processes crucial for nitrogen transformation. ● Tidal flooding may exceed the design capacity of bioreactors, leading to overflows or bypasses, which many compromise efficiency. ● Tidal flooding can result in increased sedimentation that may clog the system and reduce effectiveness.	Christianson et al. 2012; Cao et al. 2022; Johnson et al. 2022
Green roofs	Green	● No sensitivity to tidal flooding	
		● Tidal flooding can introduce large volumes of water possibly diluting concentration of pollutants and disrupting settled sediments, which	Hogan and Walbridge 2007; Liu et al. 2008; Semadeni-Davies 2012; Hoss et al.

Wet detention ponds	Hybrid	may resuspend and release captured pollutants back into the water. ● Increased water volumes resulting from tidal flooding may also lead to overflow which not only reduces the pond's structural capacity but also risks erosion of the pond banks, affecting its structural integrity and function.	2016; Liu et al. 2016; Johnson et al. 2022
Dry detention ponds	Hybrid	● Tidal flooding can inundate these ponds effectively reducing their capacity to detain pollutants. ● Frequent tidal influxes may degrade the structure and functionality of the ponds, particularly if they are not designed to handle mixed water flows or saline conditions.	Hogan and Walbridge 2007; Liu et al. 2008; Hoss et al. 2016; Liu et al. 2016; Johnson et al. 2022
Permeable Pavement	Green	● Sediments brought in by tidal waters may clog the pores of the pavement, reducing its permeability and effectiveness in draining stormwater. ● Frequent or severe inundation due to tidal flooding may reduce the infiltration capacity of permeable pavement.	Hoss et al. 2016; Johnson et al. 2022
Riparian buffers	Green	● Extended periods of inundation from tidal flooding can result in water logging which stresses plants and can lead to reduced vigor or death, reducing the buffer's ability to detain pollutants. ● Tidal flooding may alter the natural flow of water potentially increasing erosion rates of buffer zones, damaging the buffer structure and function.	Osborne & Kovacic 1993; Kovacic et al. 2000; Liu et al. 2008; Seavy et al. 2009; Liu et al. 2016; Johnson et al. 2022
Constructed wetland	Green	● Tidal flooding can alter the hydrology of constructed wetlands, potentially overwhelming the system with water and disrupting its normal operation.	Osborne & Kovacic 1993; Kovacic et al. 2000; Liu et al. 2008; Liu et al. 2016; Johnson et al. 2022

Table 1: Lists each urban BMP class, type, potential tidal flooding sensitivities and cited relevant literature.

4.3.1 Wet & Dry Detention Ponds

Wet and dry ponds are both designed to remove sediment, nutrients, and other pollutants, but they function slightly differently (Burton 2020; EPA 2021a). A dry pond is intended to temporarily hold water before releasing it to a nearby waterbody (Fig. 2). Between rainfall events, a dry pond appears as a grassy depression. When it rains, the pond fills with water and retains it for up to 72 hours, allowing sediment and nutrients to settle out. Dry ponds help control peak flows of stormwater runoff, reducing nutrient input (Metropolitan Government of Nashville). Wet ponds, in contrast, maintain a permanent water pool and often include plants and a wetland area (Fig. 3). They remove pollutants by allowing sediment to settle as water flows from one end of the pond to the other and through biological uptake, as plants absorb excess nutrients (EPA 2021a). Wet pond water levels can rise significantly during storms, like dry ponds. Due to their longer water retention time, wet ponds typically remove more pollutants (Burton 2020). Relevant literature for wet and dry detention ponds has generally focused on impacts of effectiveness of these BMPs under potential changes in storm magnitude and frequency (Christianson et al. 2012; Semadeni-Davies 2012; Strauch et al. 2013; Liu et al, 2016; Butcher et al. 2017; Job et al. 2020; Fowdar et al. 2021; Tirpak et al. 2021; Cao et al. 2022; Johnson et al. 2022). Although this is not directly related to tidal flooding, these studies demonstrate how the design of BMPs typically begin with consideration of average rainfall recurrence intervals (Claytor & Schueler 1996; Kadlec & Knight 1996; Berndtsson 2010; Gallo et al. 2012; Hunt et al. 2012). The capacity of wet and dry ponds was designed with historic rainfall recurrence intervals in mind. However, the altered relationship of floodwater volumes resulting from tidal flooding can lead to uncontrolled discharges if the pond overflows (Semadeni-Davies 2012; Johnson et al. 2022). This reduces the retention time for floodwater in both wet and dry ponds undermining their ability to treat stormwater and manage runoff effectively during tidal flooding events. Changes in annual volumes of floodwater brought on by tidal flooding may affect the minimum drainage area requirements to sustain both dry and wet ponds (Johnson et al. 2022). Expanding the capacity of wet and dry ponds is difficult and likely cost prohibitive for most jurisdictions as the ponds are typically integrated with other urban utilities requiring extensive planning and coordination with various municipal and engineering entities.

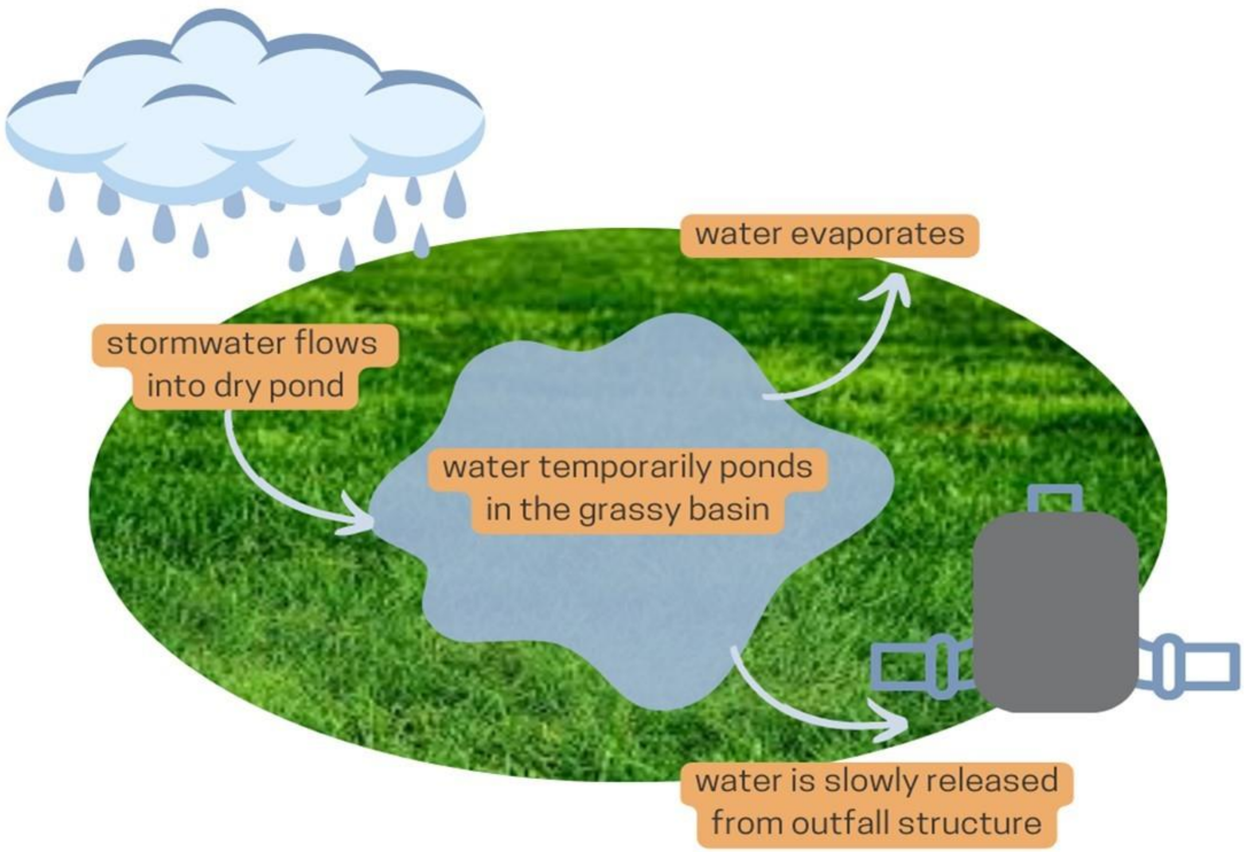

Figure 2: Design of a dry detention pond (Source: Metropolitan Government of Nashville)

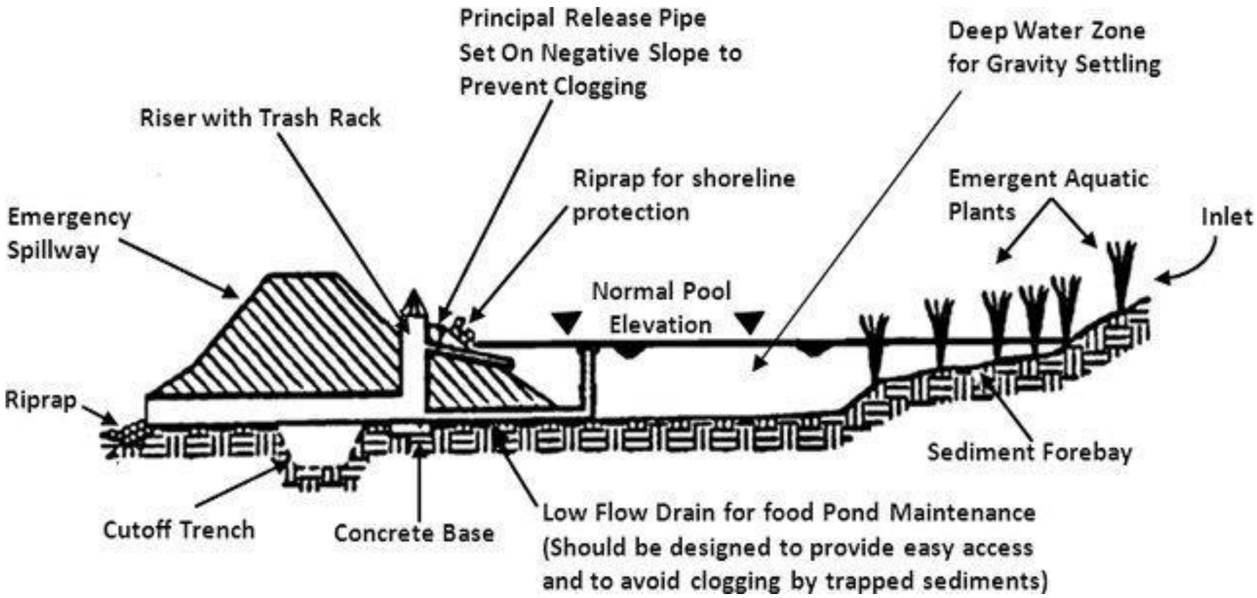

Figure 3: Typical Design of Wet Detention Pond (Source: Hung et al. 2012)

4.3.2 Riparian Buffers, Constructed Wetlands,

Constructed wetlands and riparian buffers designed to mitigate the impacts of stormwater runoff on water quality and aquatic ecosystems. They serve as natural filters, helping to remove sediment and nutrients from runoff. Riparian buffers are strips of vegetation along water bodies that help to protect water quality by filtering pollutants and reducing erosion (EPA 2021c). Constructed wetlands, on the other hand, are engineered systems that mimic the functions of natural wetlands, using vegetation, soils, and microbial processes to treat water (EPA 2015). Studies have demonstrated that riparian buffers and constructed wetlands become less effective with more frequent and severe rainfall events (Osborne & Kovacic 1993; Liu et al. 2008). This is because their capacity to absorb and filter runoff is lower when the soil is already saturated. Increased storm intensity can also reduce retention time and increase the frequency or magnitude of flushing events, releasing nutrients and sediment (Kovacic et al. 2000, Liu et al. 2008). Tidal flooding is also likely to result in similar effects. Extended periods of inundation from tidal flooding can result in water logging of riparian buffers and constructed wetlands which may increase erosion rates and reduce the retention time for nutrients and sediments contained in both BMPs. Consistent inundation from tidal flooding may damage the structure and function of riparian buffers and constructed wetlands overtime, reducing their lifespan.

4.3.3 Biofiltration

Biofiltration systems, like rain gardens, designed to capture and treat stormwater runoff. It typically consists of a depressed area filled with a soil mix and planted with vegetation, often including native plants. When stormwater enters the biofiltration area, it is temporarily stored and allowed to infiltrate into the soil (VA DEQ 2011). The soil and vegetation help filter out pollutants and remove nutrients from the runoff. Biofiltration practices are well suited to small sites in urbanized settings and can filter stormwater from small to medium storms (VA DEQ 2011; EPA 2021b). Studies have demonstrated performance of biofiltration practices can decrease with short runoff contact time, channelization, large storm events, high runoff velocities and discharge rates (Strauch et al. 2013; Liu et al. 2016). Increased frequency of tidal flooding can affect many of these factors. Tidal flooding may introduce water volumes that exceed the design capacity of these biofiltration systems. Given that these biofiltration systems are often placed in residential areas and have smaller capacities, it is likely that the extent of inundation of tidal flooding will play a large role in the effectiveness of these systems. Depending on where these biofiltration systems are located, it is likely that the vegetation used in these systems is not salt tolerant as they were built with only stormwater runoff in mind. Given tidal flooding is likely bringing water in from a more saline source, the vegetation used to remediate nutrients could be negatively impacted (Cao et al. 2022). Taken together, these indicate a likely reduction in the ability for biofiltration systems to retain their full function in the wake of increased tidal flooding. However, these systems generally have greater flexibility on sizing and an enhanced adaptation ability. Biofiltration systems can easily be updated to increase capacity for tidal flooding and retrofitted with vegetation that may be more resilient to higher salinity waters.

4.3.4 Future Research

While the research outlined in this section provides valuable insights into the effects of increased water flow on urban BMPs, they predominantly focus on rain-driven scenarios rather than the unique challenges of tidal flooding. This highlights the need for future research to explore how the nuances of tidal flooding may implicate urban BMP design and implementation. Facing the escalating risks posed by tidal flooding, it is crucial to fortify the resilience of best management practices to ensure they continue to mitigate non-point source pollution effectively. Such targeted research is imperative for informing the strategic enhancement of BMP designs, ultimately leading to the development of robust, adaptive urban stormwater management systems capable of withstanding the complexities brought about by changing climate conditions and rising tidal threats. Research that focuses on the potential sensitives of urban BMPs to tidal flooding ensures that urban infrastructures not only comply with current standards but are also prepared to meet future environmental challenges.

5 Conclusion

Tidal flooding is becoming an increasing concern for coastal communities throughout the Chesapeake Bay (Ezer 2018). Recent research has indicated that tidal flooding can introduce substantial amounts of nutrients into coastal zones, sometimes exceeding the annual load allocations set by existing TMDL frameworks (Macías-Tapia et al. 2021; Macías-Tapia et al.

2023). This represents a potential critical gap in our current understanding and management of nutrient inputs calls for an urgent integration of tidal flooding dynamics into the Chesapeake Bay's nutrient management strategies. To address this, it is essential that management frameworks are evolved to not only include impacts of tidal flooding on nutrient. This report recommends the following:

a. Tidal flooding should begin to be considered in the Chesapeake Bay Program's Watershed model in the anticipated Phase 7 update to completed in 2025.
b. Data collection should be expanded across multiple watersheds with diverse land uses to assess how variations in land use influence nutrient contributions during tidal flooding events. This includes agricultural areas whose main nutrient source is fertilizer application, industrial areas who introduce both nutrients and other pollutants, such as heavy metals, through runoff, and urban areas with varying degrees of impervious surfaces that affect the speed and volume of runoff entering water bodies (Arnold & Gibbons 2007; Elrashidi et al. 2013). Residential areas themselves could be further differentiated by factors such as the presence of green spaces, the density of development, and the types of sewage and stormwater management systems in place (Macías-Tapia et al. 2023).
c. Future research should quantify the rates, durations, and frequencies of tidal flooding to explore their relationship with nutrient loading, enabling a clearer understanding of how different inundation rates influence nutrient contributions during such events.
d. The differential impacts of nutrient loading due to tidal flooding on phytoplankton dynamics should be explored across various regions of the Chesapeake Bay.

e. Community science initiatives should be leveraged to collect the extensive data required for analyzing nutrient loads during tidal flood events across the Chesapeake Bay. The Macías-Tapia et al. (2021) and (2023) studies found success in using community scientists to collection water samples during tidal flooding events, providing a cost-effective method to gather extensive water quality data across large areas impacted by tidal flooding. Engaging the community not only aids in comprehensive data gathering but also fosters environmental awareness and local stewardship.
f. Future research should prioritize the exploration of how tidal flooding impacts urban Best Management Practices (BMPs).
g. The planning, siting, and design of Best Management Practices (BMPs) should explicitly consider the effects of tidal flooding.

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