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SPECIAL ISSUE Achieving the Water Quality Goals of the Chesapeake Bay: A Comprehensive Assessment of System Response

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Adapting to an Uncertain Future: Water Quality Management in Chesapeake Bay

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ABSTRACT

The Chesapeake Bay has been at the forefront of large-scale efforts to reverse human-induced eutrophication in coastal waters. While significant progress has been made, 15 years of intensive implementation efforts reveal that outcomes in many areas have fallen short of water quality goals. Future program goals and implementation plans will increasingly be challenged by uncertainties and limits in the effectiveness of nonpoint source programs and in the estuaries' response to changing pollutant inputs and environmental conditions. This paper argues that policy changes are needed to adapt to these management realities. We outline three policy alternatives—tiered implementation of an existing Total Maximum Daily Load (TMDL), changes in the accounting and modeling of nonpoint sources, and policy sandboxing—that together offer practical pathways to accelerate learning and improve outcomes of implementation programs.

1 | Introduction

Since the 1980s, funding and regulatory programs to improve the living resources[1] of the Chesapeake Bay have focused primarily on reducing anthropogenic eutrophication. In the 1990s, the federal government and states developed a modeling and planning process to guide programs to reduce point and nonpoint nitrogen (N) and phosphorus (P) loads (sediment was added later). In the early 2000s, the U.S. Environmental Protection Agency (EPA) and the Bay states refined Bay water quality standards (USEPA 2003a, 2003b, 2004) with numeric water quality criteria for dissolved oxygen (DO) and water clarity that were deemed sufficient to support an end goal of protecting living resources (called the "designated use" of the waterbody). Less than a decade later, EPA determined the standards had not been met. EPA mandated Bay-wide N and P load targets as authorized under section 303d of the federal Clean Water Act (CWA) called Total Maximum Daily Load (TMDL) (USEPA 2010). The load reductions mandated by the TMDL were informed by a suite of deterministic models that relate nutrient load reductions to achievement of Bay water quality criteria (USEPA 2010; Hood et al. 2021).[2] EPA recognized uncertainties in the complex causal chains linking nutrient management intentions to changes in estuarine water quality and used what was considered "conservative" estimates of key model parameters (USEPA 2010). The federal, state and local partnership, called the Chesapeake Bay Program (CBP), then agreed to implement management actions by 2025 that the EPA's model estimated would achieve the TMDL target and water quality criteria at a future, unspecified date.

These efforts have produced notable successes in reducing nutrient pollutants in the face of increased human and animal populations and associated land use change, climate change, and other stressors. Federal CWA regulatory requirements have motivated state and local governments to spend billions of dollars upgrading public wastewater treatment plants to tertiary

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treatment levels. Consequently, N and P loads from wastewater treatment ("point" sources) have fallen dramatically since 1985 (Sabo et al. 2022; Zhang et al. 2023). Atmospheric N deposition has also been dramatically reduced, driven by Clean Air Act requirements for cleaner fuels in the electric utility sector. Billions of dollars of federal and state grant support have facilitated the installation of agricultural and urban best management practices (BMPs).

Despite the level of effort, water quality improvements in the Bay have lagged behind expectations. Although EPA models estimate that N and P loads have been reduced between 1985 and 2023, loads remain well above the TMDL targets. As of 2022, only 30% of the tidal portions of the Bay have attained water quality criteria, a level only slightly above 1985 conditions (CBP 2025). This situation has brought new attention to the technical and economic feasibility of achieving TMDL targets and attaining Bay water quality standards.

A recent consensus scientific report released by the Chesapeake Bay Program Science and Technical Advisory Committee (STAC) reviewed empirical evidence to identify the reasons for the limited progress toward achieving Bay water quality goals (STAC 2023). While water quality changes are directionally correct, the magnitude of improvements has not matched the expectations made by the CBP model. The report concludes that failure to achieve TMDL nutrient targets stems from the inability to substantially reduce agricultural and urban nonpoint source nutrient loads. Accumulated evidence highlights the uncertainties and limitations in achieving sufficient behavioral change and converting nonpoint source management actions into nutrient reductions (Easton et al. 2025). Within the estuary, nutrient load reductions have likewise not produced the expected water quality improvements for a number of possible reasons (STAC 2023).

This paper outlines practical approaches to planning and implementation that directly address these uncertainties, while continuing to improve water quality and living resource outcomes. Three policy alternatives are offered. First, given the uncertainty in achieving Bay water quality goals, we propose a tiered approach to TMDL implementation that establishes interim nutrient reduction targets aimed at enhancing living resource outcomes. Second, we propose developing new progress indicators that shift focus from modeled to observable outcomes, more directly acknowledge uncertainty, and incentivize improvements in reducing nonpoint source load. Third, we recommend administrative sandboxing as a mechanism to encourage and facilitate policy experimentation and development. Each alternative addresses an epistemic uncertainty in achieving Bay water quality goals.

These alternatives are illustrative, not exhaustive, of the possible responses to uncertainties in achieving water quality goals. The alternatives are consistent with an adaptive management approach, built on flexible and phased approaches to implementation that rely on "learning while doing" (NRC 2001; Shabman et al. 2007; Freedman et al. 2008). We emphasize options that not only offer promise to improve program outcomes but that are administratively feasible within existing regulatory and administrative structures.

2 | Uncertainties in Achieving Chesapeake by Water Quality Goals

2.1 | Current Chesapeake Bay Water Quality Policy

The living resource designated use (DU) of the Bay is expressed as five major habitat types of the Chesapeake Bay and its tidal tributaries that support assemblages of aquatic organisms (USEPA 2003a): shallow water (Bay grass use), open water (fish and shellfish use), deep water (seasonal fish and shellfish use), deep channel (benthic invertebrates), and migratory fish (spawning and nursery use) (Figure 1). The numeric water quality criteria (WQC) that are defined to secure attainment of the designated use (DU) in each of the five habitat types include numeric values for DO, water clarity/submerged aquatic vegetation (SAV), and chlorophyll a (chl-a) (Tango and Batiuk 2013). Multiple DO criteria apply across the habitats, while water clarity/SAV and chl-a apply to specific habitats (i.e., shallow water and select regions of the open water habitat, respectively). The Bay is further divided into 92 spatial segments (Figure 1), with each being assigned up to five habitat types, as appropriate. Thus, full attainment of the Bay water quality goals requires meeting multiple DO, water clarity/SAV, and chl-a criteria in five different habitats, and across 92 different regions (segments) of the Bay.

In planning to meet the WQS, Bay nutrient reduction programs have historically focused on meeting deep water DO criteria in the main channel (Linker et al. 2013). These areas are the most susceptible to summer hypoxia and are the most challenging criteria to attain. The CBP estimates the effect of nutrient loads from across the watershed based on how the loads influence DO in the deep-water habitats, referred to as eutrophication units. Final TMDL nutrient targets are driven by deep water DO targets, with modeling suggesting that millions of additional kilogram load reductions are needed to bring these areas into attainment (USEPA 2010). To achieve the TMDL, state and federal agencies rely on permitting programs that establish numeric effluent limits on regulated wastewater treatment plants. Bay jurisdictions also require urban municipal and industrial stormwater systems to develop plans to reduce nutrient loads. Even when a waterbody is designated as impaired under the Clean Water Act, EPA has limited legal authority to impose regulatory requirements on agricultural nonpoint sources through the TMDL process. Except for large confined animal feeding operations (CAFOs), the CWA exempts most agricultural runoff from federal permitting requirements. Instead, implementation relies largely on state and local voluntary programs, often supported by federal funding and incentives. Agricultural nonpoint source incentive programs compensate land managers for a portion of the cost to install a BMP (Shortle et al. 2012; Ribaudo 2015; Ribaudo and Shortle 2019).

The absence of regulatory authority over agricultural nonpoint sources presents a challenge to the federal government in securing nutrient reductions. To provide reasonable assurances that nonpoint source reductions will be achieved, EPA and the Bay jurisdictions agreed to an accountability framework. The CBP establishes a watershed implementation planning process (WIP) where state and local governments

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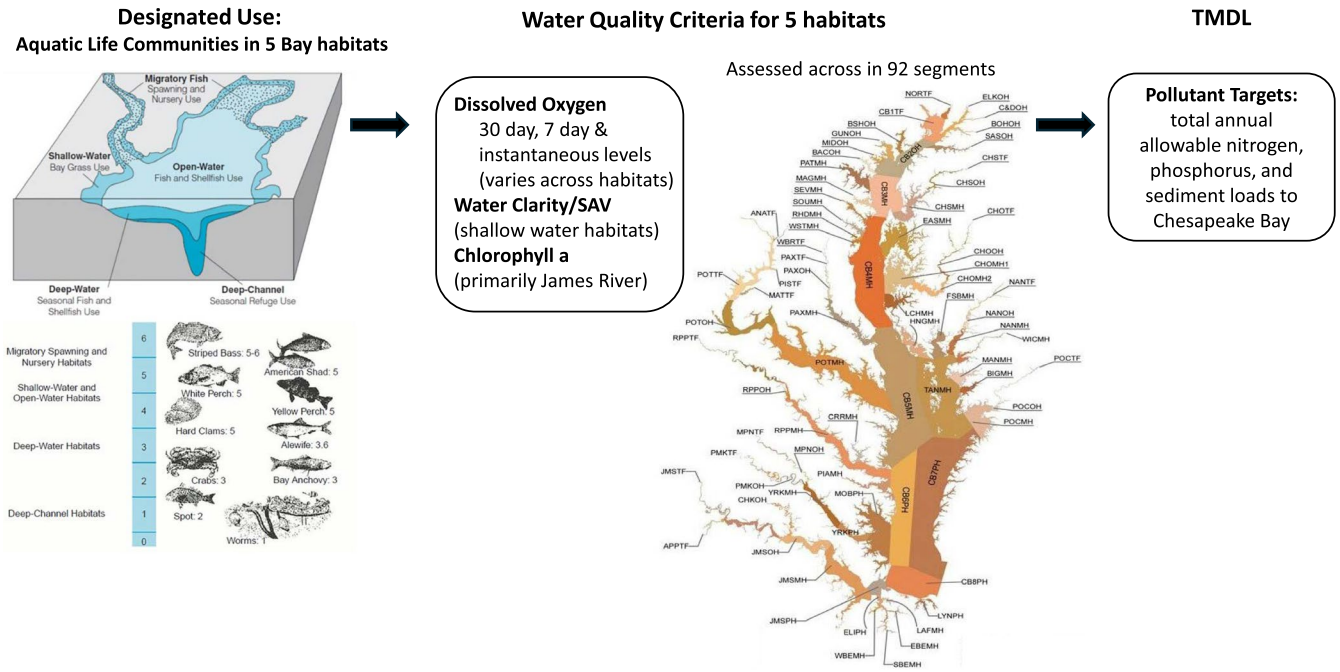


FIGURE 1 | Chesapeake Bay water quality standards and TMDL segments.

identify practices and technologies that will be used to meet the TMDL pollutant targets, short- and long-term timelines for implementation of those practices, and a system of tracking implementation progress. The CBP uses a model, CAST (Chesapeake Assessment Scenario Tool), as the exclusive way to estimate how WIP plans and actions translate into pollutant reductions. The CAST model provides estimates of average annual load of N, P, and sediment delivered from each land-river segment to the Chesapeake Bay over 10 years of typical weather conditions (1991–2000). CAST has been independently reviewed by the Chesapeake Bay Program's STAC, which documented both strengths and limitations relevant to planning and accountability (Easton et al. 2017). Model inputs include land use, nutrient inputs (including air deposition), and CBP-approved best management practices (Hood et al. 2021; Devereux and Rigelman 2014).

Within the accountability framework, jurisdictions annually report actions taken (practices installed) to meet their WIPs and CAST provides an estimate of N, P, and sediment loading to the Bay. A verification process confirms whether practices have been installed. State and local jurisdictions' TMDL obligations are considered met when CAST predictions of pollutant reductions meet or exceed TMDL targets. The CBP manages updates, inputs, and changes to the CAST model through a formal consensus-based administrative structure of federal and state managers, technical experts, and partner input. CBP partners agreed to meet the TMDL pollution control obligations by 2025. The deadline does not specify that the WQS be met or that pollutant reductions be realized by 2025, but rather that the management practices predicted by CAST are sufficient to meet the TMDL pollutant target loads for nutrients and sediment by 2025 (USEPA 2010). The CBP then assumes that attainment of final TMDL load targets and Bay water quality standards will occur at some unspecified date in the future. When the 2025 deadline was missed, EPA subsequently established a new 2040 deadline.

2.2 | Challenges Facing Bay Water Quality Policy

CBP planning and implementation programs aim to meet TMDL targets and water quality standards by influencing nutrient management and treatment across a complex causal chain within the 166,530 km^2 watershed (Figure 2). Although some observed pollutant levels and water quality trends generally move in the expected direction, evaluations along the causal chain reveal several critical areas in which outcomes diverge from model predictions. While uncertainty related to natural variability is systemic across the causal chain, the focus of this assessment is on epistemic uncertainty around the causal mechanisms linking management actions to outcomes. We subdivide the assessment into three main sections—watershed nutrients, estuary water quality response, and living resource response.

First, nonpoint source management programs (orange, Figure 2) have generally not produced the expected level of nutrient reductions. Reducing nonpoint sources is essential to meeting TMDL targets. As of 2023, CBP estimates agricultural and urban nonpoint sources and natural sources account for an estimated 80% and 85% of the total N and P, respectively, entering the Bay. However, despite substantial increases in federal/state funding, nonpoint source programs have not generated the scale and type of BMP adoption to make appreciable reductions in nonpoint source loads. As estimated by the CAST model, agricultural and urban nonpoint source N loads are falling at an annual rate of 0.14 million kg/year/year between 2009 and 2024 (CBP 2026). At the current reduction rate, more than a century of implementation would be required to achieve the TMDL target (Easton et al. 2025).

Monitoring data from stations across the watershed reveals significant uncertainties in the source and transport of nonpoint source nutrient loads. Challenges include accurately quantifying and mapping nutrient inputs, evaluating the effectiveness

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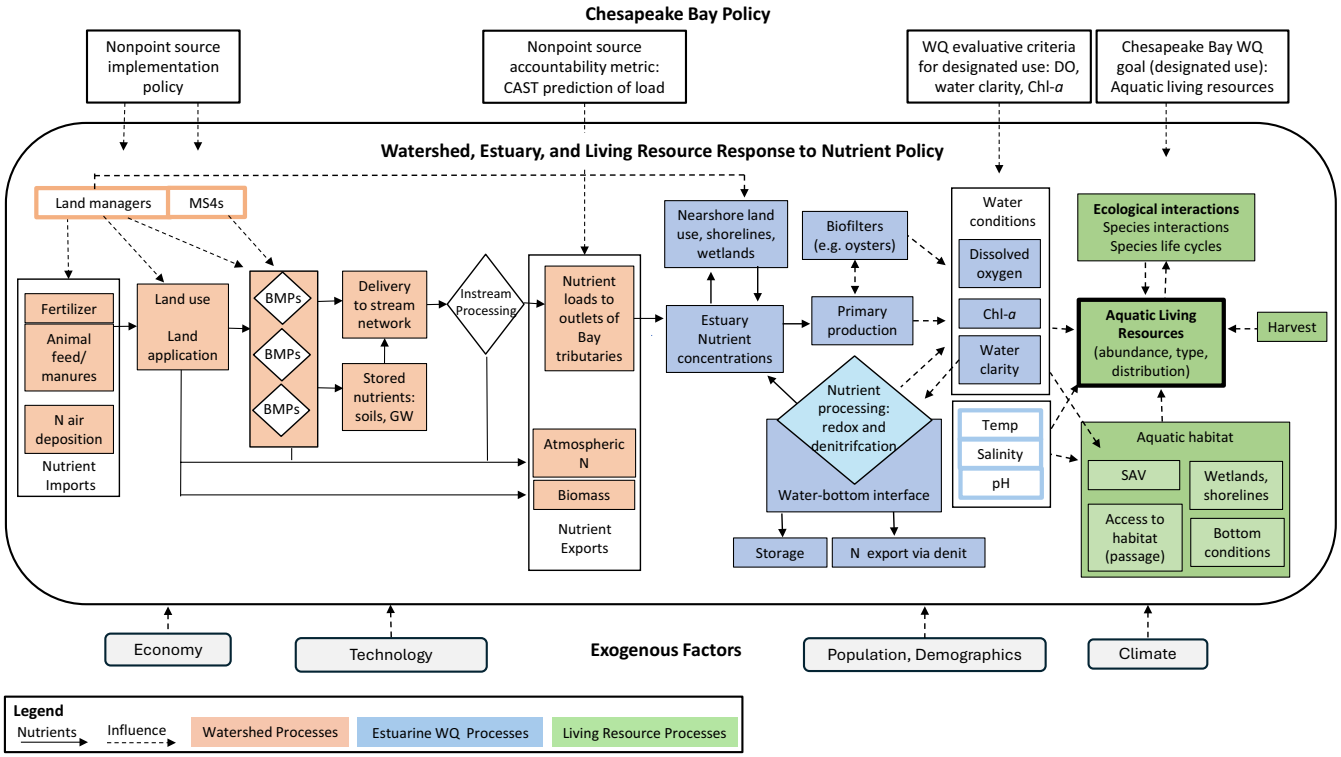


FIGURE 2 | System responses required to translate nonpoint source nutrient policies into improvement in Chesapeake Bay living resources.

of BMPs, and understanding the fate, transport, and timing of nutrients throughout the system. Several studies (Easton et al. 2025; Zhang, Murphy, et al. 2024; Ator et al. 2020) indicate that the CAST model consistently overestimates P load reductions. Although CAST suggests that TMDL targets for P are closer to being achieved than those for N, Zhang, Murphy, et al. (2024) report that measured tributary P loads exceed CAST estimates by 940,000 kg/year, even after accounting for lag times between a management change and full realization of load reductions. In some key areas, such as the Coastal Plain, nutrient loads are increasing despite CAST projections of stable or declining trends. These inconsistencies highlight CAST's limitations to accurately identify mechanisms driving observed nutrient patterns.

The CBP planning and implementation programs have proven largely ineffective at addressing the large regional nutrient mass imbalances, defined as the difference of nutrient imports and exports from a watershed, that exist throughout the watershed (Easton et al. 2025). Conventional incentive programs have encouraged the adoption of a subset of practices that minimally disrupt farm profitability but are not particularly effective at altering nutrient balances (Easton et al. 2025; Stephenson et al. 2022). Studies have noted persistent challenges in achieving N, P, and sediment reductions in areas of the watershed with intensive animal and crop production even under substantial BMP implementation efforts (Webber et al. 2024; Fox et al. 2021; Fisher et al. 2021).

Several environmental factors outside of CBP control weaken the expected water quality response to nutrient reductions in the estuary (blue in Figure 2). Long-term monitoring data from estuary stations show that Bay waters are steadily warming, which weakens the expected DO response to nutrient reductions, even when nutrient loads are in decline (Hinson et al. 2022; Frankel et al. 2022; Ni et al. 2020; Batiuk et al. 2023). In response, TMDL nutrient targets are adjusted downward to compensate for the warming effect and to meet current DO criteria. Additionally, shifts in precipitation patterns since the 1990s, marked by more frequent and intense storm events, introduce additional nutrient loads into the Bay (Modi et al. 2021; Wagena et al. 2018; Murphy et al. 2022) further complicating efforts to improve water quality.

While Bay water quality has slowly improved, progress toward attainment varies substantially across Bay segments and habitats. Between 70% and 80% of migratory and spawning and open water habitats have attained the DO criteria, with some of the remaining nonattainment areas close to attainment. However, DO criteria in deep water and deep channel habitat exhibit large and persistent attainment deficits and the rate of DO improvement in the deep channel continues to lag improvements elsewhere (Zhang, Murphy, et al. 2018; Zhang, Murphy, et al. 2025). In addition, preliminary analysis using the CBP estuary model suggests that the model overestimates DO response to realized nutrient and sediment load reductions, particularly in the deep-water habitats (STAC 2023). Submerged aquatic vegetation (SAV) coverage in shallow habitats falls well short of stated goals. A recent synthesis of Bay water clarity conditions concludes that, while clarity is improving, future conditions are unlikely to resemble the conditions reflected in Bay water quality criteria (Turner et al. 2026).

Although CBP management actions are directed toward achieving numeric water quality conditions, enhancement and protection of aquatic resources is the ultimate management

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objective (Figure 2, green). Direct evidence linking water quality changes to measurable improvements in living resources remains inconclusive. This is due in part to the complexity of overlapping environmental changes and ecological interactions, and in part to the lack of significant, system-wide improvements in key indicators, such as DO (Rose et al. 2023). While CBP employs a suite of models to predict how management actions affect chemical conditions in the estuary (particularly nutrient levels and DO), the CBP does not estimate how changes in DO and habitat influence the composition or abundance of living resources.

2.3 | Addressing Uncertainties and Articulating Tradeoffs

Collectively, the uncertainties described above suggest that full achievement of Bay water quality standards is uncertain and, at best, remains a long-term prospect (STAC 2023). Figure 3A presents a conceptual illustration of how costs may change across different levels of WQS attainment (DO, water clarity/SAV, and chl-a) across all 92 estuary segments. Because there is uncertainty in both how effectively nonpoint-source reductions can be achieved and how reliably those reductions translate into water quality improvements, the exact cost of reaching any level of attainment is unknown (dotted blue curves). In general, however, the cost of bringing additional segments into attainment is expected to rise at an increasing rate. This reflects both the increasing incremental costs of nonpoint source controls and the diminishing DO response to further nutrient reductions (STAC 2023; Kaufman et al. 2014; Price et al. 2021; Wainger 2012). Earlier analyses, conducted during the development of the WQS, suggested that the Bay water quality goals were physically and economically attainable (USEPA 2003b; Maryland Department of the Environment 2004).

The response gaps described above also suggest the cost-attainment curve has effectively shifted left, increasing the possibility that full attainment may be technically infeasible under current policy and technologies. That is, the cost curve in Figure 3 may never intersect 100% attainment. Pennsylvania, which bears much of the responsibility for meeting deep channel DO criteria because of the Susquehanna River's influence, has not produced an EPA-approved WIP able to achieve the TMDL target (USEPA 2022). Gomez et al. (2024) estimate that meeting the TMDL by 2050 given expected increases in animal numbers and crop yields would require a 30% reduction in fertilizer and feed conversion ratios and a 9% reduction in agricultural land. For context, total N imports into the watershed have remained relatively constant during the TMDL period (Sabo et al. 2022), highlighting the difficulty of achieving the necessary reductions.

The cost of attainment heightens attention on the public benefits achieved with the expenditure of resources to achieve the WQS. A primary public benefit associated with achieving WQS arise from improvements in aquatic living resources (Figure 3B). Living resources are generally expected to respond favorably to improved and enhanced habitat conditions (e.g., more usable areas with adequate DO). However, living

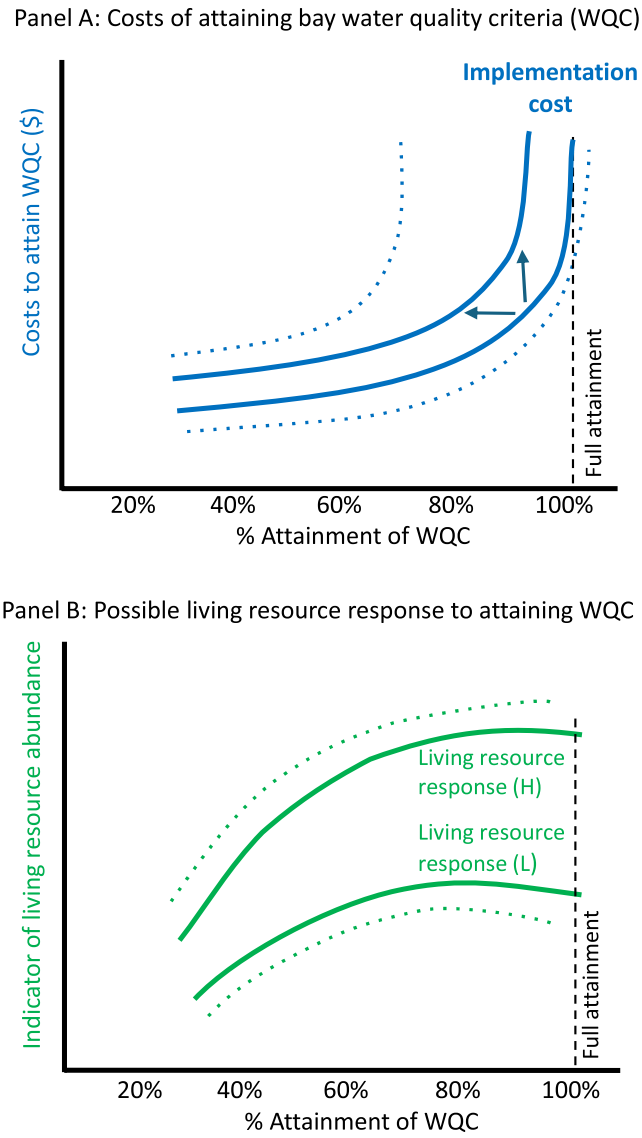


FIGURE 3 | Conceptual costs and responses of attaining Chesapeake Bay water quality criteria. Horizontal axes show the weighted portion of the Bay meeting water quality standards (currently in the low 30%). Panel (A) indicates that the cost of attainment increases at an increasing rate when approaching full attainment (as expected) and is likely shifting left, reflecting the response gaps that will require additional effort and costs to achieve any level of attainment. Panel (B) shows potential living resource response to improved water quality is likely nonlinear with respect to attainment levels, the specific response (H or L) dependent on the condition of the factors important to living resources as water quality improves. Dotted lines emphasize uncertainties in response.

resource abundance may eventually decrease as nutrient loads are reduced and water quality approaches full attainment. For example, lower nutrient loads needed to achieve 100% attainment of DO standards in the deep channel may restrict primary production in other bay segments, which could limit fish biomass (Breitburg, Craig, et al. 2009; Breitburg, Hondorp, et al. 2009).

The extent and nature of living resource improvements depend strongly on where, how much, and when water quality enhancements occur. Whether living resources follow a high

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(H) or low (L) response trajectory to water quality improvements (Figure 3B) depends on a variety of factors, including water temperature, salinity, structural habitat, disease, and commercial and recreational harvest (Fabrizio et al. 2021; Rose et al. 2023). If these factors already limit the carrying capacity for fish, shellfish, and crustaceans, improvements in DO alone may yield only modest ecological responses (response L, Figure 3B). Stronger biological responses would require targeted investments that address these additional limiting factors. The risk of pursuing an unattainable water quality goal driven solely by CWA mandates is that resources may be diverted from management actions that could generate greater benefits for living resources (STAC 2023).

The structure of the WQS and the legal imperative to attain the numeric water quality criteria do not require the CBP to articulate or manage the ecological relationships depicted in Figure 3B. The WQS establishes necessary but not sufficient conditions for improving living resource outcomes. There has been no management imperative to assess how or whether living resources would respond to water quality improvements. Because of the legal mandates of the WQS and the TMDL, N and P, not living resources, have become the de facto management currency of the CBP (STAC 2023).

The accumulated evidence calls these historical management premises into question. We offer a set of policy alternatives aimed at improving adaptability and responsiveness to the uncertainties and tradeoffs involved in meeting water quality standards and reducing nonpoint source loads. First, we propose a "tiered" approach to TMDL implementation, which could accelerate improvements in living resources even if final TMDL targets are not fully met. Second, we recommend improving nonpoint source programs by explicitly acknowledging and addressing the inherent uncertainties in nonpoint source management (Wagena et al. 2019). This will require a shift away from deterministic modeling and accounting frameworks that overlook uncertainty and discourage efforts to improve collective understanding of nonpoint source dynamics. Finally, we introduce a structured process, sandboxing, for developing and evaluating new rules and programmatic approaches within regulatory and administrative settings.

3 | Tiered Approach to Implementing the TMDL

A key element of adaptive decision-making is the continuous development and reevaluation of goals based on new information and improved understanding of system response. Considering the current challenges to achieving Bay WQS, policymakers could consider two policy alternatives to the current TMDL implementation process: (1) formally revise WQS using existing CWA processes to reflect evolving physical and economic constraints, and (2) maintain existing WQS and TMDL targets but adjust the implementation strategy and timeline to focus on achievable interim management goals. The first option involves a formal CWA process known as a use attainability analysis. This option may face socio-political challenges due to concerns about perceived backsliding on prior water quality commitments. The second option, a tiered approach to TMDL implementation, does not alter TMDL targets or WQS but would spatially and temporally prioritize implementation based on potential living resource benefits (Stephenson et al. 2025).

3.1 | A Tiered Approach to Implementation of the Bay TMDL

The distinguishing features of a tiered approach to Bay TMDL implementation are summarized in Table 1. A tiered approach acknowledges the substantial questions of cost and feasibility of achieving the WQS (Figure 3A) by establishing 10- to 15-year interim nutrient & sediment goals. The final TMDL targets remain in place, but the interim goals serve as planning waypoints. The CWA does not place deadlines on achievement of final TMDLs targets. Given the focus on improving nonpoint source outcomes, the tiered approach would not require any change in ongoing point source permit obligations, which would continue to be subject to existing requirements.

Planning and implementation in a situation where goals are costly and uncertain creates the need for priority setting. The tiered implementation approach prioritizes water quality improvements based on their potential to generate living resource benefits (Figure 3). This shifts the focus of water quality planning from DO attainment in the deep water/main channel segments toward other habitats and locations where improvements are likely to yield larger and immediate benefits for living resources. For example, improving water quality conditions in open and shallow water habitats can provide more direct benefit to many key fish species (forage fish, recreational/commercial species, etc.) than improvements in deep water habitats. These habitats are typically found near shorelines and in Bay tributaries (Figure 4). While deep water hypoxia has traditionally received management attention, several shallow and open water habitats also show DO attainment deficits (Zhang, Tango, et al. 2018; Zhang, Shenk, et al. 2024). Improving conditions in

TABLE 1 | Approaches to implementing the Chesapeake Bay TMDL.

Planning objectives	Tiered approach	Conventional approach
Implementation planning horizon	10–15 year interim nutrient & sediment goals	10–15 year to achieve final TMDL targets
Planning priorities for nutrient reduction	Local areas for living resource benefit	Deep channel DO
Type of implementation	Water quality + habitat restoration	Water quality
Final TMDL nutrient and sediment targets	Same	Same
TMDL permittee obligations	Same	Same

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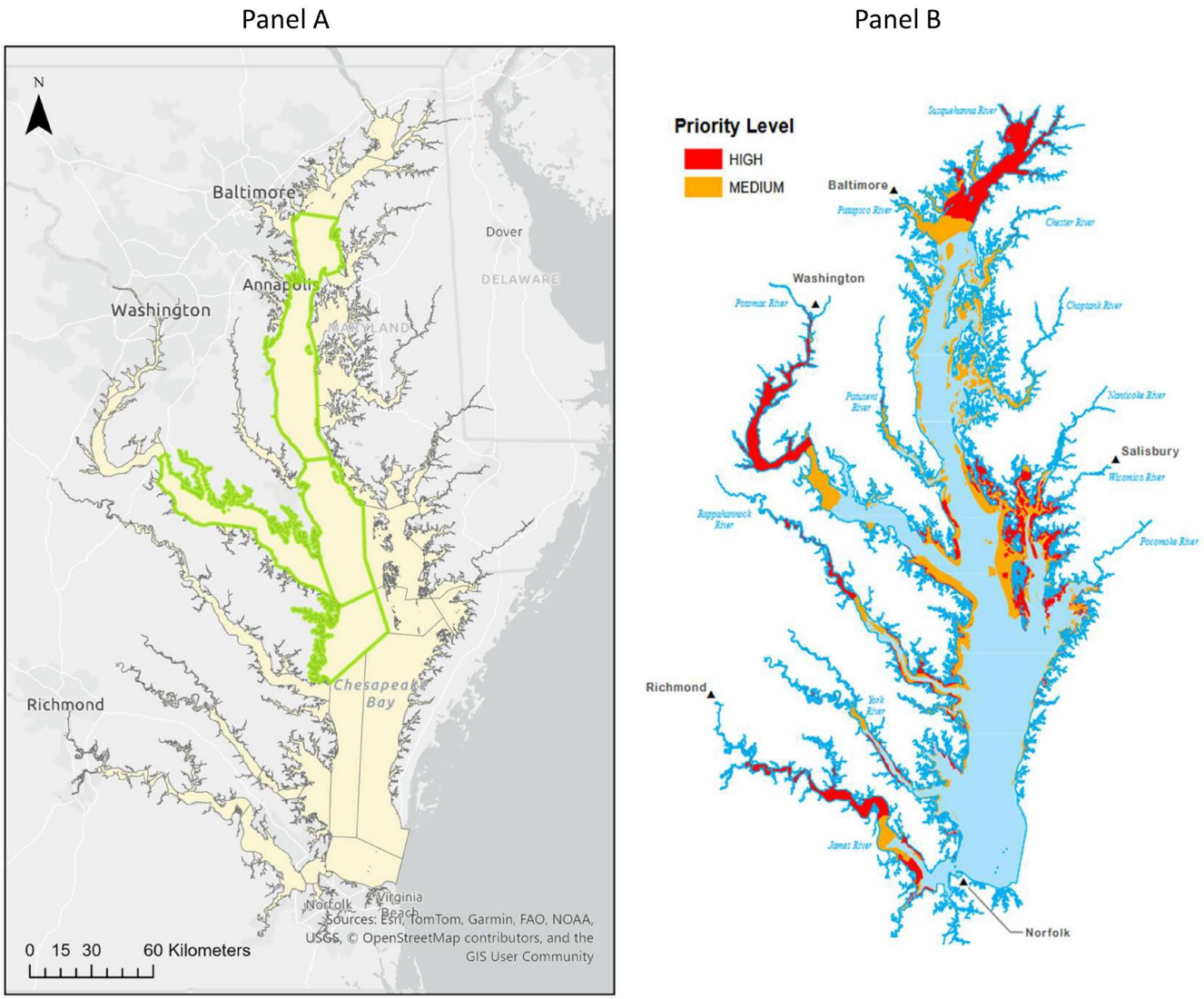


FIGURE 4 | Panel (A) shows the four segments of Chesapeake Bay that contain target deep water and deep channel habitats. The final TMDL pollutant load targets are driven by attainment of DO criteria in deep water habitats in these segments. Panel (B) shows the result of a 2008 effort to prioritize water quality improvements (high and medium priority) based on potential impact on over 20 key aquatic species (Chesapeake Bay Program 2008). A tiered approach to implementing the TMDL would set interim load reduction goals to achieve habitat improvements in these areas.

these regions may also require smaller overall nutrient and sediment reductions, making improvements more feasible.

The tiered approach broadens planning and analytical attention on other factors impacting living resources. Besides DO, water clarity/SAV and chl-a exhibit notable deficits in ecologically important areas of the Bay. Although long term water clarity has improved, spatial variability and localized drivers suggest that targeted load reductions in specific areas could yield substantial benefits for living resources (Testa et al. 2019; Testa et al. 2022; Harding et al. 2019). The tiered approach to Bay TMDL implementation also expands consideration of other habitat attributes, such as shoreline conditions and wetlands, that affect the potential living resource response to water quality conditions (Figure 3B shifts in living resource response to water quality improvement).

3.2 | Implementing a Tiered Approach to Bay TMDL

To realize these benefits, a tiered implementation strategy would require the development of new tools and changes to water quality planning processes. Planning and management tools must be adapted to support smaller scale water quality and living resource management objectives (Cummings et al. 2006). Specifically, a tiered approach to TMDL implementation requires identifying how living resources are likely to respond to changes in water quality and other environmental conditions. This process would include:

1. Identifying areas where improvements in water quality and habitat conditions have the greatest potential to enhance Bay living resources.

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2. Identifying the sources and effects of nutrient and sediment loads on local bay water quality.
3. Establishing interim nutrient and sediment goals for Bay segments that align water quality improvements with desired living resource outcomes.

3.2.1 | Identify Areas and Opportunities for Improving Living Resources

Within a tiered TMDL, the key management challenge is to determine where improvements in DO, water clarity/SAV, and/or chl-a are most likely to improve Bay habitat conditions. Because the WQS and historical water quality management have not routinely considered living resource response to water quality conditions, new analytical tools and planning approaches would be needed.

Habitat models statistically relate observed local densities or abundances of life stages of specific species of fish and shellfish to the presence of environmental and water quality variables. Relevant variables include water quality conditions (e.g., DO, salinity, temperature, pH, chl-a, water clarity), physical habitat characteristics such as shoreline conditions, bottom type and quality, water depth and velocity, and the presence of key aquatic habitats like oyster reefs, marsh, and SAV. Habitat models have been developed and applied to many of these species (Fabrizio et al. 2021; Secor 2009; Schlenger et al. 2022).

A species' distribution and abundance reflect combinations of these water-quality and physical-habitat factors. Habitat models identify the conditions that provide the most *potential* to support increased species abundance, but do not attempt to predict the exact population levels that result from specific habitat change. Although population and food web responses may be more directly relevant to management decisions, they carry significantly greater uncertainty than habitat-based analyses. In the context of the Chesapeake Bay, habitat suitability modeling has a practical advantage: it links water quality improvements to living resource abundance using available data, balancing relevance and uncertainty (Rose et al. 2023).

Under a tiered approach, habitat suitability analyses for key living resource species would be conducted at the local segment scale (STAC 2023). An integrated planning and analytical process would identify the species (or classes of species) that define living resource management targets (Rose et al. 2026). Each area of the Bay is likely to be influenced by the same general set of factors important to habitat suitability for each life stage/species combination, but the values and relative importance of these factors will vary among segments. Some of these factors, such as DO and water clarity, are directly managed under the TMDL, and the extent to which nutrient and sediment loads can improve water quality conditions varies by location. Other factors, such as shoreline conditions and tidal wetlands, can significantly improve living resource habitat but are not managed directly under the TMDL, even though they remain subject to management control. Additional environmental drivers such as temperature, salinity, and current are largely outside direct management control but still strongly influence living resources.

Local conditions in each segment would be evaluated to determine the potential for management actions to improve habitats. Segment-habitat combinations would be evaluated based on the potential for water quality improvements (dissolved oxygen, water clarity/SAV, or chl-a) would enhance habitat quality. Some segment-habitats may be ranked as having low improvement potential because water conditions (e.g., DO and water clarity/SAV) are already good (attaining) or because living resource habitat and response are dominated by other habitat factors that may be limiting living resource response independent of water quality conditions. Habitat analyses can reveal species-specific sensitivities and potential tradeoffs. For example, forage-fish abundance is particularly sensitive to shoreline conditions (CBP and NOAA 2023). Water quality improvements may have limited impact on such species if shoreline habitat conditions are poor or degrading. Such tradeoffs must be recognized and managed within a tiered implementation framework.

3.2.2 | Identify the Source and Effect of Nutrient and Sediment Loads on Local Water Quality

The tiered approach requires answering the technical question: What spatial distribution of nutrient load reductions can produce specific water quality improvements and corresponding habitat enhancements in a given segment? Each Bay segment receives nutrient input from both an "upstream" watershed and estuarine sources, and the relative influence of these inputs varies across the Bay's 92 segments. Upstream nutrient sources typically dominate water quality conditions in the oligohaline segments of the Bay, while mesohaline and polyhaline segments are more affected by estuarine source nutrients. Improving water quality in mesohaline and polyhaline segments often requires nutrient reductions from other regions of the Bay. For example, nutrient loads in the upper Bay are largely driven by flow and loads from the Susquehanna, whereas local sources play a larger role in the lower Bay. Ongoing improvements to the CBP estuarine models are expected to provide refined estimates of the relative contribution of nutrient sources across Bay segments.

3.2.3 | Establish Interim Nutrient and Sediment Goals Across the Regions

Because nutrient levels at any one point in the Bay can result from various combinations of upstream watershed contributions, establishing interim reduction goals will require policy decisions among CBP partners, similar to those made during the development of the original TMDL. While a tiered framework does not prescribe specific quantitative rules for selecting segments or assigning interim load goals, it provides a systematic basis for identifying where nutrient reductions are most likely to yield meaningful improvements in aquatic living resources.

As with the original TMDL allocations, interim goals are inherently political decisions. These decisions carry important distributional implications: upstream jurisdictions that contribute to deep-channel attainment deficits may bear substantial costs, while many downstream areas realize a greater share of

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ecological benefits. Under a tiered framework, interim goals for upstream jurisdictions would generally be less stringent than final TMDL requirements, reflecting a near-term focus on improvements in shallow and open-water habitats rather than deep-channel dissolved oxygen criteria. In contrast, interim efforts focused on local improvements, such as in southern rivers and coastal plain systems, may more closely align costs with expected ecological and community benefits.

Although the specific allocation of interim goals would ultimately be negotiated through the CBP, the tiered approach makes these distributional considerations more transparent and underscores the importance of stakeholder engagement to ensure political feasibility and a shared understanding of tradeoffs. Optimization analyses can further support this process by identifying cost-effective opportunities for achieving habitat improvements and the selection of interim targets.

The tiered approach also broadens TMDL planning and implementation beyond water quality. Habitat suitability analyses may reveal that improving physical habitats (marshes, shorelines) may yield greater living resource benefits than nutrient load reductions alone. For instance, a local jurisdiction may be assigned less stringent interim limits if near shore habitat improvement offers greater ecological returns. The tiered approach could increase flexibility to evaluate and pursue temporal and spatial trade-offs that would maximize benefits to living resources.

3.2.4 | Planning Challenges and Opportunities to a Tiered Approach to TMDL Implementation

A tiered approach to TMDL implementation emphasizes adaptive management based on local scale understanding of how management actions influence pollutant loads, water quality, and habitat conditions. The tiered approach acknowledges the limitations of existing modeling tools at these scales. Shallow water habitats are more diverse and less well understood compared to deep water habitats, and outcomes at finer spatial scales often diverge from modeled outcomes. Shallow water habitats exhibit considerable diversity in biophysical conditions. Large-scale estuary models may overlook unique local conditions and dynamics, such as diurnal DO cycles. Furthermore, many of the likely high-priority shallow water areas are situated in coastal watersheds where uncertainty about nonpoint source loads is the greatest.

The tiered approach places a priority on addressing the uncertainties that challenge current Bay modeling. The CAST model can still contribute to long term water quality planning and be an element of the accounting framework, but its limitations (particularly in representing localized processes) mean it cannot serve as the sole tool for the tiered planning process. Rather than replacing CAST or relying on finer-scale models to fix prediction gaps, the tiered approach broadens the evidentiary base by pairing CAST with enhanced local monitoring, empirical trend analysis, target modeling, and habitat-focused indicators. This does not eliminate uncertainty; it relocates it to a scale where discrepancies between expected and observed outcomes can be more directly identified and used to inform adaptive adjustments. In this way, the tiered approach provides a structured mechanism to confront, rather than obscure, the uncertainties that are particularly acute in shallow, more diverse, and less well-understood habitats.

4 | Nonpoint Source Accountability Framework

An effective response to the nonpoint source challenge is essential to achieving water quality improvements in the Bay. However, the current nonpoint source accountability framework limits learning and adaptation to the nonpoint source response gaps (Easton et al. 2025; STAC 2023). Shifting accountability toward water quality outcomes, rather than tracking effort, offers opportunities to accelerate adaptation and improvement in nonpoint source management.

The existing accountability framework incentivizes and tracks management effort (e.g., BMPs installed) and CAST converts effort into predicted pollutant reductions. Because CAST does not quantify uncertainties, the planning proceeds under the assumption that CAST accurately reflects underlying causal relationships and pollutant outcomes. This directs management attention toward generating enough CAST credit to meet TMDL targets, rather than toward achieving water quality outcomes. This creates two limitations: (1) it diverts managerial attention from observed pollutant outcomes, and (2) it restricts the types of policy designs jurisdictions are allowed to pursue. Indeed, this concern is consistent with the technical reviews of CAST, which urged consideration of uncertainty and limits in model representation (Easton et al. 2017).

Because CAST is the only approved tool for estimating nonpoint source reduction credit, the accountability system creates incentives for participants to "game" the model to receive TMDL credit rather than evaluate the ambient pollutant conditions (Lim et al. 2023; Bitterman and Webster 2024). The collaborative process for updating CAST often becomes a zero-sum game over model credit, delaying improvements in nonpoint-source understanding. As a result, water quality managers rely heavily on a model that they simultaneously question (Lim et al. 2023).

Gaming the model inhibits search and learning about the nonpoint source challenge. Jurisdictions devote substantial effort to identifying uncounted BMPs to obtain additional CAST credit, while avoiding updates that could increase modeled loads (Royer et al. 2016; Virginia Soil and Water Conservation Districts 2026). Identifying uncounted BMPs does not change water quality outcomes nor advance understanding about causal factors influencing outcomes. Agricultural stakeholders often believe CAST underestimates BMP performance (Blankenship 2023), even though monitoring data frequently suggest CAST overestimates reductions. The large divergences between monitored and model loads in some areas of the watershed are rarely acknowledged as evidence that the TMDL requirements have not been met. Conversely, there is little urgency in identifying and addressing sources of loads that may be undercounted in the model. When under-reported fertilizer uses and animal livestock numbers were discovered (Blankenship 2022), jurisdictions resisted incorporating the

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new data because doing so would raise model loads and increase target obligations.

The framework also discourages policy innovation (Easton et al. 2025). When new policy or management approaches are proposed, jurisdictions typically ask whether the resulting pollutant reductions can be credited in CAST. If not, they avoid pursuing them because any gains achieved may not count toward their TMDL obligations. Innovations such as spatial targeting of nonpoint source resources (Fleming et al. 2022), outcome-based nonpoint source incentive programs (Stephenson et al. 2022), and addressing nutrient mass imbalances have strong conceptual support but are constrained by the CBP accounting framework (Easton et al. 2025; STAC 2023).

Spatial targeting, for instance, is supported by extensive research showing that nonpoint-source loads are unevenly distributed and that focusing on high-loading areas would improve effectiveness and reduce costs (Fleming et al. 2022; Lintern et al. 2020; Sharpley et al. 2009; McDowell et al. 2024). Yet CAST cannot incorporate many targeting designs. "Pay for outcomes" or "pay for success" programs, which reward actual pollutant reductions rather than practice installation, are often proposed as a way to incentivize cost-effective practices, promote technological innovation, and emphasize quantification and verification of outcomes (Fleming et al. 2022; Shortle et al. 2021). Yet, the CBP must formally approve all nutrient control technologies (BMPs) and integrate them into CAST before they can receive credit, and removal efficiencies are based on generalized estimates that may not reflect site-specific conditions. The approval process for new practices may take years, further stifling innovation.

Finally, the scientific literature further highlights the variability and uncertainty inherent in BMP performance, the accuracy of model inputs, and nutrient use behavior (Koch et al. 2014; Aguilar and Dymond 2019; Macrae et al. 2021; Daryanto et al. 2017a, 2017b; Roland et al. 2022; Kleinman et al. 2019; STAC 2023; Stephenson et al. 2018; Easton et al. 2025). CAST cannot analyze variation, risk, and robustness of causal relationships, limiting its usefulness as an accountability tool.

4.1 | Accountability for Outcomes

CBP could incorporate more outcome-based metrics into the accountability framework. One alternative is to make greater use of monitoring data from the extensive network of riverine monitoring stations across the watershed as evidence of TMDL progress (Zhang, Shenk, et al. 2025). Trend-analysis tools could be used to identify statistically significant declines in nutrient loads and estimate the likelihood of meeting nutrient targets. Declining trends could constitute formal evidence of progress, while jurisdictions with increasing loads might be required to provide detailed documentation and analyses about their nonpoint source efforts.

Tying accountability more directly to observable outcomes could encourage additional investments in localized monitoring and assessment. One locality has already invested in new monitoring stations because of dissatisfaction with CAST crediting (Blankenship 2025). Outcome-based metrics of progress could involve a range of possible intermediate but observable conditions. For example, monitoring whether soil phosphorus levels are declining can provide evidence of long-term management success. Jurisdictions could be allowed to propose outcome indicators that reflect local conditions while motivating progress on nonpoint source pollutant reductions. The CBP could further support the development of finer-scale models and datasets by state and local jurisdictions to improve understanding of how management actions translate into pollutant outcomes. These tools may help explain observed patterns of pollutant loads, support spatial targeting, quantify nutrient mass imbalances, and enable performance-based incentive programs. While CAST could remain the primary tool for watershed planning, integrating more outcome-based metrics would promote deeper understanding of nonpoint source dynamics and improve management decisions.

Shifting to outcome-based accountability would require the CBP to acknowledge the inherent uncertainty in nonpoint source pollution reduction efforts. Unlike point sources, nonpoint source loads are variable and difficult to quantify precisely. Metrics/indicators of success should reflect this reality, using probabilistic or trend-based approaches to track progress rather than relying solely on deterministic targets with unacknowledged errors.

5 | Encourage Institutional Innovation Through Sandboxing

The changes discussed above highlight the need for policy change to accelerate the rate of improvement in reducing nonpoint source loads. However, given uncertainty, any policy innovation involves failure risk, including the generation of unintended consequences. Policy-makers may be justifiably reluctant to consider implementing large-scale policy changes in the face of this risk. Sandboxing offers an adaptive middle ground on how to encourage, test, and evaluate potential innovations without disrupting the broader program operations or creating unacceptable levels of failure risk.

Sandboxing is a formal process for testing new rules and programmatic approaches within structured regulatory environments. Originally developed for highly regulated industries such as finance (Allen 2019), sandboxing has been recently proposed for use in conservation programs (Higgins and Male 2019; O'Sullivan 2021). In the context of the CBP, sandboxing would allow jurisdictions to temporarily deviate from standard procedures and programmatic rules to trial new implementation strategies with a limited, well-defined scope. Sandboxing includes identifiable metrics of success and a commitment to scale successful sandboxing through the organization/program.

The process begins with a proposal to test a new rule or approach (Figure 5). The regulatory or adminstrative agency collaborates with the sandbox proposer to establish an isolated environment of sufficient size and autonomy to implement, test, and evaluate the potential change. The sandbox must

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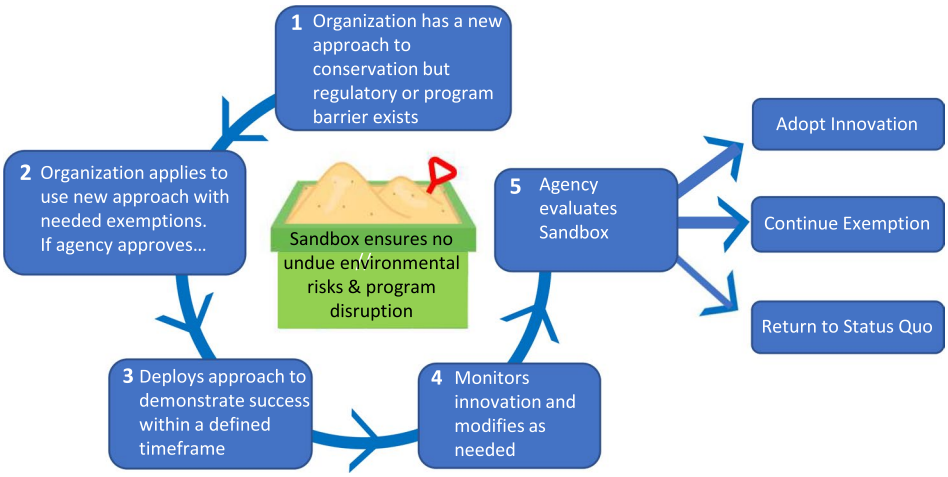


FIGURE 5 | The sandboxing process (figure adapted from Higgins and Male 2019).

include a clear plan and a method for assessing outcomes. The agency commits to reviewing the results and deciding whether to maintain the status quo, continue the sandbox, or adopt the proposed change.

Sandboxing differs from "pilot" programs and regulatory/administrative exemptions/waivers. Pilot programs can be created and trialed under existing institutional structure, do not require third party approval to proceed, and are not always implemented with a formal assessment process or a commitment to extend the pilot after demonstrated success. Regulatory waivers are case-specific exemptions from a specific regulatory requirement that do not carry any implications for larger systematic changes. In contrast, sandboxing is designed to test scalable innovations with structured oversight.

Within the CBP context, sandboxing could be particularly valuable to nonpoint source management. For example, EPA could allow jurisdictions to develop and test alternative nonpoint source accounting systems for crediting nutrient reductions using finer-scaled models and more intensive monitoring of localized outcomes. If successful, these approaches could be integrated into the Bay Program and scaled across the region, encouraging investment in outcome-based strategies.

Sandboxing could also support changes to the incentive structure, for both land managers and conservation staff. Current programs often pay a fixed share of practice costs, which may not reflect the actual water quality benefits. A sandbox could allow a local conservation district to experiment with performance-based payments tied to pollutant reductions (Collins et al. 2022). Staff incentives could also be redesigned to reward outcomes—such as signing up high-impact farms or achieving measurable nutrient reductions—rather than simply executing contracts. For example, more professional and financial incentives could be credited to staff who sign up first-time land managers or farm operations with larger estimated nutrient losses, seeking out farm operations that will secure more watershed load reductions achieved per contract (Collins et al. 2022). By creating space for experimentation and evaluation, sandboxing offers a practical pathway for institutional innovation within the CBP.

Several CBP advisory committees have encouraged active testing of regulatory sandboxing by the CBP (CBP Local Government Advisory Committee 2023; STAC 2023). Some local governments have offered several sandbox possibilities. Montgomery County Maryland has suggested developing lower cost, but reliable ways to document outcomes for tree planting efforts (Ottomanelli 2025). For sandboxing to advance, however, it will require the active commitment of EPA and relevant partners to develop and support the sandbox process.

6 | Conclusions

The CBP is entering a new phase of water quality management marked by significant uncertainty. Future water quality improvements will depend largely on addressing nonpoint sources. Nutrient cycles have been dramatically altered by agricultural production systems and by people's landscape and food preferences. How, and to what extent, nonpoint source loads affect water quality remains a challenge. Behavioral responses to technology adoption and nutrient use are complex and poorly characterized, and the diversity of site-specific conditions and nutrient loss pathways complicates efforts to improve water quality (Shortle and Horan 2017). The magnitude of Bay water quality improvements resulting from nutrient load reductions also remains uncertain (Duarte et al. 2009). Irreversible landscape changes and shifting climatic conditions complicate predictions about when and to what extent water quality improvements will occur.

To increase the effectiveness of Chesapeake Bay water quality programs, planning and implementation must more directly address these uncertainties (Hershner 2011). The three alternatives proposed here—tiered TMDL implementation, nonpoint source accountability, and sandboxing—are offered as practical policy responses to strengthen learning and adaptability in the face of uncertainty. These approaches create more direct feedback loops between planning intentions and outcomes, alert managers and stakeholders to response gaps, and encourage experimentation with new strategies.

The experience with nonpoint source management in the CBP demonstrates the limitations of assessing implementation

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success exclusively through deterministic models. Precise model predictions generate the illusion of accuracy and have focused attention on gaming the watershed model to obtain credit rather than toward improving water quality. Including ambient water quality outcomes as evaluation metrics would highlight where pollutant reductions are lagging behind or exceeding expectations. Greater focus on observed outcomes could encourage the development and use of new causal models, stimulate investment in monitoring to reduce gaps in knowledge, and strengthen stakeholders' engagement with local water quality conditions.

Experimentation is needed to improve management effectiveness. While all experiments carry a risk of failure, that risk is an inherent and necessary consequence of learning. Sandboxing offers a structured way to test policy, regulatory, and administrative innovations, evaluate their impacts, and decide whether they should be scaled, revised, or abandoned. By institutionalizing experimentation, CBP can accelerate collective learning about which approaches produce meaningful improvements.

Tiered TMDL implementation likewise enhances opportunities for learning by allowing managers to evaluate progress incrementally, identify where nutrient reductions are feasible, and prioritize locations with the greatest potential to enhance living resources. Crucially, the tiered approach broadens attention to habitat factors beyond water quality that are essential for living resource improvement.

These policy alternatives complement a wider set of proposed policy reforms to improve Bay water quality, such as improved spatial targeting of nonpoint source investments (Fleming et al. 2022), performance-based incentives (Stephenson et al. 2022), and policies to address regional nutrient mass imbalances (Easton et al. 2025). However, without mechanisms to systematically identify and address knowledge gaps and to encourage innovative designs, such reforms will not realize their full potential.

Collectively, these reforms require enhanced use of ambient monitoring data and the development of alternative modeling approaches to evaluate program outcomes and to strengthen understanding of causal processes that link management actions to those outcomes. This likely requires some reallocation of existing resources and may necessitate additional support. However, when properly structured, such an investment can create efficiencies and improve program effectiveness. One possible outcome appears certain: continuing along with the current management trajectory will lead to disappointment with future results.

Author Contributions

Kurt Stephenson: conceptualization, investigation, validation, visualization, formal analysis, project administration, data curation, writing – review and editing, methodology, supervision. **Denice Wardrop:** conceptualization, investigation, formal analysis, project administration, writing – original draft, supervision, data curation, writing – review and editing, methodology. **Kenny Rose:** conceptualization, investigation, methodology, formal analysis. **Zachary Easton:** conceptualization, investigation, writing – review and editing, validation, methodology, formal analysis, project administration, data curation. **William Dennison:** conceptualization, investigation. **Leonard Shabman:** conceptualization, methodology, writing – review and editing, formal analysis, investigation.

Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data that support the findings of this study are openly available in Chesapeake Bay Stat at https://data.chesapeakebay.net/.

Endnotes

[1] Under the bay water quality standards, living resources are defined as classes of aquatic life, such as fish shellfish, that naturally occur in 5 different bay habitats (see discussion below).

[2] Sediment was subsequently added to the list of pollutants in the TMDL.

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