Scientific and Technical Advisory Committee: Knowledge Gaps, Uncertainties, and Opportunities Regarding the Response of the Chesapeake Bay Estuary to Restoration Efforts

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About the Scientific and Technical Advisory Committee

The Scientific and Technical Advisory Committee (STAC) provides scientific and technical guidance to the Chesapeake Bay Program (CBP) on measures to restore and protect the Chesapeake Bay. Since its creation in December 1984, STAC has worked to enhance scientific communication and outreach throughout the Chesapeake Bay Watershed and beyond. STAC provides scientific and technical advice in numerous ways, including (1) technical reports and papers, (2) discussion groups, (3) assistance in organizing merit reviews of CBP programs and projects, (4) technical workshops, and (5) interaction between STAC members and the CBP. Through professional and academic contacts and organizational networks of its members, STAC ensures close cooperation among and between the various research institutions and management agencies represented in the Watershed. For additional information about STAC, please visit the STAC website at www.chesapeake.org/stac.

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Glossary of Select Key Terms and Abbreviations

STAC: The Chesapeake Bay Program's Science and Technical Advisory Committee

SAV: Submerged Aquatic vegetation, or the vascular plants that inhabit sediments

Triblet: a conversational term to describe the small tributary waters connected to larger mainstem Bay tributary estuaries.

Tidal Prism: the volume of water in an estuary or inlet between mean high tide and mean low tide, or the volume of water leaving an estuary at ebb tide. It is used to estimate flushing rates.

Pycnocline: a layer in brackish or saline waters in which water density increases rapidly with depth.

Summary

As part of the Chesapeake Bay Program's (CBP's) Science and Technical Advisory Committee (STAC) initiative "Achieving Water Quality Goals in the Chesapeake Bay: A Comprehensive Evaluation of System Response", an Estuary Working Group was formed to generate an assessment of scientific knowledge gaps, uncertainties, and recent ecosystem changes to consider in light of CBP's impending goal of full implementation of management measures (Total Maximum Daily Load [TMDL] agreements and associated necessary stakeholder actions) that are being finalized and designed to achieve living resource-based nutrient targets by 2025.

This document summarizes aspects of the knowledge gaps, uncertainties, and associated needs and opportunities relating to our understanding of how the Chesapeake Bay estuary has responded to previously implemented management plans, and what features of the ecosystem may slow or enhance its response to future management actions in the face of expected continuations of climatic change.

The CBP operates under the principles of adaptive management, with well-articulated long-term outcomes being sought through comprehensive evaluation of management alternatives, articulation of uncertainty, and processes for revising management goals, strategies, and models as new information arises. In this report, we have evaluated the estuarine ecosystem dynamics through the lens of adaptive management, with an eye toward the CPB’s stated long-term objectives. In this light, recognition of key uncertainties in the estuarine dynamics leads us to suggest adaptive pathways forward. To meet its long-term objectives effectively, it is our scientific assessment that the following steps would be fruitful for CBP and STAC to undertake:

1) ***Shift the management and science focus*** from one of slowing and preventing ecosystem degradation to one of ***accelerating ecosystem restoration and recovery*** – that is, toward mitigating impacts via the TMDL and accelerating the ***restoration of hydro-biogeochemical processes underlying targeted ecosystem services and as needed to meet CBP goals (e.g., wetlands, submerged aquatic vegetation (SAV) restoration)***.
2) Promote ***collaborative research integration approaches*** in which model uncertainty and predictions guide applied field research and monitoring, and where monitoring and research guide improved models, thus improving capacity to forecast system responses to management actions and climate change and to identify fundamental uncertainties.
3) Focus research efforts on spatial and temporal scales relevant to stakeholders and decision makers; for example, understanding the dynamics of ecosystems at the ***land-sea interface (triblets)*** in Chesapeake Bay restoration.
4) Investigate the impact of ***tipping points and improve our understanding of critically important ecological thresholds*** and their role in estuarine restoration dynamics.
5) Account for ***climate change*** in Chesapeake Bay restoration and expectations of recovery.
6) Use ***shallow water habitats*** as a testbed for integrating the land-sea interface, tipping points, and climate change using monitoring, modeling, and research approaches. In particular, we present the shallow water benthos as an exemplar that could be further pursued as a demonstration of the potential power of the first five steps —that is, as an exemplar of an ecosystem where there has been prior successful application of an integrative monitoring, modeling, and research approach at the land-sea interface.

7) Develop a ***future vision*** of Chesapeake Bay management that a) better embraces and addresses decision making in the face of uncertainty by incorporating adaptive management; b) considers potential major interventions; and c) uses an outcomes-based framework.
8) Identify ***new tools, approaches, and personnel*** that could feature in Chesapeake Bay restoration science and analysis.

In this document, each of the eight steps above is discussed in terms of the key attributes of the associated topics, the potential changes that could help address highlighted concerns, and finally, specific steps regarding what the CBP and its partners (including the STAC as well as STAC members and their affiliated institutions) can collectively undertake to enhance the restoration of Chesapeake Bay. The topics were selected based on their importance to the Chesapeake Bay ecosystem, their topical relevance to existing and anticipated trends, and the degree of previous STAC attention.

I. Background and Introduction: Chesapeake Bay Restoration Science and Water Quality Changes in Response to the TMDL Management Concept

Chesapeake Bay estuarine science programs: Early Chesapeake Bay researchers developed the foundations of estuarine science, making the Chesapeake Bay arguably the best-studied estuary in the world. The University of Maryland's Chesapeake Biological Laboratory (CBL) was established in 1925, as the first marine laboratory in the world to be focused on coastal and estuarine science, rather than ”blue-water” oceanography, and was a landmark event in estuarine science. Other landmark events for Chesapeake Bay estuarine science included the formation of the Virginia Institute of Marine Science (VIMS) in 1940 (originally named the Virginia Fisheries Laboratory), the formation of Johns Hopkins University's (JHU's) Chesapeake Bay Institute (CBI) in 1947[1], the formation of the Smithsonian Institution's Smithsonian Environmental Research Center (SERC) in 1965, and the establishment of the University of Maryland Center for Environmental Science (UMCES) in 1973, which combined CBL and other natural resources laboratories into an independent research campus of the University System of Maryland. Investigators at these research institutions have been collaborating for over 70 years and, in 1964, began a partnership originally referred to as the Chesapeake Bay Research Council, which was formally organized as the Chesapeake Research Consortium (CRC) in 1972. At the time of CBI's formation, researchers from the Chesapeake Bay and the North Carolina Sounds came together to establish the Atlantic Estuarine Research Society (AERS). Then in 1971, they joined with the New England Estuarine Research to form what is now known as the Coastal &

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[1] Although JHU formally closed its Chesapeake Bay Institute in Shady Side, Maryland (MD), in 1991, the university has continuously maintained relevant programs of study and it faculty and students have continued to contribute to Chesapeake Bay research through directly related research programs in the Whiting School of Engineering, the Krieger School of Arts and Sciences, and the Bloomberg School of Public Health in Baltimore, MD. The university was a founding member of the Chesapeake Research Consortium (CRC) and continues to be an active member.

Estuarine Research Federation (CERF), the preeminent international scientific society focused on estuarine science. In addition, the science journal *Chesapeake Science* evolved over time into the international journal *Estuaries & Coasts*, which is CERF's societal journal.

In large part due to the early scientific efforts, Chesapeake Bay advocacy groups, such as the Chesapeake Bay Foundation (formed in 1967) and various members of the Alliance for the Chesapeake Bay (formed in 1971), were alarmed by the Chesapeake Bay's decline. The 1980's marked the start of stronger legislative backing and more widespread public support for Bay research (McCloskey 1985). In 1984, the first Chesapeake Bay Agreement was signed, marking the beginning of the Chesapeake Bay Program (CBP) Partnership (hereafter “the Partnership”), which has the US Environmental Protection Agency (EPA) as a partner, and the EPA’s Chesapeake Bay Program Office (CBPO) as the lead administrative and coordinating organization. Section 117 of the 1972 Clean Water Act further strengthened the structure and coordination of the CBP Partnership among State, Federal, and Local governments. This codified the CBP to be directed by the Executive Council, which are signatories to the Chesapeake Bay Agreement. The Partnership has since grown to include nine principal partners, including six states and the District of Columbia, along with 19 other federal agency partners, nearly 40 state agencies, more than 20 academic institutions, over 60 non-governmental organizations (NGOs), and almost 2,000 local governments. Meanwhile, the CRC has expanded to include seven major institutions in the region that now include Old Dominion University (Norfolk, VA), The Pennsylvania State University (State College, PA), and Virginia Tech (Blacksburg, VA). These institutions are actively embracing collaborative work with all CBP-partnering institutions, particularly through the CRC’s almost 50-year history of coordinating STAC, and organizing and promoting collaborative workshops and symposia among researchers and managers.

Chesapeake Bay eutrophication science and the TMDL: Since the early days of estuarine science, Chesapeake Bay researchers have been recognized as world leaders in eutrophication science. Following Hurricane Agnes, a signature event of Chesapeake Bay ecological change in June 1972, the research focus in Chesapeake Bay was directed to understanding the impacts of eutrophication. Excess nutrients were linked to algal blooms, hypoxia/anoxia events, and aquatic grass die-backs by a series of field, mesocosm, and laboratory studies (e.g., Kemp et al. 1983; Officer et al. 1984). The findings contributed to the establishment of:

a) the Chesapeake Bay Program in 1983, which was a multi-state partnership within the EPA to understand and restore Chesapeake Bay;
b) an integrated monitoring strategy in 1984-1985 that spanned the freshwater-estuarine gradient and considered physical, chemical, and biological variables; and
c) Chesapeake Bay-wide modeling efforts that grew to include estuarine, watershed, atmospheric, and living resources models.

These management, monitoring, and modeling efforts were groundbreaking and have provided researchers and resource managers with a wealth of diagnostic and predictive capacities. The CBP capabilities were central to an understanding, prior to 2010, that Chesapeake Bay water quality was largely unimproved, even after 25 years of watershed activities, establishing the need for a “pollution diet.” The diet was established in 2010 to accelerate Chesapeake Bay restoration, creating the historic Chesapeake total maximum daily load (TMDL) watershed regulatory program, which is the largest such program in the nation. The Chesapeake Bay TMDL set annual watershed limits of 185.9 million pounds of nitrogen (N), 12.5 million pounds of phosphorus (P), and 6.45 billion pounds of sediment, equating to a 25 percent additional reduction in N, a 24 percent additional reduction in P, and a 20 percent additional reduction in sediment loads relative to the estimated annual average loads already achieved under 2009 conditions.

The TMDL objective was to achieve living-resource-based water quality standards of dissolved oxygen (DO), water clarity, and chlorophyll. Primarily, the nutrient reductions were for the reduction of hypoxia and improvement of open-water, deep-water, and deep-channel DO concentrations to levels that would provide useful living resource habitat. The water clarity standard was established to improve water-column light conditions for SAV through lower nutrient and sediment loads, and to achieve nutrient limitation of epiphytic algal growth on SAV that also reduces their light harvesting capacity.

The CBP goal was to implement the management actions to achieve the TMDL nutrient targets by 2025. An interim 2017 Midpoint Assessment (CBP 2017a) was completed to assess management progress toward the 2010 TMDL program's targets as well as to adjust the targets as needed to capture updated research and information regarding best management practice performance, land use and land cover conditions, population growth, Conowingo Reservoir (in the lower Susquehanna River where it discharges into Chesapeake Bay) infill, and impacts from climate change. This report emphasized the facts that despite some clear success stories with respect to the TMDL, restoration was falling short of its goals and additional headwinds faced the restoration, including population growth, intensified land use, climate change, and the infill of Conowingo Dam (CBP (2017).

The considerable monitoring and modeling capacity in Chesapeake Bay supported an extensive assessment of ecological change in response to nutrient loads throughout the estuary. This work allowed for the creation of integrated analyses and assessments which led to many synthesis papers (e.g., Orth et al. 2017; Lefcheck et al. 2018; Testa et al. 2018; Zhang et al. 2018), and a rigorous geographically explicit report card (https://ecoreportcard.org/report-cards/chesapeake-bay/).

Recent Changes in Chesapeake Bay eutrophication status: The synthesis efforts and other scientific studies have recently shed much light on the successes and recalcitrance of Chesapeake Bay restoration. There are many large complex restoration efforts around the world (e.g., Baltic Sea, coastal Japanese waters), but Chesapeake Bay is unique in the size, scale, and complexity of the restoration effort. Nearly 50 years of modeling and four decades of monitoring in Chesapeake Bay and tributary rivers have allowed for an examination of the spatial and temporal patterns of water quality change in response to watershed restoration activities. Here, we summarize several key results from these studies:

> (1) Clear signs of successful water quality remediation in some Chesapeake regions have been associated with upgrades to wastewater treatment plants (WWTP) in the Back River, Potomac River, James River, Patuxent River, and Patapsco River (Figure 2), due to measurable reductions in nutrient concentrations and algal biomass (e.g., Boynton et al. 2014; Testa et al. 2022; Fisher et al. 2021). The point-source improvements were observed in waters local to the WWTP facility, which are generally located in oligohaline

and tidal freshwater regions of tributaries, and provide clear evidence that if substantial, TMDL-guided reductions have the expected estuarine water quality impact.

(2) Water quality along the mainstem of Chesapeake Bay responds to both proximate and distant nutrient inputs. An analysis of gauged and modeled N and P inputs to all 92 Chesapeake Bay water quality segments (https://www.chesapeakebay.net/what/maps/tag/segments) indicates that total nitrogen (TN) and total phosphorus (TP) loads decreased by approximately 25 percent between 1989-1991 and 2012-2014. In response, N and P concentrations declined in the vast majority (97% for TN, 92% for TP) of segments where loads were reduced (Testa et al. 2018). Although reductions in point sources often accounted for the proximate load declines, reductions in atmospheric N deposition were also associated with reduced nitrogen concentrations and loads across the watershed. With these reductions, non-point source pollution now represents the greatest threat and challenge to restoring the Chesapeake Bay's health. This conclusion is reinforced by degrading water quality trends in Coastal Plain watersheds (e.g., Choptank, Chester Rivers; Figure 2) where non-point source pollution poses the greatest risk to water quality. It is unclear whether these trends reflect transport lag times, recent changes in land use and land management, or other mechanisms that influence the fate and transport of nutrients and sediment.

(3) Dissolved oxygen (DO), one of the main targets of water quality restoration, has shown a complicated response to nutrient load changes. Although the overall summer hypoxic volume did not change over the past 35 years, some metrics of oxygen

conditions improved. In particular, the deep-water DO criterion improved by 22% (Zhang et al. 2018) in recent years, as the severity and duration (~20-30 days shorter) of low oxygen conditions were reduced in lower Chesapeake Bay regions during later summer (e.g., Murphy et al. 2011; Testa et al. 2018), and is consistent with slightly smaller nitrogen loads from the Susquehanna River. This reflects a positive oxygen response to a relatively modest load reduction. Moreover, the positive oxygen response appears to have stimulated other positive impacts on the Chesapeake Bay, such as the conversion of ammonium to nitrate under oxygenated conditions, which could stimulate permanent N loss via denitrification (Testa et al. 2018). Additionally, it appears that warming over the past 35 years has limited the otherwise positive oxygen response to the TMDL (Ni et al. 2020; Frankel et al. 2022).

(4) Recent patterns in TN load and concentration reductions have been linked to a resurgence of SAV in many regions of the Chesapeake Bay (Lefcheck et al. 2018). Most notably, SAV has shown clear recoveries in low salinity regions of the Chesapeake Bay (e.g., Susquehanna Flats, the broad, shallow region near Havre de Grace, MD where the Susquehanna River discharges into the Bay) over the last several decades (Gurbisz and Kemp 2014; Gurbisz et al. 2017), and more recently in mesohaline regions of the Chesapeake Bay. The intense precipitation of 2018-2019 interrupted this positive trajectory, combined with declines in eelgrass (*Zoster marina*) in the polyhaline Chesapeake Bay regions associated with limited light availability and warming temperatures.

In summary, there are clear examples of TMDL-associated watershed nutrient load reductions that have led to well-documented declines in estuarine nutrient availability and improvement in some measures of habitat (SAV) and water quality (DO). There are, however, persistently degraded tidal waters throughout the Chesapeake Bay, despite these regional and local improvements, suggesting that we have not attained the true TMDL. This shortcoming may reflect inadequate management action or limitations in our understanding of system behavior and management prescriptions. Three underlying sets of uncertainties lead to this shortcoming. First, we have an incomplete understanding of how lag times affect observable outcomes. For example, dynamic changes in the Chesapeake Bay's ecosystem result from lagged influence of groundwater inputs, watershed and estuarine storage of nutrients, and recovery of biological communities that modulate the estuary's response to the TMDL. Second, there are feedbacks and non-linear interactions between nutrient and light availability, DO concentrations, and ecosystem engineers like eastern oysters (*Crassostrea virginica*) and SAV habitats that may slow or speed up responses to nutrient reductions. Third, climate change continues to challenge our understanding of system behavior and response to management strategies. Beyond these three sets of uncertainties, the TMDL framework does not account for how the Chesapeake Bay's condition depends on more than nutrient and sediment loads, with some aspects of ecosystem health being more related to anthropogenically driven factors than others. In addition to concerns associated with climate change and sea-level rise, specific potential threats that require continuing evaluation include excess carbon loads, shifting environmental flows and hydrologic regimes, heat stresses, and continuing anthropogenic chemical releases, including new chemicals of recently identified and emerging concern.

Integrating with watershed and living resources: Estuarine biogeochemistry occupies the natural interface between the watershed and estuarine living resources, and also an administrative and analytical linkage between these two other aspects of Chesapeake Bay restoration. Estuarine science and management outcomes need to be integrated with the issues and topics of watershed science and living resources science. Obvious connections and linkages exist between nutrient, sediment, and toxicant loads from the watershed to the estuary, including the timing and means of delivery to estuarine regions. Similarly, the connections between the estuarine issues of land-sea interface, ecological tipping points, and climate change are important to connect to the living resources of the Chesapeake Bay.

II. A Strategy for Advanced Analysis and Understanding of Past, Current, and Future Water Quality Change Related to TMDL Targets

There is a duality in the role of the Scientific and Technical Advisory Committee (STAC) in the Chesapeake Bay Program (CBP). First, there are responsive actions that STAC takes on behalf of the CBP—reviews of various initiatives, advice in response to specific questions and needs of the CBP, most of which currently revolve around the Total Maximum Daily Load (TMDL). Second, there are proactive actions that STAC takes based on STAC members' ideas and initiatives. Some examples of STAC proactive actions have been the pushes for increased focus on adaptive management, more formal recognition and addressing of uncertainties, and direct consideration of potential impacts of climate change.

Likewise, there is a duality in the way that CBP pursues restoration through adaptive management. The reactive mode, which can be understood as *passive adaptive management,* responds to new discoveries that arise from existing monitoring and research by updating models, making new predictions, and considering whether new interventions are needed. The reactive mode, however, does not anticipate the discoveries; it just has the capability to detect and respond to them. In contrast, the proactive mode, which can be understood as *active adaptive management*, designs research and monitoring to resolve specific uncertainties that are relevant to management decisions, then, based on the results of those investigations, responds by updating models, making new predictions, and adjusting management strategies in accordance. Although the CBP has some proactive elements, the anticipated shortfall in reaching the 2025 goals, and the work of STAC to understand why this is occurring, show the need for more proactive work.

The steps and discussions in this document comprise an overall strategy that represents what we consider to be critical topics relevant to both the reactive and proactive roles of STAC, and have implications for passive and active adaptive management by the CBP. The strategic vision explored here considers post-2025 TMDL science, which is in line with CBP needs (reactive). The approach taken, however, is proactive through a focus on investigating the land-sea interface, ecological tipping points, and the impact of climate change as key ongoing and future factors. The examples that we choose to discuss - the resurgence of SAV and complex spatial and temporal changes in DO - are also a combination of reactive and proactive thinking, in that both quantities are long-studied issues within the TMDL context, but both also are active areas of current thinking and research. Below, we discuss in detail, the eight key elements of this strategy.

1) **Shift the management and science focus from one of slowing and preventing ecosystem degradation to one of accelerating ecosystem restoration and recovery;** build upon the historical focus on slowing and preventing degradation processes.

Chesapeake Bay research and management partners (federal, state, academic) have been, to date, largely focused on diagnosing the causes of Chesapeake Bay degradation in order to recommend actions to resource managers and policymakers to prevent degradation, and then allow the eutrophic Chesapeake Bay to recover through reduced nutrient and sediment loads. Toward this end, proactive management of Chesapeake Bay has used input from scientists, engineers, and academic researchers to develop aggressive multi-faceted management strategies that have been implemented through a series of Chesapeake Bay Program Watershed Implementation Plans (WIPs).

Although the strategy has not always been sufficient, some successes have now been realized, and we see that restoration is achievable. Within this context, however, we also think that the future trajectories of restoration have yet to be fully explored. In order to accelerate the Chesapeake Bay's recovery, we propose a conceptual shift in scientific focus from degradation science to restoration science. To accelerate restoration, we need to sustain TMDL efforts, but work to better understand and predict:

(a) how to proceed with restoration under alternative management and climate change scenarios;
(b) how to meaningfully scale up from small scale restoration to wide-spread efforts; and
(c) accordingly, where and how to best spend our restoration dollars to achieve nutrient reductions and habitat restoration.

Historically, the process of restoration has been seen as a return to previous conditions. The Society for Restoration Ecology defined restoration in 2004 as “the process of assisting the recovery of an ecosystem that has been degraded, damaged, or destroyed” (SER 2004), with recovery implying a return to “normal.” But in the face of climate change, other pressures, and a broader understanding of what restoration entails, some authors have called for a new definition (Martin 2017). We find the following definition from David Martin to be compelling: “Ecological restoration is the process of assisting the recovery of a degraded, damaged, or destroyed ecosystem to reflect values regarded as inherent in the ecosystem and to provide goods and services that people value” (Martin 2017). This definition acknowledges that “recovery” of an ecosystem may be best defined in terms of human values and allows for a changed understanding of the ecosystem in light of external driving forces such as climate change.

Much of the management of Chesapeake Bay and other estuarine systems around the world has traditionally focused on managing for ecosystem condition. But in the face of unprecedented change due to population and land use change, combined with the impacts of climate change, the management focus may benefit from a shift toward also managing for resilience. Resilience has traditionally been defined in terms of resistance to change and recovery from disturbance. Within this context, achieving resiliency is challenged by an on-going acceleration in rates of change in human impacts.

Therefore, resilience needs to be viewed as recovery from disturbance, adapting to new physical constraints associated with climate change, and ultimately learning from these processes to improve our resilience. Resilience also can transcend the boundaries between the natural ecosystem and the human communities associated with Chesapeake Bay. Building resilience for Chesapeake Bay can be coupled to building the resilience of its communities.

2) **Promote collaborative research integration approaches;** apply diagnostic science to understand the underlying processes and predictive science to forecast future trajectories. Both activities require approaches that successfully integrate monitoring, modeling, and research.

Collaborative integration: To ensure that monitoring, modeling, and research are effectively integrated to support both diagnostic and predictive science, we are calling for a collaborative integration approach. Although this integrative approach is not a new idea, we argue that it has yet to be fully addressed in the CBP, specifically with regard to integrated research. Moving forward, activities that have been traditionally carried out by separate groups could be better coordinated and cross-fertilized. Cross-cutting activities led by CBP teams, such as the Goal Implementation Teams, STAC, and the Scientific, Technical Assessment and Reporting (STAR) team (https://www.chesapeakebay.net/who/how-we-are-organized), can create initiatives that integrate and synthesize science, and Chesapeake Research Consortium (CRC; https://www.chesapeake.org/stac/crc/)-sponsored symposia and workshops can aid in developing better collaborative integration.

Connections between modeling, monitoring, and research: Effective adaptive management depends on the strategic coordination of modeling, research, and monitoring to improve outcomes. Although modern research strives to integrate these broad research areas, inefficient communication among scientists and water quality managers having different areas of focus and expertise may hinder cross-collaboration and thus limit our collective capacity to inform resource management. Promoting targeted monitoring to assess management-oriented hypotheses represents a compelling strategy to overcome these divides (Nichols and Williams 2006; Vereecken et al. 2015). In contrast to surveillance monitoring, model-based monitoring and research can strengthen the capacity to draw inferences about the system's behavior and, importantly, predict future conditions. Integrated monitoring, modeling, and research can be viewed under an overall moniker of 'Building Environmental Intelligence.' Environmental intelligence can be defined as the ability to acquire and apply environmental data, but it also can be defined as communicating good science effectively in a timely manner to facilitate implementation of environmental protection/restoration. This latter definition builds on an environmental intelligence pyramid (Figure 1).

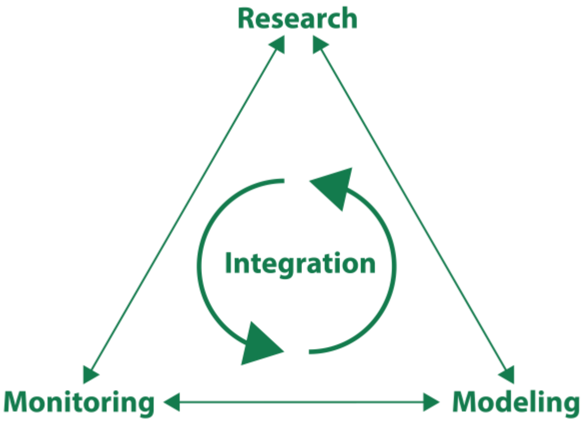

Figure 1: *Environmental Intelligence* pyramid where integrating monitoring, modeling, and research contribute to the generation of environmental intelligence.

Although integrated modeling, monitoring, and research for many estuarine topics, such as the land-sea interface, ecological tipping points, and climate change have long been a feature of the CBP, we believe continued advancement of their integration can enhance achievement of long-term management objectives. Such advances in the integration of these efforts likely require substantial buy-in from academic partners which may be achieved with incentives or other initiatives, as has recently been done with targeted RFPs (Orth et al. 2017; Lefcheck et al. 2018).

3) **Focus research efforts on spatial and temporal scales relevant to stakeholders and decision makers, for example understanding the dynamics of ecosystems at the land-sea interface (triblets) in Chesapeake Bay restoration (Understand the Terrestrial-Estuarine Transition Zone (T-zone)*;*** recognize and address this important interface between the watershed and estuary by emphasizing the role of "***triblets"*** in restoration.)

   The regulatory models used to set the TMDL, and indeed much of the historic research in the Chesapeake Bay region, have focused on the mainstem, extending from the Susquehanna Flats to the mouth of Chesapeake Bay. Water quality conditions in the mainstem are strongly tied to the exchange of impaired freshwater, largely supplied by the Susquehanna River, and oceanic waters along the paleochannel that forms the spine of the Chesapeake Bay system (Figure 2). More recent research has focused on the exchange between the Chesapeake Bay's major tributaries and its mainstem. A combination of empirical comparative studies (e.g., Jordan et al. 2017; Patrick et al. 2017) and novel modeling applications (e.g., Liu et al. 2018) have advanced understanding of how interactions between watershed discharge and oceanic inflows affect sub-estuarine circulation patterns. However, we have much to learn about how

> these dynamic exchanges affect hydro-chemical conditions and habitat in the sub-estuaries. Even less is known about the role of the thousands of smaller, nested waterways feeding the major tributaries to the mainstem, yet these “triblet” units and their river corridors likely represent critical land-water connectors to consider from both a research and management perspective. For example, the research that is available suggests that these triblets are hotspots for nutrient removal and retention (e.g., Boynton et al. 2008) and when SAV occupy shallow waters, their high productivity can substantially reduce nutrient concentrations (e.g., Gurbisz et al. 2017). This nutrient retention improves local water quality, but it also would have the effect on limiting export of nutrients downstream to support deep water hypoxia.

The terrestrial-estuarine transition zone, or T-zone, has recently been recognized as a critical but overlooked landscape area connecting watersheds and coastal waters (Boomer et al. 2019; Ward et al. 2020). A large portion of the Chesapeake Bay’s living resources occur within these shallow water zones. Further, the highest density of development and human activity also occurs within this zone. The T-zone is defined as “*the area of existing and predicted future interactions among tidal and terrestrial or fluvial processes that result in mosaics of habitat types, assemblages of plant and animal species, and sets of ecosystem services that are distinct from those of adjoining estuarine, riverine, or terrestrial ecosystems*” (California State Coastal Conservancy 2015) . Notably, the T-zone extends much farther inland than coastal wetland-upland boundaries, where base level conditions (e.g., sea level) influence water table position and ground- and surface-water exchange. It includes areas affected by tidal surges, well inland beyond tidal wetlands. The T-zone's extent is influenced by the tide's vertical range, topographic relief of the catchment and its waterways, and catchment geology (Ensign and Noe 2018). In the Chesapeake Bay’s Western

Shore, the T-zone extends to the fall line, where the geologic contact creates an abrupt change in topographic relief and a barrier to inland migration of base-level flooding. On the Chesapeake Bay’s Eastern Shore, the flat topography created by the accumulation of unconsolidated sediments imposes limited constraints to the T-zone’s inland migration as sea-level rise occurs. The T-zone currently extends more than 30 miles inland from the major tributaries' mouths (see Figure 2).

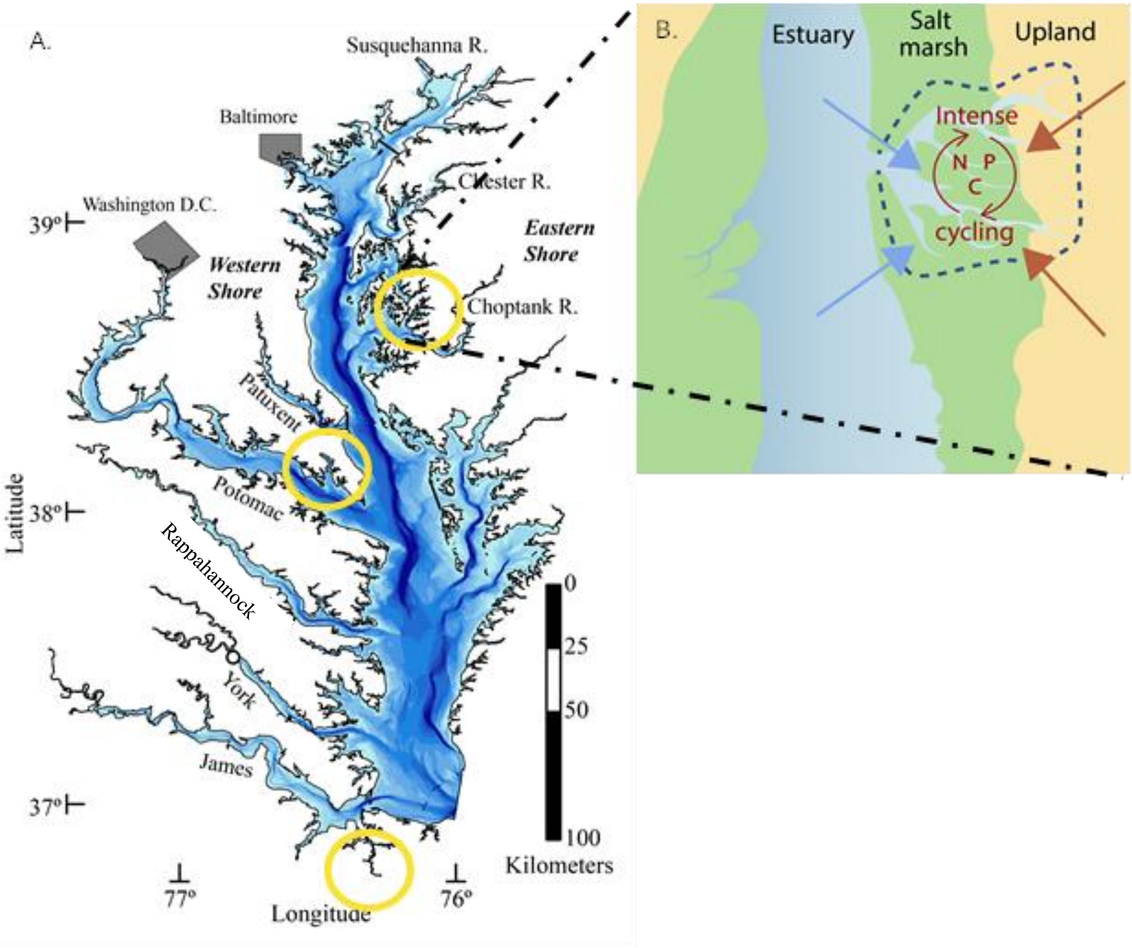

Figure 2: (A) Nested estuarine systems likely influence land-water connections, but much less is known about how the combination of watershed discharge and oceanic inflows influence hydrochemical patterns and habitat conditions within the tributaries; even less is known regarding the smaller triblets (examples circled in yellow). (B) The dashed line indicates the current extent of the terrestrial-estuarine transition zone (T-Zone), which we understand to be a hot spot for cycling of watershed nutrients, including substantial loss rates through burial and uptake. Note, N = nitrogen, P = phosphorus, and C = carbon.

Within the T-zone of the Chesapeake Bay, waterways and their adjacent river corridors represent critical hydrologic connections that concentrate watershed discharge, regulate exchange, and influence the distributions of living resources (Ward et al. 2020). These waterways include thousands of smaller waterways or triblets that drain catchments typically ranging between 50 to 150 km^2 and support extensive expanses of submerged aquatic vegetation beds, oyster reefs, and wetlands (Boomer et al. 2019). Especially in the northern half of the Chesapeake Bay, human activities tend to concentrate along triblets. Recreational and commercial access to the Chesapeake Bay waters has led to extensive shoreline development. Stakeholders have expressed concern about degraded waters affecting access to fishable and swimmable waters in their backyards (CBP 2017b; Boomer et al. 2019). Importantly, these smaller, nested waterways likely are more responsive to human stresses but also watershed management efforts than the Chesapeake Bay's mainstem. Thus, stakeholders may be more willing to contribute to a triblet's comprehensive watershed plans through improved land and shoreline management. For all of these reasons, triblets represent a compelling landscape unit for watershed management and research.

The diversity of habitats along a triblet reflects the dynamic hydrochemical gradients created by shifting circulation patterns and changes in flow velocities. Estuarine turbidity maximum zones that form at the convergence of riverine and oceanic waters perhaps represent the most familiar example of sediment control within the Chesapeake Bay's system (Langland and Cronin 2003; North et al. 2004). However, more subtle controls on nutrient and sediment distribution occur throughout the T-zone (Ensign and Noe 2018). Above the micro-tidal zone, river stage approaches base level, and channel flow velocities slow significantly. As a result, deposition rates of carbon- and nitrogen-rich sediments increase significantly. The deposition is significant enough to limit coastal marsh sediment accretion as sea-level rise occurs. In the downstream areas of the triblets and T-zone, sedimentation rates increase again due to sediment supply by the mainstem of the Chesapeake Bay and shoreline redeposition (Colman et al. 1992). Variable sedimentation rates along a triblets' downstream axis ripples through the system, affecting nutrient availability, light penetration, and habitat conditions (Batzer et al. 2018; Noe and Hupp 2009).

In addition to shifts associated with changes in flow velocities, a cascade of biogeochemical constraints along the T-zone waterways influence nutrient and sediment delivery to the Chesapeake Bay's mainstem. Most of these processes primarily affect the dynamic of phosphorus (P), arguably the most critical element driving algae blooms and eutrophication in the low salinity regions of estuaries (Carpenter 2008; Froelich 1988). Estuaries often are considered permanent sinks for P removal due to sedimentation of organic P, authigenic calcium-bound P, and iron-bound P (Lenstra et al. 2018). However, recent studies indicate P dynamics are highly variable across estuarine space and time. For example, the high salinity influxes cause P desorption and release from suspended sediments (Statham 2012). Changes in carbonate chemistry also can influence phosphorus dynamics. Riverine waters generally are supersaturated with respect to the partial pressure of carbon dioxide (pCO_2) and much less buffered than sea water (Aufdenkampe et al. 2011); the more acidic riverine discharge that extends oligohaline conditions to downstream reaches can dissolve calcium minerals previously deposited in marine waters, resulting in the co-release of P (de Jonge and Villerius 1989). Redox conditions represent a third key driver affecting nutrient dynamics and transport to the mainstem. Reduced conditions trigger iron-sulphate dynamics that result in a rapid release of P (Caraco et al. 1989; Jordan et al. 2008). While we have a conceptual understanding of how estuarine circulation and resulting hydrochemical gradients influence nutrient dynamics, less is known about when and where these processes occur within a complex, nested estuarine and triblet system like Chesapeake Bay (Wang et al. 2016). The direction and magnitude of these biogeochemical processes remain largely unknown (Statham 2012; Ward et al. 2020) and unaccounted for in the TMDL framework (Boomer et al. 2019).

Hydrochemical gradients shift throughout triblet corridors in response to tides, weather anomalies, and sea-level change, similarly to the Chesapeake Bay's mainstem. Spatial and temporal variations depend upon a triblet's bathymetric profile and shoreline geomorphology, its orientation to the estuary's mainstem, and prevailing winds, watershed conditions, and supply of terrestrial and oceanic waters. For example, the lag time generated by increased friction in more shallow and constrained estuaries slows the timing of tidal exchange throughout the river-estuarine corridor (Dronkers 1986), whereas channel dredging increases tidal exchange and amplitude (Chant et al. 2018; Ross et al. 2017). Highly managed catchments hardened by development or channelized by extensive artificial drainage have resulted in flashier river systems and degraded freshwater deluges contributing to declining sub-estuarine conditions (Wetz and Yoskowitz 2013). However, variability in the combination of these factors presents significant challenges to identifying which triblet systems are most susceptible to human stressors or where best management practices could provide exceptional benefits to the Chesapeake Bay's living resources. Indeed, no two triblets are the same, and there are few comparative triblet studies to enable us to rank key drivers affecting triblet residence time or understand how best to mitigate human impacts. Characterizing human impacts on triblet hydrodynamics (e.g., residence time) and condition would provide critical information to watershed and coastal managers. The CBP could support the development of a triblet database that blends watershed land-use, estimates of nutrient load, residence times (e.g., model-computed), and maps and logs of the implementation of Best Management Practices (BMPs) and restoration activities.

Modeling: The CBP model used to develop the TMDL for nutrients and sediment is based largely on how non-tidal discharges from major rivers affect hydrochemical gradients along the mainstem of the Chesapeake Bay. Despite the importance of the T-zone, the bioreactivity of triblets, and the importance of coastal areas to stakeholders, these landscape elements are not explicitly represented in the Chesapeake Bay model. Instead, tidal water watershed impacts are based on an extrapolation of modeled data from non-tidal segments, coastal wetlands are included as part of the estuarine model, and none of the significant biogeochemical processes affecting habitat quality and species distributions are incorporated into the model structure (https://www.chesapeakebay.net/what/programs/modeling/phase-7-model-development). Modeling these shallow waters is essential to refining the TMDL and advancing Chesapeake Bay restoration goals.

Given the vast number of triblet systems, evaluating the response of a triblet system to a management strategy presents a significant challenge. Simple estuarine characterizations, such as tidal prisms and flow return estimates provide rapid indicators of residence time and may provide useful metrics for identifying more vulnerable triblet systems. However, more detailed assessments of triblet responses to watershed and coastal management actions, navigation dredging, and climate change generally require complex simulation models. Indeed, shallow estuarine model applications demonstrate the exciting potential for emerging technologies such as high-resolution remote sensing data and unstructured-grid models to evaluate the effects of watershed and coastal management strategies more precisely (e.g., Liu et al. 2018; Tian et al. 2022). Given the extensive resources that these more informative model applications require, effective decision support likely requires coordinated implementation of both modeling approaches (Ward et al. 2020). For example, rapid indices can provide a compelling basis to select a range of sub-systems to study through a comparative study of model applications. Completing the circle of potential emerging technologies, complex simulation model results can reveal the utility or reliability of the indices and provide guidance for their refinement. In addition, variation and unexpected outcomes in the model predictions can inform monitoring and research efforts.

Monitoring and Research: Coordinated monitoring and research programs provide opportunities to advance decision support by exploring underlying hypotheses embedded in the modeling tools, and by evaluating whether a system is responding as predicted. Several challenges, however, have limited our capacity to link these research efforts. First, physical access to triblets may be limited. Existing monitoring programs are mainly from boats or limited road access for stream sampling. Second, the sheer number of triblets (i.e., thousands), along with the variability in physicochemical conditions within each triblet system, presents a challenge to developing a compelling framework for collecting and interpreting observation data. Accessibility to reliable positioning data, low-cost continuous field monitoring equipment, and high-resolution remote sensing data, however, presents new opportunities to investigate triblet functions and responses to management interventions, especially when applied as part of a targeted surveillance program. A model-based sampling framework can inform the design of the sampling program across a range of conditions, thus providing a more effective and efficient opportunity to test our understanding of system processes. Even simple conceptual models can be used to improve monitoring programs. For example, cyanobacterial harmful algae blooms (HABs) are associated with nutrient-enriched waterbodies that also have long low flushing rates, elevated water temperatures, calm surface waters, and persistent stratification (Paerl and Otten 2013). Further, early studies suggest that HABs originate and spread from a small number of triblets within a tributary system (Morse et al. 2013). A simple, targeted monitoring program could test this paradigm across Chesapeake Bay, if based on a sample of triblet system models drawn to represent a range of estimated turnover times and watershed conditions.

In conclusion, our lack of understanding of very shallow waters in the triblets of the Chesapeake Bay and the associated transition zone from the watershed to the estuary presents a major challenge to effectively assessing and predicating water quality in these ecosystems. Improved modeling and monitoring of these environments can help us better understand the relative relationship of watershed loads and their pathways through tidal waters, the vulnerability of these shallow systems to long-term change, and our ability to predict living resources in these environments.

4) **Investigate the impact of tipping points and** improve our understanding of critically important ecological thresholds and their role in estuarine restoration dynamics.

Ecological 'tipping points', also known as ecological thresholds, are ecosystem states where small changes in environmental conditions result in large or rapid shifts in ecological status or function. These tipping points may involve chemical reactions, food web interactions, or biological responses to external forcing. Because the relationship between the x-axis variable (e.g., the controlling variable) and the y-axis variable (the ecosystem state) change dramatically near a tipping point, the types of interactions involved are non-linear, and thus difficult to predict. For example, riverine water quality trends suggest that a watershed retains anthropogenic P until its buffering capacity is exceeded; beyond this, P inputs to downstream waters accelerate significantly and recovery is slow (Goyette et al. 2018; Kleinman et al. 2019). In addition to buffering capacity, non-linear ecosystem responses can evolve from lag times associated with transport processes (e.g., legacy nutrients in groundwater).

Developing a better predictive understanding of these tipping points and their causes will be an important feature of future restoration research that specifically targets thresholds and other non-linear behavior. Chesapeake Bay restoration science could focus on developing early restoration signals to provide more immediate feedback on implementation effectiveness of various TMDL actions. Several STAC workshops have focused on highlighting our understanding of, and identifying, tipping points in the estuarine waters of Chesapeake Bay. The most comprehensive STAC workshop on this topic was "Thresholds in the recovery of eutrophic coastal ecosystems" (Kemp and Goldman 2008). In this report, the authors identify two examples with contrasting trajectories underlying ecosystem change:

1) Degradation trajectory in which continued stress suddenly exacerbates ecosystem health concerns. For example, increased nutrient inputs result in more algae, increasing turbidity and reducing light penetration. The reduced light leads to less benthic microalgae, causing sediment nutrient release and resuspension, further exacerbating the problem.
2) Restoration trajectory in which improved management initially provides limited benefits until adequate time allows a suite of conditions to align and reveal measurable progress toward the targeted outcomes. For example, there is lag time between when reduced nutrient inputs occur and when they lead to less algae, better light penetration, and more benthic microalgae. These benthic microalgae absorb nutrients and reduce resuspension, resulting in improving water quality conditions.

   The key link between these two trajectories was identified as water clarity and its control over light penetration to sediments.

Case study - water clarity tipping point: In a detailed study of the Corsica River, a triblet of the Chester River on Maryland's Easter Shore, Boynton and others (2009) investigated a water clarity 'tipping point' as it was realized in a shallow, 1-meter-deep tributary of the Chester River. Boynton et al. (2009) built a series of linked, non-linear relationships that estimate algal biomass in response to nutrient loading as indicated by Secchi disk depths. They found that relatively small but distinct changes in water clarity resulted in significant shifts in water quality conditions throughout the sub-estuarine system. Their results revealed that 1% incident light corresponds to the minimum light requirement for microalgae, and that 15% incident light corresponds to the minimum light requirements for some SAV species. For example, a 20 cm increase in Secchi depth expanded the sub-estuary zone where more than 15% of sunlight penetrates to the benthic zone, from 0.4 to 0.6 km^2, and areas where light penetration increased by at least 1% expanded from 1.2 to 2.1 km^2. This area is almost double the 1%+ lighted area with only a 20 cm increase in Secchi depth. They also found that with a Secchi depth of 1.2 m, nearly 85% of the entire Corsica River estuary would be 1%+ lighted area, thus essentially restoring the system's natural benthic function. A Secchi depth of 1.2 m has been observed intermittently over the2005-2008 period, so it is not a hypothetical value, but an achievable degree of light availability. Water clarity is a product of hydrochemical gradients along an estuarine system, or triblet corridor, thus it is strongly influenced by watershed condition and management, shoreline management, and channel activity, as well as weather patterns, geologic setting, and oceanic influence. These low thresholds perhaps explain why or how human activities have imposed a disproportionate influence on habitat conditions throughout Chesapeake Bay. While these drivers are expected to vary among sub-estuarine systems, results from the Corsica River study provide an initial basis to characterize benthic conditions throughout Chesapeake Bay's vast areas of shallow waters.

Importantly, the suite of statistical relationships also can inform numerical models to evaluate system conditions at a high-resolution, that are more relevant to coastal managers.

Case study - dissolved oxygen tipping point: In a detailed study of Chesapeake Bay's coastal marine zone, Kemp et al. (1990) investigated linkages between N dynamics and DO concentrations. They observed that shifts in nitrification (conversion of ammonium to nitrate) and denitrification (conversion of nitrate to nitrogen gas) occurred at distinct threshold concentrations of DO. When DO levels in bottom water fell below 100 μM (3.2 mg/L), nitrification essentially ceased. Since the rates of denitrification were shown to be directly dependent on nitrification rates (as nitrate is a primary reactant in the denitrification process), reduced bottom water oxygen levels essentially control the overall rates of both nitrification and denitrification. The cessation of coupled nitrification/denitrification in conditions of low bottom water oxygen levels means that the seasonal anoxia/hypoxia, or dead zone, in the deep central channel of Chesapeake Bay limits the ability of the microbes to process nitrogen in a way that leads to permanent removal. A secondary consequence of hypoxia-induced shutdowns of coupled nitrification-denitrification is that ammonium accumulates in bottom waters (Testa and Kemp 2012) and can be transported to areas where it supports algal growth. The other important nutrient implicated in Chesapeake Bay eutrophication is P. When bottom water oxygen levels reach anoxia or even hypoxia, the surficial sediments become anoxic. This has a dramatic effect on phosphorus chemistry: in oxic sediments, phosphorus is bound into ferric oxides, the oxidized forms of the generally abundant iron in coastal sediments; but when anoxia prevails, the iron dissolves and phosphorus is released from the sediments. Thus, the net result of low bottom water DO is to make more nitrogen and phosphorus bioavailable for algae uptake, accelerating the blooms that often have led to the low oxygen levels in the first place.

Case study - Submerged Aquatic Vegetation tipping point: The presence of SAV has a significant impact on sedimentation rates, nutrient absorption, and water clarity. With leaves extending one to two meters above the Chesapeake Bay bottom, SAV beds have the ability to slow currents and reduce wave-induced motion (Gruber and Kemp 2012; Ganju et al. 2021). This effect allows fine particles to settle out, and the SAV roots and rhizomes further act to bind these sediments, reducing resuspension. The SAV and their epiphytes absorb water column nutrients, which limits nutrient availability in the water column, slows phytoplankton growth, and reduces light absorption rates. As a result of these processes, water clarity within SAV meadows is much clearer than adjacent unvegetated areas, and this water clarification extends beyond the meadows into adjacent waters (Gurbisz and Kemp 2014). Thus, SAV beds behave as giant filters that strain the water column of suspended particles and nutrients. This phenomenon of SAV water clarity improvements can be clearly observed from aerial images (Gurbisz et al. 2017).

Rapid diebacks and sudden regrowth suggest that environmental thresholds affect the establishment and maintenance of SAV beds in shallow waters of Chesapeake Bay. The Susquehanna Flats present a notable case study. Over the past two decades, a variety of aerial images and ground-based measurements documented the non-linear recovery of SAV across the Susquehanna Flats following Hurricane Agnes in 1972 (Gurbisz and Kemp 2014). For years, only sparse patches of vegetation had reestablished across the former meadow. These gradually coalesced into a continuous sparse meadow, but then jumped to a continuous dense meadow during the prolonged drought during 1999-2002. This resurgence was facilitated by the prolonged low sediment and nutrient river inputs during the low flow conditions. A recent analysis (Lefcheck et al. 2018) has linked nutrient reductions to the resurgence of SAV in Chesapeake Bay, providing a lesson on ‘staying the course’ and allowing the time for benthic communities to recover and cross tipping points that allow for the self-sustaining processes to initiate. Recent work has even demonstrated that these recovered SAV beds can generate high pH conditions though intense photosynthesis that allow for the precipitation of calcium carbonate that could buffer against acidification if transported to other Chesapeake Bay regions (Su et al. 2020).

Scientific response to tipping points

Monitoring: Very careful and extensive monitoring could help determine the thresholds associated with the various tipping points. There is often a hysteresis effect along a nutrient loading gradient, so that increasing nutrients will lead to an ecological response curve that tracks very differently to a response curve of decreasing nutrients, where additional nutrient reductions or longer time spans may be needed for restoration patterns to emerge in observations (Kemp et al. 2005). Thus, monitoring along both trajectories is necessary to establish the tipping points for degradation vs. the tipping points for restoration. Fairly precise measurements of water clarity can help to assess the 1% and 15% thresholds, with more than monthly Secchi depths required and more frequent measures of Photosynthetically Active Radiation (i.e., the part of the light spectrum plants can use to growl; PAR) and light attenuation (Turner et al. 2022). Measurements of precise near bottom DO levels, preferably in real time, can assist in determining bottom water

DO levels that highly control sediment nutrient dynamics and the associated availability of pollutants. Annual surveys by the Virginia Institute of Marine Science (VIMS) can permit the assessment of SAV dynamics at least on an annual basis. Finally, eutrophication is defined in terms of ***rate* processes** (Nixon 1995), and the monitoring program has drifted away from measuring the rates of primary production and respiration that ultimately determine oxygen concentrations. For example, rates of water-column respiration are the dominant oxygen consumer in deeper Chesapeake Bay waters (Li et al. 2016), are highly sensitive to warming, and have proven a reliable indicator of restoration (Testa et al. 2022). These rates, however, vary substantially over space and time and must be better understood to validate the increasing number of shallow water models (e.g., Tian et al. 2022).

Modeling: Models that incorporate the physical and ecological feedbacks that determine tipping points or thresholds need to be formulated so that the monitoring data can be used to test these modeled outcomes. The ability of models to extrapolate specific site measurements to Chesapeake Bay-wide forecasting of ecological processes needs to be explored to gauge the relative importance of various different tipping points. With this approach, for example, one could more effectively forecast the degree of nutrient reductions needed to reverse degradation or enhance restoration. As the CBP develops the next generation of its physical, biogeochemical, and ecological models for estuarine systems, attention could be given to identifying, measuring, and predicting those factors that are most closely associate with tipping points to better understand when and how they have been reached in the past and anticipate and perhaps control when and how they may be reached in the future. In other words, the next CBP models could look both forward towards a restored Chesapeake Bay as well as backward at a degraded Chesapeake Bay.

Research: There are many questions as to the mechanisms of various ecological feedbacks. In addition, ecological tipping points in one part of the vast Chesapeake estuary need to be tested in other parts of the estuary, particularly with regard to salinity regimes. The discovery of pockets of coupled nitrification/denitrification due to oyster biofiltration, leads to the question of whether spatial variability is inherent in estuaries. Much of the previous research on Chesapeake Bay has been documenting the decline of various features. Now that there are positive signs of recovery, a shift in the research focus to restoration ecology may be beneficial. Determining how to accelerate or enhance restoration is becoming increasingly important, including research on in-estuary BMPs that can augment watershed restoration actions.

5) **Account for climate change in Chesapeake Bay restoration and expectations for recovery;** the underlying physical environment has changed since the TMDL was set.

Observations of existing climate change: Several features of Chesapeake Bay have already been altered by climate change, and have been documented in a suite of previous STAC reports (e.g., Najjar et al. 2010). Stated simply, the Chesapeake Bay is more expansive, saltier, and warmer. These changes have been occurring for as long as we have instrument records. Water temperature has been monitored since 1938 at the Chesapeake Biological Laboratory dock (https://cblmonitoring.umces.edu/). The increase in temperature has been over 1^{o}C, and has been accelerating over the past few decades. Satellite analyses of sea surface temperatures over the past thirty years show that waters adjacent to urban developments and power plants have warmed due to runoff from impervious surfaces and cooling water discharges, respectively (Ding and

Elmore 2015). Sea level rise has been measured at several tide gauges around the Chesapeake Bay, with the oldest in Baltimore Harbor extending back to 1902. Relative sea level rise, which is the combination of land subsidence and sea level height, has been about 25 cm over the past one hundred years, again accelerating over the past few decades (Boesch et al. 2013; Boesch et al. 2018). This relative sea level rise has increased the cross-sectional area of the mouth of Chesapeake Bay, and this expansion is allowing more tidal excursion into and out of the Chesapeake Bay as well as more effective penetration of the salt wedge of incoming oceanic water, resulting in saltier Chesapeake Bay water by approximately 2 salinity units, below the pycnocline. In addition, sea level rise has inundated coastal salt marshes. The low relief along much of Chesapeake's shoreline means that landward migration of the salt marshes is occurring rapidly, and tracts of salt marsh have been converted to open water as a result. This is particularly pronounced in southern Dorchester County and Blackwater Wildlife Refuge where annual changes in open water vs. salt marshes can be observed.

Future climate changes: Evidence suggests climate change has already imposed significant impacts on the Chesapeake Bay system. Stakeholders already are acknowledging an emerging pattern of more frequent intense storms, intermittent droughts, and warmer night temperatures. Changes to the timing, magnitude, frequency, and duration of rain events affect the fate and transport of nutrients and sediment delivered to the Chesapeake Bay system. More subtle changes, however, may have equally significant effects on structure of the Chesapeake Bay ecosystem. For example, the increase in atmospheric carbon dioxide results in higher $p\mathrm{CO}_2$ dissolved in Chesapeake Bay, driving acidification that may add additional stress to organisms that produce calcium carbonate (e.g., oysters, clams, snails). In contrast, SAV thrive under higher dissolved inorganic carbon conditions and their growth is enhanced, but the effects of acidification on phytoplankton and other living resources are still largely unknown. The warmer, wetter winters that regional climate models are predicting will have implications for the exchange of terrestrial and estuarine waters within the sub-estuarine systems, and thus for the timing and delivery of sediments, nutrients and toxicants into Chesapeake Bay. Future climate projections suggest increases in winter-spring freshwater discharge (Ni et al. 2019) which would likely drive the establishment of a stratified water column that may accelerate the establishment of seasonal hypoxia and anoxia in bottom waters (e.g. Murphy et al. 2010). The flashier runoff patterns of mini-droughts, punctuated by intense rain events, will have implications for Chesapeake Bay. Sediment mobilization occurs following mini-drought conditions due to lack of terrestrial vegetative cover, and combined with intense storms, can wash these sediments and associated nutrients and toxicants into the Chesapeake Bay. Organisms that can withstand pulsed events may thrive, like the increasingly abundant SAV widgeon grass (*Ruppia maritima),* but organisms sensitive to these events, like the declining SAV eelgrass (*Zostera marina)* may suffer (Lefcheck et al. 2017). There is much speculation about the frequency and intensity of tropical storms and hurricanes in future climate scenarios. The significant impacts of previous tropical storms (e.g., Tropical Storms Agnes in 1972; Isabel in 2003; Lee in 2011) on Chesapeake Bay biota means that if there is a change in the frequency or severity of tropical storms, there could be dramatic impacts on Chesapeake Bay.

Restoration progress in the face of climate change: The headwinds of climate change do indeed provide challenges to our ability to make restoration progress. Although observed trends over the last century of higher temperatures, precipitation volumes, and precipitation intensity in the

Chesapeake region have been well documented, we have begun to observe positive environmental changes in watershed management response to future climate risk. Water quality has improved significantly due to nutrient reductions directly attributable to wastewater treatment upgrades (e.g. Fisher et al. 2021; Testa et al. 2022) and the improvements in air quality resulting from point source and mobile source emissions of nitrogen oxides (Ator et al. 2019). The challenge of climate change will increase, but if we meet the acceleration of climate change impacts with accelerated restoration actions, we can continue to make progress.

Threats from climate change raise concerns regarding capacity to restore Chesapeake Bay to historic conditions and highlight the importance of managing for ecosystem functions in the face of climate change. Much of the management of Chesapeake Bay (and estuarine systems around the world) has traditionally focused on managing for ecosystem condition, in particular a past, known condition. In the face of unprecedented change, this focus on management of ecosystem condition may benefit from a shift to managing for *resilience*, which has been traditionally defined in terms of resistance to change and recovery from disturbance. Managing for resilience requires identifying targeted, measurable endpoints and the underlying processes affecting those endpoints. Our collective challenge to addressing resilience is the collective limits to our understanding of those features that influence resilience and how we might manage for it. Resilience may need to be viewed as the ability to recover from disturbance, maintain similar ecosystem services in the face of climate change, and ultimately learning from these processes to improve resilience.

The fact that many factors are changing simultaneously means that some features will be synergistic while others will be antagonistic (Figure 3). This interplay between positive and negative impacts creates a challenge for management. An example of a synergistic impact is the combination of high temperature and flashy runoff which selects against the SAV species eelgrass (*Zostera marina*), but enhances the SAV species widgeon grass (*Ruppia maritima*) (Lefcheck et al. 2017). An example of a contrasting (or antagonistic) impact, is the advection of more oxygenated seawater into Chesapeake Bay due to sea level rise and increased gravitational circulation vs. the increasing oxygen demand by respiring bacteria and reduced oxygen solubility brought on by increased temperatures (St-Laurent et al. 2019). Regardless of whether these impacts are synergistic or contrasting, the difficulty is in predicting and managing for either eventuality.

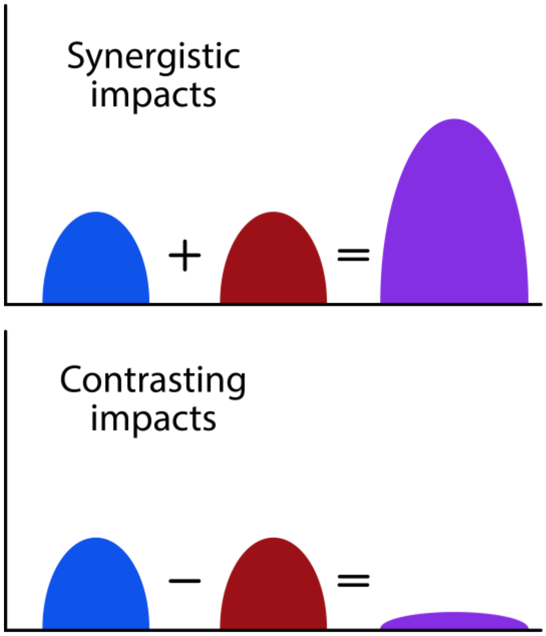

Figure 3: Contrast between synergistic impacts that amplify multiple responses to stressors (top) versus contrasting impacts that may cancel each other out, where benefits compensate for harms. There are a much larger collection of possible interactions described in the literature.

While some aspects of climate change can be extrapolated based on past and current trends, there are other aspects that cannot be extrapolated from existing trends. The decoupling of historical trends from future projections means that we will be dealing with future unknowns. Ecological tipping points are only one aspect of non-linearities that occur with changing conditions. Science, like management, will need to be adaptive. As new features and feedbacks become evident, monitoring, modeling and research will need to adapt to contemporary and future climate change, where climate patterns (e.g., frequency of major storms) deviate from historical patterns.

Scientific response to climate change

Monitoring: The long-term monitoring of Chesapeake Bay predates the establishment of the Chesapeake Bay monitoring program and has been crucial in being able to observe climate change. Maintaining and expanding this monitoring will help to capture the climate related changes occurring in Chesapeake Bay. Annual surveys of SAV have become an iconic monitoring data set, but equivalent monitoring of salt marshes has not occurred at a Chesapeake Bay-wide scale. The rapid changes occurring with salt marshes, due to relative sea level rise, could make this type of monitoring more essential for climate change assessments. Furthermore, the lack of high-quality inorganic carbon data has made it difficult to assess trends in Chesapeake Bay acidification. Therefore, additional inorganic carbon data could facilitate more complete monitoring of changes in the dissolved inorganic carbon concentrations via alkalinity, pH, or pCO_2. Finally, using new technologies to measure a subset of metabolic rates (e.g., water-column respiration) could allow us to assess climate effects on these major oxygen consumption processes and to determine whether they are represented accurately in the modeling suite.

Modeling: The impacts of various climate change scenarios will be, and are already, modeled to anticipate changes (Irby et al. 2018; Ni et al. 2019; Tian et al. 2022). In addition, the synergistic impacts of a variety of changes (e.g., temperature, salinity, and chemical composition of seawater) need to be modeled by integrating results of specific experiments and observations.

Modeling can also help discern whether observed changes are due to climate change or other sources, such as modifications in land use or changes in human populations and behavior.

Research: The implication of climate change on the Chesapeake Bay's living resources is a critical factor in determining management strategies. The combined impacts of climate change will need to be investigated, especially since most existing research assesses the impact of single variables. The combination of multiple climate change factors can lead to unanticipated outcomes, and developing a nimble research capacity to investigate these unanticipated outcomes would be prudent. To that end, large scale experimental simulation facilities like mesocosms will aid climate change research.

6) Use ***shallow water habitats*** as a testbed for integrating the land-sea interface, tipping points, and climate change using monitoring, modeling, and research approaches.

Chesapeake Bay has extensive shallow-water (<2 m) habitats, while the estuary-wide average depth is ~6 meters, despite the existence of deep channels in the mainstem and some of its tributaries. These shallow-water habitats are also of high scientific interest, by virtue of their role in modulating watershed inputs en route to the open Chesapeake Bay, along with their historic and contemporary hosting of extensive SAV populations, and the extensive benthic-pelagic interactions that occur in these environments. The majority of these shallow-water habitats (a) occur in the tributaries; (b) comprise of large expanses of the land-water fringe; and (c) are environments used frequently for human recreation . Thus, understanding the restoration potential of these habitats is a critical need for understanding the overall restoration of Chesapeake Bay and the impact of the restoration on society.

A key feature of shallow water habitats is the dominant role that benthic processes play in biogeochemical cycles and associated water quality (Figure 4). Prior studies have illustrated that once the total water depth of a system falls below 10 meters, sediment oxygen uptake begins to dominate total oxygen consumption (Boynton et al. 2018). Because the same processes that consume oxygen in sediments also generate ammonium and phosphate, sediments are also a key source of recycled inorganic nutrients to the water-column. In most estuarine environments, the amount of organic matter in sediments is the ultimate control on sediment oxygen consumption and nutrient recycling. Thus, if shallow tributaries at the *land-sea interface* are hotspots for deposition of land-based organic materials, then they can also be expected to be hotspots for nutrient recycling. While there is clear evidence for such benthic recycling hotspots in eutrophic triblets (Boynton et al. 2009; Testa et al. 2019), past monitoring of benthic respiration and nutrient recycling has not emphasized these locations.

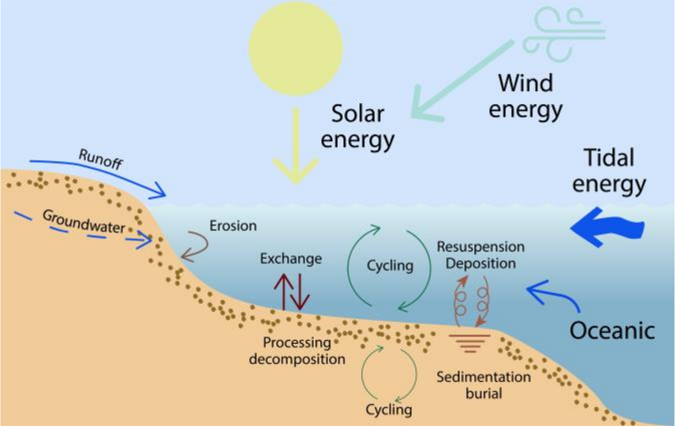

Figure 4: Conceptual representation of key transport and exchange processes that process watershed and estuarine particulate materials in shallow water sediments. These processes involve the input of watershed materials, the erosion of wetlands or shorelines, and the wind and wave-induced resuspension of materials that is balance by deposition to sediments. Deposited materials are also remineralized in sediments and the water-

Many of the shallow water habitats in Chesapeake Bay are less than 2 or 3 meters deep where there is the potential for light to reach the sediment surface. One important implication of this light penetration is the stimulation of SAV growth in many shallow water habitats. In addition, and in large part related to SAV growth, the nature of sediment nutrient recycling in shallow systems is also highly sensitive to the amount of light reaching the sediment surface. High organic matter deposition rates to sediments can drive high rates of sediment oxygen consumption and nutrient recycling when the sediments are ‘dark’, but if sufficient light reaches the sediment surface, benthic microalgae and/or SAV can achieve net growth, producing oxygen and sequestering nutrients (Boynton et al. 2009). Thus, modest improvements in the clarity of water in these habitats can permit shallow water benthos to switch from consuming oxygen and producing nutrients (and maintaining degraded water quality), to producing oxygen and consuming nutrients to enhance water quality. Although this example of a *tipping point* in shallow water ecosystems has been well-described conceptually and experimentally, the detailed combinations of factors have not been clearly elucidated to date, owing primarily to the fact that comprehensive measurements to support long-term time-series analyses and modeling has heretofore not been heavily emphasized for shallow habitats.

Shallow water habitats are highly sensitive to climate change, given their sensitivity to predicted changes in temperature, watershed inputs associated with elevated precipitation, and other physical forces (Figure 5). Future predictions of elevated precipitation may have outsized impacts on shallow habitats because elevated sediment loads to these systems, under higher stream discharge rates, will likely increase particulate matter deposition and elevate turbidity - and Secchi depth in waters closest to land is most sensitive to suspended sediment (Testa et al. 2019). Dissolved oxygen dynamics may also be disproportionately affected by future warming. Given that shallow water temperature is highly responsive to changes in air temperature, warming-induced reductions in oxygen solubility will ultimately push summertime oxygen concentrations closer to the 30-day oxygen criteria of 5 mg/L even under normal daytime conditions. In addition, the vulnerability of shallow waters to nighttime hypoxia is highest under the warmest conditions (Tyler et al. 2009), due to reduced solubility and elevated respiration rates. Finally, there is evidence for declining solar radiation associated with increased cloudiness in Chesapeake Bay and other regions, and studies in shallow waters have shown that nighttime hypoxia is more likely following cloudy days (Tyler et al. 2009). Future modeling in shallow waters combined with the maintenance of sentinel shallow water continuous monitoring sites will help better inform climate effects on shallow water habitats in both the near and long-term.

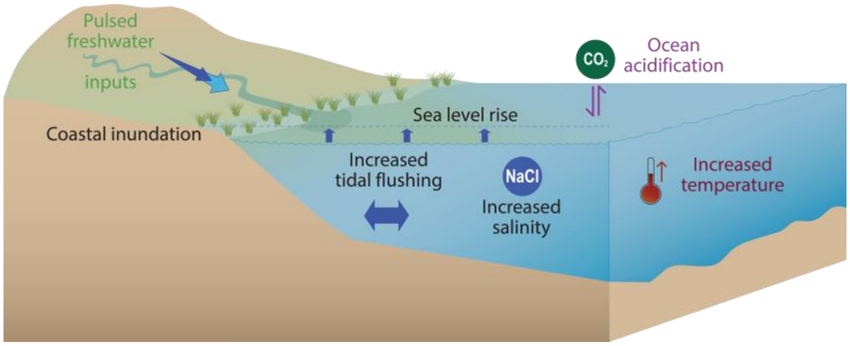

Figure 5: Conceptual representation of key climate-induced changes in estuaries, including shallow waters, such as larger and more extreme precipitation events, elevated temperature, sea level rise (and associated increases in salinity and tidal flushing), coastal inundation,

Scientific response to Shallow Water habitats

Monitoring: Early recognition of the value of shallow-water habitats for supporting living resources (oysters, SAV) led to the establishment of the most concentrated monitoring of short-term (hourly and less) water quality variations in shallow environments that exists worldwide (http://eyesonthebay.dnr.maryland.gov/). High-frequency monitoring data permit an understanding of eutrophication and climate processes in shallow waters that would otherwise be impossible, such as diel cycling hypoxia (Boynton et al. 2009), temperature extremes, and SAV growth (Moore et al. 2012). When high frequency monitoring has been combined with high spatial resolution water quality mapping (O'Leary et al. 2016), scientific insights have been even more extensive. Although the high-frequency "Continuous Monitoring" (ConMon) program has been incredibly successful in Chesapeake Bay, the program relied primarily on fixed deployment platforms (e.g., piers) close to the shore that were restricted to locations permitted by landowners. In addition, platforms were typically deployed for only 3 years, while long-term sentinel sites were less frequently maintained (with notable exceptions in the Corsica River, Susquehanna Flats, Baltimore Harbor). Future monitoring could consider emerging technology (drones, Automated Vehicles) or more targeted, spatially extensive sensor deployments to advance our understanding of the shallow-water benthos.

Modeling: The Chesapeake Bay Program Water Quality and Sediment Transport Model (WQSTM) historically targeted the quantification of eutrophication responses in the mainstem of Chesapeake Bay, with less emphasis (and grid cells) in the shallow–water habitats (https://www.chesapeakebay.net/what/programs/modeling/phase-7-model-development). As a result, the majority of truly shallow-water environments in the Chesapeake Bay ecosystem are poorly resolved by the WQSTM. Improvements in computing power, gridding schemes, and model sophistication now permit a more flexible and spatially-resolved generation of models that specifically reproduce key aspects of water quality and related ecological processes in shallow waters, including diel cycling hypoxia, microphytobenthic production, and sediment-water interactions.

Research: There are a number of both basic empirical research questions and synthetic ecosystem studies that help elucidate shallow water habitat change. Basic biogeochemical measurements help identify the role of shallow water sediment nutrient and oxygen cycling and the fate of watershed-derived organic materials. Modeling efforts help quantify the role of fine-scale physical processes on water quality, such as residence time (high residence time enhances algal growth, oxygen depletion), wave-induced resuspension and shoreline erosion and their impacts on light availability, and the role of benthic primary producers (benthic algae, SAV) on nutrient cycles. Finally, synthetic spatial and temporal analyses could leverage data and models to identify tipping points, understand feedbacks (e.g., SAV self-reinforcing growth through sediment trapping), and link specific watershed features (BMP implementation) to shallow, nearshore habitats.

7) Develop a future vision of Chesapeake Bay management that a) better embraces and addresses decision making in the face of uncertainty by incorporating adaptive management; b) considers potential major interventions; and c) uses an outcomes-based framework.

Scale of future visioning: The shift from focusing on preventing ecosystem degradation to a restoration focus means that we may need to start crafting a future vision for Chesapeake Bay that does not simply attempt to revert to some historical reference point for water quality and living resources within the Chesapeake Bay. The restoration focus points the way to a future that provides an estuary that represents multiple linked outcomes. These outcomes include a healthy and sustainable ecosystem that collectively meets societally agreed upon needs and expectations, while also incorporating expected changes in Chesapeake Bay attributes due to human population growth, land use changes, and widespread impacts of climate change (Figure 6). The vision can be continually informed by developing early restoration signals to provide more immediate feedback on implementation effectiveness of various TMDL actions. The future vision may also encompass novel management approaches such as facilitated migration of key species, genetic engineering for climate change adaptation, or large-scale engineering interventions (e.g., nutrient scrubbers, bottom water aeration). Natural infrastructure and green engineering innovations (e.g., e.g., living shorelines, restored wetlands, floodplains, and riparia and vegetated waterways) to deal with widespread stormwater runoff issues could also accelerate restoration (Herbstritt et al. 2019; Boomer et a. 2021; Bilkovic et al. 2022). Managing Chesapeake Bay for a new species composition that leads to new fisheries (e.g., blue catfish (*Ictalurus furcatus*), white shrimp (*Penaeus setiferus*)) requires a coupled science and management approach. These future approaches will rely on use of existing Chesapeake Bay data, creating new data streams and creating new ways of analyzing and communicating these data. All of this “new” emphasis could benefit from continued nutrient reduction actions to reach TMDL goals, which is the ultimate tool to improve water quality.

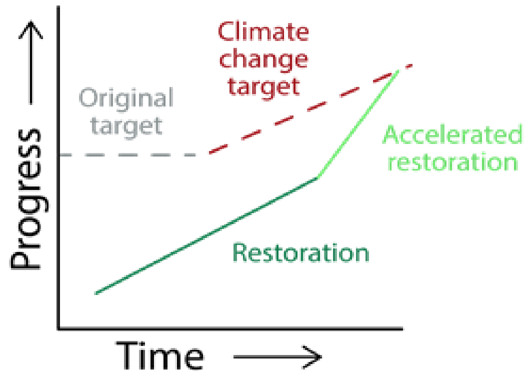

Figure 6: Conceptual representation of degradation and restoration trajectories that may be altered in response to climate change and other stressors, making the original TMDL target more difficult to achieve, requiring adaptive management or new perspectives on restoration goals.

Future vision of research and management interactions: The future vision for Chesapeake Bay could also apply to the way that the research and management community interact. Adaptive management may benefit from a faster turnaround due to the accelerating pace of change. Employing the CBP analytical team to work directly with researchers could help develop new research avenues, and shorten the time from research analyses to incorporation into management considerations. Using some of the Goal Implementation Team funding for directed research could be effective and may be expanded. Agency and academic research that will directly aid management can be encouraged. Forming collaborative networks of researchers and managers can be enhanced by activities like the biennial Chesapeake Research and Modeling Conferences.

Coupled research and management: Better coupling between researchers and resource managers may help develop 'steely-eyed' resource managers, who will stay the course of implementation of restoration activities in light of political impatience or apathy, and who are supported by practical and applied researchers who provide a strong scientific underpinning for restoration activities. Fortunately, the CBP and its wide variety of partners have set a national, if not international, example of these types of collaborative management for decades. Our vision also recognizes new advances in management, research, and modeling to support the new missions in shallow-water modeling, which require the incorporation of mechanistic models for wetlands, benthic algae, SAV, and living organisms. Specific ways in which new shallow-water modeling can be facilitated include:

(1) Leveraging the growing in-house technical capacity of the Chesapeake Bay Program Partnership;
(2) Expanding support for diverse stakeholder synthesis teams that address specific science needs of the CBP;
(2) Launching specific shallow water model development teams that include observational scientists;
(3) Further integrating social scientists into water quality modeling and assessment; and
(4) Better integrating watershed and estuarine coupling in assessments.

8) Identify *new tools, approaches, and personnel* that could feature in Chesapeake Bay restoration science and analysis.

A whole series of changes are happening in the Chesapeake scientific community. Changes in human resources, observational science, analytical capacities, synthesis capacities, and modeling capacities are occurring and are discussed below.

Human resources: Changes in human resources that is becoming evident is the need to diversify both the environmental and scientific communities working on Chesapeake Bay restoration, but also the communities that are engaged to inform management decisions. The existing water quality criteria and restoration goals could benefit from continual updating with voices and perspectives that represent the wide range of stakeholders in the watershed and beyond. This continual updating includes collaborating with communities who will be most directly impacted by restoration goals and actions and seeking to break barriers in their access to information and enhance active participation. This updating could be facilitated by targeted workshops and wider and easier access to data sets and modeling output through visualization. While providing a more inclusive and equitable climate for the broad community could be an emphasis for all organizations and institutions involved in the Chesapeake restoration effort, the focus on shallow waters could provide new opportunities to engage the communities that live and work in these environments.

Observation revolution: There is an 'observation revolution' occurring as our ability to measure the environment is dramatically expanding. Remote sensing with satellites, aircraft, and drones is constantly improving our ability to obtain large scale synoptic data (e.g., Ding and Elmore 2015, Landry et al. 2021). The expansion in the use of *in situ* sensors provides detailed temporal data and underwater remotely operated vehicles can obtain unique data sets (e.g. Beatty et al. 2021). The expansion of citizen science programs (e.g., Chesapeake Monitoring Cooperative) provides new data streams to Chesapeake scientists.

Analytical capacity increasing: The ability to process 'big data' by using statistical analyses for time course and spatial data sets is improving (e.g., Liang et al. 2022), along with rapidly advancing Geographic Information Systems (GIS) techniques (Landry et al. 2021, Sun and Scanlon 2019).

Synthesis capacity increasing: The ability of scientists to integrate expanded data sets can be accelerated through funded synthesis activities. The recent success of the synthesis of SAV data (SAV SYN; Orth et al. 2017; Orth et al. 2022) has spawned additional synthesis activities that are now underway and we are hopeful that a similar emphasis on collaborative integration of data interpretation and synthesis can continue to be emphasized by the CBP Partnership as it moves forward.

Modeling capacity increasing: Chesapeake Bay modeling has been recently expanded through the establishment of the Phase 7 modeling effort and the associated collaborations between researchers and Chesapeake Bay Program modelers, expanding the modeling capacities.

III. Concluding Statements

This report describes results of an effort aimed at providing constructive steps to the CBP and its partners to better understand and improve their already strong efforts towards Chesapeake Bay *protection* to more constructively focus on Chesapeake Bay *restoration*, within the context of remaining knowledge gaps and uncertainties. We provided a brief summary of the history of Chesapeake Bay restoration, management, and estuarine science, to provide context for our assessment of ways to fill in our scientific gaps and peer forward toward a revised set of goals and activities.

As we look forward, we envision that the pressure of climate change combined with an expectation of tipping points in the estuarine response to *both* TMDL-related restoration activities and climate change impacts will require an improved next-generation suite of monitoring, data analysis, and modeling tools to better quantify uncertainties in restoration outcomes. Developing these new tools is in addition to considerations of other anthropogenically controlled factors such as population and land use changes, which are already within the domain of factors that the CBP and its partners consider as they plan for the future.

Many of the gaps we have identified are focused on the intersection of the watershed and the estuary, what is sometimes called the “T-zone”, where wetlands, small streams, and extremely shallow waters exist. We argue that these nearshore, shallow water habitats are critical environments for which to study these interactions because they:

(a) are located where many people use and interact with tidal waters,

(b) are poorly understood relative to the overall Chesapeake Bay ecosystem,

(c) have natural features of nutrient retention and biogeochemical feedbacks that may cause positive tipping points in ecosystem recovery, and

(d) are habitats for critical living resources, such as SAV, marshes, and fisheries nursery areas.

Indeed, the lack of models and monitoring to understanding these particular shallow waters prevents us from assessing the water quality standards there and understanding how they relate to watershed features. Moreover, a new emphasis on shallow waters could allow for the CBP to better engage with local communities and expand assessments of the social, cultural, and economic impacts of restoration.

While the challenges remain substantial, we envision a forward-looking program that will seek an even more greatly accelerated progress toward Chesapeake Bay restoration and resilience through filling scientific gaps, motivating creative estuarine interventions, and applying new analytical skills and tools to ever-evolving efforts of monitoring, modeling, and management.

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