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Restoration of the Chesapeake Bay: lessons for other ecosystems

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With over 40 years of history, the multi-jurisdictional effort to restore the health of the Chesapeake Bay ecosystem has yielded some positive outcomes with water quality and natural resources showing measurable signs of improvement. The lessons learned from this multi-year, multi-jurisdictional restoration effort can provide understanding and guidance for ecosystem restoration efforts elsewhere. The 10 "lessons learned" from this effort, identified by a group of scientists and policy and program leaders whose experience in the Chesapeake Bay restoration spans its entire history, are that programs and practitioners should: 1) assure the presence and maintenance of strong and effective leadership; 2) be appropriately transparent everywhere and at all times, sharing both what is known and what is not known; 3) engage everyone, welcoming and encouraging participation from all; 4) secure long-term funding and support from multiple sources; 5) empower participation by seeking, soliciting, and using active participation from all voices; 6) use science to inform and confirm; 7) employ monitoring and modeling consistently and continuously in a manner that allows for ongoing improvement and evolution; 8) communicate conditions effectively and frequently, both good news and bad news; 9) be adaptable in incorporating new information and insights while maintaining clear, strong, and measurable goals and avoiding backsliding; and 10) ensure accountability, including mandatory action when voluntary action proves insufficient.

KEYWORDS

Chesapeake Bay, ecosystem restoration, adaptability, transparency, engagement, accountability, communication, governance

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1 Introduction

Extending over 11,600 km^2 along the Atlantic coast of the United States (US), Chesapeake Bay is one of the world's largest and best studied estuaries (Figure 1). It is a highly productive ecosystem in which fresh water that enters from its 165,800 km^2 drainage basin mixes with ocean waters over its more than 300 km length. Chesapeake Bay's watershed extends over six US states and the District of Columbia, the nation's capital, with a human population of over 19 million people. It includes forested landscapes, extensive agricultural lands, small towns, expanding suburbs, and four metropolitan areas each with more than 1 million residents.

After the middle of the 20th Century, it became apparent that the Chesapeake Bay was experiencing environmental challenges familiar to many coastal ecosystems in developed nations around the world. Changes in land use, intensification of agriculture, and increased urbanization had led to increased sedimentation and eutrophication (Boesch, 2002; Kemp et al., 2005). Additionally, toxic agricultural and industrial chemicals were causing both acute and chronic effects (Rattner et al., 2004; Velinsky et al., 2011). Together with overfishing of many of its natural resources (e.g., oysters *Crassostrea virginica*, blue crabs *Callinectes sapidus*, river herrings *Alosa* spp., and striped bass *Morone saxatilis*), the Chesapeake Bay had become a severely impaired estuary by the late 1970s (Horton, 2003; Houde, 2011; Kennedy, 2018).

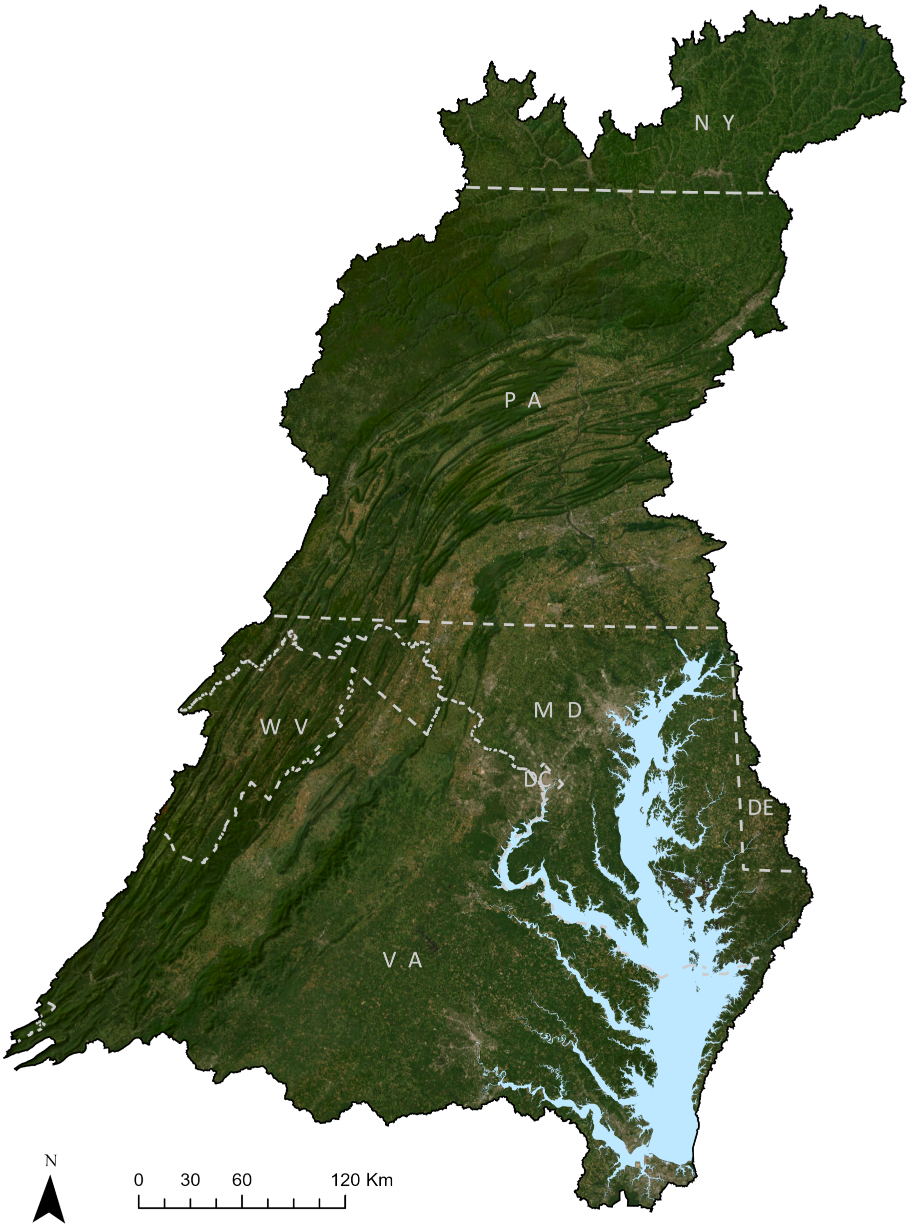

FIGURE 1
Map of Chesapeake Bay and its watershed including the states of Delaware (DE), Maryland (MD), New York (NY), Pennsylvania (PA), Virginia (VA), and West Virginia (WV) and the District of Columbia (DC). Source: Chesapeake Bay Program Office.

A multi-decade, multi-jurisdictional, large-scale restoration effort, known as the Chesapeake Bay Program, initiated in 1983, resulted from a recognition of these threats to the integrity of the estuarine ecosystem. Restoration, in this sense, does not entail recreating historical conditions. It was always recognized that conditions, such as human population growth and development, would continue to exert additional pressures. Rather, restoration involves reversing the degradation of the ecosystem to regain its functionality and improve its productivity and capacity to meet the needs of society. While multiple authors have documented much of the science grounding the restoration effort (e.g., Boynton and Kemp, 2000; Boesch et al., 2001; Kemp et al., 2005; Miller et al., 2011; Orth et al., 2017; Testa et al., 2018), only a few have evaluated its effectiveness, with most of those evaluations dating back nearly twenty years (e.g., Swanson, 2001; Ernst, 2003; Horton, 2003; Hanmer, 2005; Hoagland, 2005; National Research Council, 2011; Chesapeake Bay Program Scientific and Technical Advisory Committee, 2023).

Now, in 2025, the target date for achieving many of the commitments under the 2014 Chesapeake Bay Watershed Agreement (Chesapeake Executive Council, 2014), and after forty years of the beginning of the restoration effort it is timely to assess the lessons we have learned. The objective of this paper is to take stock of those lessons, identifying and describing the most important and transferable of them. A failure to assess and consider lessons like those described in this paper risks continued use of ineffective tools and methods (Nilsson et al., 2016).

The authors of this paper have collectively more than 400 years of experience related to the degradation and restoration of the Chesapeake Bay ecosystem that extends from the early 1970s. We have compiled a list of 10 lessons related to this ecosystem restoration campaign based on this deep experience. These lessons represent the conclusions of those responsible for developing and implementing policies (RB, RH, VH, WM, AS, AT), advocating for restoration (RH, AS, AT), conducting and synthesizing science (DB, WD, CH, TM, DW), and communicating to the public (KB, TH). The lessons were identified through a loosely structured expert elicitation in which initial responses were characterized, prioritized and refined among the authors.

These lessons learned reflect both achievements and shortcomings, as the Chesapeake Bay Program's efforts have fallen short of several key outcomes associated with its restoration goals. The federal and state leadership has charged their staffs to revise the 2014 Chesapeake Bay Watershed Agreement, to include measurable and time-bound outcomes, and to simplify and streamline the Program's structure by 2026 (Chesapeake Executive Council, 2024). We believe these lessons provide important guidance for that process, just as they should also prove instructive to the global campaign for restoring ecosystems during the present decade and into the future (United Nations, 2019).

2 History of Chesapeake Bay ecosystem restoration

Concerns about the health of the Chesapeake Bay came to a head in 1972 following the pervasive effects of Tropical Storm Agnes. The storm produced record stormwater runoff throughout the Chesapeake Bay watershed (Sellner, 2005) and the delayed and partial recovery of the estuarine ecosystem prompted intense press coverage as well as a federally mandated study conducted from 1977 to 1982 (Macalaster et al., 1982). The study drove the 1983 signing of the first Chesapeake Bay Agreement by the US Environmental Protection Agency on behalf of the federal government, the states of Pennsylvania, Maryland, and Virginia, the District of Columbia, and the Chesapeake Bay Commission, a tri-state organization representing the legislatures of Pennsylvania, Maryland and Virginia (Chesapeake Bay Agreement Signatories, 1983).

This 1983 Agreement was very general, establishing the Chesapeake Executive Council representing the signatories to "implement coordinated plans to improve and protect water quality and living resources of the Chesapeake Bay estuarine system" (Table 1). Subsequent, more comprehensive and specific Agreements followed in 1987, 2000, and 2014, augmented by executive directives and specific commitments interspersed between those landmark Agreements (Chesapeake Executive Council, 1987; 2000; 2014). These Agreements cover protection and restoration of living resources, vital habitats in the estuary and its rivers, and water quality impairments by nutrient and sediment pollution and chemical contaminants. They progressively broadened to cover land use, including conservation, development, transportation, and public access, as well as education and community engagement. Notably, goals and outcomes related to climate resiliency were included for the first time in the 2014 Chesapeake Watershed Agreement.

The Chesapeake Bay Program, codified under the authority of the federal US Clean Water Act in 2000, has served as the functional epicenter of the restoration effort undertaken pursuant to these Agreements. The Chesapeake Bay Program operates as a largely voluntary, predominantly collaborative partnership among the signatories to the Agreements. Those signatories now also include the three other watershed states of Delaware, New York, and West Virginia, with the US Environmental Protection Agency (EPA) serving a leadership role in the coordination of the Agreement signatories' restoration activities and representing other federal agencies. The inclusion of the Chesapeake Bay Program within federal law (33 US Code Section 1267) has contributed substantially to the long-term financial investment by the US federal government in the restoration effort, including critical staff support, technical analysis and data management. The Chesapeake Bay Program has a complex management structure, with staff and advisory committees and goal implementation teams and workgroups within those teams (Figure 2).

TABLE 1 The major agreements, statutes, and directives that have guided ecosystem under the Chesapeake Bay Program.

Year	Instrument	Scope
1983	Chesapeake Bay Agreement of 1983	Established Chesapeake Executive Council to assess and oversee implementation of coordinated plans to protect water quality and living resources of estuarine systems.
1987	1987 Chesapeake Bay Agreement	Set objectives and commitments to goals related to: living resources; water quality; population growth and development; public information, education and participation; and public access. *Develop, adopt and implement basin-wide strategy to equitably achieve by year 2000 at least a 40 percent reduction of nitrogen and phosphorus entering main stem of Bay.*
2000	Chesapeake 2000	Commitments to specific goals for: living resource protection and restoration, vital habitat protection and restoration, water quality protection and restoration, sound land use, and stewardship and community engagement. *By 2010, correct the nutrient- and sediment-related problems in the Bay and tidal tributaries sufficient to remove them from the list of impaired waters under the Clean Water Act.*
2000	Clean Water Act Amendments	Chesapeake Bay Program codified in Section 117 of the Federal Clean Water Act.
2010	Chesapeake Bay Total Maximum Daily Load (TMDL)	*Established by the U.S. Environmental Protection Agency as required under the Clean Water Act, setting limits for nitrogen, phosphorus and sediment pollution by jurisdiction and major river basin and requiring Watershed Implementation Plans.*
2014	Chesapeake Watershed Agreement	Sets goals and outcomes for: sustainable fisheries, vital habitats, water quality, toxic contaminants, healthy watersheds, stewardship, land conservation, public access, environmental literacy, and climate resiliency. *By 2025, have all practices and controls installed to achieve the water quality standards as articulated in the Chesapeake Bay TMDL.*
2026	Chesapeake Watershed Agreement Revision	Executive Council directed proposed revisions to the Agreement by December 2025 and to Chesapeake Bay Program structure and processes by mid-2026, as guided by findings of the report *A Critical Path Forward for the Chesapeake Bay Program Partnership Beyond 2025.*

The italicized text describes those commitments to achieve reductions in nitrogen and phosphorus pollution responsible for pervasive eutrophication.

The Chesapeake Bay Program's statutory authority resides within the US Clean Water Act, rather than in laws that govern natural resources, land uses, navigation, etc. Hence, from the start, the Chesapeake Bay Program has had its central focus on water quality and its impacts on estuarine living resources, particularly as a result of eutrophication due to excessive inputs of nitrogen and phosphorus nutrients (Kemp et al., 2005). However, the authorizing legislation and the series of agreements adopted by the Chesapeake Bay Program partners over the past four decades have also included goals and outcomes related to fisheries, habitats, education and land conservation deemed critical to the collaborative restoration efforts. Thus, in the paper we will focus primarily on lessons derived from activities conducted under the aegis of the Chesapeake Bay Program, while recognizing that there are other actions not under its purview that contribute to ecosystem restoration.

In 2009, after falling far short in achieving the specific pollution reduction goals contained in the 1987 and 2000 Agreements (Table 1) (Chesapeake Bay Program, 2009), the EPA conveyed to the state signatories its intention to drive restoration actions that would assure nutrient and sediment load reductions under the US Clean Water Act's Total Maximum Daily Load (TMDL) provisions (U.S. Environmental Protection Agency, 2009). The EPA's action was consistent with the 2000 Chesapeake Bay Agreement in which the signatories had acknowledged the need for a Chesapeake Bay TMDL should they fall short of the reduction goals by 2010. In response, the EPA and the watershed states together committed to the collaborative development, issuance and implementation of the Chesapeake Bay TMDL, unprecedented in the level of shared decision making and complexity compared with the over 50,000 TMDLs throughout the United States approved by the EPA at that time (U.S. Environmental Protection Agency, 2010).

Watershed implementation plans (WIPs) were developed that provide a roadmap on how each of the seven watershed jurisdictions would achieve their assigned pollutant load reductions for nitrogen, phosphorus, and sediments by source and location, based on an integrated suite of computational models (Linker et al., 2013). These WIPs are currently based on their third phase of refinement. In the 2014 Chesapeake Watershed Agreement the signatories committed to have all practices and controls installed by 2025 needed to achieve the Chesapeake Bay's dissolved oxygen, water clarity/submerged aquatic vegetation, and chlorophyll *a* water-quality standards as articulated in the Chesapeake Bay TMDL (Chesapeake Executive Council, 2014). With the publication of the Chesapeake Bay TMDL by the EPA on behalf of the seven watershed jurisdictions and the subsequent development of WIPs by the jurisdictions, decades of voluntary commitments to nutrient and sediment pollutant load reductions were converted into mandatory requirements under the US Clean Water Act. Further, possible federal interventions were documented by the EPA within the TMDL if the EPA deemed an individual jurisdiction's pollutant abatement actions and progress were inadequate towards meeting the interim 2017 targets and 2025 end goals which were established collectively by the signatory partners (U.S. Environmental Protection Agency, 2010).

Multiple indicators demonstrate that Chesapeake Bay restoration efforts have at least stemmed and, in some cases, reversed ecosystem declines. Nitrogen, phosphorus and sediment loads have decreased on a flow-adjusted basis (Ator et al., 2020); water quality has improved in much of the estuary, with lower nutrient concentrations and higher dissolved oxygen levels (Zhang et al., 2018); and the area of submerged aquatic vegetation has increased (Lefcheck et al., 2018). However, the accomplishments are mixed and generally slower than many anticipated. Advanced treatment of effluent from hundreds of wastewater treatment facilities along with air pollution controls have accomplished significant reductions in nutrient pollution, whereas agricultural

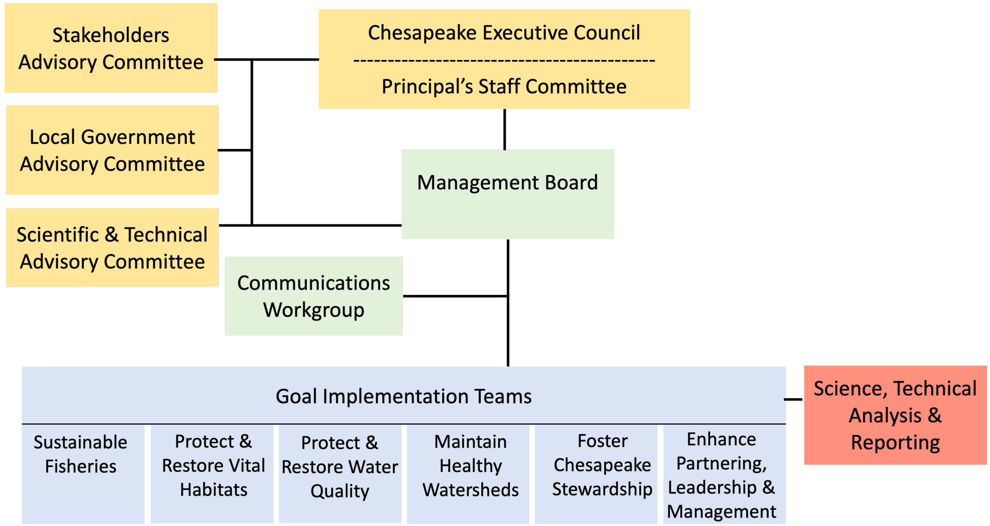

FIGURE 2
The organizational structure of the Chesapeake Bay Program (Chesapeake Bay Program, 2022). An agricultural advisory committee was added in 2024.

nutrient pollution loads have fallen far short of targets and urban stormwater pollutant loads are largely unchanged or increasing (Boesch, 2019; Zhang et al., 2023). Restoration of forested stream buffers and wetlands as specified in the 2014 Chesapeake Watershed Agreement was also well "off course," having reached only 10% and 5% implementation of the 2025 goal in 2022, respectively (Table 2). Recovery of ecologically important oyster populations has fallen far short of the 2000 Agreement's ten-fold increase goal despite substantial investments (Schulte, 2017); however, oyster populations and reefs have been substantially restored in 11 sanctuary restoration sites, as committed in the 2014 Watershed Agreement. Commercial harvests of oysters are substantially higher in the most recent decade than in the previous several decades. The text-book recovery of Chesapeake Bay striped bass populations seen in the 1990s now shows signs of reversal. Recent striped bass recruitments have been at levels similar to those that provoked concern in the mid-1980s. In addition, climate change impacts such as the warming of the waters of the Chesapeake and sea-level rise present new challenges to the ecosystem restoration effort (Najjar et al., 2010). For example, additional nutrient pollution load reductions, beyond those included in the original 2010 Chesapeake Bay TMDL, have been accepted based on models simulating the impacts of climate change on achieving estuarine dissolved oxygen goals (Linker et al., 2024). Nonetheless, severe oxygen depletion, or hypoxia, would now be much more expansive, extend farther down the bay and last longer had the observed nutrient load reductions not occurred (Frankel et al., 2021).

In 2022, the Chesapeake Executive Council acknowledged that the practices and controls called for by the WIPs would not be in place by the 2025 deadline (Chesapeake Bay Program, 2024). As of 2023, the Chesapeake Progress website claimed, based on modeling, to have practices in place that would achieve 57% of nitrogen load reductions and 67% of phosphorus load reductions compared to 2009 loads as called for under the Chesapeake Bay TMDL, although the rate of these load reductions has been slowed in recent years. These estimates have, however, been called into question, particularly with regards to load reductions experienced by the estuary (Ator et al., 2020; Zhang et al., 2023) and over-estimation of the effectiveness of management actions (Chesapeake Bay Program Scientific and Technical Advisory Committee, 2023).

Around the same time, the Chesapeake Bay Program Scientific and Technical Advisory Committee issued *Achieving Water Quality Goals in the Chesapeake Bay: A Comprehensive Evaluation of System Response*, commonly referred to as the CESR report (Chesapeake Bay Program Scientific and Technical Advisory Committee, 2023). It found that not only was there a management effort implementation gap, but also a response gap that suggests that nonpoint-source pollution controls have not been as effective as credited in the Chesapeake Bay Program's watershed model. It recommended implementing new, performance-based approaches that target financial incentives for effective controls on high nutrient loss areas and operations. The report also observed that the nutrient load reductions to date have not produced the expected improvements in water quality and suggested opportunities to prioritize management actions in locations that can significantly improve living resources, e.g., shallow water habitats.

In 2022, the Chesapeake Executive Council charged the Chesapeake Bay Program to recommend "a critical path forward that prioritizes and outlines the next steps for meeting the goals and outcomes of the Chesapeake Bay Watershed Agreement leading up to and beyond 2025." The resulting *Beyond 2025* report proposed no specific steps to meet the lagging outcomes but rather recommended a process for amending the goals and outcomes of the existing 2014 Watershed Agreement and for simplifying and streamlining the partnership's structure and processes (Chesapeake Bay Program, 2024). As mentioned in the Introduction, at the end of 2024 the Chesapeake Executive Council charged the Chesapeake Bay Program with accomplishing this by mid-2026. Thus, the

TABLE 2 Summary of the status of outcomes specified under the Chesapeake Watershed Agreement as of July 2024 as reported on the Chesapeake Progress website.

Outcome	Recent Progress	Outlook
Sustainable Fisheries		
Blue crab abundance	Decrease	On course
Blue crab management	No change	Completed
Fish habitat	Increase	On course
Forage fish	Increase	On course
Oysters	Increase	On course
Vital Habitats		
Black duck	Increase	Off course
Brook trout	No change	Off course
Fish passage	Decrease	On course
Forest buffers	Increase	Off course
Stream health	Increase	On course
Submerged aquatic vegetation	Increase	Off course
Tree canopy	Increase	Off course
Wetlands	Increase	Off course
Water Quality		
Watershed Implementation Plans	Increase	Off course
Water quality standards attainment & monitoring	Increase	On course
Toxic Contaminants		
Toxic contaminants research	Increase	On course
Toxic contaminants policy and prevention	No change	Off course
Healthy Watersheds		
Healthy watersheds	No change	Off course
Land Conservation		
Land use methods and metrics development	Increase	On course
Land use options evaluation	Increase	On course
Protected lands	Increase	On course
Public Access		
Public access site development	Increase	On course
Environmental Literacy		
Environmental literacy planning	Increase	Uncertain
Student	Decrease	Off course
Sustainable schools	Increase	On course
Stewardship		
Stewardship	No change	Uncertain
Stewardship		
Diversity	No change	Off course
Local leadership	Increase	On course
Climate Resiliency		
Climate adaptation	Increase	Off course
Climate monitoring and assessment	Increase	On course

Recent Progress toward achieving the specified outcomes is indicated over the most recent reporting period. Outlook represents the forecasted trajectory for whether the outcome is on course to be achieved. For each outcome a link to the supporting assessment is provided at https://www.chesapeakeprogress.com/outcome-status.

recognition, reflection, and addressal of the lessons learned from the previous decades of effort is foundational to moving forward. As many other restoration efforts find themselves at such a pivot point, we expect that these lessons have general applicability.

3 Lessons learned

We organize the ten lessons learned as elicited among the authors into three broad themes (Figure 3): governance, implementation and adjustment. While there are overlaps among the lessons and the themes, we find this categorization helpful in thinking about the entire lifecycle of restoration efforts from aspiration to achievement of program goals.

3.1 Governance lessons

3.1.1 Assure strong and effective leadership

Our experience convinces us that strong and effective leaders must be in place for adoption of and progress toward goals in a restoration program (Gallagher, 2012). Leadership that involves setting a vision and making key decisions toward achieving goals that ensure long-term success is an essential element for over the duration of large-scale restoration efforts, thus it must transcend individual leaders.

The Chesapeake Bay restoration effort, like many major ecosystem restoration programs, encompasses multiple political jurisdictions and levels of national, state, and local government (Gerlak and Heikkila, 2006). Such collaborative and inherently polycentric governance necessitates the continuous participation of effective leaders who can unite diverse players in establishing and meeting restoration goals (Rittlemeyer et al., 2024).

The level of effective leadership inevitably waxes or wanes at national and state levels, and not always in harmony. This results in periods when there is governmental support for advancing restoration commitments and actions, counterposed with times when governmental leaders' agendas run counter to restoration trajectories and progress becomes difficult, incremental, stalled, or,

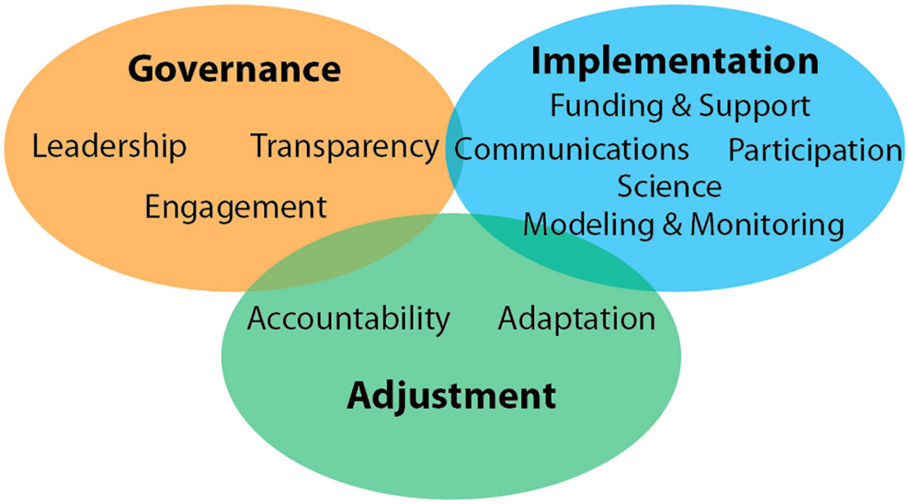

FIGURE 3
Ten lessons learned as elicited among the authors and grouped major themes.

at worst, set back (Ernst, 2003). To help mitigate these dynamics, effective leadership must be the norm (this lesson), transparent (Lesson 3.1.2), and encompass expansive engagement (Lesson 3.1.3) to ensure progress continues to be made in the varying political climates. Even though there will be times with different political philosophies, having a shared management structure in place and a well-informed public will help mitigate backsliding.

The progress made to date in Chesapeake Bay restoration would not have been possible without multi-faceted leadership, both in level and geography. A successful leadership elixir requires multi-level involvement both among and within organizations, political assemblies, science institutions, governments, businesses and the citizenry. Leadership is never only at the top, or just in the trenches. It is the depth and breadth of leadership that matters. And when one entity falls weak, there must be adequate opportunity for another to become strong. This allows for transitions — politically and with employees and even volunteers — while maintaining momentum. Much like a Rubik's cube, leadership shifts frequently as we proceed towards each finish line, sometimes taking years if not decades. Sometimes it even requires us to go in new directions to get to the same goal.

From the very beginning, leadership of the Chesapeake Bay restoration effort was high-level, inter-jurisdictional, and collective. The chair of the governing Chesapeake Executive Council, presently consisting of the six state governors, the Mayor of the District of Columbia, the Chair of the Chesapeake Bay Commission, and the Administrator of the EPA, representing the federal agencies, rotates regularly by election. The Chesapeake Executive Council represents the governmental leadership and political voice of the region. It wields power over the activities and expenditures of each regional jurisdiction and the EPA, thereby tying restoration activities to the executive and legislative priorities of the state and federal jurisdictions.

The Chesapeake Bay Program achieves broader leadership engagement with citizens, local governments, scientific, technical, and agricultural experts through four standing advisory committees: the Stakeholders (formerly Citizens) Advisory Committee, the Local Government Advisory Committee, the Science and Technical Advisory Committee, and the Agricultural Advisory Committee that was added in 2024 (Figure 2). These four committees, respectively, provide leadership to the effort from the broader communities of:

- Stakeholders, in particular the advocacy community in non-governmental organizations, often the most vocal voice for progress;
- Local governments, the place where the responsibility and burden of implementation often lies;
- Scientists and engineers, including those from universities and research centers, a community key to identifying and reviewing appropriate processes, data, and research needed to achieve goals; and
- Farmers and producers, including persons involved in delivery of public and private technical assistance and cost-shared funding as well as agricultural research and businesses related to the land-based production of food, fuel, and fiber.

In addition to the formal intergovernmental and advisory arrangements, Chesapeake Bay ecosystem and watershed restoration has been sustained by leadership through which has been termed advocacy coalitions (Koebele, 2019). These are groups of individuals, including, in this case, agency professionals, scientists, environmental advocates and stakeholders, who share beliefs and loosely work together to influence policy. As is the case with the authors of this paper, such actors can remain engaged over many political transitions and have provided direction and continuity to the Chesapeake Bay ecosystem restoration. Across the Chesapeake Bay watershed, the number of advocacy organizations now numbers in the hundreds, addressing a wide array of different conservation, restoration and protection issues and with their geographic focus ranging from small creeks and rivers to the entire Chesapeake Bay watershed.

The Chesapeake Bay Program structure, one of shared and devolved leadership, is in some ways typical of large restoration programs (Gerlak and Heikkila, 2006). To date, it has helped ensure continuity of action over the last 40 years and achieve substantial nutrient pollution reductions despite the continued growth of pollution sources such as people and intensive agriculture (Ator et al., 2020; Zhang et al., 2023). Through its management structure, the Chesapeake Bay Program maintained consistent and, over time, increasing levels of funding; at least partially adapted when missing program goals; and restructured to incorporate new approaches (e.g., accountability reporting and a Strategy Review System) and goals (e.g., education; diversity, equity, inclusion, and justice).

However, after 40 years with repeated shortfalls in achieving some its core goals and outcomes, both scientific (Chesapeake Bay Program Scientific and Technical Advisory Committee, 2023) and legal (Mueller, 2024) assessments have called into question the resolve, adaptability and accountability of the Chesapeake Bay Program. Has its political and professional leadership become less interested and ambitious and more tentative? Strong and effective leadership will be required as the existing 2014 Chesapeake Bay Watershed Agreement is amended and implemented.

3.1.2 Be transparent

Systemic transparency in making information and decision-making accessible to the public and stakeholders must accompany strong and effective leadership (Lesson 3.1.1) for success to occur. As noted in environmental restoration efforts addressing superfund sites (Drew et al., 2004), biodiversity (Bull et al., 2018), reforestation (Slingsby, 2020), urban planning (Marantz and Ulibarri, 2019), or global environmental governance (Gupta et al., 2020), early establishment and consistent maintenance of transparency is critical.

From the outset, the restoration effort must clearly articulate a commitment to a principle of transparency. It must reflect this commitment through openness at all times with all audiences at all levels regarding objectives, implementation steps, knowledge gaps, measures of success, and decision points. For example, whenever there is a change in restoration goals or timelines, the rationale must be fully transparent.

Being transparent about what is not known is just as important as clarity on what is known (Gregory et al., 2012). To maintain the credibility of the restoration effort there should be: ready establishment and communication of existing trends and future needs; assurance to the public and interested groups that comments and participation are welcome; updates on challenges and progress; and avoidance of "surprises" whenever possible.

As part of its commitment to transparency, the restoration effort must also embed open accessibility to comprehensible information, ranging from raw data to analyses of those data. This commitment must be a part of the organizational culture to ensure that transparency survives changes in leadership and technology. This commitment to transparency must include explanation of model-simulated progress versus monitored progress. Time and effort must be invested in communication through online and the media to ensure accurate descriptions of status and trends.

The Chesapeake Bay Program made a commitment to transparency in numerous ways from its beginning and it has evolved and deepened over time. For example, broad participation in its various workgroups and committees is sought from stakeholders such as the business sector, non-government organizations, state and federal agencies, academia, and, most recently, socially vulnerable communities, including those of color. Moreover, born in a time when communication to stakeholders occurred through traditional media, newsletters and public meetings, the coordinated Chesapeake Bay restoration effort came of age during the Internet era and, therefore, has been challenged at times in providing full public access to both meetings (via livestreaming) and diverse sources of information such as original and synthesized data. These challenges arise when securing concurrence of the multitude of partners on the level of public access to some or all of the underlying data and information and the nature of the accompanying public messages.

3.1.3 Engage everyone

"Engagement" implies a more active, two-way dialogue and collaborative effort among the public, organizations, institutions, governmental agencies and the ultimate decision-makers. Broad engagement at all stages of the ecosystem restoration process is critical to sustained advances. The Chesapeake Bay Program has long sought active engagement across governmental agencies, non-governmental organizations, the scientific community and interested individuals within its formal management structure (Figure 2) and beyond. Over time, it has adjusted this structure and collaborative decision-making procedures to broaden participation.

Engaging everyone helps the governance body overseeing restoration acquire information, support the work of the restoration effort, and convey outcomes to the public. This provides opportunities for collaborative learning (Vodden et al., 2005), allows the receipt and review of ideas and options, and gives participants the opportunity to either accept or reject information and conclusions (Gaddis et al., 2007). Engagement reflects the willingness to listen, potentially making those engaged more receptive to decisions. It helps assure the validity of consensus reached on key issues, whether they be actions, timeframes, levels of effort, progress, needs, or investments.

The Chesapeake Bay Program has evolved over the past four decades by putting into place institutional structures and procedures to ensure its partners were informed about decisions, procedures, and other changes (Chesapeake Bay Program, 2022). Participating agencies, organizations and institutions, along with stakeholders, are regularly consulted on decisions through its committees and workgroups (Figure 2). The governance of the Chesapeake Bay Program is committed to partnership-based collaborative decision making, which then empowers state and federal agencies and other organizations to implement agreed policies and programs towards shared goals and objectives. Participation by the public can span a somewhat similar spectrum representing: inform, consult, involve, collaborate, and empower (International Association for Public Participation, 2024). There is an increasing level of impact on decision-making at each level, with the appropriate level of public participation depending on the decision's goals, time frame, resources, and potential impact. For a population so numerous and an area so expansive as the Chesapeake Bay and its watershed, the public has been informed, with consultation through empowerment largely left to the state jurisdictions.

Nonetheless, non-governmental organizations representing public interests have informed, involved and empowered citizens in way that has influenced decisions and outcomes. For example, the Chesapeake Bay Foundation, a prominent regional non-governmental organization, serves as the "outside" guardian of public interest, using not only education and advocacy, but also litigation to apply this pressure (Mueller and Tannery, 2006; Ramey, 2025). The growth of the RiverKeeper movement has also been an important recent development in this area, providing very focused local attention to the condition of particular waterways feeding Chesapeake Bay. The Choose Clean Water Coalition is an umbrella group of over 300 organizations throughout the watershed. Such groups not only advocate for improvements, but also often collect data through citizen science programs that inform restoration policies and program implementation.

The Chesapeake Bay Program has, however, reached out to communities or sectors directly influenced by the agreed goals, outcomes and actions by the partnership. A notable example was the systematic outreach and engagement with hundreds municipal wastewater authorities and wastewater treatment plant operators across the watershed prior to adoption of the basinwide wastewater treatment permitting strategy in 2004 (U.S. Environmental Protection Agency, 2004). This resulted in the most significant nutrient reductions achieved to date, without impactful litigation. The recent creation of the Agricultural Advisory Committee recognizes the importance of engaging a particularly responsible and heavily affected sector to achieve better results.

We caution that this engagement must not devolve into what Karl et al. (2007) describe as "inform, invite and ignore." Engagement is an active, ongoing process that must occur continuously through the process if the restoration program is to gain from the jurisdictional and public insights and knowledge, reflect their values, and promote sustained commitment. For any ecosystem restoration to make progress toward its goals, it is critical that all potentially interested groups and individuals know that they are welcomed and encouraged to participate and they understand their inputs will be considered.

3.2 Implementation lessons

3.2.1 Secure long-term funding and support

Large-scale ecosystem restoration carries a high price tag and securing sustainable funding and consistent organizational support for key components of multi-year or multi-decade programs is always challenging (Borgström et al., 2016). The Chesapeake Bay Program provides several common needs among the Program's signatories that require continuous support, such as system-wide water quality and biological resources monitoring as well as modelling to test and evaluate multiple courses of action. Program leaders and engaged stakeholders must continually remind political leaders and funding sources of these needs and their essential role in meeting commitments and goals. Watershed and river "report cards," based on the results of these monitoring programs, are evolving and providing a place for citizen understanding and engagement, as well as an effective means for communication with political leaders about the importance of sustained funding and support (University of Maryland Center for Environmental Science, 2024).

Unexpected funding needs will arise, whether prompted by natural disasters or changes in strategies (Walters, 1997). Thus, there is a need for some degree of flexibility in reallocating funds or securing supplemental financing. Still, it should be recognized that there are always limitations in fungibility among resource sectors, agencies and jurisdictions. Application of funds to produce outcomes efficiently is also critical. For example, the CESR report concluded that the substantial financial incentives for voluntarily reducing agricultural nutrient pollution have been insufficient to support adoption of practices with the largest pollutant reduction benefits (Chesapeake Bay Program Scientific and Technical Advisory Committee, 2023). Without tying these incentives to performance, additional funding of existing implementation efforts is unlikely to produce the intended nutrient pollution reductions.

Identifying appropriation and subsequent distribution of funds across the restoration effort can be contentious. For many years, the Chesapeake Bay Program utilized a "budget steering committee" to identify sources and amounts as well as distribution paths for its federal funds. Such a committee can help to leverage funds from various sources, identify new funding sources and mechanisms, and draft and submit proposals for funding. With much of the federal funding less discretionary now than it was in the past, the committee is no longer a functional element of the restoration effort, but collaborative decision making on funding priorities and allocations still occurs through the Chesapeake Bay Program's implementation teams, committees and workgroups.

The states of Maryland and Virginia established long-term dedicated funding to support the pollution reduction work of the effort; however, the other primary watershed state, Pennsylvania, did not until 2024. This illustrates an innate challenge for watershed management wherein "its costs and benefits are distributed unevenly, but cooperation is required to make it work" (Kerr, 2007). Maryland and Virginia also established a stream of income for Chesapeake Bay restoration via a wastewater user fee, a voluntary automotive license plate fee, or voluntary tax contributions. Pennsylvania generates similar income via voluntary license plates, but it is not dedicated exclusively to restoration in the Chesapeake Bay watershed.

Local funding can also provide complementary support as can non-profit and other private sector funding. This is especially true where, as in the case of the Chesapeake Bay, there is a strong and broad interest in both the restoration and the resource itself. Finally, private foundations can also provide funds; some in the Chesapeake region target advocacy and ecosystem restoration through collaborative funding of priorities established in consultation with other stakeholders through organizations like the Chesapeake Bay Funders Network.

3.2.2 Empower participation

Participation involves not only the scale of public participation, as described above, but also by individuals across various levels of government, actors, and stakeholders. There must be a commitment not only to participate but also to provide others with the opportunity to participate. Decisions across multiple jurisdictions in large restoration efforts require all interested parties to weigh in continuously on discussions, decisions, and outreach. It is equally important for all participants to understand their respective roles and responsibilities within these shared decision-making processes (Chesapeake Bay Program, 2022).

Committed participation can be difficult for local government staffs and volunteers who face fiscal constraints for travel and conflicting schedules and priorities. But absent active participation, dissension may well arise on the adoption or implementation of a policy. Actors poorly engaged during earlier stages may delay or curtail progress. Again, the increased use of live-streaming of many meetings has lowered barriers of participation.

In the Chesapeake Bay Program, there are multiple organizational levels designed to empower effective, long-term participation. Of critical importance, permanent staff from the federal and state signatories, universities and non-governmental organizations populate active goal implementation teams (Figure 2) — through which they provide relevant data and information. Additionally, volunteer members of the standing advisory committees representing stakeholders, local governments and science and technology provide independent assessments and feedback on policies formulation and implementation. At the end of 2024, the Chesapeake Executive Council also added an Agricultural Advisory Committee. However, because of widespread disenchantment in the duplication and timely responsiveness of this governance structure (Chesapeake Bay Program, 2024), the Chesapeake Executive Council (2024) charged the Chesapeake Bay Program to develop and implement a simplified and streamlined structure and process that supports the partners in achieving their commitments in an effective, efficient and inclusive manner.

The recognition of inadequacies in diversity, equity, inclusion, and justice within ecosystem restoration and other environmental efforts has recently stimulated new efforts to empower more diverse participation. Much of the focus on environmental justice has been on health disparities (Wilson, 2010); however, human health concerns have often not been a primary focus of ecosystem restoration work. There is now an emerging nexus of interest, e.g., those recognizing that some of the most pressing pollution problems differentially affect communities of color and other disadvantaged groups. Actively engaging with these groups and empowering their voices remains a challenge.

3.2.3 Use science and inform and confirm

Science plays an essential role in ecosystem restoration. Using science and technology as the basis for key decisions not only enhances effectiveness but improves credibility and public confidence. It is critical to gather, update, and incorporate scientific data and understanding in setting clear goals and in quantifying achievements towards those goals. At the same time, it should be understood that the value of science lies not just as a transactional commodity for use in decision-making, but in its accrual of human understanding of the ecosystem in which we must exist, while also accepting that science is just a part of decision making (Culberson, 2024).

Our experience suggests that the role of science is not just critical for informing actions taken, but at all stages. Early on, it is important to establish processes and procedures for ensuring independent scientific peer review followed by formal partner acceptance of methods used to analyze and interpret data critical to assessing progress towards the goals of the restoration. Thereafter, scientifically-based and accepted approaches should be used to interrogate data and information to understand system responses (or lack thereof) to management actions and to adapt restoration approaches.

As important as science is to the ecosystem restoration and its direction and credibility, the reality is that science will be lacking or incomplete in many instances where decisions need to be made. Ecosystem restoration is not alone in this challenge for decision making. Societal decisions concerning actions taken in response to climate change are an obvious example (Lewandowsky et al., 2014). But this should not prevent the decisions from being made; rather, it requires characterization of the uncertainty and risk to inform those decisions (National Research Council, 2009). US federal law often relies on a "best available science" standard (e.g., Magnuson Stevens Fisheries Conservation and Management Act) and the benefits of such a standard are well-established (Miller et al., 2018). Establishing and enforcing principles of scientific integrity are equally important (Nek and Eisenstadt, 2016).

The Chesapeake Bay Program, in recognition of the essential role of science, has used the following four approaches simultaneously to incorporate science into decision making.

Integrating scientific expertise within the operational structure: Staff members with scientific training and experience are employed by federal and state agencies or by universities while embedded in the Chesapeake Bay Program. They provide much of the modelling, analyses of monitoring results, and assessments on an ongoing basis, while external researchers also are engaged in special studies. Suggestions from the scientific community often result in changes in analytical methods and models used.

Establishing an independent scientific advisory committee: The Chesapeake Bay Program's Scientific and Technical Advisory Committee (Figure 2) consists of approximately 40 regional scientists with a wide range of disciplinary expertise. It provides an independent and objective source of advice and review, operating in two modes: (1) a reactive capacity providing science-based opinions to the restoration effort sought by leadership or other advisory committees; and (2) a proactive capacity that encourages the exploration of new concepts, emerging challenges and independent assessment.

Building partnerships between operations and scientific institutions: In its long history of science-based decision-making, the Chesapeake Bay Program has confronted challenging decisions with substantial economic implications. For example, Virginia and Maryland have faced difficult and sometimes conflicting management decisions in setting thresholds for sustainable harvests of blue crabs. Initially, the scientifically-based numeric goals were refined with state legislators and state fishery managers input (Ernst, 2003) through efforts coordinated by the Chesapeake Bay Commission. Then, led by independent scientific experts, the continued collaborative efforts yielded specific crab population thresholds based on quantitative models built, calibrated, and verified by decades of scientific research, monitoring, analysis, and interpretation. Blue crab fishery management decisions continue to be based on governmental agency and scientific interpretations of data from fishery-independent population surveys (Miller et al., 2011). Changes in management of the blue crab harvests along with public reports on the health of the blue crab fishery continue to guide decision-making.

Involving political leaders: The above example of changes in the management of blue crab harvest were only successful due to the collaborative engagement of scientists directly with state political leaders who were members of the tri-state Chesapeake Bay Commission. It is critical that those political leaders who are involved must be well-briefed, well-staffed, well-connected, drawn from and representing different regions, and with a remarkable drive to get things done.

3.2.4 Employ modeling and monitoring continuously while adapting to outcomes, insights and management information needs

Previous authors have noted that a successful restoration effort incorporates early development of monitoring networks that establish current conditions and trends. Nilsson et al. (2016) identified three essential elements of restoration: planning, implementation, and monitoring. They argued that absent effective monitoring programs there is no basis for evaluating whether restoration efforts are achieving intended results. They posited that monitoring must be used in continuous assessment rather than as a simple pre- and post-restoration contrast. Indeed, analyses of monitoring data are critical throughout the restoration process, supporting the on-going assessment of both accomplishments and shortfalls, providing a feedback loop for strategic and policy decision-making.

Similarly, development, maintenance, and refinement of modeling are integral to the planning and assessment that Nilsson et al. (2016) identified as essential. Modeling allows for projections of possible outcomes under alternative management actions, including levels of effort. For analysts and decision-makers, monitoring and modeling together provide critical data, stated assumptions, and quantitative predictions of outcomes. For the general public — whose sources of information range from neighbors' observations to environmental groups' advocacy to newspaper articles and TV reports — clear, consistent information derived from both monitoring data and modeling projections can provide continued understanding and thus support.

Chesapeake Bay ecosystem restoration has, from its inception in 1983, placed an emphasis on estuarine monitoring that has evolved into a watershed-wide monitoring system of hundreds of stations in tidal and non-tidal waters. These are sampled by dozens of field crews and analytical laboratories across an array of agencies, institutions, and organizations. Well into the fourth decade of operation, these monitoring networks continue to generate water quality and biological data spanning numerous sub-basins across the Chesapeake watershed. For example, the inclusion of atmospheric inputs occurs through use of regional air deposition data. In 2012, the Chesapeake Bay Program also instituted the acquisition of land use/land cover data covering the entire 165,800 km^2 watershed at 1 meter resolution through the work of the Chesapeake Conservancy and its collaborators. The resulting data support better understanding of land-change trends over time, interpretation of aquatic monitoring data, and watershed model refinement, calibration and scenario simulation.

In parallel to coordinated operation of estuary-wide and watershed-wide monitoring networks, the Chesapeake Bay Program partners developed a collective approach to analysis and interpretation of the data generated. Using independent scientific reviews of the employed statistical analysis procedures to ensure fully consistent and state-of-the-art approaches to data interpretation has yielded consistent messaging of current status and long-term trends across the region. Increasingly, research scientists have also used these monitoring data to gain new understanding of the dynamics and responses of the ecosystem. Over the past two decades, this has resulted in a flood of peer-reviewed scientific publications employing the monitoring data.

There was also early recognition that restoration of such a large, multi-jurisdictional waterbody as Chesapeake Bay required the development and application of sophisticated modeling to capture the roles and influences of the many pollutant sources across the watershed and airshed. Connecting pollutant sources and inputs to impacts on water quality and biological communities also required dynamic models of the estuary. The result was the development of linked airshed, land use change, watershed, and estuarine biophysical models. The evolution of these models through repeated refinement and incorporation of emerging scientific knowledge and computational improvements have yielded a system of models now in its sixth generation (Linker et al., 2013). To promote improvements, there are periodic independent scientific and technical reviews of the models focused on matching the evolving management needs with the skill and accuracy of the models (Brady et al., 2018; Easton et al., 2017).

Because the estuarine model was used to determine the pollutant load reductions required to achieve estuarine water quality standards and the watershed model was used to negotiate the geographic allocation of required reductions, they are not without controversy (Chesapeake Bay Program Scientific and Technical Advisory Committee, 2023). The use of the watershed model in allocating load reductions to meet the Chesapeake Bay

TMDL had to contend with political influences that resulted in some unintended outcomes (Lim et al., 2023). These included difficulty in updating the model in substantive ways, "gaming" of the process among competing jurisdictions, and protracted debates over input parameters, such as the accuracy of fertilizer sales. Even with these limitations, Lim et al. noted that the watershed model went through a major structural change to Phase 6, successfully withstood political challenges, and is accepted as basis for decision making.

Because of the large number of local-level governmental entities that must implement practices that govern pollutant loads, the Chesapeake Bay Program developed a simpler tool derived from the watershed model, the Chesapeake Assessment Scenario Tool (CAST), for use in more localized pollution reduction strategies. Critics, however, have argued that the Chesapeake Bay Program has been over-reliant on modeled pollutant load reduction estimates. The modeling incorporates many assumptions about the effectiveness of on-the-ground pollution reduction practices as well as the time required for manifestation of their effects (National Research Council, 2011; Boesch, 2019; Chesapeake Bay Program Scientific and Technical Advisory Committee, 2023). Observations based on actual water quality monitoring evidence has discrepancies with modeled estimates (Ator et al., 2020). These discrepancies may be due to lag-times not included in the modeling, higher variability in real-world observations susceptible to meteorological extremes, or overestimates of the degree of implementation or effectiveness of the on-the-ground practices. In any case, such discrepancies can undermine public trust, necessitating effective education and communication. To address these concerns, the Chesapeake Bay Program has recently developed a TMDL Indicator that combines stream monitoring data and modeled projections to estimate annual pollution loading rate reductions in response to management actions in the context of the Chesapeake Bay TMDL (Zhang et al., 2024).

The Chesapeake Bay Program commitment to ongoing monitoring and modeling is not without its challenges, including its ongoing and often escalating costs. Difficult decisions often confront the restoration effort, requiring a balancing the scale and scope of such monitoring within budget constraints. Decisions are often contentious and are best made when informed by: 1) defensible multi-stakeholder evaluations of the impacts of proposed changes to the monitoring program; and 2) delineated impacts of the ending of the monitoring and its individual data collection efforts. Early in the 40-year history of collaborative approach to designing, implementing and funding the of partners' shared monitoring networks, the Chesapeake Bay Program committed to continued evaluation and evolution of those networks to meet the management decision making needs of the involved management agencies and organizations (Tango and Batiuk, 2016). A recent example has been the initiation a fine-scale monitoring program at multiple locations across the Chesapeake Bay watershed focused on agricultural lands and sources. This was in direct response to an interagency report (Chesapeake Bay Program, 2021) which stated "We lack a coordinated effort to further monitor, interpret, and produce findings about the relation between agricultural conservation practices and water quality response, and to other services such as soil health, stream condition, and habitat".

3.2.5 Communicate conditions effectively and frequently

Providing the public with accurate and comprehensible descriptions of outcomes is key to continued public support (National Academy of Sciences, Engineering, and Medicine, 2017). It is also important to report progress toward established goals credibly and on a regular basis in a clear, specific, measurable, and honest manner (DeAngelis et al., 2020). Clarity and honesty are particularly important when one of the jurisdictions has sprinted ahead or fallen behind. Communicating bad news or uncertainty when it occurs is essential to maintaining credibility. The tendency towards being positive in communications even when the measured progress is neutral or even trending downward needs to be actively confronted and avoided.

The Chesapeake Bay Program established a Communications Office to serve as a unified voice on the overall restoration effort in communicating policies, actions, information and results. As part of its responsibilities, it coordinates a workgroup of media professionals representing the signatory parties as well as non-governmental representatives. It works to establish collaboration and coordination in delivering easily understood information. For example, the Communications Office worked to develop a common set of environmental "indicators" to track progress, using clearly understood measurements such as area of restored wetlands, or length of streamside forest buffers, or mass of pollution discharged by wastewater treatment plants.

Chesapeake Bay ecosystem restoration has also benefitted from the *Bay Journal*, an independent news medium committed to reporting regularly on the Chesapeake Bay Program decisions, the status of various restoration activities, measures of progress, and related issues. This near-monthly publication and its frequently updated website informs a broad swath of the public, including educators, scientists, agency staff, elected officials, and the general public clearly, accurately and independently, providing a significant level of transparency (Lesson 3.1.2). While it receives some funding from the Chesapeake Bay Program, most of its support comes from foundations and more than six thousand individual donors.

Finally, it must be recognized how important it is to have people living near Chesapeake Bay as well as throughout the watershed feel some level of connection with their local waterways. Without pressure from people who want to fish, crab, swim, boat, hike past, and gaze on the creeks, rivers, and the Bay or just know that their local waters are safe to drink, there would not have been the subsequent support from local, state and federally elected and appointed leaders to agree on the policies and the funding needed for implementation of restoration actions.

3.3 Adjustment lessons

3.3.1 Be adaptable

Much of what has been set out above leads to the obvious conclusion that strong clear goals, when well-understood and supported by the public, contribute significantly to achieving restoration outcomes. But with restoration of entire ecosystems requiring sustained efforts over many years, even decades, adjustments to those goals and outcomes due to changing environmental conditions, the success or failure of actions taken, or newly available data and approaches are inevitable. Adjustments to ecosystem restoration strategies, financial limitations and decisions, and other driving forces are more likely than not over decades. Zedler (2017) argued that being adaptable is essential in the restoration of large aquatic ecosystems, in part because climate change is constantly redefining what is achievable, but, more fundamentally, adjustment is needed when measures taken do not yield desired outcomes. Restoration efforts for the California Bay Delta ecosystem now recognize this reality by mandating restoration planning embrace an adaptable framework (Nagarkar and Raulund-Rasmussen, 2016; Wiens et al., 2017).

The question becomes how to remain flexible to change while maintaining credibility and public support. The public can embrace and accept the inevitable changes that adaptability generates when the restoration program is credible and when the new information prompting the adaptation is also credible. Absent a strong rationale based on new, reliable information (e.g., data suggesting adjustments to geographic load allocations for cost-effective pollution reduction), changes in goals need to avoid backsliding whenever possible.

The Chesapeake Bay Program deliberately and consciously incorporated flexibility in its strategies, policies, and goals based on the best available science and information, the financial realities of the times, and numerous other factors. Changes such as strategic thinking about the efficacy and cost-benefit of certain pollution reduction practices or the addition of incentives for other such practices are but two examples. The Chesapeake Bay Program did not, however, deliberately and consciously embrace the actual concept of "adaptive management" as quickly as did other restoration efforts (Boesch, 2006). It was not until the adoption of the 2014 Watershed Agreement that "adaptive management" became a core principle of the restoration effort (Chesapeake Executive Council, 2014). This delay led to instances of a less than rigorous comparison of model projections with observed outcomes that is characteristic of formal adaptive management. In its CESR Report, the Chesapeake Bay Program Scientific and Technical Advisory Committee (2023) recommended an expanded adaptive management process that employs decision science supported by analytical tools to support decision-making under uncertainty. It noted that monitoring and research should be better targeted to support such adaptive management.

3.3.2 Ensure accountability

Clear and challenging goals require an accountability system. The key is to maintain the credibility of those goals whether progress occurs, as new facts arise, and as elected officials come or go. The main task is to hold all associated with the restoration effort publicly accountable, in the sense of being expected to justify its actions and decisions. No participant should see an advantage in attacking the goals or the methods to reach them. Additionally, all participants should engage in evaluating what is working and what is not, in identifying areas of strength and weakness as progress is made, and in proposing remedial action when appropriate. In this way, all who are involved are accountable for the end results.

While specific goals that are definitive and reflective of the best available science are essential, for there to be true accountability there must be broad agreement that those goals are defensible and achievable, even when they are conceived as challenging and ambitious "stretch" goals. When challenges to meeting those goals arise, however, the signatories as well as interested parties and organizations can pressure reluctant members, holding them accountable. This is essential to prevent a consensus driven process from devolving into agreement on the "lowest common denominator".

Among ecosystem restoration goals, there should be a small number of numeric goals that are simple and understandable, such as the aforementioned 1987 Chesapeake Bay Agreement's goal to reduce nutrient pollution loadings by 40% watershed-wide (Chesapeake Executive Council, 1987). Over time, the goals may evolve in number and complexity. In the Chesapeake Bay ecosystem restoration effort, the 40% watershed-wide goal evolved into to specific pollution reduction allocations for each signatory state as well as for each major river basin (U.S. Environmental Protection Agency, 2010).

A culture of accountability, in addition to a comprehensive framework of accountability, must be built into all elements of an ecosystem restoration program. As noted previously, the culture should solicit and incorporate participation and leadership by informed and active stakeholders of all types; this breeds an internal culture of accountability. For the Chesapeake Bay Program, this culture evolved from a number of actions such as reporting on results presented at the annual Chesapeake Executive Council meeting; the focus of the media on Chesapeake Bay and the various restoration actions; and the creation and engagement of the aforementioned standing advisory committees. The use of independent, subject-specific participatory teams and panels (e.g., independent expert panels to review the effectiveness of on-the-ground pollution reduction practices); creation of sub-watershed pollution reduction implementation plans; financial support from private funders for the development and use of independent reporting tools; and regulatory and ligatory actions have all combined to re-enforce the need for accountability in all aspects of how the Chesapeake Bay Program operates.

Ultimately, the restoration effort needs to ground accountability in measured achievements. For example, in the Chesapeake Bay Program, this meant using water quality modeling data to parameterize the estuarine biophysical model in order to improve its realism. Although the new TMDL Indicator (Zhang et al., 2024, 2025) is a significant step forward, reconciling modeled pollution reduction estimates that incorporate lag times with actual water quality observations remains to be fully resolved.

Finally, statutory and regulatory backstops, as well as verification requirements for on-the-ground implementation of pollutant load reducing practices and systems, can assist in ensuring accountability. For the Chesapeake Bay, requiring pollutant concentration or load limits in wastewater discharge permits under the authority of the federal Clean Water Act provided accountability through regulation. However, the EPA has been recently criticized by its own Inspector General (Office of Inspector General, 2023), as well as by a legal scholar (Mueller, 2024), for not holding jurisdictions accountable for achieving the non-point source pollutant reductions under the Chesapeake Bay TMDL. Verification began far too late and it remains a difficult and controversial element of the restoration effort. One of the more frequent arguments against verification is why spend time and funds going back to confirm what was done when there remain many pollution reductions still to accomplish? On the other hand, the unwillingness or inability to verify the on-the-ground implementation of practices and systems is a major failure in accountability.

4 Actionable Recommendations

The lessons learned from the Chesapeake Bay restoration effort over more than 40 years reflect the tremendous challenges and complexities of restoring ecosystems that span upland, riverine, and estuarine habitats and multiple jurisdictions. The lessons do not focus merely on science or process or policy or politics, but on all of these in combination. For the Chesapeake Bay restoration effort, they reflect examples of interdependent commitments and actions that have, in fact, not only helped halt the aggressive degradation of a treasured natural resource, but also placed it on a trajectory toward substantial rehabilitation, if not full "recovery." In addition, the commitments and actions have begun to integrate this rehabilitation with the impacts of and adaptation to climate change, although, clearly, challenges lie ahead. While the effort has yet to achieved all of the goals and outcomes to which it committed, it has yielded substantial progress due in no small part to the learning described in this paper, even the face of continued human population growth, land development, intensified agriculture, and climate change.

Notwithstanding these accomplishments, the Chesapeake Bay Program Scientific and Technical Advisory Committee (2023), the EPA's Office of Inspector General (2023) and others have drawn attention to the substantial and recalcitrant gaps in achieving outcomes, not only as related to nonpoint-source pollution, but also in restoring stream buffers, wetlands and other important habitats (Table 2). With the charge by the Chesapeake Executive Council to revise the goals and outcomes of the 2014 Watershed Agreement and to simplify and streamline the partnership's structure and processes, the ten lessons presented here should not be forgotten, but followed through on, in ways suggested below. While our perspectives deal specifically with the Chesapeake Bay Program, we believe they are broadly relevant to other regional ecosystem restoration efforts across the country and around the world.

1. *Strong and effective leadership*. From the vantage point of the authors' long experience in Chesapeake Bay and watershed restoration, strong leadership has time and time again been critical. At times, it has come from political leaders, federal and state agencies, scientists and scientific institutions, and non-governmental organizations. However, we currently observe a certain fatigue, acceptance of perennially missed outcomes, and distraction of attention by other issues, such as climate change, which of course must be integrated with ecosystem restoration. Meanwhile, with the changing climate now being realized, there is an urgent need for ambitious leadership to restore the Chesapeake Bay as a more resilient ecosystem.
2. *Transparency*. The Chesapeake Bay Program has continued to make its processes and products more and more publicly accessible. At the same time, this has made the Chesapeake Bay Program bewilderingly complex and overwhelming. Simplifying and streamlining the structure and processes present an opportunity to maintain transparency while improving clarity on the most important issues.
3. *Engagement*. The Chesapeake Executive Council directed that changes in the 2014 Watershed Agreement reflect "a renewed and greater emphasis on engaging all communities of the watershed as active stewards of a health and resilient Chesapeake Bay and its watershed." Community-based restoration is obviously appealing, however focusing predominantly on improvements in localized environments is not guaranteed to be effective in reversing the degradation of the estuary downstream. Effective integration of community-based efforts such as stream restoration with the Watershed Implementation Plans for pollution reduction is essential for producing both meaningful local benefits, such as living resources and green spaces, and ecosystem-wide results.
4. *Funding and support*. The Chesapeake Bay Program has been fortunate to have sustained funding and strong public and political support for the past four decades. This should never be taken for granted. Achieving outcomes is the best way to ensure support continues. However, there should be steadfast emphasis on greater efficiency in the use of financial and human resources in achieving verifiable outcomes. For example, the Chesapeake Bay Program Scientific and Technical Advisory Committee (2023) concluded that just more funding of existing implementation efforts is unlikely to produce the intended outcomes for nonpoint-source nutrient reduction. Such changes in these programs and policies need to be effected.
5. *Participation*. Building on the current level of representation within the Chesapeake Bay Program's

management structure, there is a need for more participation of and direct involvement in shared decision making by even more leaders from the business, agricultural, urban planning, energy, climate resiliency and socially vulnerable communities. These leaders must bring expertise and experience in dealing with the challenges now facing Chesapeake Bay and watershed restoration.

6. *Science to inform and confirm*. The science underpinning the goals and outcomes of the 2014 Chesapeake Watershed Agreement is rather mature and has not changed fundamentally during the past 20 years. Prudently, the Chesapeake Executive Council's charge recognizes the need to incorporate emerging scientific understanding and issues. Priority should be given to science (including social science and engineering) directed to informing and confirming solutions to achieve recalcitrant outcomes and to adaptation to and mitigation of climate change.
7. *Modeling and monitoring*. The Chesapeake Bay Program has had exceptionally sustained capacity for environmental modeling and monitoring. Moving forward, modeling should better incorporate uncertainties and monitoring should assimilate continuous observations and data generated through citizen monitoring. Recent advances in comparing model expectations with monitoring observations, such as the TMDL Indicator, are encouraging, with more work to do for incorporation into adaptive management. New analytical techniques employing Artificial Intelligence are already being used for understanding water quality and land use patterns and trends.
8. *Communications*. The emergence of social media along with the diminution of environmental coverage in regional news media presents both challenges as well as opportunities. Sources of information must be objective and trusted.
9. *Adaptability*. Although the 2014 Chesapeake Watershed Agreement included a commitment to adaptive management, the present management framework embodied in the Chesapeake Bay Program's Strategy Review System (https://www.chesapeakebay.net/what/what-guides-us/decisions/srs) is focused on formulaic reviews of each outcome and associated work plans on a biennial basis. Science needs are identified but not compelled and there is not regular reconciliation of expectations and observed results called for under true adaptive management. Thus, approaches to achieving the outcomes are seldom adjusted as a result. Restoration accomplishments will depend on a more comprehensive application of adaptative management that includes technical improvements, such as effective integration of monitoring and modelling, but also concerning management decision making (Chesapeake Bay Program Scientific and Technical Advisory Committee, 2023; Chesapeake Bay Program, 2024). Adaptation should be conditioned not just by evolving scientific understanding, as indicated in the Chesapeake Executive Committee charge, but by adjusting management approaches based on outcomes.
10. *Accountability*. The Chesapeake Executive Council's charge does not set new deadlines, but states that revised goals and outcomes should be measurable and time bound, with timeframes sufficient to accomplish the outcomes as quickly as possible. Accountability must go beyond publicizing outcomes by jurisdiction to include consequences for failing to deliver on commitments. Those agencies with statutory responsibilities for legal commitments to the public for restoring clean water must take definitive actions in enforcing accountability across all the parties responsible for implementation actions.

5 Discussion

The lessons discussed here are broadly applicable to almost any ecosystem restoration effort, regardless of scale and challenge. This conclusion arises, in part, because the Chesapeake Bay watershed includes within it an enormous variety of conditions, threats, and scales crossing multiple jurisdictional boundaries. The innumerable creeks, streams, and rivers that crisscross the watershed; the ubiquity of encounters with both tidal and non-tidal wetlands; and the expansive presence of tidal shorelines, all suggest that the same rules and lessons likely apply to coastal ecosystems almost anywhere. Having said this, we recognize that few large-scale ecosystem restoration campaigns around the world have the public awareness, political will, legal bases, technical and scientific research capacity, and financial resources as the Chesapeake Bay region.

Among those campaigns that are of comparable or larger scale and complexity are those dealing with the Baltic Sea in Northern Europe and the Laurentian Great Lakes in North America. Both have water quality improvements at their core, but extend to cover vast watersheds and address habitats, toxic substances, living resources, biodiversity and invasive species, and maritime activities. Their origins predate the Chesapeake Bay agreements and their scope extends over several political jurisdictions, in fact over multiple nations, making for inherently more complex management challenges. They too offer lessons that could be applied to regional coastal ecosystem restoration broadly, including the Chesapeake Bay Program.

The Baltic Sea has a surface area 32-times that of the Chesapeake Bay and its catchment area is 10-times greater, hosting a human population residing in 11 separate nations that is nearly five-times greater (Reusch et al., 2018). Under the Convention on the Protection of the Marine Environment of the Baltic Sea, the Helsinki Commission (HELCOM) implements plans and directives through its contracting parties, the nine littoral nations and the European Union. Paralleling the Chesapeake Executive Council, the Heads of Delegation are responsible for

HELCOM decisions and national implementation of binding commitments. Nearly coincident with the 1987 Chesapeake Bay Agreement commitment to a 40% reduction of nitrogen and phosphorus inputs, in 1988 HELCOM ministers stipulated that emissions of nitrogen and phosphorus should be reduced by 50%. After not reaching such reductions, HELCOM launched the Baltic Sea Action Plan (HELCOM, 2021) in 2007 that set new targets requiring a decrease in nitrogen and phosphorus loads by 16 and 70%, respectively, from 1997–2003 loads. Increasingly refined models have been used to allocate maximum allowable inputs among sub-basins and countries. In addition to actions addressing eutrophication, the Baltic Sea Action Plan encompasses biodiversity, hazardous substances and litter, sea-based activities, and horizontal topics including climate change, monitoring, maritime spatial planning, economic and social analysis, hot spots, knowledge exchange and awareness raising, and financing.

Substantial reductions in nutrient loads to the Baltic have been achieved from the 1980s for both nutrients, largely as a result of advanced wastewater treatment. As with Chesapeake Bay, reductions from agricultural nonpoint sources have lagged in some countries more than others (Thorsøe et al., 2022). Notably, Denmark has achieved reductions in nitrate loads of 30 to 52% in agricultural catchments, as verified by monitoring, as a result of regulatory requirements and outcome-based subsidies (Peterson et al., 2021). Nonetheless, nutrient and chlorophyll concentrations in the open Baltic Sea show little signs of recovery, because of the persistence and recycling of phosphorus, which is the limiting nutrient due to the prevalence of nitrogen fixation. Still, had not loads been significantly reduced since the 1980s, oxygen-free bottom areas would now be 82% larger (Ehrnsten et al., 2024). Even if loads are not further reduced, oxygen-free bottoms will likely largely disappear in the coming decades. This delay in response is because of the long residence time of water in the Baltic Sea of about 30 years. The phosphorous retained is recycled until it is either buried or leaked to the ocean. The residence time of water in the Chesapeake Bay is only about six months and excess organic production limited more by nitrogen, which is lost to the atmosphere through denitrification. Thus, recovery of water quality should occur within just a few years once Chesapeake Bay TMDL loading levels are reached.

A lesson learned from the Baltic Sea for the Chesapeake Bay region is to pay attention to biogeochemistry, monitor closely and be patient. HELCOM's holistic assessments (HELCOM, 2023), its appraisals in collaboration with the scientific community of climate change impacts (HELCOM and Baltic Earth, 2024), and a policy-driven and solution-orientated research and development program (Snoeijs-Leijonmalm et al., 2017) also serve as exemplars for the Chesapeake Bay and other regional coastal restoration programs.

The International Joint Commission was created to deal with transboundary and water-use issues between the U.S. and Canada in 1909. Its responsibilities were expanded in 1972 with the Great Lakes Water Quality Agreement, which was amended in 1987 and 2012 (Canada and the United States of America, 2012). The purpose is to restore and maintain the chemical, physical and biological integrity of the waters of the Great Lakes through basin-wide management actions using an ecosystem approach that integrates the interacting components of air, land, water and living organisms, including humans. Currently, efforts are being coordinated and enhanced across national and state or provincial governments through the United States' Great Lake Restoration Initiative and the Canada's Great Lakes Ecosystem Initiative. The United States and Canada now have over 40 years of collaborative history in the use of an ecosystem approach to protect and restore the Great Lakes. There too, the approach remains a work in progress, with needs and challenges remarkably similar to our lessons learned from Chesapeake Bay (Ludsin et al., 2024). These include: setting clear and accountable goals; securing input and support from all stakeholders; accommodation of existing governance structure; securing sustained programmatic support that can adapt to changing conditions and priorities; developing integrative science that involves monitoring, research, modeling and evaluation; and developing clear, transparent lines of communication.

Initially inspired by the Chesapeake Bay Program, the National Estuary Program (NEP) is a non-regulatory program administered by the U.S. Environmental Protection Agency that seeks to improve the waters, habitats and living resources of 28 estuaries across the United States. Most of these programs include waters and watersheds lying in just one state, but a few, such as the Partnership for the Delaware Estuary and Long Island Sound Study cover two states. The NEP provides assistance to the states, local governments and other partners to develop and implement a Comprehensive Conservation and Management Plan (CCMP) based on local priorities to guide their efforts. Some NEP programs, such as the Tampa Bay Estuary Program and San Francisco Bay Estuary Partnership, have become substantial and influential institutions, but others lack the managerial and technical capacity and authority, but also face the complexity, of the large, multi-jurisdictional campaigns discussed above. One of the challenges facing the NEPs has been insufficient financial support and authority to actually implement the CCMPs. Over the past 40 years the NEP programs have been experiments in collaborative governance in which watershed partnerships have ebbed and flowed, changed, and at times disappeared (Imperial, 2023).

Just as the ten lessons we draw from the Chesapeake Bay restoration experience are useful in advancing coastal watershed-scale restoration around the world, there are valuable lessons to be drawn from the successes and shortcomings of the NEPs as well as from large, international endeavors such as in the Baltic Sea and Great Lakes. As the partners in the Chesapeake Bay Program work to revise the goals and outcomes of its 2014 Watershed Agreement and to simplify and streamline the partnership's structure and processes there is much to consider in creating pathways by which these goals and outcomes can be fully achieved in the coming decades. The future Chesapeake Bay Program and where it is headed moving forward from there will depend on the revised Chesapeake Watershed Agreement as well as guide ecosystem restoration under changing environmental conditions and fully account for these lessons learned over the prior four decades of collaborative work by the partners.

Author contributions

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Conflict of interest

Authors RH was employed by HOPE Impacts, LLC.

The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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